Design of a Hybrid Magnetic and Piezoelectric Polymer Microactuator

by

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Declaration

This thesis contains no material which has been accepted for the award of any other degree or diploma, except where due reference is made in the text of the thesis. To the best of my knowledge, this thesis contains no material previously published or written by another person, except where due reference is made in the text of the thesis.

Yao Fu

December 22, 2005
Abstract

Microsensors and microactuators are considered to be the most crucial elements of micro-electromechanical systems (MEMS) and devices. There has been growing interest in the development of new microactuator technologies with an increasing requirement for low cost microswitch arrays providing large air gap and large force at the same time. In particular, large air gap/large force microactuators are essential for high voltage switching in automobile electronics, test equipment switchboards and in network remote reconfiguration. The necessity to reduce the size of actuators and at the same time increase the force and the air gap has placed severe constraints on the suitability of current microactuator technology for various applications. This has led to the development of new actuator technologies based on novel materials or modifying existing systems. As an effort in this direction, this thesis presents the details of the work on the design, fabrication and testing of a new hybrid microactuator, combining electromagnetic and piezoelectric actuation mechanisms.

The design and fabrication of electromagnetic actuators using planar coils and a soft magnetic core has long been established. However, in many instances these designs are constrained by difficulties in the fabrication of the multi layer planar coils, which is tedious, often resulting in a low yield. Hence device performance is limited by the maximum coil currents and thereby the maximum force able to be generated. In order to overcome these problems, a hybrid actuator combining the electromagnetic system along side of a piezoelectric actuation is proposed. This has been demonstrated to assist in enhancing the total force and consequently achieving larger actuator displacements. In this research a hybrid microactuator with a footprint of 10 mm² was designed, fabricated and tested. It can generate 330 μN force and cover 100 μm air gap as a microswitch.
Piezoelectric actuation has been used for many applications, due to its high precision and speed. In these applications, piezo-ceramic materials, such as PZT and ZnO were commonly used because they exhibit large piezoelectric coefficients. However, there are also some difficulties associated with their use. Piezoelectric ceramic materials are usually brittle, and have a relatively large Young’s modulus, thus limiting the achievable strain. Furthermore, the deposition technologies required for preparing thin/thick films of these ceramic materials need extensive optimization. Patterning these films into required structures is also difficult. Hence, piezoelectric polymer polyvinylidene fluoride (PVDF) is chosen in this work in spite of the fact that these materials have relatively lower piezoelectric coefficients. However, the low numerical Young’s modulus values of these polymers facilitates large strain in the piezoelectric actuators.

The hybrid microactuator designed in this work comprises a piezoelectric composite polymer cantilever with a planar electromagnetic coil structure beneath. The composite cantilever consists of polarized piezoelectric polymer PVDF with an electroplated permalloy layer on one side. The device includes a permalloy core at the centre of a copper micro coil with a permanent magnetic film attached on the other side of the silicon wafer (substrate) and is aligned axially with the permalloy core. The cantilever is suspended from an electroplated 150 μm high nickel post.

Initially the principle was tested using hand wound electromagnetic coils with permalloy wire as the core. The performance of such a hybrid actuator was evaluated. In the next stage, a microactuator was fabricated using completely planar micro technologies, such as high aspect ratio SU-8 lithography, laser micromachining, microembossing, as well as copper and permalloy electroplating.

This micro device was designed by modelling and finite element method simulation using ANSYS 7.1 and CoventorWare electromagnetic and piezoelectric solvers respectively. This helped in understanding the critical aspects of the design at the same time leading to the determination of the optimum parameters for the cantilever, micro coils and the core. An analytical model has also been developed to validate the numerical results obtained from finite element analysis.

The devices were tested and the experimental data obtained were compared with the simulation results obtained from both the finite element calculations and from the
analytical model. Good agreement was found between the experimental results and the simulation.
Acknowledgments

Above all, I would like to express my special thanks to my supervisors, Professor Erol C. Harvey, Dr. Muralidhar K. Ghantasala and Associate Professor Geoffrey M. Spinks for their advice, encouragement, guidance and support to carry out and complete this research. I would also like to acknowledge the funding of this work by the chancellor of Swinburne University of Technology and by the Cooperate Research Centre (CRC) for MicroTechnology in Australia.

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# Nomenclature

## List of Variables

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<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
<th>SI unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>Cross section area of beam</td>
<td>$m^2$</td>
</tr>
<tr>
<td>${c}$</td>
<td>System stress-strain matrix</td>
<td>$N/m^2$</td>
</tr>
<tr>
<td>${D}$</td>
<td>Electric flux density matrix</td>
<td></td>
</tr>
<tr>
<td>${d}$</td>
<td>Piezoelectric strain coefficient matrix</td>
<td>$m/m$</td>
</tr>
<tr>
<td>$d_{31}$</td>
<td>Piezoelectric strain coefficient for length (n=1 direction)</td>
<td>$m/V$</td>
</tr>
<tr>
<td>$d_{32}$</td>
<td>Piezoelectric coefficient for width (n=2 direction)</td>
<td></td>
</tr>
<tr>
<td>$d_{33}$</td>
<td>Piezoelectric coefficient for thickness (n=3 direction)</td>
<td></td>
</tr>
<tr>
<td>$g_{31}$</td>
<td>Piezoelectric stress coefficient for length</td>
<td>$V/m$</td>
</tr>
<tr>
<td>$g_{33}$</td>
<td>Piezoelectric coefficient for thickness</td>
<td>$N/m^2$</td>
</tr>
<tr>
<td>${E}$</td>
<td>Electrical field matrix</td>
<td>$V/m$</td>
</tr>
<tr>
<td>$E, Y$</td>
<td>Young's modulus</td>
<td>$N/m^2, Pa$</td>
</tr>
<tr>
<td>$E_m, E_2$</td>
<td>Young's modulus of the elastic layer</td>
<td>$N/m^2, Pa$</td>
</tr>
<tr>
<td>$E_p, E_1$</td>
<td>Young's modulus of the piezo-layer</td>
<td>$N/m^2, Pa$</td>
</tr>
<tr>
<td>$F$</td>
<td>Force</td>
<td>$N$</td>
</tr>
<tr>
<td>$h$</td>
<td>Thickness of the composite beam</td>
<td>$m$</td>
</tr>
<tr>
<td>$h_p, t$</td>
<td>Thickness of the piezo layer</td>
<td>$m$</td>
</tr>
<tr>
<td>$H_c$</td>
<td>Magnitude of the coercive force</td>
<td>$kOe$</td>
</tr>
<tr>
<td>$h_m$</td>
<td>Thickness of the elastic layer</td>
<td>$m$</td>
</tr>
<tr>
<td>$H_z$</td>
<td>Vertical component of the magnetic field</td>
<td>$Tesla$</td>
</tr>
<tr>
<td>$I$</td>
<td>Current</td>
<td>$Amp$</td>
</tr>
<tr>
<td>$I_m, I_2$</td>
<td>Moment of inertia about the neutral axis of area 1</td>
<td>$m^4$</td>
</tr>
<tr>
<td>$I_p, I_1$</td>
<td>Moment of inertia about the neutral axis of area 2</td>
<td>$m^4$</td>
</tr>
<tr>
<td>$K$</td>
<td>Inverse bending radius</td>
<td></td>
</tr>
<tr>
<td>$\Delta l$</td>
<td>Change in film length in meters</td>
<td>$m$</td>
</tr>
<tr>
<td>$L, l, x$</td>
<td>Length of the cantilever</td>
<td>$m$</td>
</tr>
<tr>
<td>Symbol</td>
<td>Description</td>
<td>Unit</td>
</tr>
<tr>
<td>--------</td>
<td>------------------------------------------------------------------------------</td>
<td>-------</td>
</tr>
<tr>
<td>MGXX</td>
<td>Coercive force vectors along X axes</td>
<td>kOe</td>
</tr>
<tr>
<td>MGYY</td>
<td>Coercive force vectors along Y axes</td>
<td>kOe</td>
</tr>
<tr>
<td>MGZZ</td>
<td>Coercive force vectors along Z axes</td>
<td>kOe</td>
</tr>
<tr>
<td>$M_z$</td>
<td>Magnetization of the permanent magnet</td>
<td>Tesla</td>
</tr>
<tr>
<td>$n$</td>
<td>Number of coil turns</td>
<td></td>
</tr>
<tr>
<td>${p}$</td>
<td>Permittivity matrix</td>
<td></td>
</tr>
<tr>
<td>$Q$</td>
<td>Radius of curvature of the strip</td>
<td>m</td>
</tr>
<tr>
<td>${S}$</td>
<td>Strain matrix</td>
<td></td>
</tr>
<tr>
<td>${T}$</td>
<td>Stress matrix</td>
<td>N/m², Pa</td>
</tr>
<tr>
<td>$V$</td>
<td>Volume of the permanent magnet</td>
<td>m³</td>
</tr>
<tr>
<td>$w$</td>
<td>Width of the beam</td>
<td>m</td>
</tr>
<tr>
<td>$\alpha_1$, $\alpha_2$</td>
<td>Angles subtended at the point by a radius</td>
<td></td>
</tr>
<tr>
<td>$\varepsilon$</td>
<td>Dielectric matrix</td>
<td>F/m</td>
</tr>
<tr>
<td>$\delta$</td>
<td>Tip deflection of the cantilever</td>
<td>m</td>
</tr>
<tr>
<td>$\mu_0$</td>
<td>Magnetic permeability of free space $4\pi \times 10^{-7}$</td>
<td></td>
</tr>
<tr>
<td>$\sigma_{s1}$</td>
<td>Stress in the PVDF (material 1) layer</td>
<td>N/m², Pa</td>
</tr>
<tr>
<td>$\sigma_{s2}$</td>
<td>Stress within the permalloy layer</td>
<td>N/m², Pa</td>
</tr>
</tbody>
</table>
# List of Abbreviations

The list of abbreviations used in this thesis is shown below:

<table>
<thead>
<tr>
<th>Abbreviation</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>AFM</td>
<td>Atomic force microscope</td>
</tr>
<tr>
<td>DRIE</td>
<td>Deep reactive ion etching</td>
</tr>
<tr>
<td>EDM</td>
<td>Electric discharge machining</td>
</tr>
<tr>
<td>F(+)</td>
<td>Induced magnetic force under a positive current</td>
</tr>
<tr>
<td>F(-)</td>
<td>Induced magnetic force under a negative current</td>
</tr>
<tr>
<td>HARM</td>
<td>High-aspect-ratio micromachining</td>
</tr>
<tr>
<td>LIGA</td>
<td>Lithography, electroforming and moulding</td>
</tr>
<tr>
<td>MEMS</td>
<td>Micro-optoelectromechanical systems</td>
</tr>
<tr>
<td>MVDI</td>
<td>Magnetic virtual displacements</td>
</tr>
<tr>
<td>MXWF</td>
<td>Maxwell surfaces force</td>
</tr>
<tr>
<td>MST</td>
<td>Microsystems technology</td>
</tr>
<tr>
<td>MMF</td>
<td>Magneto-motive force</td>
</tr>
<tr>
<td>PC</td>
<td>Polycarbonate</td>
</tr>
<tr>
<td>PCB</td>
<td>Printed circuit board</td>
</tr>
<tr>
<td>PET</td>
<td>Polyethylene terephthalate</td>
</tr>
<tr>
<td>PMMA</td>
<td>Polymethyl methacrylate</td>
</tr>
<tr>
<td>PS</td>
<td>Polystyrene</td>
</tr>
<tr>
<td>PVDF</td>
<td>Polyvinylidene fluoride</td>
</tr>
<tr>
<td>PZT</td>
<td>Lead zirconium titanate</td>
</tr>
<tr>
<td>RF</td>
<td>Radio frequency</td>
</tr>
<tr>
<td>RIE</td>
<td>Reactive ion etching</td>
</tr>
<tr>
<td>RMF</td>
<td>Required magnetic force without piezoelectric actuation</td>
</tr>
<tr>
<td>RMFP</td>
<td>Required magnetic force with piezoelectric actuation</td>
</tr>
<tr>
<td>SEM</td>
<td>Scanning electron microscope</td>
</tr>
</tbody>
</table>
Chapter 1  Introduction

1.1  Research Motivation

Sensors and actuators are the key components of any control system, which responds to variations of a given process or environmental parameter by a defined set of actions. While sensors serve to gather information from the environment the actuators are required to perform useful actions. The concept of miniaturization of systems has led the research into a whole new world of micro- and nanotechnology, which has brought another revolution akin to microelectronics in the 1960s. The development of microsensors has already reached a high level of maturity. This is only true to a lesser extent for microactuators. The down scaling of actuators is more difficult due to the limitation of forces and displacements that can be generated in a micro device. Surface related effects such as friction and adhesion are becoming more dominant due to an increased surface-to-volume-ratio. Thus, the research on the challenges related to the design of high performance microactuators has moved to the centre stage of scientific interest. Research and development efforts are globally directed towards exploiting different actuation principles as effectively as possible at the same time exploring the development of new and novel concepts for specific applications.

Microactuators can broadly be defined as devices or mechanisms typically in the (tens of) micron size range which exhibit controlled movement of physical parts and may or may not be intrinsic to the device. Microactuators are the key components in many applications and these application areas are growing steadily. Inkjet print-heads (e.g. Hewlett-Packard or Epson), read/write heads for hard disk drives and digitally addressable micro mirror arrays for display technology (Texas Instruments Inc.) are some of the most important examples related to information technology and consumer electronics applications. In fact, they are among the most successful devices in all microsystem technology. In the field of robotics and medical instrumentation, microsurgical
tools, micromanipulators, grippers and microbearings are rapidly gaining importance. More recently, microswitches (Chong et al., 2002; Ruan et al., 2001; Suzuki, 2001) and electromechanical filters are being developed for high frequency applications, now summarized under the name radio frequency micro electromechanical systems (RF-MEMS). Further examples are piezo-driven fuel injection nozzles/valves and airbag deployment units in automotive engineering (Analog Devices Inc.; Lucas Novasensor), fluidic valves and mixers in microchemical reaction technology, or analytical chips in biotechnology. The market potential for microactuators is very high due to their wide applicability leading to their increasing penetration of nearly all areas of life.

Although the development of actuators for applications involving microsystems exploits the same principles routinely used in the macro world, it is important to be aware of the scaling laws. If a linear dimension of a given system is taken as L, the reduction in one dimension can alter different quantities in different ways. For example, surface to volume ratio increases with decreasing dimensions, which has important implications in micro systems. While the mass and weight scale as $L^3$, surface scales as $L^2$ and surface tension scales as $L$. Considering the applied or generated forces in such actuators/systems, the electrostatic force between two parallel plate scales as $L^2$, assuming the electric field strength is constant. Similarly, the magnetic force acting between two current carrying conductors scales as $L^3$. The implications of these scaling laws have to be taken into consideration in the design and development of microactuators for wide ranging applications.

Microactuation mechanisms based on different principles and materials have to be chosen carefully for a given application. Piezoelectric microactuators generate large forces over small displacements when a voltage is applied across the piezoelectric material. They are presently being used in many well known applications, such as inkjet printheads, microvalves, micromotors, and microgrippers. The main advantage of this actuation principle is its high precision, high speed and mechanical power. The most widely used piezoelectric ceramic materials are PZT (lead zirconium titanate) (Zurn and Hsieh, 2001) or zinc oxide (Jenkins and Cunningham, 1997) due to their large piezoelectric coefficients. However, there are also some difficulties associated with their use. Piezoelectric ceramic materials are usually brittle, and have a relatively large Young’s modulus, thus limiting the achievable strain. Further, the deposition technologies re-
quired for preparing thin/thick films of these ceramic materials need extensive optimization. Patterning these films into the required structures can also be a challenge. Piezoelectric polymers, such as polyvinylidene fluoride (PVDF), can overcome some of these difficulties even though they have relatively low piezoelectric coefficients. The low Young's modulus of PVDF has the potential of enabling relatively large strain piezoelectric actuators. On the other hand, questions of chemical stability or process compatibility may limit the applicability of this polymer, making it necessary to carefully design the micromachining process and the microstructuring of the actuators.

In a similar way, magnetic and electrostatic actuators also provide relative advantages depending on the application. For example, bearings are conventionally designed using electromagnetics whereas micromotors are more popularly fabricated using electrostatic principles. However, the magnetic microactuators can achieve larger forces over larger air gaps than their electrostatic counter parts. Magnetic actuation is a more robust actuation mechanism than electrostatics, because it can operate in conductive fluids and the lower electric field gradients present in magnetic microactuators will not attract appreciable quantities of dust particles. These advantages make magnetic microactuators an attractive alternative for micro-electromechanical system (MEMS) devices, such as microswitches. The design and fabrication of electromagnetic actuators using planar coils and a soft magnetic core has long been established. However, in many instances these designs are constrained by difficulties in the fabrication of the multi layer planar coils, which is tedious, often resulting in a low yield. Furthermore, device performance is limited by the maximum coil currents and thereby the maximum force able to be generated. One of the solutions to overcome such difficulties with individual actuator mechanisms is to develop a synergistic approach, by combining more than one actuation mechanism in a single system. This has been the motivation for the development of a hybrid actuator combining the electromagnetic system along side with piezoelectric actuation. This has been demonstrated to assist in enhancing the total force and consequently achieving larger actuator displacements.

Hybrid microactuators combine two or more actuation principles to maximize their respective advantages and minimize their drawbacks. They have been developed to build compact devices for versatile applications, reducing the energy consumption and increasing reliability. A hybrid stack actuator (Clephas and Janocha, 1998) consisting of
piezoelectric and magnetostrictive transducers was designed for use in a linear motor. A silicon microvalve combining electromagnetic and electrostatic actuation was reported by Bosch and Heimhofer in 1993. Similar actuators using other mechanisms were also developed for different applications.

There are a large number of different applications which require large gap/force actuators (e.g. telecommunication, automotive, high power electronic applications etc.). While fibre optical systems are becoming increasingly common in telecommunication networks, conventional twisted pair wiring will remain the dominant method for connecting consumers to a local switching network. As a consequence, there is a large demand for low cost, compact switching arrays that can be installed at the local street level. Such switching arrays must enable remote reconfiguration of local wiring networks, preferably out of the service provider's business office. The application of a micro-engineered solution to such a switching array will enable new levels of automation and remote network reconfiguration, resulting in a significant reduction in network operating costs. The large deflections required in such switches have led to the choice of a hybrid actuator approach adopted in this thesis.

1.2 Objectives

The objective of this work is to design and develop hybrid microactuators using two different principles and mechanisms which

- Can provide large possible forces (larger than that could be obtained by using any one mechanism alone) over a maximum air gap.
- Require minimum power consumption.
- Are suitable for different environmental conditions.

To meet the demand of covering large deflections in combination with a large switching force, a hybrid microactuator was designed, combining a piezoelectric polymer actuator with the magnetic actuation principle. The actuator design parameters were optimized by modelling and finite element analysis (FEA) simulation, using piezoelec-
tric and electromagnetic solvers of the commercially available FEA software packages CoventorWare and ANSYS.

The hybrid device consists of a composite piezoelectric polymer cantilever on the top and a planar copper microcoil fabricated on a silicon substrate with a permalloy core in its centre. A permanent magnet is attached to the bottom of the silicon substrate. The composite cantilever consists of polarized piezoelectric polymer polyvinylidene fluoride (PVDF) with an electroplated permalloy layer on one side. The hybrid microactuator was fabricated by employing several specialized MEMS processes, such as high aspect ratio SU-8 lithography, laser micromachining, micro-embossing and electroplating. The devices were tested and the experimental data obtained were compared with the simulation results from both the finite element calculations and with the analytical model. Reasonable agreement was found between the experimental results and the simulation.

1.3 Outline of the Thesis

To achieve the objectives of this research, the very first step was to understand the current status of the field of microactuators. Chapter 2 reviews the current literature of different microactuation principles, their applications and the relevant fabrication techniques. The theoretical/analytical background required to understand the piezoelectric and magnetic actuation principles is presented in Chapter 3. As the hybrid actuator designed later combines these two actuation principles it is essential to get a clear understanding of the actuation principles and the materials used.

Chapter 4 describes the details of the design and optimization of the piezoelectric actuator with a composite unimorph cantilever by applying the finite element method using the software packages of ANSYS and CoventorWare. Following are the fabrication process details used for fabricating the polymer cantilever having the desired profile by using laser micromachining, electroforming, punching (micro imprinting) and electroplating techniques.

Chapter 5 discusses the hybrid actuation principle combining piezoelectric and magnetic forces. The procedures followed and the results obtained using the finite element package ANSYS 2D for static electromagnetic simulation are further presented in
this Chapter. A triangle distribution force model, which was formulated based on the analysis of the simulation results, is also presented.

Chapter 6 provides the details of fabrication and assembly process followed in the physical realization of the designed hybrid microactuator. Chapter 7 discusses the test results of the fabricated devices. The thesis concludes with a summary of this work and recommendations for future research in Chapter 8. A number of important outcomes of this research are highlighted.
Chapter 2  Literature Review

2.1  Introduction

The objective of this research work, as outlined in the preceding Chapter, is to design, model, fabricate and test a hybrid actuator, which can produce a large force with a relatively large gap. Many actuation mechanisms were considered and reviewed, before zeroing on to a system based on a selected combination of piezoelectric and electromagnetic actuation principles. Section 2.2 gives a brief background facilitating the understanding of the relevant micro mechanisms before providing a comprehensive review of the literature in Section 2.3, which is especially relevant to the present work. The subsequent Section 2.4 covers the information related to microfabrication techniques which were used in this project.

2.2  MEMS

Microactuators are among the most important components which led to the revolutionised concept of micro-electromechanical systems (MEMS). The simplest and earliest actuating elements are microcantilevers. The idea of using silicon as a mechanical material for realising such cantilevers and beam structures, besides exploiting its well known electronic properties first appeared in the 1970’s, and was reviewed in a widely recognized article by Kurt Petersen in 1982 (Petersen, 1982). In the late 1980’s microactuators received increasing attention, when electrostatically driven micromotors started to appear in UC Berkeley by R.S. Muller’s group (Fan, Tai and Muller, 1989; Fujita, 1998). Since then, many types of microactuators utilising various driving forces and principles have been developed.
2.2.1 What is MEMS?

Micro-electromechanical systems (MEMS) are miniaturized systems that combine mechanical and electrical components, with the possible addition of optical, chemical or biological functions. They are fabricated using some of the processing techniques routinely employed in integrated circuit (IC) processing with typical minimum feature sizes in the range of micrometers and overall sizes in the range of a few millimetres. Many of these devices (or systems) have the ability to sense and actuate on the micro scale to control or perform a given function, and to generate effects on the micro/macro scale as required by a given application.

MEMS, an acronym that originated in the United States, is also referred to as microsystems technology (MST) in Europe and micromachines in Japan. Regardless of terminology, the uniting factor of MEMS devices lies in the manufacturing technology, which is based on batch processing. The most well known implementation of batch processing has been achieved in IC technology, which has reached a level of extreme worldwide sophistication. However, this technology is limited to the fabrication of essentially two-dimensional (planar) electrical components. Micromechanical components are fabricated by employing IC technology as a base and adding specific micromachining technologies featuring a 3-D capability and other essential functions. Processes such as bulk and surface micromachining, as well as high-aspect-ratio micromachining (HARM) selectively remove parts of the silicon or add additional structural layers to form the mechanical and electromechanical components. While integrated circuits are designed to exploit the electrical properties of silicon, MEMS, in addition, takes advantage of its mechanical properties.

In its most general form, a microsystem includes mechanical microstructures, microsensors, microactuators and microelectronic circuits, possibly integrated onto the same silicon chip, but more likely integrated in a hybrid manner. Microsensors detect changes in the system’s environment by measuring mechanical, thermal, magnetic, chemical or electromagnetic information or phenomena. Microelectronic circuits process this information and induce a controlled reaction of the microactuators, reacting to some form of effect in its environment.
MEMS devices are very small; their components are usually microscopic. Levers, gears, pistons, as well as motors and even steam engines have all been fabricated by MEMS. However, MEMS is not just about the miniaturization of mechanical components or making things out of silicon (in fact, the term MEMS can actually be misleading as some micromachined devices are not mechanical in any sense, for example, Hall sensors). MEMS is a manufacturing technology; a paradigm for designing and creating complex mechanical devices and systems as well as their integrated electronics using batch fabrication techniques.

Inspired by Richard Feynman’s early vision presented in his famous speech entitled “There’s plenty of room at the bottom” in 1992 (Feynman, 1992). MEMS has gradually made its way out of research laboratories and into everyday products. In the mid-1990’s, MEMS components began appearing in numerous commercial products and applications including accelerometers used to control airbag deployment in automobile vehicles, pressure sensors for medical and automotive applications, and inkjet printer heads. Today, MEMS devices are also found in projection displays and for micropositioners in data storage systems. However, the greatest potential for MEMS devices lies in new applications within telecommunication (optical and wireless), life science and process control areas.

MEMS has several distinct advantages as a manufacturing technology. In the first place, the interdisciplinary nature of MEMS technology and its micromachining techniques, as well as its diversity of applications, has resulted in an unprecedented range of devices and synergies across previously unrelated fields (for example biology and microelectronics). Secondly, MEMS with its batch fabrication techniques enables components and devices to be manufactured with increased performance and reliability, combined with the obvious advantages of reduced physical size, volume, weight and cost. Thirdly, MEMS provides the basis for the manufacture of products that cannot be made by other methods.

However, there are many challenges and technical obstacles associated with miniaturization that need to be addressed and overcome before MEMS can realize its overwhelming potential.
2.2.2 MEMS applications

Well established MEMS applications include automotive airbag sensors, medical/automotive pressure sensors, inkjet printer heads and overhead projection display units.

Automotive airbag sensors, besides pressure sensors, were among the first commercial high volume devices using MEMS. They are in widespread use today in the form of a single chip containing a smart sensor, or accelerometer, which measures the rapid deceleration of a vehicle on hitting an object. The deceleration is sensed by piezoresistive or capacitive means, being converted into a voltage. An electronic control unit must recognize the crash situation and safely distinguish it from other harmless situations by a dedicated algorithm, generating a signal to trigger an explosive unit, thus blowing up the airbags.

Figure 2.1: One of the first commercial accelerometers for airbag applications.
Analog Devices ADXL-50 (Analog Devices, 1994)

Another highly successful device is the miniature disposable pressure sensor used to monitor blood pressure in hospitals. These sensors connect to a patient’s intravenous (IV) line and monitor the blood pressure through the IV solution. For a relatively low price ($10), they replace the early external blood pressure sensors that cost over $600 and had to be sterilized and recalibrated for reuse. These older expensive devices measure blood pressure with a saline-filled tube and diaphragm arrangement that has to be connected to an artery with a needle.
(a) Disposable blood pressure sensor connected to an IV line (Motorola);
(b) Disposable blood pressure sensors (Perkin-Elmer Applied Biosystems);
(c) Intracardial catheter-tip sensors for monitoring blood pressure during cardiac catheterisation, shown on the head of a pin (Lucas Novasensor).

Figure 2.2: Disposable blood pressure sensors.

Inkjet printer heads achieve very high production volumes that even exceed those of automotive sensors or of medical pressure sensors. Inkjet printers use a series of nozzles to spray droplets of ink directly on to a printing medium. Depending on the type of inkjet printer the droplets are formed thermally or piezoelectrically.

One of the more recent highly successful MEMS devices is the Digital Micromirror Device (DMD) from Texas Instruments, used for a variety of display applications.
The device contains over a million tiny pixel-mirrors, each measuring 16 µm by 16 µm and being capable of twisting by ±10°, over 1000 times a second (Figure 2.4). Light from a projection source impinges on the pupil of the lens (or mirror) and is reflected brightly onto a projection screen.

Figure 2.4: The MEMS digital micromirror device.
(Texas Instruments Inc.)

The experience gained from these early devices has made MEMS an enabling technology in many fields, including new biomedical applications (BioMEMS) and wireless communication comprising both optical (referred to as micro-optoelectromechanical systems, MOEMS) and radio frequency (RF) MEMS.

2.2.3 MEMS Fabrication Methods

There are three main classes of MEMS related process families. Bulk micromachining is the oldest silicon based microsystem technology, exploiting the substrate as the base material for forming mechanical structures. Surface micromachining was invented in the late 1980’s, using a sacrificial layer technique to exploit a thin film layer (mostly polysilicon) as structural material. High-aspect-ratio microstructure technology (HARMST) can be used with materials other than silicon. It was started with the invention of the LIGA technology (a German acronym for Lithographie, galvanische Abformung, translated into lithography, electroforming and moulding).

Conventional macroscale manufacturing techniques, e.g. injection moulding, turning, drilling etc, are good for producing three dimensional (3D) shapes and objects, but
can be limited in terms of low complexity for small size applications. MEMS fabrication, by comparison, uses high volume IC style batch processing that involves the addition or subtraction of two dimensional layers on a substrate (usually silicon) based on photolithography, thin film technology and chemical etching. As a result, the 3D aspect of MEMS devices is due to patterning and interaction of the 2D layers. Additional layers can be added using a variety of thin-film and bonding techniques as well as by etching through sacrificial ‘spacer layers’.

Materials for Micromachining

The review paper by Petersen in 1982 led to the widespread acceptance of micromachined silicon as a structural material. It has been successfully used as substrate material in the microelectronics industry and will continue to be used there for many more years in the future for several reasons: silicon is abundant, inexpensive, and can be processed to unparalleled purity. In combination with thin film technology, many functions can be added that are not inherent to silicon itself. Photolithography is used for structural definition on the sub-micron scale. Silicon microelectronic circuits are batch fabricated (a silicon wafer contains several hundred or even more than one thousand identical chips, not just one).

Other crystalline semiconductor materials, including germanium (Ge) and gallium arsenide (GaAs) are used as substrate materials for special applications, but silicon is unique in its ability to readily form an oxide (SiO$_2$), which is chemically inert and electrically insulating. The homogeneous crystal structure of silicon gives it the electrical properties needed in microelectronic circuits, but silicon also has desirable mechanical properties.

Silicon is dominant as a substrate for MEMS, particularly when electronic functions need to be included. For other applications non-semiconductor materials are gaining importance, including ceramics, polymers, metals, and so on. In fluidic applications, which require larger chip areas and do not include sophisticated electronic functions, polymers are more prominent than silicon.
Bulk Micromachining

Bulk micromachining involves the removal of part of the bulk substrate. It is a subtractive process that uses wet anisotropic etching and/or a dry etching method such as reactive ion etching (RIE), to create large pits, grooves, membranes, cantilevers and channels. Materials typically used for wet etching include silicon and quartz, while dry etching is typically used with silicon, metals, plastics and ceramics.

Wet etching describes the removal of material from a substrate (typically a silicon wafer) by immersion into a liquid bath of a chemical etchant. These etchants can be isotropic or anisotropic.

Isotropic etchants etch the material at the same rate in all directions, and consequently remove material laterally under the etch masks at the same rate as they etch through the material; this is known as undercutting (Figure 2.5 (a) and (b)). The most common recipe of an isotropic silicon etchant is HNA (Schwartz and Robbins, 1976), comprising a mixture of hydrofluoric acid (HF), nitric acid (HNO$_3$) and acetic acid (CH$_3$COOH). Isotropic etchants are limited by the geometry of the structure to be etched. Etch rates can slow down and in some cases (for example, in deep and narrow channels) they can nearly stop due to diffusion limited factors. However, this effect can be minimized by agitation of the etchant, resulting in structures with nearly perfect and rounded surfaces (Kovacs et al., 1998).

Anisotropic etchants etch faster in a preferred direction. Potassium hydroxide (KOH) (Seidel, 1987; Seidel et al., 1990; Price, 1973) is the most common anisotropic etchant, as it is relatively safe to use. The geometry of structures formed in the substrate depends on the crystal orientation of the wafer and on the mask alignment. Most of the anisotropic etchants etch rapidly in the (110) crystal direction and less rapidly in the (100) direction. The (111) planes etch much more slowly, by about two orders of magnitude. Figure 2.5 (b) shows examples of anisotropic etching on (100) and (110) silicon. Silicon wafers are grown with the desired orientation by precisely aligning a crystallographically oriented seed crystal. A very high dopant level of boron can reduce the etch rate in KOH dramatically, coming close to an etch stop. This can be used to selectively etch regions in the silicon leaving doped areas unaffected.
Dry etching relies on plasma-based or in some cases also vapour-phase-based methods, using suitable reactive gases or vapours. The most common form for MEMS is reactive ion etching (RIE) which utilizes additional energy in the form of radio frequency (RF) power to drive the chemical reaction. Energetic ions are accelerated towards the material to be etched within a plasma phase supplying the additional energy needed for the reaction; as a result the etching can occur at relatively low temperatures (typically 150° - 250°C, sometimes room temperature). RIE is not limited by the crystal planes in the silicon and, as a result, deep trenches and pits, or arbitrary shapes with vertical walls can be etched. Deep reactive ion etching (DRIE) is a much higher-aspect-ratio etching method that involves an alternating process of high-density plasma etching (as in RIE) and protective polymer deposition. Etch rates depend on temperature, concentration and material to be etched.
Surface Micromachining

Surface micromachining was initiated in the 1980’s and is the most recent MEMS production technology. It uses a thin film layer deposited on top of a substrate (usually silicon) as a structural material. Thus, the substrate only serves as a carrier. In addition, a second thin film layer is used as a so-called sacrificial layer. Its purpose is to provide a gap between the substrate and the structural material, where desired, by removing it in a later process step. This allows the generation of freely movable structures. Hence the process usually involves films of two different materials: a structural material out of which the free standing structures are made (in most cases polycrystalline silicon, also called polysilicon, sometimes silicon nitride or aluminium) and a sacrificial material, defining the width of the gap of the free standing mechanical structure (usually a silicon dioxide).

![Process Sequence Diagram]

Figure 2.6: Polysilicon surface-micromachining process sequence.

These layers (or thin films) are deposited and subsequently dry etched in sequence, with the sacrificial material being commonly removed by wet etching technology to release the final structure. More recently, dry etching techniques have been applied for this step to minimize the so-called sticking problem. Each additional layer is
accompanied with an increasing level of complexity and a resulting difficulty in fabrication. A typical surface micromachining process is shown in Figure 2.6. This basic process sequence of surface micromachining is divided into four modules:

1) **Substrate passivation:** After a blanket n⁺ diffusion to define the substrate ground plane, the silicon wafer is passivated with a layer of 150 nm LPCVD silicon nitride deposited on top of a layer of 500 nm thermal SiO₂ (not shown in the figure).

2) **Sacrificial layer deposition and patterning:** A 2 µm thick LPCVD sacrificial phosphosilicate glass (PSG) layer is deposited and patterned as shown in Figure 2.6 (a) and (b).

3) **Structural polysilicon deposition:** The 2 µm thick polysilicon structural layer is then deposited by LPCVD at 610°C as shown in Figure 2.6 (c), and then patterned by reactive-ion etching (RIE) in order to achieve the nearly vertical sidewalls illustrated in Figure 2.6 (d). The Poly-Si layer must be doped by phosphorus to render a high electrical conductance. This can be done after deposition by POCl₃ or in situ (Bustillo et al., 1994).

4) **Microstructure release, rinse, and dry:** In the last steps, the wafer is immersed in aqueous hydrofluoric acid HF (typically 10:1 diluted or buffered HF) to dissolve the sacrificial PSG layer. The wafer is rinsed in deionized water and then dried. The method of drying must be adapted in such a way to avoid its collapse and adhesion of the structure to the substrate—a phenomenon known as “stiction.” The final cross section is shown in Figure 2.6 (e). By repeating these basic sacrificial oxide and structural polysilicon fabrication steps while including anchor points and other structural features, one can build very complex structures. Examples of these are the Sandia National Laboratory’s five-level Sandia Ultra-Planar Multi-Level MEMS Technology (SUMMiT) (Sniegowski et al., 1997) and the Microelectronics Centre of North Carolina (MCNC) three-level Multi-User MEMS Process (MUMPS). MCNC offers the MUMPS program for a domestic prototyping and proof-of-concept foundry service. Bosch offers a so-called epi-poly process as a foundry service, featuring an increased height of the structural polysilicon layer of approximately 10 µm. The five-level Sandia SUMMiT process (14 masks, 240 process steps) is the most complex polysilicon surface micromachining
technology reported to date. A distinguishing feature is the use of chemical-mechanical polishing.

The final success of the surface micromachining process depends on the ability to remove all of the sacrificial layers for freeing the structural elements so that they can be actuated. This step is responsible for curtailing the yield (percentage of the devices on a wafer that function properly) and reliability of fabricated MEMS due to the phenomenon known as stiction. Stiction refers to the sticking of structural elements either to the substrate or to adjacent elements. Capillary forces from rinsing liquids, as well as electrostatic and van der Waals forces can produce permanent adhesion after the system has dried.

### 2.3 Microactuators

Microactuators are devices that convert energy from one form into another, for example, from electric, magnetic or hydraulic into mechanical energy (Judy, 2001; Madou, 2001). They are essential in complex microsystems for performing physical functions. Remarkable progress has been achieved in the field of microactuators, even though it is less mature than the field of microsensors. Research and development efforts have been directed towards using different actuation principles (Dufour and Sarraute, 1999; Fujita, 1998) and designing various structures for specific applications.

Among the first devices were simple mechanical resonant structures agitated by electrostatic forces, where humidity induced change of mass leads to a change of resonance frequency (Howe, 1987). Other prominent devices are bulk micromachined valves and membrane pumps, exploiting e.g. piezoelectric or thermo-pneumatic forces (Van, 1988). In 1988 the first rotational electrostatic micromotor implemented in polysilicon surface micromachining technology was demonstrated as shown in Figure 2.7. Such devices later formed the basis of more complex micro-dynamical systems, being supplemented by additional springs, cranks, gears and other rotational elements (Fan, 1987).
Since then, a lot of research effort has been focussed on improving the performance of such actuators and along the way, many interesting and commercially valuable applications have been found. Existing devices are most frequently driven by electrostatic forces and to a lesser extent also by thermal, magnetic or piezoelectric forces. Each actuation principle has its own advantages and limitations making it the optimal choice for an appropriate set of applications.

Typical design parameters for microactuators are the forces, displacements, power, efficiency, linearity, repeatability, and bandwidth which are related to the response time. These can be optimized for any given actuator to achieve the best possible performance in any application. Further, it is also important that a microactuator can be fabricated economically using available batch processing technologies for fabrication. The goal of mechanical microactuation is the generation of forces, usually leading to mechanical motion. Therefore, different principles of actuation have to be judged according to their desired design priorities for the parameters mentioned above.

Design considerations for various types of forces may be different for micro-scale devices as compared to conventional macroscale systems. This is due to the different scaling characteristics of various physical parameters. For example, large-scale systems are influenced by inertial effects to a much greater extent than smaller ones, whereas
surface effects become more prominent in the latter case. This is due to the fact that inertial forces typically are linked to seismic masses, which scale with the volume, whereas surface forces are proportional to the surface area. Furthermore, thin films which are used for batch fabrication of microactuators (Thielicke and Obermeier, 2000) often exhibit material properties that differ from those of bulk materials, including intrinsic stress induced by high temperature processing and deposition.

Microactuators can be generally classified as being either multi-component or solid-state (Goldfarb, 1999). Multi-component microactuators incorporate two (or more) bodies, which perform work by exerting a mutual force between them. The forces typically generated in these types of actuators are based on electrostatic, electrothermal or electromagnetic principles. Solid-state microactuators perform work by utilizing material deformation phenomena within a single body. Examples of this type are piezoelectric ceramics, shape memory alloys, magnetostrictive alloys, electrostrictive ceramics, and photostrictive materials. Table 2.1 lists some typical types and properties of microactuators.

<table>
<thead>
<tr>
<th>Property</th>
<th>Multi-component (mutual force)</th>
<th>Solid-state (material deformation)</th>
</tr>
</thead>
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<tr>
<td></td>
<td>Electrostatic</td>
<td>Electrothermal</td>
</tr>
<tr>
<td>Work/unit vol. (J/m³)</td>
<td>3.4 x 10³</td>
<td>2.8 x 10⁴</td>
</tr>
<tr>
<td>Displacement</td>
<td></td>
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</tr>
<tr>
<td>Bandwidth</td>
<td>KHz</td>
<td>1kHz</td>
</tr>
<tr>
<td>Applications</td>
<td>Comb drives capacitance motor</td>
<td>Electromagnetic micro-motor</td>
</tr>
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<td>Current status of de-</td>
<td>R&amp;D, some commercial</td>
<td></td>
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</tbody>
</table>
2.3.1 Electrostatic Microactuators

Electrostatic microactuators have been constructed out of metal or heavily doped semiconductors and designed with flexures, rotary or linear bearing surfaces. They have been used extensively in MEMS devices since it is relatively easy to fabricate closely spaced conductive plates with narrow gaps in between. The fundamental principle behind electrostatic actuators is the attraction of two oppositely charged plates. Electrostatic forces are inversely proportional to the distance between the plates, usually preventing large displacements unless high voltages are used (tens to hundreds of volts). Well-known designs are the lateral comb drive developed at Berkeley by R.S. Muller’s group (Tang, Nguyen and Howe, 1992), and the rotary electrostatic micromotor (Fan, Tai and Muller, 1989; Hirano and Fan, 1998). More recently, electrostatic comb-drive actuators have been designed for large deflections up to 150 µm with a response time of less than 1 ms (Grade, Jerman and Kenny, 2003), operating at less than 150 V.

However, due to the inverse square relationship of Coulomb forces with the distance (between the two arms of an actuator), they usually work in small gaps and require high voltage. The large voltage requirements often prevent electrostatic microactuators from being conveniently driven with typical on-chip circuits and voltages. In addition, high voltages on small features may create high electric field gradients that attract dust particles. Also, electrostatic actuators will not function in conductive fluids and are not safe in humid environments.

2.3.2 Thermal Microactuators

Thermal actuation has been used extensively in the design of microactuators. One of the earliest and most commercially successful applications of this principle is thermal inkjet print heads (DeVoe, 2003), where an electric resistance heater is used to locally vaporize the ink, thus forming a bubble, causing a sharp rise in liquid pressure which leads to the ejection of an ink droplet. Thermal actuation is based on a broad spectrum of principles, such as thermo-mechanic or thermo-pneumatic expansion, sometimes in combination with the bimetal effect or with the shape memory alloy effect, etc. Many thermal microactuators are based on a bimorph design (Ataka et al., 1993), taking advantage of a considerable difference in the thermal expansion coefficients of adequately
chosen materials that are laminated together (Kovacs, 1998). A typical example of a thermally actuated bimorph cantilever is presented by Ataka et al. in 1993. With a length of 500 µm, a width of 100 µm, and a thickness of 6 µm a tip vertical deflection of 150 µm and a lateral deflection of 80 µm is achieved. The thermo-mechanical deflection of beams or diaphragms can be employed in microvalves, micropumps, inkjet printer heads (Bassous, 1975) and in bistable microdevices (Baker and Howell, 2002). Bimorph thermo-mechanical actuators can achieve large forces and deflections at the expense of a relatively large power consumption. However, there is one serious drawback to this bimetal principle. It is very sensitive to a change in ambient temperature, which will lead to unintended deflections. This aspect usually limits the application of such devices to temperature controlled environments.

Thermo-pneumatic actuation uses the thermal expansion of a gas or liquid or the phase change between liquid and gas to create considerable force. This is employed in the inkjets, as mentioned above.

Also, a special class of materials known as shape memory alloys (SMAs) can undergo a radical change in shape and size by a phase transition, when heated. A reversible thermo-mechanical transformation of the atomic structure of the metal takes place at certain temperatures. At low temperatures, the SMA keeps its desired deformed shape in the martensitic state. When the SMA is heated up above a threshold temperature, the deformed martensite is transformed back to the austenitic state. SMA wires and thin films are the two most prominent structures used in SMA microactuators (Benard and Kahn, 1998; Krulevitch and Lee, 1996; Wolf and Heuer, 1995) for microfluidic applications and microgrippers (Huang et al., 2003). Their most prominent application is in so-called stents used for stabilizing arteries in cardiovascular diseases.

### 2.3.3 Magnetic Microactuators

Magnetic microactuators often follow the conventional macroscopic design, despite the significant challenge involved in integrating ferromagnetic cores, rotors and copper coils (Ahn, Ki and Allen, 1993; Guckel, 1998; Guckel and Christenson, 1993). Even though magnetic actuation employed in conventional motors or solenoids is the most successful principle used on a macro scale, MEMS magnetic devices are still rela-
tively unestablished. This is due to the fact that 3D coils are difficult to fabricate by typical MEMS technologies. Successful commercial devices are magnetic read/write heads for computer disk drives (Hirano and Fan, 1998).

Magnetic microactuators can achieve large forces over wider air gaps than their electrostatic counter parts. They can operate at low voltages but use comparatively large currents. As a result, the power dissipation is high. Magnetic actuation is a more robust mechanism than electrostatics. These advantages make it attractive to do research in this field. Extensive work has been done by several groups (Cho and Ahn, 2002; Ghantasala et al., 2000; Guckel, 1998; Judy and Myung, 2002; Lagorce et al., 1999; Liu et al., 1995; Wagner and Benecke, 1990). Even though different structures are used in these examples, the force is always generated between the electric coil and the magnet. Figure 2.8 shows four different examples. A cantilever beam microactuator is shown in Figure 2.8 (a) (Lagorce, Brand et al., 1999), designed by Allen’s group. A polymer magnetized in the thickness direction is screen printed on the free end of a copper cantilever beam. On the other side of the substrate a planar square coil produces the magnetic field gradient necessary for the actuation of the magnet. Figure 2.8 (b) shows a torsional microstructure achieved by passing current through an integrated coil (Judy et al., 1994; Judy and Muller, 1995). A ferromagnetic microactuator constructed with on chip coils for micromotors developed by Christensen that used assembled windings is shown in Figure 2.8 (c) (Guckel et al., 1993). A micromotor with integrated windings first presented by Ahn and further developed by his lab is shown in Figure 2.8 (d) (Ahn et al., 1993).

(a) Schematic view of a magnetic cantilever beam microactuator (Lagorce et al., 1999).
(b) Flap structure actuated about two torsion bars by the magnetic field generated by an integrated coil (Judy and Muller, 1997).

(c) Micromotor constructed with assembled windings (Guckel et al., 1993).

(d) Micromotors constructed with integrated windings (Ahn et al., 1993).

Figure 2.8: Some examples of magnetic microactuators.
The most commonly used magnetic materials in MEMS devices are either soft ferromagnetic materials, such as Ni, permalloy (Ni$_{19}$Fe$_{81}$), and CoFeCu or hard magnetic materials, e.g. Sm-Co, and NdFeB (Judy and Myung, 2002). Permalloy, typically consisting of 81% Fe and 19% Ni, is being used extensively in magnetic MEMS devices. The reason for this is a combination of a relatively high saturation flux density, low hysteresis losses, and nearly zero magnetostriction, which has driven their use in macroscopic and microscopic sensors, actuators and systems. The permalloy layer for these applications is fabricated using a simple electroforming process developed over the years (Liu et al., 1995; Ren and Gerhard, 1997; Wright and Tai, 1997).

Hard magnetic or permanent magnetic materials are more appropriate in some cases. The successful fabrication of permanent magnets (Cho and Ahn, 2002; Lagorce et al., 1999) enables a fully integrated magnetic MEMS microactuator. Some new polymer magnets were also developed (Budde and Gatzen, 2002).

The fabrication involves surface micromachining (Bustillo et al., 1998) and bulk micromachining (Kovacs et al., 1998), as well as a classical electroplating process.

### 2.3.4 Piezoelectric Microactuators

Piezoelectric microactuators generate large forces but only small displacements by applying a voltage to the piezoelectric materials. Typically used constructions are the bimorph (Robertson, 1979; Todals et al., 1979) and multi-layer structures. In addition, more and more unimorph composite beams (DeVoe, 2001; Elvin et al., 2001; Kueppers and Leurerer, 2002; Zurn and Hsieh, 2001) are employed to meet the increasing requirements of special applications.

The piezoelectric principle can be used in many applications, such as electric fans (Todals et al., 1979) hydrophones (Lau et al., 2001), microphones (Lee et al., 1996; Schellin and Hess, 1992), inkjet printers, control valves (Roberts and Li, 2003), micro pumps (Yoseph and Chang, 2000), tactile sensor (Dargahi et al., 2000), acoustic control (Li et al., 2001) and micromotors (Ruprecht et al., 1996), etc. Figure 2.9 shows a typical piezoelectric microactuator. The main advantages of this actuation principle are its high precision, speed and mechanical power.
In these applications, piezoelectric ceramic materials such as zinc oxide (Jenkins et al., 1997) and PZT (Kueppers and Leuerer, 2002; Zurn and Hsieh, 2001) are most commonly used, because they exhibit large piezoelectric coefficients. However, there are also some difficulties associated with their use. Piezoelectric ceramic materials require advanced deposition facilities and technologies to prepare thin films, they are usually brittle, and have a relatively large Young’s modulus, thus limiting the achievable strain. Some composite active polymers (Friese et al., 2003; Janos and Hagood, 2003) composed by piezoelectric ceramic materials and epoxy were fabricated to compensate for these disadvantages. Piezoelectric polymers such as PVDF and its copolymers can overcome some of these difficulties even though they have a relatively low piezoelectric coefficient. Low numerical Young’s modulus values of these polymers (Sun and Mills, 2002; Xu et al., 2002) have the potential for enabling relatively large strain piezoelectric actuators.

The special characteristics of piezoelectric polymers have attracted the attention of many researchers from many different disciplines. A lot of devices were designed from these materials since the 1980s. A long list of papers and patents can be found in the Piezo film sensors technical manual from Measurement Specialist. In some of these devices, PVDF has been used mostly in the form of a thin foil, either stretched or mounted. The ability to pattern PVDF into required shapes and sizes is highly desirable in order to increase the range of applications, particularly in the millimetre to micrometre scale. Several different methods have been employed to pattern PVDF, including the use of an excimer laser (Izumi et al., 1998), UV light source (Katan et al., 1998), x-rays
(Manohara et al., 1999; Duca et al., 1998) and hot embossing (Ruprecht et al., 1996). Each method has its own strengths and problems. Excimer laser ablation will change the UV-VIS photo absorption spectrum of PVDF polymer (Izumi et al., 1998). Heat diffusion can easily damage the piezoelectric effect on PVDF and can also burn the edge of the pattern (Fu et al., 2001). A direct pattern transfer into PVDF is possible through x-ray induced etching (Manohara et al., 1999). However, the x-ray fabrication is much more expensive than laser ablation and also the maximum achievable etch depth is only 9 µm. Hot embossing PVDF will take the risk of damaging the piezoelectric effect in PVDF polymer because the most favourable moulding temperatures for PVDF ranges from 175°C to 185°C. One group in Japan (Fujitsuka et al., 1998) uses an electro spray deposition method to deposit thin layer PVDF on the substrate biased with a voltage of 8-15 kV.

2.3.5 Hybrid Microactuators

As all the microactuation principles have their advantages and disadvantages, microactuators combining two or more actuation principles have been developed for versatile applications in order to compact the devices, reduce the energy consumption and increase the reliability. A hybrid stack actuator (Clephas and Janocha, 1998) consisting of piezoelectric and magnetostrictive transducers was designed for use in a linear motor. A silicon microvalve combining electromagnetic and electrostatic actuation was reported (Bosch et al., 1993) ten years ago. In this case the magnetic force was used to implement a large deflection and the electrostatic force was used for keeping the valve in its closed position with nearly zero power consumption. DARPA (www.darpa.mil/dso, 2004) has put a large amount of funding into developing new types of hybrid electromechanical actuators and devices that take advantage of the high energy density of smart material transduction elements. Other hybrid actuators (Haruna et al., 2000; Michelena et al., 2002; Robert et al., 2003; Sheng et al., 2000) combining piezoelectric, magnetostrictive, electrostatic, and hydraulic actuation were employed. Figure 2.10 shows a microswitch, combining thermal and electrostatic actuation, fabricated by Robert et al.
2.4 Processing Techniques

The processing technologies used for fabricating a wide variety of microactuators are based on bulk or surface micromachining processes discussed earlier. However, many of these actuation principles are not necessarily using silicon as the base material. Hence, the fabrication technologies employed in realizing such microactuators expanded beyond the conventional silicon-based technology spectrum into LIGA, Electrical Discharge machining (EDM), Deep Reactive Ion Etching (DRIE) and other methods. Some of these relevant techniques along with the basic lithography process are discussed below.

2.4.1 Photolithography

Photolithography (Madou, 2001; Thompson, 1994) is the photographic technique to transfer copies of a master pattern onto the surface of a chosen substrate (usually a silicon wafer). The substrate is usually covered with a thin film of some material, e.g. silicon dioxide (SiO₂), aluminium, titanium, or other metal or dielectric layers. A layer of an organic photosensitive polymer, a so-called photoresist, which is sensitive to ultraviolet radiation, is then deposited on the substrate. A photomask consisting of a glass
plate (transparent) coated with a chromium pattern (opaque), is then placed in contact with the photoresist coated surface. The wafer is exposed to the ultraviolet radiation transferring the pattern on the mask to the photoresist which is then developed in a way very similar to the process used for developing photographic films. The process is shown schematically in Figure 2.11. The radiation causes a chemical reaction in the exposed areas of the photoresist of which there are two types; positive and negative. Negative photoresists become less soluble after exposure to radiation, and thus the unexposed areas can be removed by treatment with an appropriate solvent. Positive resists, on the other hand, increase their solubility upon exposure, enabling the exposed regions to be removed in the solvent developer. The resulting photoresist pattern is either the positive or negative image of the original pattern of the photomask.

A chemical is used to attack and remove the uncovered oxide from the exposed areas of the photoresist. The remaining photoresist is subsequently removed, leaving a pattern of oxide on the silicon surface. The final oxide pattern is either a positive or negative copy of the photomask pattern and serves as a mask in subsequent processing steps, which can include etching steps of different kinds of layers or steps for doping the substrate.
The oldest photolithographic technique is contact printing. In this technique the mask is first visually aligned to the previous pattern on the wafer. Next, the mask is pressed into hard contact with the resist-coated wafer, which is then flood exposed through the mask with ultraviolet light. In a modification of this technique, which became popular in the early 1970s, the mask and the wafer are separated by a small, accurately controlled gap during exposure. This technique, known as soft contact or proximity printing, minimizes mask and wafer damage caused by contact, but at the expense of resolution. Around 1973 projection lithography, in which the mask image is projected onto the wafer by means of a 1:1 reflective or refractive optical system, was developed. Since the mask is no longer in direct contact with the wafer, the technique offers largely increased mask life times and a marked reduction in defect density. With wafers increasing in size every few years, the task of designing optics capable of forming an accurate image over larger and larger areas represents a continuing challenge. To accommodate larger wafers and improve resolution, a photolithographic technique was developed in the mid-1970s that involves exposing a small area (on the order of 1 to 2 cm$^2$) and stepping this pattern over a large diameter wafer. This technique improves resolution and alignment accuracy. Step and repeat systems are commonly designed with reduction optics by a factor of five to ten.

The minimum size of the features that can be printed by photolithography is ultimately limited by the wavelength of the exposing radiation just as the resolution of the optical microscope is limited by the wavelength of the light used for imaging. Photolithographic systems typically achieve minimum features comparable in size to the exposure wavelength. Advanced circuits are currently manufactured with feature size below 0.5 μm dimension by using G-line ($\lambda=436$ nm) or I-line ($\lambda=365$ nm) step and repeat systems with 5-10 times reduction. With the use of excimer laser light (KrF, 248 nm), features of 180 nm have been achieved, and with ArF (193 nm) features of less than 100 nm are now possible. The most advanced optical lithography systems available today can produce features with dimensions down to 90 nm, by exploiting, advanced methods, such as phase-shift masks or off axis illumination schemes. With these methods, the resolution limit has been extended successfully into the sub-wavelength regime.

For a photoresist to be useful for MEMS manufacturing, it must not only have high sensitivity and the ability to resolve small features, but also must be capable of be-
ing spin coated into thin and continuous films that will adhere to a variety of substrates ranging from metals and semiconductors to insulators. It must also be able to withstand exposure to high temperatures and corrosive etching environments, such as strong acids or a plasma beam without loss of adhesion or line definition.

Resist materials can be classified as positive and negative on the basis of their radiation response as illustrated in Figure 2.11. Polymethyl methacrylate (PMMA) is a classic positive photoresist. Other positive photoresists, such as AZ series products are also extensively used in MEMS fabrication. SU-8 is a newly developed, popular negative photoresist for high aspect ratio microstructures.

2.4.2 High-Aspect-Ratio Micromachining

High-aspect-ratio micromachining (HARM) includes processes that involve micromachining as a tooling step followed by injection moulding or embossing and, if required, by electroforming to replicate microstructures in metal from moulded parts. It is one of the most attractive technologies for replicating microstructures at a high performance-to-cost ratio and includes the LIGA technique. Products micromachined with this technique include high aspect-ratio fluidic structures, such as moulded nozzle plates for inkjet printing and microchannel plates for disposable micro-titre-plates in medical diagnostic applications. The materials that can be used are electro formable metals and plastics, including acrylate, polycarbonate, polyimide and styrene.

LIGA is an important tooling and replication method for high-aspect-ratio microstructures. The technique employs high energy x-rays generated by synchrotron radiation to expose thick acrylic resist of PMMA under a lithographic mask as shown in Figure 2.12. The exposed areas are chemically dissolved and, in areas where the material is removed, metal is electroformed, thereby defining the tool insert for the subsequent moulding step. LIGA is capable of creating very accurately defined microstructures down to the sub-µm range with structural heights up to 1000 µm. The practical application of LIGA is limited by the need to have access to an x-ray synchrotron radiation source. A compromise which combines some features of LIGA with surface micromachining, eliminating the need for exposure to x-rays has been developed and is known as SLIGA (Sacrificial LIGA) (Bryzek et al., 1994).
It replaces the thick PMMA photoresist with polyimide as the electroplating mould, thus enabling compatible conventional IC batch processing. HARM production methods have provided radically new ways to produce micromachined parts for MEMS devices at relatively low cost. In particular, techniques such as SLIGA enable the production of MEMS components with much lower manufacturing infrastructure in terms of investment, facilities and access to advanced materials and technology.

(a) Expose the PMMA photoresist through a mask by x-rays;
(b) Developed the patterned photoresist;
(c) Electroformed a metal structure;
(d) Over plated the electroformed structure;
(e) Metal tooling for replication;
(f) Moulded replication using the metal tooling.

Figure 2.12: The LIGA process.
(Research Center Karlsruhe, Germany)

Other micro replication techniques can be combined to generate a preform for the tool insert. These include laser ablation, ultra-violet (UV) lithography and mechanical micromachining, such as electric discharge machining (EDM) and diamond milling. EDM is a relatively new approach that uses machine shop production techniques and offers the capability to form parts on the micro scale, provided the material exhibits sufficient electrical conductivity. Unfortunately, as a spark erosion technique, it is not a
batch process and therefore rather slow. Nevertheless, it has found many applications in MEMS prototype fabrication.

**SU-8 2000 Negative Tone Photoresist**

The development of a novel epoxy resin based negative tone SU-8 photoresist has changed the technology of fabricating high aspect ratio structures in particular. The major advantage of using this resist is that it can be used for fabricating reasonably high aspect ratio structures (aspect ratio from 10 to 20) using both conventional UV radiation based lithography as well as deep x-ray based lithography (used in LIGA). This has in fact made the LIGA process more economically feasible with respect to the exposure beam time and subsequent processing times.

SU-8 is a high contrast, negative tone, epoxy type photoresist first developed and patented by IBM, based on EPON resin commercially available from MicroChem and other companies. It has been widely used within the MEMS community for many years for fabricating miniaturised mechanical (Lorentz *et al.*, 1998), electrical (Song and Ajmera, 2003), and microfluidic devices (Henry *et al.*, 1998), as well as for rapid prototyping, delivering the master mould for injection moulding and electroplating (Henry *et al.*, 1998; Shew *et al.*, 2003; Song and Ajmera, 2003). As a special feature, SU-8 photoresist can provide outstanding high aspect ratio microstructures (Lorenz *et al.*, 1998; Puhmann *et al.*, 2002). Recently, Mark Allen’s group (Chung and Allen, 2005) has demonstrated a fabrication process using uncrosslinked SU-8 as a sacrificial material. Uncrosslinked SU-8 can be selectively removed in the presence of a wide range of materials. Therefore SU-8 is a promising photoresist for microfabrication.

The photoresist is prepared by dissolving the resin in an organic solvent and adding a photo initiator. The quantity of the solvent determines the viscosity and thereby the available thickness range, which can be varied between 750 nm and 200 μm, even up to 500 μm by using appropriate process conditions with a conventional spin coater and a hot plate. Very thick layers (such as 1 mm and beyond) can be achieved by multiple coating/baking steps.

An improved formulation of SU-8 is SU-8 2000, where the standard GBL (gamma butyrolactone) solvent is replaced by cyclopentanone. The excellent imaging
characteristics of SU-8 are maintained. The exposed and subsequently crosslinked portions of the film are rendered insoluble to liquid developers, allowing the precise formation of high aspect ratio photoresist structures. Such resist structures can be used favourably as a mould for subsequent electroplating, due to their relatively high chemical and thermal stability (glass transition temperature $T_g > 200^\circ$C). SU-8 2000 has high optical transparency above 360 nm, which makes it ideally suited for imaging nearly vertical sidewalls in very thick films.

SU-8 2000 is most commonly exposed with conventional near UV (300-400 nm) radiation. Upon exposure, cross linking proceeds in two steps: (1) formation of a strong acid during the exposure process, followed by (2) acid-initiated, thermally driven epoxy cross linking during the post exposure bake (PEB) step. Processing of SU-8 is a more challenging task than processing of Novolak/DNQ resists. Every process step influences strongly the results obtained and has to be adapted individually to the desired application. Requirements to the process design increase with increasing layer thickness. Process optimization means always to look for a trade-off between various structural features because of interrelations between the single process steps. For example, the soft bake has to result in a sufficiently dry resist film to prevent mask sticking. On the other hand, the photo acid must have enough mobility to allow for uniform cross-linking, i.e. good lithographic performance. To transfer the latent image formed during exposure into a stable structure, a post exposure bake is necessary. The degree of cross-linking is controlled by both the exposure dose and bake conditions. Relaxation times are necessary to reduce internal stress and have to be extended with increasing layer thickness.

2.4.3 Hot Embossing

Polymer microfabrication methods are becoming increasingly important as low-cost alternatives to the silicon or glass-based MEMS technologies. Currently, the most widely used replication process to fabricate channel structures based on polymer substrates for microfluidic applications is hot embossing. Channel widths between 0.8 µm and 100 µm have been produced by this method. Becker (Becker and Gartner, 2000) fabricated a channel with a cross section of 100 µm x 40 µm by polymer hot embossing (Becker and Dietz, 1998).
The micro-fabrication process of hot embossing itself is rather straightforward. After fabrication of the master, it is mounted in the embossing system together with the planar polymer substrate. Both are heated separately in a vacuum chamber to a temperature just above the glass transition temperature $T_g$ of the polymer materials, which is typically of the order of 50-150ºC. The vacuum is necessary to prevent the formation of air bubbles due to entrapment of air in small cavities. It also allows water vapour (which during the process is driven out of the polymer substrate) to be removed. Additionally, it increases the lifetime of nickel tools, as it prevents corrosion of the nickel at these high temperatures. The tool is brought into contact with the substrate and then embossed with a controlled force. Typical embossing forces are of the order of 0.5-2 kN/cm$^2$. Still applying the embossing force, the tool substrate sandwich is then cooled to just below glass transition temperature $T_g$.

To minimise thermally induced stresses in the materials as well as replication errors due to the different thermal expansion coefficients of tool and substrate, this thermal cycle should be as small as possible. After reaching the lower cycle temperature, the embossing tool is mechanically driven apart from the substrate, which now contains the desired features. This is usually the most critical step, as now the highest force acts on the polymer microstructure, particularly if a structure with vertical walls and a high aspect ratio is desired. Therefore, an automated mould release is crucial for a higher production yield. Overall cycle time of the embossing process for materials such as PMMA is of the order of 5-7 min. The microstructured polymer wafer can now be processed further.

Figure 2.13 shows a schematic of a typical hot embossing set-up. The arrangement of the mould insert along with the substrate, heating and cooling system within a force frame is shown in this Figure. High structural resolution achievable with hot embossing can be seen in Figure 2.14, with part (a) showing the embossing tool, fabricated with an advanced silicon etch process, and part (b) showing the resulting channel structure in PMMA. This structure represents a two-dimensional channel array with microchannels of less than 1 µm in width.
Figure 2.13: Schematic diagram of a hot embossing machine.

(a) Embossing tool fabricated by advanced silicon etching.
(b) Resulting channel array structure.

Figure 2.14: High resolution microstructure fabricated by hot embossing.

The master for hot embossing is most commonly fabricated by etching the pattern on a silicon wafer (Bacon and Kenny) or by electroplating a nickel shim (Simdekova et al., 2002).

**Pattern formation in hot embossing**

Schift *et al.* (Schift, 2001) investigated pattern formation during hot embossing of polymer film and observed how a microcavity is filled from the borders during hot embossing of the thin polymer film. The height profile of a partially filled stamp cavity obtained using an Atomic Force microscope (AFM) is shown in Figure 2.15. The forming of mounds during squeezed flow into a cavity was shown in Figure 2.16.
(a) AFM height profile for a partially filled rectangular cavity.
(b) A schematic of the squeeze flow of a polymer into a stamp cavity.

Figure 2.15: The height profile of a partially filled stamp cavity.

(a) Polymer melt is squeezed into the cavity and flows up the cavity walls.
(b) and (c) Instability results in the growth of the central capillary wave peak until it touches the cavity top.
(d) Polymer melt flows into the cavity until it is fully mounded.

Figure 2.16: Forming of mounds during squeezed flow into cavity.

Thin films of PMMA were spin coated onto silicon substrates. The masters were produced from silicon wafers, which were structured using electron beam lithography. RIE was used to transfer the resist pattern into silicon dioxide, providing the necessary hot embossing stamp. Prior to embossing, the substrate was heated to temperatures
higher than 100°C above the glass transition temperature. The silicon stamp was then pressed against the polymer using embossing pressures of up to 100 bar. In order to demould the polymer, the substrate was cooled to 70°C.

Schift has observed the embossing patterns are strongly dependent on embossing stamp geometry, embossing parameters, and polymers. In addition, there is a characteristic wavelength which should depend on the structure height and the stamp-substrate spacing, which influences the electrostatic force and the dielectric constant of the polymer (Schift et al., 2001).

During hot embossing, the polymer should be sufficiently cooled before demoulding to avoid the formation of viscous fingering patterns as shown in Figure 2.17 and care should be taken to ensure a uniform distribution of embossing pressure to avoid a dewetting behaviour of the polymer.

![Formation of viscous fingering patterns.](image)

**Figure 2.17:** Formation of viscous fingering patterns.

Hot embossing is widely used in the fabrication of many polymeric devices, such as DNA separation and detection chips, etc (Lee et al., 2001). A cross fluidic channel with a cross section of 100 x 40 μm² was embossed for this purpose; as well as channel structures for capillary electrophoresis (Becker and Dietz, 1998). Structures with inclined walls are particularly easy to emboss, as during deembossing only very low frictional forces occur.

The manufacture of CDs, based on imprinting in polycarbonate, is a good example of a large volume commercial application of the embossing technique. Work by Chou showed that embossing can be used to make features as small as 25 nm using a technique called nano-imprint lithography, which is similar to hot embossing. It was
also employed in microstructure products on the threshold of industrial fabrication, such as micromotors, plastic optical waveguides, plastic self-filling micro pumps, as well as micro- and nanotiterplates (Weber et al., 1999). The applications indicate that this method is well suited for the production of planar polymer microstructures from rapid prototyping to high volume production.

The future work on hot embossing will concentrate on the extension of the material range (e.g. towards high $T_g$ materials like PEEK, metals, glass and ceramics), the shortening of the complete process cycle and the optimisation of the process parameters particularly to minimize stresses during the embossing and in the de-embossing stage. The hot embossing machine HEX03eT made by JENOPTIK is based on materials testing machines. These machines can apply very high forces, while movements can be carried out with micron precision (Roetting et al.). In the present project, hot embossing is used as an efficient tool to fabricate the polymeric microcantilevers.

### 2.4.4 Laser Micromachining

Laser ablation is a widely used technology for the fabrication of microfluidic devices (Roberts et al., 1997; Pethig et al., 1998; Wang et al., 2002). Excimer laser drilling of holes in ceramic materials is a technical solution whenever the application requires tight diameter tolerances (such as ± 5 μm); drilling blind holes, milling of channels (± 1 μm depth control); the absence of slag or material build-up on the backside of the substrate; and also no micro-cracking of the material (Jin et al., 2002). Furthermore, laser micromachining can also be applied for surface cleaning (Jin and Ghantasala, 2002). In this process, the energy of a laser pulse is used to break bonds in a polymer molecule and to remove the decomposed polymer fragments, yielding a cleanly machined region. A typical laser ablation set up consists of an excimer laser, which delivers light pulses at 193 nm (ArF) or at 248 nm (KrF) with typical pulse frequencies of 10-1000 Hz, a mask or aperture, and a xy table on which the substrate is mounted. The mask defines the ablated region, while the complete pattern is made by moving the substrate on the xy-stage underneath the mask. Depending on the energy available per laser pulse and on the substrate material, typical ablation rates per laser pulse range between some hundred nm up to 5 μm (Pethig et al., 1998). With this technology a wide range of polymer materials, including polymethyl- methacrylate (PMMA), polystyrene (PS),
polycarbonate (PC), polyethylene terephthalate (PET) and some photoresists have been structured. Most laser micromachining processes are not parallel and hence not fast enough for effective MEMS fabrication. Nonetheless, they have the utility in prototype micromachining or in making moulds. Excimer laser micromachining used is particularly suitable for organic materials (plastics, polymers etc.) because no burning or vaporization effects occur when material is removed. Hence, material adjacent to the machined area is not melted or distorted by thermal effects. Laser light is also used for different purposes, in other microsystems related applications, as well. The best known among these are laser trimming of resistors in hybrid technology and rapid annealing of thin film layers by laser to improve crystal texture. Further applications are the drilling of small holes and etching induced by laser.

2.4.5 Electroplating

Electroplating is a process for metal and/or metal alloy deposition by electrolysis from a salt solution, which has been used for a wide variety of applications ranging from simple metallization of surfaces to decorative coatings, corrosion resistant coatings etc. The potential of this technique for fabricating microstructures of different patterns and shapes is only exploited lately. The first major commercial application was its use in the fabrication of electromagnetic coils and other magnetic structures for different components of computer hard disks. Furthermore, refinement in this technology has led to the use of this technique in the plating of sub-micron-wide copper interconnections for high end pentium microprocessors.

Electroplating technology has been dealt in detail by many text books (Harrison and Thompson, 1973) and (Bockris and reddy, 1970). Though it is extensively used for metallising surfaces, it is not possible to electrodeposit thin films of all elements in the periodic table using water based electrolytes. Elements such as Ti and Al can only be deposited from organic electrolytes, while other metals such as Mg, Nb, Ta and W can only be plated from molten salt electrolytes.

Faraday’s law is the most basic law of electrochemistry, which describes the plating process. Deposition of a metal by electroplating requires an electrolyte. An electrolyte should ideally have suitable salt of the metal dissolved in a solution at a reasonable
temperature and in sufficient amounts. It should have good electrical conductivity in order to prevent excessive heating of the bath at the same time facilitating the possibility of plating at high current densities. Also, its pH value should be within a certain range, so that reduction of the metals occurs before evolution of hydrogen.

When a metal is dipped into a solution containing ions, some of the surface atoms in the metal lattice become hydrated and dissolve in the solution. Simultaneously, some of the ions in the solution become attached to the lattice and are deposited. The rates of these two opposing reactions are controlled by potential differences existing at the metal solution interface. For each metal and solution there is a specific potential at a given temperature, at which the two rates are precisely equal. If no external potential is imposed this equilibrium potential is established at the interface.

\[ M \leftrightarrow M^{n+} + ne^- \]  

(2-1)

The electroplating is normally carried out using a power supply, operating either in constant voltage or in constant current mode, at any given time. The cathode is the substrate onto which the metal has to be plated. It needs to have a conducting surface. Typical materials to be plated are copper, nickel, gold and permalloy (Lin et al., 1995).

Electroplating through patterned photoresist masks has become essential for producing metallic microstructures in the form of coils (Timm and Wilfried, 2002), cantilevers or any other shape required. The processing sequence starts with the deposition of a conducting metallic seed layer on the substrate (glass or silicon), unless they are good electrical conductors themselves. A given photoresist is spun and patterned on top of the seed layer. This forms the mould for plating. Hence, it is always important to choose photoresists which are chemically resistant to acidic or alkaline plating solutions depending on the material to be plated. After the plating step, the photoresist is stripped and the seed layer is etched. This through mask plating technology has been commercially exploited in the fabrication of hard disk drives (Rai-Choudhury, 1997).
2.5 Summary

Micro-electromechanical systems (MEMS) have been developing rapidly for a wide variety of applications in the last decade. A wide range of materials were used in the design and fabrication of MEMS devices and many advanced microfabrication techniques were developed. Microactuators are one of the key components in MEMS devices and employ many different actuation principles for different applications. Each actuation principle has its own advantages and drawbacks. From this literature review it is evident that there is a need to fill the technology gap for microactuators that are especially suitable for covering large forces and large actuation gaps. A hybrid actuation approach combining different actuation principles seems to be the best way to satisfy the desired requirements. Hence, this project aims to work on the design and fabrication of a hybrid actuator, which can provide large enough forces to obtain the deflection over relatively large air gaps. At the same time processes are modified to optimise existing fabrication technologies for realising such hybrid devices. These will be further discussed in the forthcoming Chapters.
Chapter 3  Theoretical Background

3.1 Introduction

As indicated at the end of the last Chapter, this work mainly aims at designing a microactuator having a relatively large air gap compared to any existing single actuator based systems. The design of such a hybrid actuator requires a clear understanding of the actuation principles and the materials used. After carefully considering all the important aspects, piezoelectric and electromagnetic systems are considered suitable for this application. This Chapter in its first part provides the fundamental aspects of piezoelectric materials, especially of polyvinylidene fluoride (PVDF) and their applications. The actuation principles of two kinds of piezoelectric actuators, unimorph and bimorph, and the theoretical background are described further. This is followed by fundamental aspects of magnetic materials, and the theory behind micro magnetic actuation.

3.2 Piezoelectric Actuation

3.2.1 The Piezoelectric Effect

Piezoelectricity (in ancient Greek piezen stands for to squeeze or to press, thus piezoelectricity derives from pressure induced electricity) is a property of certain materials in which the application of a mechanical stress induces an electric charge, and in converse the application of an electric field across the material creates a mechanical strain. These properties are called the direct piezoelectric effect and the inverse piezoelectric effect respectively (Measurement Specialties, 1998; Niu and Eun, 2003; Unworth, 1992). It was first discovered by the brothers Pierre and Jacques Curie in 1880 in some crystals. The piezoelectric effects was later found to occur within a wide range of materials, most prominently in dielectrics and ceramics, such as quartz (SiO₂), alumin-
ium nitride (AlN), or lithium niobate (LiNbO₃), but also in semiconductors (GaAs), polymers and many other materials.

One of the first practical applications of this technology was made in the 1920’s by the French scientist Langevin, who developed a quartz transmitter and receiver for underwater sound - the first SONAR. Before World War II, researchers discovered that certain ceramic materials could be made piezoelectric when subjected to a high polarizing voltage, a process analogous to magnetizing a ferrous material.

By the 1960’s, researchers discovered a weak piezoelectric effect in whale bone and tendon. This started an intense search for other organic materials that might exhibit piezoelectricity. In 1969, Kawai (Heiji, 1969) found very high piezo-activity in the polarized fluoro-polymer, polyvinylidene fluoride (PVDF). While some other polymers, such as nylon and PVC also exhibited this effect, none of them are as highly piezoelectric as PVDF and its copolymers.

The most widely recognized analytical description of the piezoelectric effect was published by a standard committee of the Institute of Electrical and Electronics Engineers (IEEE Standard committee, 1998). This committee formulated linearized constitutive relations, describing piezoelectric continua which form the basis for the model of piezoelectric behaviour that is presently in general use. The linearized constitutive relations are typically represented in a compressed matrix notation as follows:

\[ F = k_e E L^2 - k_p x L \]  

(3-1)

where \( F \) is the actuation force, \( E \) is the electric field strength, \( L \) represents actuator size, \( x \) is the actuator displacement, and \( k_e \) and \( k_p \) are intensive constants associated with the elastic and piezoelectric material properties respectively.

3.2.2 Some Piezoelectric Materials

Some of the popularly used piezoelectric materials are quartz, barium titanate, cadmium sulphide, lead zirconium titanate (PZT), zinc oxide (ZnO), aluminium nitride (AIN), and polymers such as (PVDF, PVC).
The most extensively used natural piezoelectric materials are crystals – quartz and tourmaline. In synthetic piezoelectrics, ceramics formed by many tightly compacted monocrystals are well known. The best known within this group are lead zirconium titanate (PZT), barium titanate, and lead niobate. For aligning the dipoles in these monocrystals in the same direction (i.e., to polarize or pole them), they are subjected to a strong electric field during their fabrication process. Above a certain temperature, known as the Curie point or Curie temperature, the dipole directions in ferroelectric materials have random orientation. To align the dipoles, fields around 10 kV/cm are commonly used at temperatures slightly above the Curie temperature. The ceramic is then cooled while maintaining the field. When the field is removed, the crystallites cannot reorder in random form because of the mechanical stresses accumulated, resulting in a permanent electric polarization. PZT can be grown in thin film form by sputtering and by a sol-gel process. A piezoelectric material PZT with a relative dielectric constant of more than 1000 was reported in the literature. (Fynn and Tavrow, 1992). The sol-gel technique can be used to deposit a 1 µm thick film by repeated spin coatings and a pyrolysis step. Abe et al. (Abe and Reed, 1994) prepared PZT films by sputtering from a composite target and found substrate heating during deposition to be crucial to transform the films into the perovskite phase during subsequent annealing. A problem with these materials relates to their temperature sensitivity and aging (loss of piezo properties) when approaching the Curie temperature.

Similarly, ZnO films with very good piezoelectric characteristics were obtained by applying plasma magnetron sputtering. Using this technique, highly oriented ZnO films have been deposited on SiO$_2$, polycrystalline silicon, and bare silicon substrates by different groups. Muller (Muller, 1987) found the best thin film crystallinity at a sputtering power of 200 W with a 10 mTorr ambient gas mixture consisting of an equal mix of oxygen and argon. The distance between the substrate and target measured about 4 cm with the substrate temperature maintained at 230°C during deposition. Tjhen et al. (Tjhen and tamagawa, 1991) characterized the thin film properties of sputtered ZnO and sol gel deposited PZT and found the electrical properties of both to be sensitive to substrate materials, stress and surface conditions. ZnO thin films are used commercially in acoustic sensors from Honeywell Corp. Microphone chips incorporate ZnO films deposited on a silicon substrate, including signal conditioning circuitry. Besides PZT and ZnO, AlN is another thin film piezoelectric material popular within the sensor industry.
Polymers such as PVDF lacking central symmetry, also display piezoelectric properties. Like traditional piezo materials, PVDF converts mechanical energy to electrical response as well as electrical signals to mechanical motion. Compared to quartz and ceramics, piezoelectric polymers are more flexible and lighter in weight. In addition, they are rugged, inert, and available at low cost. Some typical piezoelectric materials are compared in Table 3.1.

Table 3.1: Comparison of some piezoelectric materials (Niu and Eun, 2003).

<table>
<thead>
<tr>
<th>Material</th>
<th>Piezoelectric constant (pC/N)</th>
<th>Dielectric constant</th>
<th>Curie temp (ºC)</th>
<th>Coupling coefficient</th>
</tr>
</thead>
<tbody>
<tr>
<td>Quartz</td>
<td>$d_{14}=0.73$</td>
<td>$\varepsilon_1=4.52$</td>
<td>550</td>
<td>0.1</td>
</tr>
<tr>
<td>PZT (depending on composition)</td>
<td>$d_{33}=80-593$ $d_{31}=-94-274$ $d_{15}=494-784$</td>
<td>$\varepsilon_3=425-1900$</td>
<td>193-490</td>
<td>0.69-0.75</td>
</tr>
<tr>
<td>PVDF (Kynar)</td>
<td>$d_{31}=23$ $d_{32}=4$ $d_{33}=-35$</td>
<td>$\varepsilon=4$</td>
<td>&gt;150</td>
<td>0.2</td>
</tr>
<tr>
<td>ZnO</td>
<td>$d_{15}=-12$ $d_{33}=12$ $d_{31}=-4.7$</td>
<td>$\varepsilon_3=8.2$</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Sol-gel PZT</td>
<td>$d_{33}=220$ $d_{31}=-88.7$</td>
<td>$\varepsilon=1300$</td>
<td>-</td>
<td>0.49</td>
</tr>
</tbody>
</table>

3.2.3 Polyvinylidene Fluoride (PVDF) – a Piezoelectric Polymer

Piezoelectricity seems to be a fundamental property of many organic polymers. A finite and measurable piezoelectric effect has been observed in many synthetic polymers, as well as in many biological materials. These include the collagen phase of bones, tendons, and skin, as well as the DNA molecule, proteins, amino acids and plant leaves. In many of these materials, the origin of the effect has been connected to the presence of dipoles and to the lack of symmetry of the crystals. The largest piezoelectric response reported so far in polymers has been observed in polyvinylidene fluoride (PVDF) and its copolymer with vinylidene trifluoride P(VDF-TrFE). It was first found
in 1969 by Heiji in poled PVDF. He described that “a new type of piezoelectric effect has been discovered in elongated and polarized films of polymers, particularly of poly(vinylidene fluoride) (PVF2).”

Recently, the advent of a copolymer of PVDF poly(vinylidene fluoride-trifluoroethylene) with high energy density (~1 J/cm$^3$) has been reported (Xu, Cheng and Zhang, 2002). It exhibits a very high stroke level with high load capability and a high displacement voltage ratio. This copolymer can be spin coated on a silicon substrate to form a transducer (Fiorillo and Dario, 1987). The advantage of this copolymer over PVDF is that it can be poled by corona discharge at high temperature after spin coating. These engineering materials could provide a sensing solution for vibration sensors, acceleration and shock sensors, passive infrared sensors, solid state switches, and acoustic and ultrasonic sensors.

**Physical properties of PVDF**

The physical properties of the PVDF has been studied by many scientists (Broadhurst and Davis; Osada and Derossi, 2000; Xu, 1991). Polyvinylidene fluoride (PVDF) is a semi-crystalline high molecular weight polymer with the basic repeating unit (CH$_2$ - CF$_2$), the structure of which is head-to-tail, i.e., CH$_2$ - CF$_2$ - (CH$_2$-CF$_2$)$_n$ - CH$_2$-CF$_2$. The origin of the piezoelectric effect in PVDF can be attributed to the non-symmetrically aligned electronegative fluorine atom in each monomer. The charge times the displacement from alignment in the planes of the unit cell characterizes the dipole contribution. The monomer unit has a dipole moment of 7.0 x 10$^{-30}$ Cm perpendicular to the chain direction. If all the monomer dipoles were aligned along the field direction, a maximum microscopic polarisation of 0.1 Cm$^{-2}$ could be obtained. However, semi-crystalline PVDF is approximately 50%–65% crystalline and the observed polarisation of 0.065 Cm$^{-2}$ confirms its dipolar origin. PVDF has at least four major crystalline phases designated as $\alpha$-, $\beta$-, $\gamma$-, and $\delta$-form, differing from each other by chain packing and conformation. The non-polar alpha phase and the highly polar beta phase, as shown in Figure 3.1, are the most relevant phases for practical ferroelectric and piezoelectric applications. Among these, the alpha phase is the most common structure; consisting of a series of non-polar anti-parallel chains, whereas the beta phase has
the hydrogen and fluorine atoms arranged in a series of polar parallel chains, resulting in a maximum dipole moment per unit cell.

PVDF is inherently polar. The hydrogen atoms are positively charged and the fluorine atoms are negatively charged with respect to the carbon atoms in the polymer. In the liquid phase, the molecules continually change shape due to rotations about the carbon-carbon bonds. The average dipole moment of a group of molecules in a liquid region is zero in the absence of an electric field because of the random orientation of the individual dipoles. Under the application of an electric field, the polymer chains inside the crystallites align themselves along the field by rotating the dipoles about the chain axis. The piezoelectric response of PVDF polymers is the result of a net polarization. Mechanical stretching is often used in order to convert the alpha phase to the beta phase.

![Figure 3.1: Schematic view of the α-, and β-PVDF phases.](image)

**Poling**

As described by Kawai, piezoelectricity appears in PVF2 (PVDF) films after the following treatment. The films were stretched several times the original length at 100-150°C. A static electric field (about 300 kV/cm) was applied to such films along their thickness and the temperature was raised gradually from room temperature to 90°C and then slowly cooled. The threshold temperature to give a persistent polarization was about 60°C, while the most suitable temperature for polarization was 90°C.
PVDF can be poled by stretching the film by some 300% elongation at about 50°C. This stretching converts the type α polymer to type β. An electric field is then applied to the electrode polymer film whilst it is held at a temperature of about 90°C in oil. This aligns the domains to achieve saturation polarization. The plastic deformation of the film is permanent although there is some slight elastic recovery as expected for a thermoplastic material. These domains become locked in position in the crystalline structure when the film is cooled down, as shown in Figure 3.2 (Lovinger, 1984). Though the mechanical stretching results in the formation of the β-phase, the –CF₂ dipoles are still randomly oriented in the plane perpendicular to the axis of mechanical tension. Therefore, electric field poling is necessary to rotate the dipoles towards the direction perpendicular to the plane of the film, thus maximizing its piezoelectric coefficients.

The direction of polarization is generally designated as the z-axis of an orthogonal crystallographic system. The axes x, y, and z are represented as 1, 2, and 3 directions.
respectively and the shear about these axes are represented as 4, 5, and 6. This is shown schematically in Figure 3.3.

![Diagram of axes for a piezoelectric thin film](image)

Figure 3.3: Conventional identification of axes for a piezoelectric thin film (e.g. PVDF).

The most widely used piezo coefficients are $d_{3n}$ and $g_{3n}$, named piezo strain coefficient and piezo stress coefficient, possessing two subscripts. The first refers to the electrical axis, while the second subscript refers to the mechanical axis. Because piezo films are thin, the electrodes are only applied to their top and bottom surfaces. Accordingly, the electrical axis is always ‘3’, as the charge or voltage is always transferred through the thickness ($n=3$) of the film. The mechanical axis can be 1, 2, or 3, since the stress can be applied to any of these axes, as shown in Figure 3.3.

Piezoelectric materials are anisotropic. This means that their electrical and mechanical response differs depending upon the axis of applied electrical field or axis of mechanical stress or strain. Calculations involving piezo activity must account for this directionality.

The largest piezoelectric coefficient value of $g_{31}$ found in PVDF films was approximately 150 mV/g, where the x axis is in the direction of elongation. The value of $g_{32}$ was usually about one fifth of $g_{31}$. There is a slight variation of $g_{31}$ with temperatures around room temperature, but the piezoelectricity vanished irreversibly, when exceeding 80°C. The spontaneous polarization in piezoelectric PVDF films was estimated to be about 2000 kV/cm in terms of an equivalent electric field.

PVF and PVC were also given a large piezoelectricity by a similar procedure, although the threshold temperature was a little lower. The variation of the effect with temperature was also similar to that in PVDF. Usually, the piezoelectric effect in PVDF,
PVF and PVC does not decay at a time scale of several months. However, if the polarizing process is not done adequately, the effect can be small and gradually decays. In fact, the piezoelectric state in a poled ferroelectric polymer, or in any ferroelectric material, can be regarded as the remanent polarization biased electrostriction.

Piezoelectricity was also observed in polarized polycarbonate, polyethylene and polytetrafluoroethylene, although the effect was small and decayed with time. The effect could not be observed in polystyrene, cellulose triacetate, polyester, 6-nylon, and polyethyleneterephthalate. Table 3.2 lists the piezoelectricity of some polymer films.

Table 3.2: Piezoelectricity of some polymer films (thickness: 30-50 µm).

<table>
<thead>
<tr>
<th></th>
<th>$g_{31} = 4\pi d_{31}/\varepsilon_{31}$ (V/g)</th>
<th>$d_{31}$ (c. g. s)</th>
<th>Polarizing temperature (°C)</th>
<th>Polarizing field (kV/cm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Poly(vinylidene fluoride)</td>
<td>150-70$\times 10^{-3}$</td>
<td>20-10$\times 10^{-8}$</td>
<td>50-90</td>
<td>320</td>
</tr>
<tr>
<td>Poly(vinyl fluoride)</td>
<td>20-15</td>
<td>4-3</td>
<td>60-80</td>
<td>200</td>
</tr>
<tr>
<td>Poly(vinyl chloride)</td>
<td>15-10</td>
<td>1.5-1</td>
<td>50-70</td>
<td>180</td>
</tr>
<tr>
<td>Polycarbonate</td>
<td>3</td>
<td>0.3</td>
<td>120</td>
<td>200</td>
</tr>
<tr>
<td>Polytetrafluoroethylene</td>
<td>0.8</td>
<td>0.02</td>
<td>220</td>
<td>300</td>
</tr>
<tr>
<td>Polyethylene(high density)</td>
<td>0.2</td>
<td>0.005</td>
<td>125</td>
<td>200</td>
</tr>
<tr>
<td>Polypropylene</td>
<td>small</td>
<td></td>
<td>90</td>
<td>200</td>
</tr>
<tr>
<td>Poly(vinylidene chloride)</td>
<td>small</td>
<td></td>
<td>70</td>
<td>200</td>
</tr>
</tbody>
</table>

Properties of PVDF

PVDF films are typically thin, flexible, have low density and excellent sensitivity, yet piezoelectric films are mechanically tough. The compliance of PVDF films is 10 times greater than that of ceramics. When extruded into a thin film, piezoelectric polymers can be directly attached to a structure without disturbing its mechanical motion. Piezoelectric films are well suited to strain sensing applications requiring very large bandwidth and high sensitivity. As an actuator, the polymer’s low acoustic impedance
permits the efficient transfer of energy into air and other gases. Typical properties of piezo-films are listed in Table 3.3.

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Parameter</th>
<th>PVDF</th>
<th>Copolymer</th>
<th>Units</th>
</tr>
</thead>
<tbody>
<tr>
<td>T</td>
<td>Thickness</td>
<td>9, 28, 52, 110</td>
<td>Various</td>
<td>μm</td>
</tr>
<tr>
<td>d31</td>
<td>Piezo strain constant</td>
<td>23</td>
<td>11</td>
<td>$10^{-12} \frac{m/m}{V/m \cdot C/m^2}$</td>
</tr>
<tr>
<td>d33</td>
<td></td>
<td>-33</td>
<td>-38</td>
<td></td>
</tr>
<tr>
<td>g31</td>
<td>Piezo stress constant</td>
<td>216</td>
<td>162</td>
<td>$10^{-3} \frac{V/m \cdot m/m}{N/m^2 \cdot C/m^2}$</td>
</tr>
<tr>
<td>g33</td>
<td></td>
<td>-330</td>
<td>-542</td>
<td></td>
</tr>
<tr>
<td>K31</td>
<td>Electromechanical Coupling factor</td>
<td>12%</td>
<td>20%</td>
<td></td>
</tr>
<tr>
<td>Kt</td>
<td></td>
<td>14%</td>
<td>25-29%</td>
<td></td>
</tr>
<tr>
<td>C</td>
<td>Capacitance</td>
<td>380 for 28μm</td>
<td>68 for 100μm</td>
<td>pF/cm² at 1KHz</td>
</tr>
<tr>
<td>Y</td>
<td>Young’s modulus</td>
<td>2-4</td>
<td>3-5</td>
<td>$10^9$ N/m²</td>
</tr>
<tr>
<td>V₀</td>
<td>Speed of sound</td>
<td>1.5</td>
<td>2.3</td>
<td>$10^3$ m/s</td>
</tr>
<tr>
<td></td>
<td>Stretch: thickness</td>
<td>2.2</td>
<td>2.4</td>
<td></td>
</tr>
<tr>
<td>P</td>
<td>Pyroelectric coefficient</td>
<td>30</td>
<td>40</td>
<td>$10^{-6}$ C/m² °K</td>
</tr>
<tr>
<td>ε</td>
<td>Permittivity</td>
<td>106-113</td>
<td>65-75</td>
<td>$10^{-12}$ F/m</td>
</tr>
<tr>
<td>ε/ε₀</td>
<td>Relative permittivity</td>
<td>12-13</td>
<td>7-8</td>
<td></td>
</tr>
<tr>
<td>ρₘ</td>
<td>Mass density</td>
<td>1.78</td>
<td>1.82</td>
<td>$10^3$ kg/m³</td>
</tr>
<tr>
<td>ρₑ</td>
<td>Volume resistivity</td>
<td>$&gt;10^{13}$</td>
<td>$&gt;10^{14}$</td>
<td>Ohm meters</td>
</tr>
<tr>
<td>R</td>
<td>Surface metallization resistivity</td>
<td>2.0</td>
<td>2.0</td>
<td>Ohms/square for CuNi</td>
</tr>
<tr>
<td>R</td>
<td>Surface metallization resistivity</td>
<td>0.1</td>
<td>0.1</td>
<td>Ohms/square for Ag ink</td>
</tr>
<tr>
<td>tanδₑ</td>
<td>Loss tangent</td>
<td>0.02</td>
<td>0.015</td>
<td>@1kHz</td>
</tr>
<tr>
<td></td>
<td>Yield strength</td>
<td>45-55</td>
<td>20-30</td>
<td>$10^9$ N/m² stretch axis</td>
</tr>
<tr>
<td></td>
<td>Temperature range</td>
<td>-40 to 80</td>
<td>-40 to 115-145</td>
<td>°C</td>
</tr>
<tr>
<td></td>
<td>Water absorption</td>
<td>&lt;0.02</td>
<td>&lt;0.02</td>
<td>%H₂O</td>
</tr>
<tr>
<td></td>
<td>Max Operating voltage</td>
<td>750(30)</td>
<td>750(30)</td>
<td>V/mil(V/μm), DC@</td>
</tr>
<tr>
<td></td>
<td>Breakdown voltage</td>
<td>2000(80)</td>
<td>2000(80)</td>
<td>25°C</td>
</tr>
</tbody>
</table>

(Source: www.msiusa.com)
Applications

Piezoelectric polymers PVDF are widely used in sensor elements and actuators. Measurement Specialties Inc. supplies a wide range of piezo film sensors made from PVDF. It is feasible to generate power from the conversion of mechanical energy into electrical energy by bending a PVDF beam (Elvin, 2001). The idea of generating and storing electrical energy can be used for sensors in wireless communication system. Shan and his co-workers in Nanyang Technology University, Singapore use PVDF as a suspension structure in hard disks for dynamic analysis (Shan, Gao and Lin, 2001). Dargahi et al. designed a tactile sensor for an endoscopic grasper using a PVDF film (Darghai et al., 2000).

In addition, PVDF polymers are used or potentially applied in the following fields: Pressure Pick Ups: distribution of pressure on surfaces, localization of impacts, accelerometers, keyboards; Electrical Components: switches, miniature electric fan; Acoustic Components: microphones, ultrasonic detectors, hydrophones, sonar; Security Devices: intruder alarms, IER alarms, vibration sensors; Robotics: tactile sensors for robot grippers, artificial sensitive skin; Medical Instruments: catheter, pedobarography, osteogenesis, lithotrophy, medical, echography, blood pressure detector; Optical Devices: laser diameter measurement, variable mirrors.

3.2.4 Piezoelectric Actuators

When a voltage is applied to a sheet of piezo-film, it causes the film to change dimensions due to the attraction or repulsion of internal dipoles to the applied field. When a voltage of one polarity is applied, the piezo-film becomes thinner, longer and wider, whereas the opposite polarity causes the film to contract in length and width and to become thicker. An AC voltage causes the film to vibrate.

The matrix relationship between strain and electric field is given as follows (Koch, 2000; Kohnke, 1999):

$$\{S\} = [d] \{E\}$$  \hspace{1cm} (3-2)
where \( S \) is the strain produced by the electrical field \( E \), \( d \) is the piezoelectric coefficient matrix.

The amounts of deformation resulting from the piezoelectric coefficients \( d_{3n} \) are:

\[
\begin{bmatrix}
S_1 \\
S_2 \\
S_3
\end{bmatrix} =
\begin{bmatrix}
\Delta l/l \\
\Delta w/w \\
\Delta t/t
\end{bmatrix}
\begin{bmatrix}
0 & 0 & d_{31} \\
0 & 0 & d_{32} \\
0 & 0 & d_{33}
\end{bmatrix}
\begin{bmatrix}
0 \\
0 \\
E
\end{bmatrix}
\]

(3-3)

where \( \Delta l \) is the change in film length in meters, \( l \) is the original film length in meters, \( d_{31} \) the piezoelectric coefficient for length (n=1 direction) change in meters per volt, \( d_{32} \) the piezoelectric coefficient for width (n=2 direction), \( d_{33} \) the piezoelectric coefficient for thickness (n=3 direction), and \( E \) the applied electrical field across the thickness (\( V/t \)).

For example, let us assume a piezoelectric film of 3 cm length, 2 cm width and 9 \( \mu \)m thickness is subjected to an applied voltage of \( V=200 \) volts in the 3 (thickness) direction. The amount of strain \( S \) resulting from this electrical excitation is:

\[
S_1 = \frac{\Delta l}{l} = d_{31} \frac{V}{l} = 23 \times 10^{-12} \frac{m}{m} \cdot \frac{200V}{9 \times 10^{-6}}
\]

\( l = 3cm = 3 \times 10^{-2} m \)

\( \Delta l = 1.53 \times 10^{-5} m = 15.3 \mu m \)

\( \Delta t = d_{33} V = 6.6 \times 10^{-9} m \)

The setup of a piezoelectric actuator can mainly be classified in two groups, namely a unimorph or a bimorph (Popovic and Vlacic, 1999). A single piezoelectric sheet bonded to a non-piezoelectric substrate is called a unimorph, whereas two piezoelectric sheets bonded together are called a bimorph.

**Piezoelectric unimorph actuator**

Figure 3.4 shows a cross sectional view of a typical piezoelectric unimorph microactuator. When a voltage is applied perpendicular to the piezoelectric layer, this leads to a strain along its stretch direction 1. Hence, due to the firm attachment to an elastic carrier layer, a bending moment is produced. In order to simplify the problem, we assume the width of the beam is equal to unity. The following analysis has been
made on the assumption that cross-sections of the beam which are originally plane and perpendicular to the axis remain plane during bending and become perpendicular to the curved axis of the beam.

![Figure 3.4: Piezoelectric unimorph microactuator.](Popovic and Vlacic, 1999)

We consider an element cut out from the beam by two cross sections MN and $M_1N_1$. Furthermore, we assume the electrical field to cause an upward bending of the beam (Koch, 2000; Timoshenko, 1953) as shown in Figure 3.5. All forces acting on the interface between the piezo-layer and the elastic layer are uniform surface forces. They can be represented by an axial tensile force $P_1$, a compressive force $P_2$, and bending moments $m_1$ and $m_2$. The thicknesses of the piezoelectric layer and the elastic layer are $h_p$ and $h_m$ respectively, and the total thickness of the unimorph is $h$. Because there are no external forces acting on the beam, all forces acting over any cross section of the beam must be in equilibrium. Therefore,

$$ P_1 = P_2 = P $$ \hfill (3-4)

$$ \frac{1}{2} Ph = m_1 + m_2 $$ \hfill (3-5)

Setting $Q$ as radius of curvature of the strip, $E_pI_p$ as the flexural rigidity of the piezo material, $E_MI_M$ the flexural rigidity of the permalloy, then $m_1=\frac{E_pI_p}{Q}$, and $m_2=\frac{E_MI_M}{Q}$. Substituting in (3-4), we get,

$$ \frac{1}{2} Ph = \left(\frac{E_pI_p + E_MI_M}{Q}\right) $$ \hfill (3-6)
Another equation obtained from the consideration of deformation will be used in calculating $P$ and $Q$. On the interface of both layers of the beam the elongation occurring must be equal to keep the two layers in contact. The strain in the piezoelectric layer caused by the piezoelectric charge is constant for a given piezo-coefficient $d_{31}$. This generates a stress in the plane perpendicular to the applied electrical field $E$. Therefore,

$$d_{31}E + \frac{P_1}{E_p A_p} + \frac{P_2}{E_m A_m} = -\frac{A_M}{2Q}$$

(3-7)

The inverse bending radius $K$, i.e., the second derivative of the deflection, is given by:

$$K = \frac{1}{Q} = \frac{-d_{31}E}{h/2 + 2/h \left( \frac{1}{E_p h_p} + \frac{1}{E_m h_m} \right) \left( E_p I_p + E_m I_m \right)}$$

(3-8)

where $d_{31}$ is the piezo-strain coefficient, $E$ is the electric field applied on the piezoelectric cantilever, $h_p, h_m$ are the thicknesses of the piezo layer, the elastic layer and the total beam respectively, $E_p, E_m$ are Young’s moduli of the piezo-layer and the elastic layer respectively, and $I_p, I_m$ are the moments of inertia of these layers. For a cantilever beam with rectangular cross section, $I$ is given by (Timoshenko, 1953).
\[ I = \frac{wh^3}{12} \]  \hspace{1cm} (3-9)

where \( w \) and \( h \) are the width and thickness of the beam respectively. The tip deflection of the cantilever \( \delta \) can be obtained by

\[ K = \frac{\partial^2 \delta}{\partial \lambda^2} \]  \hspace{1cm} (3-10)

where \( x \) is the length of the cantilever. Using a length of 5 mm and a width of 1 mm for the cantilever dimensions, a thickness of 28 \( \mu \)m of the piezo-layer and of 5 \( \mu \)m for the elastic layer, as well as a value of 2.8 GPa for the Young’s modulus of the piezo-layer and of 150 GPa for the non-piezoelectric layer, the tip deflection as calculated from equations (3-5) and (3-7) is 67.6 \( \mu \)m.

**Piezoelectric bimorph actuator**

A bimorph is another typical setup used for piezoelectric polymer actuators. Two sheets of piezo films of opposite polarities are bonded together to form such a bending element. An applied voltage causes one film to elongate, while the other contracts, causing the unit to bend. Reversing voltage leads to a bending of the bimorph in the opposite direction as shown in Figure 3.6. The bimorph configuration converts small length changes into sizable tip deflections. However, the force developing on the tip is very limited. Increasing the thickness of the films leads to larger forces, but sacrifices displacement unless the unit can be operated at higher fields.

The amount of tip deflection \( \delta \) and of the force \( F \) generated by piezoelectric effect is given by

\[ \delta = \frac{3}{4} d_{31} \frac{l^2}{t} V \]

\[ F = \frac{3}{2} Yw d_{31} \frac{l}{t} V \]  \hspace{1cm} (3-11)
where $Y$ is Young’s modulus of the piezo-film, $t$ is the thickness of the piezo film, $l$ is the length of the bimorph cantilever and $w$ is the width of the bimorph. By applying an AC voltage, the bimorph starts vibrating, acting as a fan, similar to an insect’s wing. Although the piezo-film bimorph does exhibit a DC response, larger tip deflections can be obtained when the unit is operated at resonance, provided the quality factor is larger than one. For example, a 100 V DC voltage is applied across a 2 cm long, 5 mm wide cantilever bimorph comprised of two strips of 9 µm PVDF. The resultant tip displacement is 8.5 mm, and the generated force is 15.5 µN.

As can be seen from the equations (3-10), a larger displacement can be obtained from a longer bimorph. Larger forces can be obtained from a wider bimorph. The ratio of displacement at the resonance frequency and at the DC actuation is defined by the quality factor $Q$, which indicates a mechanical gain. A typical $Q$ value obtained for such an actuator is 20 to 25, depending on the surrounding atmosphere. For example, a 5 mm long, 70 µm thick bimorph with 120 V DC creates a tip displacement of 57 µm. With the same bimorph, however, the displacement can be 1.4 mm at the resonance frequency of 580 Hz.

For applications that require a high force, such as cooling fans, multilayer construction can be considered. The resulting output force is proportionally increased by the number of layers. Typical applications of the bimorph bender are ultrasonic generators, piezoelectric motors, and laser beam deflectors (Uchino, 1992).
3.3 Magnetic Actuation

3.3.1 Basics of Magnetics

Magnetism is concerned chiefly with the properties of permanent magnets, while electromagnetism deals with the magnetic effect of electric currents. Fundamental to all magnetic theory was built on the concept that a magnetic field is produced when a current passes through a conductor. The direction and intensity is a function of direction and amplitude of the current.

The simple circuit shown in Figure 3.7 depicts how electrical energy is converted to magnetic energy. A current source is attached to a conducting wire. The current is called the excitation current and, when used with a certain coil geometry, results in the magnetizing force, or MMF (magneto-motive force) per unit length, or the H of the coil. The appropriate unit is Oersted in the CGS system and AMP-turn per meter in the SI system. Units of MMF are Gilbert in CGS and AMP-turn in SI systems (Arnold, 2003).

![Figure 3.7: Magnetic field around a current.](image)

1 Amp-turn/meter = 0.0125 Oersted

The flow of current creates a magnetic “force field” that is concentric to the conductor. This field is called magnetic flux or B and can be symbolized by lines of flux. It stores potential energy. The units used are Weber or Vs (Volt-seconds) in the SI system, and Maxwell in CGS.
1 Weber = 1 Vs; 1 Weber = 108 Maxwell

From this beginning, scientists improved the phenomenon to perform work more efficiently. The single loop of wire was made into a coil with multiple turns (see Figure 3.8), proportionately increasing the amount of lines of flux produced by a limited amount of current. The amount of force produced can be increased drastically by inserting an iron “core” inside the coil conductors (see Figure 3.9). Flux density refers to the number of lines of flux per unit of cross-sectional area and is also sometimes referred to as induction. The unit of measure of flux density is Gauss in CGS units and Tesla in SI units. 1 Tesla = 10,000 Gauss, 1 Tesla = 1 Weber/meter$^2$, 1 Gauss = 1 Maxwell/cm$^2$

![Figure 3.8: Magnetic field in a multiple turn coil.](image1)

Flux density is one of the parameters used to determine the amount of magnetic energy stored in a given geometry. The other parameter is the MMF, described previously. When a magnetic material is inserted into a coil as shown in Figure 3.9, the resulting flux (or flux density) consists of two constituents—one being the contribution of the coil itself, the other the contribution of the iron core. These two parts are additive, the total flux being the sum of the two, e.g. $\text{FLUX}_{\text{core}} + \text{FLUX}_{\text{coil}} = \text{FLUX}_{\text{total}}$.  

![Figure 3.9: Magnetic field in coil with iron core.](image2)
The significance of this is best demonstrated by the use of normal and intrinsic demagnetization curves shown later in Figure 3.11. The intrinsic curve is representative of the magnet’s contribution, and the normal curve is the magnet plus the coil.

### 3.3.2 Terminology and Equations

**Permeability**

Not all magnetic materials respond equally to the applied MMF. In other words, different materials exhibit different flux densities when subjected to the same magnetization levels. To account for this, scientists developed a term to describe the mathematical ratio of flux density to magnetizing force. This ratio, called permeability, is a measure of the magnetic sensitivity of the material. Every magnetic material has a permeability that is numerically greater than the value of the permeability of free space (vacuum). This means that magnetic materials are more responsive to the applied MMF than the space that they occupy. Since the value of a magnetic material’s permeability is expressed relative to the permeability of free space, it is a dimensionless number. The value of the permeability of free space, however, is quite different in the two systems. Absolute permeability of free space is 1 (CGS) or $4\pi \times 10^{-7}$ (MKS). The relative permeability of some magnetic materials is listed in Table 3.4.

<table>
<thead>
<tr>
<th>Material</th>
<th>Relative permeability</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hard ferrite</td>
<td>Slightly &gt; 1</td>
</tr>
<tr>
<td>Neo-Fe</td>
<td>Slightly &gt; 1</td>
</tr>
<tr>
<td>Samarium-cobalt</td>
<td>Slightly &gt; 1</td>
</tr>
<tr>
<td>Perm. of alnico</td>
<td>3-7</td>
</tr>
<tr>
<td>MPP</td>
<td>14-350</td>
</tr>
<tr>
<td>Powdered iron</td>
<td>8-75</td>
</tr>
<tr>
<td>Silectron</td>
<td>up to 30,000</td>
</tr>
<tr>
<td>Supermalloy</td>
<td>up to 300,000</td>
</tr>
</tbody>
</table>

Unfortunately, the permeability of magnetic materials is not constant. It is observed that permeabilities will change over a range of several decades, as the excitation
level is varied. Also, real-world materials are affected by their environment, and things like temperature and mechanical shock can have a profound effect on the actual value of permeability.

**Saturation**

Although magnetic materials are more susceptible to excitation than vacuum, they have the drawback of limited flux capacity. As the applied excitation becomes higher and higher, the material reaches a point where its permeability approaches the permeability of free space and it cannot hold any more magnetic energy. This point is referred to as saturation and is characterized by the material’s saturation flux density.

Saturation is strictly a material property; it is not a function of the excitation current. A material’s saturation flux density is only a result of its metallurgy and its operating temperature.

**BH Loop**

In order to differentiate the properties of specific materials more easily, a measurement technique was devised that clearly shows all the phenomena described above. This is the hysteresis diagram, or as it is more commonly called the BH Loop. It is of basic importance for designing a magnetic instrument.

The BH loop is obtained by exciting the magnetic material sample with a controlled, varied MMF and simultaneously recording the resulting flux density induced in the sample. The loop is obtained by exciting the sample up to saturation in the positive direction and then reversing direction and exciting it in the negative direction. In a final step the direction is reversed again, returning to the positive saturation point.

Depending on the strength of the magnetic field applied, the sample may or may not reach saturation during the test sequence. This point is of particular significance in the permanent magnets, where the full potential of a material can only be realized if it is completely saturated when magnetized. It should be mentioned that for all permanent magnetic materials and for a few soft magnetic materials, the excitation source is actually an electromagnet where the amp-turns are indirectly applied to the sample.
Figure 3.10 shows a typical BH or hysteresis loop. The flux density $B$ is displayed on the vertical axis and the magnetizing force $H$ is on the horizontal axis. Note that positive and negative values of both parameters are utilized. One variation of the BH loop is the demagnetization curve commonly used to display the properties of permanent magnetic materials. The “demag” curve only represents the second quadrant of the full BH loop. This is where the material has been magnetized and now a gradual demagnetizing MMF is being applied (and thus the term demag).

For accurate results, the magnetic sample being measured should start in a completely demagnetized state. This would be the axis point $(0, 0)$ on the BH loop in Figure 3.10. At this point the excitation current is zero and the sample contains no flux. As excitation is increased slowly in the positive direction, flux builds up in the material, also in the positive direction. Generally, the excitation is increased until saturation occurs. This point of maximum excitation is signified by $(+B_m, +H_m)$, where $+B_m$ is the maximum flux density observed and $+H_m$ is the maximum MMF applied. Current then is slowly decreased to zero, to the point on the curve labelled $(+B_r, 0)$. But, as indicated in Figure 3.10, the flux does not return to zero. Instead the flux density assumes what is called the residual flux of the sample. The symbol for residual flux is $B_r$.

One of the distinguishing characteristics of real world magnetic materials is that they have “memory” of their previous excitation condition. This results in a “lag” in the response of the material when the excitation is varied. The residual flux is a manifesta-
tion of this phenomenon. (It should be noted that all magnetic materials, including core products, have residual flux values.) This lag is referred to as hysteresis, from which the name hysteresis diagram or hysteresis loop is taken.

Now the excitation is increased in the negative direction, and a demagnetizing force is applied against the sample’s inherent residual flux. Eventually, the magnetic energy, in the form of flux, is forced out of the sample and the flux. The remainder of the BH loop is simply a mirror image of the first two quadrants. The sample is driven to \((-B_m, -H_m)\), then \((-B_r, 0)\) then \((0, +H_c)\) and finally back to \((+B_m, +H_m)\).

As mentioned earlier, the flux in the “air space” within the exciting coil does contribute to the total, or normal, flux observed or measured in the BH loop. Some hysteresis graphs are equipped to correct for this and display the intrinsic BH loop of the material. This additional flux contribution is only of significance in those situations (such as Arnox and Neo-Fe) where it takes a large MMF to magnetize and demagnetize the material, or for materials such as low-permeability powder cores where it takes a significant amount of MMF to saturate the material. This subject is dealt with only rarely in the case of soft magnetic products, but in permanent magnet literature, both the normal and intrinsic demagnetization curves usually are given for high coercivity materials as shown in Figure 3.11. For intrinsic BH loops, an additional “i” subscript is added to all the defining parameters described above. In other words, \(H_{ci}\) is the intrinsic coercivity of the sample, whereas \(H_c\) is the normal coercivity. Both normal and intrinsic demagnetization curves are of significance to the permanent magnetic circuit designer.

The relationship between the magnetic field \(H\) and the magnetic flux density \(B\) in free space is \(B=\mu_0 H\), with the permeability of free space \(\mu_0\). When the magnetic field and flux density are inside the magnetic materials, the equation of free space must be adjusted to account for the magnetization \(M\) of the materials. There are many forms of this equation, one of them is \(B=\mu_0 H+M=\mu_0 H+\mu_r H\), with the relative permeability \(\mu_r\) and thus the units of \(M\) are the same as \(B\).
3.3.3 Magnetic Materials for MEMS

Magnetic materials can be classified according to their magnetic susceptibility \( x/\mu_0 \) and relative permeability \( \mu_0 \) into several categories: ferromagnetic, antiferromagnetic, paramagnetic, diamagnetic, and superconducting materials. Table 3.5 (Judy and Myung, 2002) lists the typical ranges of \( x/\mu_0 \) for each category of magnetic materials. Of these, ferromagnetic materials have been used widely in magnetic microsensors, microactuators, and microsystems. Their high relative permeability amplifies small magnetic fields into large flux densities for microsensors and their high saturation magnetization can generate strong fields for microactuation.

When ferromagnetic materials are magnetized, demagnetized, and re-magnetized, they exhibit a hysteresis behaviour as shown in Figure 3.10. Important and often quoted features of these graphs are the saturation magnetization \( M_s \), remanent magnetization \( M_r \), coercivity \( H_c \), and saturating field \( H_s \). With these parameters, ferromagnetic materials can be divided into so-called soft magnetic materials (i.e., with a small coercivity and low saturation field) and hard magnetic materials (i.e., with a large coercivity and high saturation field).
The most commonly used magnetic materials in MEMS are soft ferromagnetic materials, such as NiFe alloys (e.g., permalloy, with a typical composition of 81% Fe and 19% Ni). The combination of relatively high saturation flux density, low hysteresis losses, and near zero magnetostriction (i.e., stress in the device will not impact its magnetic performance) has driven their use in macroscopic and microscopic sensors, actuators, and systems. The most successful and often quoted commercial applications of these magnetic materials in microtechnology are the magnetic recording heads. This has been driving the development of many fabrication technologies required for applying these exotic materials.

### 3.3.4 Theory of Magnetic Actuation

Magnetic microactuation is based on the electromagnetic effect, and force is created between the electric coil and a magnet. Several magnetic microactuators with a permanent magnet and a planar coil were reported by Wagner et al. (1990) and Lagorce et al. (1990). A schematic drawing of a typical setup is shown in Figure 3.12, in which the vertical force (along the z direction) acting on the magnet (or coil) is calculated

\[
F_z = M \int \frac{dH}{dz} dV
\]  

(3-12)
where $M_z$ is the magnetization of the permanent magnet, $V$ the volume of the permanent magnet, and $H_z$ is the vertical component of the magnetic field produced by the coil. The expression of $H_z$ produced by a current loop can be obtained by integration of the Biot-Savart Law. For a short solenoid carrying a current $I$ and having $n$ turns per meter along the solenoid axis, the magnetic induction profile is graphically shown in Figure 3.13 (b).

![Figure 3.12: Examples of a magnetic microactuator.](image)

(Wagner et al., 1990)

(a) Flux line in a short solenoid.
(b) Magnetic field profile along the solenoid axis.
(c) Schematic of the solenoid.

Figure 3.13: Magnetic field in a short solenoid.

The field inside the solenoid is constant, whereas the field strength at its ends decreases because the flux lines of $B$ spread out at the ends as shown in Figure 3.13 (a). The magnetic induction at any point outside the axis is (Lorrain, 1979; Shen, 1983)
\[ B = \frac{1}{2} \mu_0 k n (\cos \alpha_1 + \cos \alpha_2) \quad (3-13) \]

Where \( \alpha_1 \) and \( \alpha_2 \) are the angles subtended at the point by a radius \( R \) at either end of the solenoid as shown in Figure 3.13(c), \( k \) is the relative permeability of the permalloy core, \( \mu_0 \) is the magnetic permeability of free space, \( n \) the number of coil turns, and \( I \) the current applied to the solenoid.

The electromagnetic force is also proportional to the volume of the permanent magnet. When the centre of the magnet is placed on the axis of the coil, all other components of force and torque vanish due to symmetry.

### 3.4 Summary

Piezoelectricity and electromagnetism are two kinds of extensively used actuation principles in MEMS applications. A large range of piezoelectric and magnetic materials are employed in microactuators. Piezoelectric polymer PVDF is a favourable material for microactuators due to its advantages, such as light, flexible, low Young’s modulus, and good chemical, as well as mechanical properties. The unimorph and bimorph actuators have been used widely in many applications. Magnetic actuation has been successfully used in the macro world for a long time. Recently many groups have demonstrated the design of electromagnetic microactuators targeting a variety of applications. Most of these actuators are based on using a soft magnetic core and metal coil. Permalloy has been one of the most ideal soft magnetic materials, due to its high permeability. These aspects have led to the selection of piezoelectric and electromagnetic mechanisms in the proposed hybrid actuator. The actual design, fabrication and testing of a hybrid microactuator using these mechanisms are presented in the following Chapters.
Chapter 4  Design, Modelling and Fabrication of a Piezoelectric Polymer Microactuator

4.1  Introduction

As reviewed in Chapters 2 and 3, piezoelectric actuation is one of the most popular actuation principles used for microactuators. A piezoelectric polymer composite cantilever was designed by using finite element method simulation, which is described in Sections 4.2 and 4.3. The aim of the design was to find the optimal parameters and dimensions of a piezoelectric cantilever to achieve large tip deflection and force. The influence of the parameters of the cantilever on tip deflection were analysed based on the simulations in 4.3.3. The surface microstructuring of the PVDF film and its effect on the beam deflection is discussed in Section 4.3.4. The following Sections of this Chapter will describe the details of fabrication and testing of the polymeric microactuator. The designed piezoelectric unimorph actuator was fabricated using punching and electroplating techniques as described in Sections 4.4.1 to 4.4.4. The microstructures on the top of the piezoelectric polymer PVDF were realised by a low temperature hot embossing process, thus avoiding the depoling of the PVDF polymer, which is described in Section 4.4.5. Section 4.5.1 provides the details of characterisation procedures of the material properties of PVDF. Finally, the experimental test results of the composite cantilever are explained in 4.5.2.

4.2  Piezoelectric Polymer Cantilever-Design

In many microsystem devices, beams, diaphragms or cantilevers are used as actuators, with several different actuation methods being employed (Dufour and Sarraute,
1999). Besides the electrostatic effect, the piezoelectric effect is most commonly used for such actuators. In this work, a unimorph cantilever beam was chosen as the basic element. It consists of the commercially available piezoelectric polymer PVDF (polyvinylidene fluoride) with a thin permalloy layer electroplated onto one side of it. The schematic of this cantilever is shown in Figure 4.1. The cross section of the cantilever beam is rectangular. The piezoelectric polymer PVDF has a thickness of 28 μm and is covered with 40 nm thick metal electrode layers on both sides consisting of a nickel and copper alloy. The PVDF polymer is polarized in a direction parallel to its thickness. The non-piezoelectric layer of the unimorph cantilever is fabricated by electroplating permalloy to a thickness of approximately 5 μm. The length of the cantilever beam is up to 6 mm and the width is 1 mm.

![Figure 4.1: Piezoelectric polymer cantilever.](image)

### 4.3 Modelling and Simulation - CoventorWare and ANSYS

It is important to have a clear understanding of the parametric effects, scaling factors, and material characteristics and their influence on the system performance for the design of any microactuator. This can efficiently be achieved through simulation and modelling, using currently available software tools. CoventorWare (Coventor, 2003) is a powerful and comprehensive finite element analysis (FEA) software package developed exclusively for the simulation of Micro Electro-Mechanical Systems (MEMS). ANSYS is another high quality FEA package for design and analysis. It has been around for a longer time and is used for modelling all kinds of problems in general engineering. As ANSYS provides a macro function, a program can be edited for the multiple simulation of the same model with changed parameters. An optimum design for a given specification can be found by adjusting parameters and dimensions. In this project, a piezoelectric unimorph cantilever has been designed using these tools. The mater-
The material properties of PVDF and permalloy are listed in Table 4.1 and Table 4.2. The piezoelectric strain coefficients in Table 4.2 have two subscripts. The first one represents the electrical field axis; the second one refers to the mechanical strain axis. The piezoelectric solvers in both CoventorWare and ANSYS are new functions and each of them has its own advantages and drawbacks. Firstly, ANSYS has the advantage of offering a programme function so that the dimensions of the model and simulation parameters can be easily changed to perform different simulation runs, while in CoventorWare each individual model with different dimensions has to be newly created. Secondly, CoventorWare is a software specially designed for MEMS devices. Following the spirit of lithography based microfabrication; it can build a 3D model by the layout of the individual mask layers. It is straightforward for a new user to build a model. In comparison, it is more difficult to build a complex 3D model using ANSYS.

Table 4.1: Material properties of PVDF and permalloy.

<table>
<thead>
<tr>
<th>Material</th>
<th>PVDF</th>
<th>Permalloy</th>
</tr>
</thead>
<tbody>
<tr>
<td>Elastic constant (GPa)</td>
<td>2.8 (low frequency)</td>
<td>150</td>
</tr>
<tr>
<td>Poisson ratio</td>
<td>0.3–0.69</td>
<td>0.25</td>
</tr>
<tr>
<td>Density (kg/m³)</td>
<td>1.78x10³</td>
<td>8.688 x10³</td>
</tr>
<tr>
<td>Permittivity (pF/m)</td>
<td>100–110</td>
<td></td>
</tr>
</tbody>
</table>

Table 4.2: Piezoelectric strain coefficients of PVDF (pC/N).

<p>| | | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>d₁₁=0</td>
<td>d₂₁=0</td>
<td>d₃₁=25</td>
</tr>
<tr>
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<td>d₂₂=0</td>
<td>d₃₂=2.2</td>
</tr>
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</tr>
<tr>
<td>d₁₆=0</td>
<td>d₂₆=0</td>
<td>d₃₆=0</td>
</tr>
</tbody>
</table>
4.3.1 CoventorWare Simulation

In CoventorWare simulation, an important feature is that it is well adapted to a typical microfabrication process, consisting of several layers fabricated on top of each other. Thus, a 3D solid model can be extracted from the 2D mask layout representing the different layers and from the sequence of process steps being related to these layers. So the program can be applied in a straightforward way for simulation of MEMS devices. The layout function allows creating 2D mask drawings. A 3D solid model can be extracted from these by using a series of deposition steps and etch steps, thus creating a depth profile. The depth values of each layer are specified by the parameters set in the process editor.

There are five meshing options available in the package, which are surface meshing, free meshing, Manhattan meshing, extrude meshing as well as merge layer and extrude meshing. Alternatively, the meshing model can be imported from other softwares packages, as well. The Manhattan model has an orthogonal geometry, i.e. all model faces (patches) are planar and are joined at right angles. The model, however, need not be aligned with the global X-Y-Z frame and may be rotated around the Z-axis. Such a model can be meshed with fully structured brick elements. The user is able to control the element size and bias, which allows a finer mesh on the boundary or in the centre of a channel. For a rectangular cantilever beam using the Manhattan model is a very good option.

A piezoelectric solver is included in the MemMech solver of CoventorWare. An important consideration in the set up of such a piezoelectric simulation model is supplying the correct material parameters. Concerning dielectric material properties, choosing the piezoelectric strain coefficients is most appropriate in this simulation. In order to apply boundary conditions in the analysis, each one of the patches of the model has to be assigned a name. The results obtained by this simulation are the displacement of the cantilever, the mechanical stress within it and the geometric distribution of the externally applied electrical potential. A modal analysis and a harmonic analysis can also be performed with this program.

Figure 4.2 gives an example of a 3D model of a cantilever beam. It consists of 2 layers, one for PVDF, the other for permalloy. The beam has a length of 5 mm, a width
of 1 mm and a thickness of 28 µm for the PVDF layer, plus an additional 5 µm for the permalloy layer. The Young’s modulus of PVDF is set to 2.8 GPa (by the supplier) and that of permalloy is 150 GPa (Khoo and Liu, 2001). The tip deflection under a potential of 100 V is obtained as 71.9 µm. Figure 4.2 (a) shows the geometric distribution of the electrical potential over the thickness of piezoelectric element and Figure 4.2 (b) the beam deflection under this potential.

(a) Distribution of the electrical potential across the PVDF polymer.
(b) Displacement of the cantilever caused by piezoelectric effect.

Figure 4.2: Simulation of a cantilever beam using CoventorWare.

4.3.2 ANSYS Simulation

In ANSYS simulation, element SOLID5, a 3D coupled-field solid finite element, was applied on the piezoelectric material PVDF, while the element SOLID45, a 3D structural solid, was applied on the elastic material permalloy. The two finite elements have the same element shapes and nodes as shown in Figure 4.3. However, SOLID5 has a 3-D magnetic, thermal, electric, piezoelectric, and structural field capability with limited coupling between the fields. This capability allows for the direct application of an excitation voltage to the piezoelectric layers. The element has eight nodes with up to six degrees of freedom at each node. When used in structural and piezoelectric analyses, SOLID5 includes large deflection and stress stiffening capabilities, whereas SOLID45 includes plasticity, creep, swelling, stress stiffening, large deflection, and large strain capabilities for structural analysis. The number of the finite elements was kept to a minimum in the simulation, as the beam is assumed to have a simple rectangular shape.
All simulations below are based on an applied voltage of 100 V, with the length and width of the cantilever varied between 1 mm and 6 mm and 0.5 mm to 2 mm respectively. The thickness of the PVDF and permalloy layers were given a range of 9 μm to 110 μm, and 1 μm to 30 μm respectively.

In ANSYS piezoelectric analysis, the constitutive equations for piezoelectricity are derived from thermodynamic considerations and are presented in the following form (Kohnke, 1999).

\[
\{T\} = \{c\} \{S\} - \{e\} \{E\} \\
\{D\} = \{e\} \{S\} + \{\varepsilon\} \{E\}
\] (4-1)

Where \(T\) represents the 6 components of stress, \(S\) represents the 6 components of strain, \(E\) represents the 3 components of the electric field, \(D\) represents the 3 components of the electric flux density, \(c\) is the system stress-strain matrix, \(e\) is the piezoelectric matrix, \(\varepsilon\) is the dielectric matrix.

An alternative form of these equations may be presented based upon strain rather than stress. They take the form

\[
\{S\} = \{cE\} \{T\} + \{d\} \{E\} \\
\{D\} = \{d\} \{T\} + \{p\} \{E\}
\] (4-3)

where \(S, T, D, E\) have the same meaning as above, \(cE\) is the compliance matrix for the elastic system, \(d\) is the dielectric matrix, and \(p\) is the permittivity matrix.
Once the material constants for the particular piezoelectric material are known, either of the above system of equations can be solved. Data supplied from manufacturers of the materials are typically for use in equations (4-3) and (4-4). When using ANSYS, some difficulty is encountered since the data must be converted into a form that can be used in equations (4-1) and (4-2), which must be performed outside of the ANSYS program.

To establish a correspondence between the manufacturer’s material constants to those required by ANSYS, it is necessary to rewrite equations (4-3) and (4-4) in the form of (4-1) and (4-2). Beginning with equation (4-3), this can be rewritten into the form

\[
[cE] \{T\} = \{S\} - [d] \{E\}
\]

and solving for \{T\} gives

\[
[cE]^{-1} [cE] \{T\} = \{T\} = [cE]^{-1} \{S\} - [cE]^{-1} [d] \{E\}
\] (4-5)

Then substituting equation (4-5) into equation (4-4) gives

\[
\]

\[
\] (4-6)

Then, comparing equation (4-5) an (4-6) with equations (4-1) and (4-2) yields

\[
[c] = [cE]^{-1}
\]

\[
[e] = [cE]^{-1} [d] = [d] T [cE]^{-1}
\]

\[
[e] = [p] - [d] T [cE]^{-1} [d]
\] (4-7)

It is also possible to write equations (4-2) and (4-4) in terms of the piezoelectric effect where the solution variable is the electric flux density. ANSYS uses voltage as a degree of freedom so that it is more convenient to use this form here.
Because the piezoelectric polymer is nearly isotropic, the elastic coefficient (stress strain coefficient) $c$ can be viewed as a constant, which is $2.8 \times 10^9 \text{ N/m}^2$. The piezo matrix for PVDF was converted as listed in Table 4.3.

<table>
<thead>
<tr>
<th></th>
<th>$e_{11}$=0</th>
<th>$e_{21}$=0</th>
<th>$e_{31}$=70</th>
</tr>
</thead>
<tbody>
<tr>
<td>$e_{12}$=0</td>
<td>$e_{22}$=0</td>
<td>$e_{32}$=6.16</td>
<td></td>
</tr>
<tr>
<td>$e_{13}$=0</td>
<td>$e_{23}$=0</td>
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<td></td>
</tr>
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<td>$e_{14}$=0</td>
<td>$e_{24}$=-70</td>
<td>$e_{34}$=0</td>
<td></td>
</tr>
<tr>
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<td>$e_{25}$=0</td>
<td>$e_{35}$=0</td>
<td></td>
</tr>
<tr>
<td>$e_{16}$=0</td>
<td>$e_{26}$=0</td>
<td>$e_{36}$=0</td>
<td></td>
</tr>
</tbody>
</table>

Table 4.3: Piezo-strain matrix of PVDF ($10^{-3} \text{ C/m}^2$).

Figure 4.4 represents the results from an ANSYS simulation of the unimorph piezoelectric cantilever with the same dimensions as used in the CoventorWare simulation. The tip deflection of the cantilever in this simulation is 69.7$\mu$m, which is almost identical with the result obtained by CoventorWare. In Figure 4.4, the increasing deflection of the cantilever is represented by different colours, varying from blue for nearly zero to red for the maximum deflection of 69.7 $\mu$m.

![Figure 4.4: Simulation of a cantilever beam by ANSYS.](image)

(The length of the beam is 5 mm, the thickness of PVDF and permalloy are 28 $\mu$m and 5 $\mu$m respectively).
The mechanical strain is generated by the piezoelectric effect of the polymer, which converts to an equivalent stress distributing along the whole beam as shown in Figure 4.5. It can be seen that the stress on the cantilever concentrates on the fixed end of the beam at the non-piezo elastic layer, while the stress distribution is nearly constant along the beam in the PVDF layer but varies across the thickness of the layer. Comparing the theoretical analysis discussed in Chapter 3, the simulation results of the two software packages are very close to the theoretical calculation.

(a) Stress distribution along the beam.

(b) Enlarged part of the clamped end.

Figure 4.5: Stress on the cantilever when the conditions in Figure 4.4 applied.
4.3.3 Parameter Analysis for the Cantilever Deflection

It can be seen from the theoretical analysis provided in Chapter 3 that the tip deflection of a unimorph cantilever is determined by its geometrical dimensions, material properties, as well as by the external electrical field. In order to design an effective microactuator with maximized deflection, it is necessary to optimize all these parameters. A detailed analysis of the effect of individual parameters on the tip deflection of the cantilevers is given below.

Influence of cantilever length, width and of applied voltage on beam deflection

The effect of the length of the cantilever on the tip deflection is shown in Figure 4.6 (a). The two curves shown in this Figure represent the tip deflection of the composite cantilever beams for two different cantilevers with PVDF thicknesses of 28 µm and 9 µm respectively. In this case, the width and the applied voltage are kept constant at 1 mm and 100 V respectively. The thickness of the permalloy layer is 5 µm. As expected, the tip deflection increases with the beam length. Furthermore, this deflection is much larger for a PVDF layer with a thickness of 9 µm compared to the one with a thickness of 28 µm. In general, the tip deflection is proportional to the square of the beam length. This Figure clearly shows that the tip deflection reached a value of 288 µm at a beam length of 5 mm for the 9 µm thick PVDF layer compared to that of 69 µm deflection noted for the 28 µm thick PVDF for the same beam length. This indicates that the thickness of the PVDF seems to have a great influence on the cantilever deflection, which was further studied.

The width of the cantilever has little effect on the beam deflection. Figure 4.6 (b) presents the relationship between the beam deflection and the width of the beam when the beam length is kept constant at 5 mm, the thickness of permalloy is 5 µm, and the thickness of PVDF is 9 µm or 28 µm respectively. The width of the beam varies from 50 µm to 2000 µm in this simulation. The curves in Figure 4.6 (b) indicate that the beam deflection deviates in a range from 1 µm for a 28 µm thick PVDF and 5 µm for a 9 µm thick PVDF. Compared to other parameters the effect of the width on beam deflection can be neglected. Therefore in the following simulation the width of the beam is fixed at 1 mm.
The tip deflection of the unimorph cantilever is proportional to the applied voltage when all the other parameters are fixed. Therefore in the following simulation the applied voltage on the cantilever was set at 100 V.

Effect of the piezo layer (PVDF) thickness on beam deflection

The cantilever beam deflection is greatly influenced by the thickness of the PVDF film as observed in the above Figure. However, the tip deflection of a composite cantilever beam depends on the thickness of both of its piezo and non-piezo layers. The effect of the piezo layer thickness is first studied and is shown below. Figure 4.7 plots the variation of the beam deflection when the thickness of the PVDF layer is varied in a range from 9 \( \mu \text{m} \) to 110 \( \mu \text{m} \). This graph clearly shows that the thinner the PVDF layer, the larger the deflection of the beam. This kind of variation in beam deflection with the
layer thickness can be explained by the fact that the induced strain on the thinner PVDF under the same electrical potential is larger due to the large electrical field (Voltage/thickness of the beam) and also the thinner cross section of the cantilever beam has less moment of inertia, therefore the deflection of the cantilever increases with the decrease of the PVDF thickness. Even though the 9 µm thick PVDF layer provides the largest deflection, it is not practical for use in most applications, as such a structure is very flexible, but provides little force. Therefore, a 28 µm thick PVDF layer was used in this design.

![Graph showing deflection of beam vs PVDF thickness](image)

**Figure 4.7: Tip deflection versus PVDF thickness.**

**Influence of thickness of the non-piezo layer on beam deflection**

As the effect of the piezo layer thickness on the cantilever beam deflection is understood, it is equally important to determine the effect of the non-piezo layer. Figure 4.8 shows the variation of the beam deflection with the thickness of the non-piezo permalloy layer, when all other parameters are kept constant. The cantilever length and width are fixed at 5 mm and 1 mm respectively, while the thickness of the PVDF layer is kept at 28 µm and 9 µm in this study. The Young’s modulus is assumed to be 150 GPa and the applied voltage is 100 V. It can be seen from the graph that for a 28 µm thick PVDF layer the deflection has a maximum of around 75 µm with a permalloy layer thickness of about 2 µm, but decreases very little up to a thickness of 5 µm. When the thickness is increased to 30 µm the deflection decreases to 9 µm. For a 9 µm thick piezo layer, the beam deflection can reach up to 700 µm with a non-piezo layer thickness of 1 µm, but decreases to 50 µm with a non-piezo layer thickness of 15 µm. Then the two curves converge after the thickness of the non-piezo layer in-
creases to values above 20 µm. This means that when the non-piezo layer thickness exceeds 20 µm, the beam deflection is mainly affected by the non-piezo layer only. In this design, a thickness of 5 µm was chosen as an optimal value for a 28 µm piezoelectric polymer, as a thinner permalloy layer might get damaged during actuation. This analysis shows that with certain material the thickness of the non-piezoelectric layer can be optimised to achieve the maximum deflection.

![Figure 4.8: Tip deflection versus the thickness of non-piezoelectric layer.](image)

**Effect of Young’s modulus of the non piezoelectric layer on beam deflection**

To evaluate the influence of the mechanical properties of the non piezoelectric material on the beam deflection of the composite cantilever, Young’s modulus of the non piezoelectric layer has been identified as the important parameter. The dimensions of the composite cantilever were set to the same value as in the previous simulation (c). The thickness of the non-piezoelectric layer was fixed at 5 µm as before. In order to achieve the maximum tip deflection of the cantilever, an optimal material of the non-piezoelectric layer can be worked out from this simulation. In this design, the Young’s modulus of the non-piezoelectric layer was varied between $10^7$ Pa and $10^{12}$ Pa. Figure 4.9 shows the relationship between the tip deflection of the composite cantilever and the Young’s modulus of the non-piezoelectric layer when the thicknesses of the cantilever are kept constant. It can be seen from the Figure that when Young’s modulus increases to 50 GPa the beam deflection increases exponentially, then at a value of 150 GPa the beam deflection reaches to a maximum of 70 µm and drops down linearly to 55 µm at a value of 1000 GPa. It shows us that an optimal material choice for the non-piezo layer could help to achieve large beam deflections.
Figure 4.9: Simulation of the tip deflection versus the Young’s modulus of the non-piezoelectric layer.

Though the curve has been drawn in logarithmic scale, the useful range from a practical material point of view is in the range of 10 GPa to 1000 GPa. It may be observed from the graph, the variation of the beam deflection is found to be 55 µm to 70 µm. This effect can be considered marginal taking into account the broad range of the Young’s modulus in this study.

The numerical results obtained from the FEA simulations were compared and confirmed with the theoretical analysis based on bi-metal theory. The optimal parameters for the piezoelectric composite cantilever are determined by the thickness, and the Young’s modulus of the non piezoelectric layer. For a given material of the non piezo layer an optimum thickness can be calculated for obtaining the maximum tip deflection. Similarly a suitable material can be selected from this kind of simulation depending on the chosen actuator configuration and the thickness of the layer. The potential materials for the non-piezoelectric layer can be metals (e.g. aluminium) or polymers, such as polyimide and Mylar. To allow the formation of a hybrid microactuator, the use of a magnetic material as the non-piezoelectric layer was considered. As a soft magnetic material thin film permalloy has Young’s modulus of 150 GPa, which is in the range of 10 GPa to 1000 GPa as discussed above. Therefore it was chosen as a good candidate material for the non-piezoelectric layer of the composite cantilever. Also it acts as a medium magnetic material in the later designed hybrid actuator.
This simulation and modelling work helped us in arriving at some of the optimal important parameters of the beam length of 5 mm (depending on the required deflection), width of 1 mm, and thicknesses of the PVDF and permalloy layers of 28 μm and 5 μm respectively. The ANSYS program, which was used in this simulation, is given in Appendix B1.

4.3.4 Surface Microstructuring of the PVDF Film and its Effect on the Beam Deflection

During the simulation studies presented above, it was realised that the surface topography of the PVDF film seems to influence the beam deflection. Conceptually, the topographical structure can be broken into two cases; (a) structures on one side of the cantilever and (b) structures on both sides of the cantilevers as illustrated in Figure 4.10.

Figure 4.10: Model of imprinted surface microstructure on the composite cantilever. (The cyan, thick layer refers to PVDF, while the yellow thin layer permalloy).

To understand this effect further, a detailed study has been carried out using one sided shapes of the surface microstructures. The structured surface consists of rectangular projections extending across the width of the beam. Corresponding to the fabrication method, two beam models need to be considered.

In the first case as shown in Figure 4.10 (a), the depth of the surface structure is small compared to the beam thickness, leaving the bottom surface flat. The permalloy layer is situated on the planar side. The top layers basically represent the PVDF. The thickness of the PVDF layer is 28 μm. In order to reduce the number of elements in the
model and simplify the simulation, the thickness of the non piezo layer was fixed at 7 μm. For comparison, the beam dimensions were kept constant at a length of 5 mm and a width of 1 mm.

Figure 4.11 shows a typical simulation of the beam deflection for such beam profiles for a given applied potential (100 V). For a planar cantilever (without any micro-structuring on the surface as shown in Figure 4.11 (b)), the tip deflection at an applied potential of 100 V is 61.9 μm, while this deflection increases to 77.8 μm with micro-structures on the top of the beam as shown in Figure 4.11 (c). This means that the surface modification of the PVDF cantilever increases the tip deflection by 25%.

In order to determine the effect of surface microstructures on the beam deflection quantitatively, models with different heights and numbers of projections were created. Figure 4.12 shows the simulation results of a microstructured cantilever with the number of projections taken as 20 and the solid part of PVDF having a thickness of 21 μm. Figure 4.12 (a) gives the potential distribution on the cantilever when a 100 V potential is applied across the thickness of the cantilever. It can be seen that on the projection part the potential is zero. Therefore, this part of PVDF does not produce any strain nor does it induce displacement. Figure 4.12 (b) shows the beam deflection under the applied potential. The end A was fixed and the beam deflection tends to increase from the fixed end A to the tip B gradually, similarly to the plane surface beam.
Figure 4.12: Structured cantilever with a projection number of 20.

Table 4.4: Simulation of tip deflection of a microstructured PVDF cantilever.

<table>
<thead>
<tr>
<th>Projection thickness (µm)</th>
<th>Deflection (µm) for number of projections</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>5</td>
</tr>
<tr>
<td>0</td>
<td>61.96</td>
</tr>
<tr>
<td>3.5</td>
<td>69.49</td>
</tr>
<tr>
<td>7</td>
<td>77.77</td>
</tr>
<tr>
<td>10.5</td>
<td>89.94</td>
</tr>
<tr>
<td>14</td>
<td>102.41</td>
</tr>
</tbody>
</table>

The tip deflections of these cantilevers were simulated and the results are listed in Table 4.4. From this Table it may be observed that as the projection thickness increase from 0 to 14 µm, the deflection achievable with 5 projections increases from 62 µm to 102.4 µm, which represent an increase of 64.5%. However, the data clearly show that the number of projections has only a marginal effect for a given projection thickness. The variation in deflection at any given projection thickness is less than 1 µm, even when the number of projections changes from 5 to 20.
It was shown in Figure 4.7 that the tip deflection increases as the thickness of the PVDF layer is decreased. The structuring of the PVDF layer enhanced the tip deflection by creating thinner cross sectional segments of PVDF layer in the cantilever. Figure 4.13 shows that the magnitude of deflection decreases with the thickness of the solid PVDF, thus increases with the thickness of the projected microstructures on the cantilever.

In the second model, the structured surfaces are on both sides of the PVDF polymer. The permalloy layer sticks to one of the structured sides. This model is based on actual features of PVDF foils being embossed at low temperature and high pressure. As this model is created by imitating the surface micromachining process in CoventorWare; the side wall of the projection structure is not vertical for this case. This causes the subsequent meshing to be very difficult. This modelling work could not be accomplished due to the limited functionality of the software.

### 4.4 Fabrication of Piezoelectric Composite Cantilevers

Even though PVDF can potentially be used in many microactuator applications, it is still a challenge for MEMS researchers to pattern and form the polymer foils into the
required shapes and sizes with high accuracy. The present work demonstrates a novel route for this purpose using laser micromachining, electroplating and punching (micro-embossing) techniques. In this work, commercially available 28 µm thick PVDF sheets were used. These sheets were coated with a metallic layer on both sides for use as electrodes. Before using this material in this investigation parts of these sheets were analysed using energy dispersive spectroscopy (EDS) to confirm the materials used as metallised electrode layers. A typical EDS spectrum of the metallised layer is shown in Figure 4.14 below. This analysis shows yield a nickel content of 27.5% and a copper content of 72.5%. This analysis helped in the selection of etchants for removing the metallised layers during different processing steps.

![Figure 4.14: Energy dispersive spectroscopy of the metal layer on PVDF.](image)

### 4.4.1 Excimer Laser Micromachining of PVDF

Excimer laser micromachining is considered as a useful tool for machining and/or patterning many polymers or their layers on different substrates. This has been shown to be an excellent method in patterning different photoresist, polyimide, polycarbonate, PET and other similar other materials. The ready availability of an excimer laser based micromachining system has prompted us to explore the possibility of applying this method for machining the cantilevers using PVDF material.

The excimer laser series 8000 (Exitech Limited, UK) is a system equipped with a Lambda Physics LPX210i laser source, operating at a wavelength of 248 nm or 193 nm depending on the gas source (KrF or ArF) used. The beam delivery system contains
beam shaping and homogenisation optics, creating a uniform square beam at the plane of the mask held on an open frame CNC controlled X-Y stage set. The double fly’s eye homogeniser has a numerical aperture (NA) of 0.01 and produces a uniform illumination over an area 12 x 12 mm$^2$ at the plane of the mask. This essentially converts the beam profile from a conventional Gaussian distribution to a flat topped one improving the overall energy and intensity uniformity. Within the cross section area of the beam this homogenizer helped in achieving an 80% beam having intensity within ± 5% RMS value, which is monitored using an online beam profiler. In mask projection machining the actual size of the mask is determined by the demagnification factor of the projection lens and the machining area required on the work piece. The lens used in this work had a 1:10 demagnification factor, a numerical aperture of 0.3, a field with a diameter of 1.5 mm and an optical resolution of 0.8 µm. The set up of the homogeniser and the projection lens produces a partial coherence factor of 0.2.

The machining characteristics of PVDF using KrF excimer laser (248nm) was analysed by initially using a 450 µm x 450 µm square pattern on the above mentioned laser micromachining system. A matrix of 7 x 10 sites was ablated by varying the attenuator setting from 0.1 to 1 (which will change the laser fluence on the sample) and the number of shots from 1 to 64. A square mask was used for etching a total area of 450 µm x 450 µm on the metallised 52 µm thick PVDF polymer. The metal deposited on both sides of the PVDF polymer was a 40 nm thick nickel-copper alloy. The fluence was varied from 0.2 J/cm$^2$ to 2.2 J/cm$^2$ by adjusting the CNC (computer numerically controlled) attenuator, consisting of a dielectrically coated plate and an uncoated compensator plate, which are rotated angularly with respect to each other in the beam, thus changing the optical transmission value continuously. The dependence of the laser energy fluence on the attenuator setting is illustrated in Figure 4.15. At a fixed fluence machining was carried out with the number of shots varying from 1 to 64. The laser repetition rate was kept constant at 50 Hz. The laser pulse energy was calibrated at the surface of the work piece using a pyroelectric energy monitor (Moletron Type-JD25).
Figure 4.15: The variation of laser fluence with the attenuator setting.

(a) Attenuator setting 1.0, 2 shots, the metal coating on the polymer is already removed.
(b) Attenuator setting 0.6, 8 shots.
(c) Attenuator setting 0.6, 32 shots.
(d) Attenuator setting 0.6, 64 shots, a square hole is machined completely through.

Figure 4.16: SEM images of metallized PVDF patterned with an excimer laser.

Typical machined patterns in these experiments are shown in Figure 4.16. It can be observed that the laser energy removed the metal layer on the polymer within only two shots at a fluence of around 250 mJ/cm². The machined depth increased with the
fluence and with the number of shots. A square hole of approximately 300 μm x 300 μm dimensions was machined using 64 shots at a laser fluence of 1135 mJ/cm² as shown in Figure 4.16 (d). Unfortunately, the edges turned out to be quite rough and could not be improved significantly, irrespective of laser machining conditions. As the number of shots was increased, the edges became worse. This may mainly be attributed to the laser absorption properties (at that wavelength) and the thermal characteristics of the PVDF polymer. This led to the conclusion that the direct excimer laser micromachining is not suitable for machining or patterning PVDF polymer foils.

In order to understand the reasons for such behaviour, the UV absorption/transmission characteristics of the PVDF material was studied. The UV-Vis-near-IR transmission spectrum of non-metallised PVDF in the wavelength range from 200 nm to 1100 nm is shown in Figure 4.17. It can be seen from the graph that the transmission increases exponentially and then approaches a constant value around 90% at wavelengths exceeding 400 nm. At the excimer laser wavelength (248 nm) the transmission is almost 70%, corresponding to an absorption rate of only 30% of the UV light in the material. This poor absorption characteristic makes it difficult to achieve sufficient absorbed energy density to obtain satisfactory ablation with the excimer laser employed.

Figure 4.17: Typical transmission spectrum of PVDF.
4.4.2 Nd:YAG 355 nm Laser Micromachining of PVDF

In the next stage, a frequency tripled (3ω) Nd:YAG laser system from Coherent Sciences Inc., USA, operating at a wavelength of 355 nm was explored for micromachining of this polymer. An yttrium aluminium granate crystal doped with neodymium is the gain medium for the Nd:YAG laser, which is optically pumped by semiconducting photodiodes. The natural wavelength of this laser is 1064 nm, which in our particular setup, was frequency tripled by crystals placed in the beam path, absorbing photons at 1064 nm and reemitting them at 355 nm. As the gain of the laser is relatively low, an internal cavity optical switch is used to allow the laser to obtain high pulse energies. No mask is required for patterning the substrate. The desired pattern of laser ablation is designed in AutoCAD or Corel-draw software and converted in the format of a plot (.plt) file accepted by the machine.

Similar to the study performed using excimer laser machining described above, an array of square patterns was machined on PVDF polymer test foil at different laser fluences and with a varying number of shots (1 to 10). In these experiments (current setting from 50% to 90% of diode power, and a thermal track at 6250), each pulse has energy of approximately 230 µJ with a repetition rate of 10 kHz giving an average power of 1.84 W. The laser spot diameter was approximately 20 µm. The ablated square shape shown in Figure 4.18 was cut out with 10 laser shots at a current setting of 80% diode power. The cutting edge damaged by thermal diffusion can be clearly seen in Figure 4.18 (b).

(a) An ablated square shape.               (b) Close-up view of the cutting edge.
Figure 4.18: Ablated PVDF by a frequency tripled Nd:YAG laser.
4.4.3 Punching of the PVDF Cantilever

As explained earlier, laser micromachining was found to be a less than ideal technique for machining the PVDF polymer. Punching is one of the most commonly used processing methods for thermoplastics (Becker and Gartner, 2000; Simdekova et al., 2002). In conventional punching, a pair of pre-heated male and female punch tools is used to cut the polymer by shear forces. A polarised piezoelectric polymer can be exposed to no more than its Curie temperature (70-90°C for PVDF), beyond which the material loses its piezoelectric characteristics. Therefore, conventional punching process cannot be directly used in this case. Instead of using male and female plug tools, a nickel shim with the required punch profile was used to cut the PVDF polymer cantilever in a home-made microembossing system. This facilitated a low temperature punching process, forming the designed profile of the piezoelectric polymer cantilever well below its Curie temperature. The nickel shim was fabricated using laser micromachining of a mould in a given polymer substrate and subsequent electroforming.

Fabrication of the nickel shim

In order to fabricate the nickel shim, a polycarbonate sheet was laser micromachined to form the mould for electroplating. The frequency tripled Nd:YAG laser (355 nm) described above was used for this purpose. As this system requires a graphical input file of the pattern, the scaled model of the pattern was drawn using Corel-draw software. A micro-channel with the required cantilever profile has been micromachined in a polycarbonate substrate with dimensions 100 mm x 100 mm x 1.5 mm as shown in Figure 4.19 (a). The typical machining conditions used in this work were a current of 18.7 Amp, a diode power of 80%, thermal track of 4880 and a repetition frequency of 10 kHz with 10 laser shots.

As it is well known that it is difficult to obtain vertical walls using the laser machining technique, the top and bottom dimensions of the fabricated structure are different. In this case, the widths of the channel at the bottom and the top were 20 μm and 65 μm respectively, with an approximate depth of 110-120 μm, as shown in Figure 4.19 (b). Figure 4.19 (c), and (d) show microscopic images focused on the top and bottom of the laser ablated polycarbonate micro-channel respectively.
(a) Profile of the micro channel on a square of 1.5 x 1.5 mm$^2$ polycarbonate board.

(b) Dimensions of the cross section of the channel.

(c) Image of the ablated micro channel (focus on bottom).

(d) Image of the ablated micro channel (focus on the top).

Figure 4.19: Profile and cross section of the ablated channel on polycarbonate material.

A nickel shim was electroplated on to the polycarbonate substrate with the laser ablated micro channel. Before electroplating, the polycarbonate substrate was cleaned using isopropanol, Jiff (a domestic abrasive cleaning cream), 10% H$_2$SO$_4$ and distilled water in a sequence, before a thin layer of silver was spray coated onto the surface of polycarbonate for using as a seed layer. Then the polycarbonate substrate was fixed onto a frame and the nickel shim was electroplated up to a thickness of around 400 µm in a nickel sulphamate bath. The bath composition and operating parameters were given in Table 4.5. The solution in the electroplating bath should be made 24 hours before the experiment. A pump and filter is turned on 3 hours before the experiment for agitation. The pH value of the electroplating bath was kept at around 4 by adjusting it with H$_2$SO$_4$ and NaOH. The temperature was set at 60ºC. The applied current was increased gently from 0.2 Amp up to 1.5 Amp in one hour, then kept constant for 18 hours, thus insuring a smooth surface finish. The top and bottom widths of the electroformed nickel structure were 16 µm and 65 µm respectively. The cross section of the punching shim acts
like a knife cutting the polymer sheets. Therefore a narrow bottom width is expected in
this shim as shown in Figure 4.20.

Table 4.5: Nickel electroplating bath composition.

<table>
<thead>
<tr>
<th>Material</th>
<th>Quantity (g/L)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Nickel sulfamate</td>
<td>Ni(SO\textsubscript{3}NH\textsubscript{2})\textsubscript{2}</td>
</tr>
<tr>
<td>Nickel chloride</td>
<td>NiCl\textsubscript{2}.6H\textsubscript{2}O</td>
</tr>
<tr>
<td>Boric acid</td>
<td>H\textsubscript{2}BO\textsubscript{3}</td>
</tr>
</tbody>
</table>

Figure 4.20: Cross section view of the electroformed nickel shim.

**Punching**

The punching of the cantilever from a PVDF polymer sheet was performed using
a home-made microembossing system (Figure 4.21) at room temperature. The proce-
dure used for this purpose is similar to the embossing technique described by Becker *et al.* A nickel shim, PVDF film and the insert were fixed in a sandwich structure between
the two aluminium plates shown in Figure 4.21. This arrangement is enclosed in a vac-
uum chamber inside the hot embossing system. A hydraulic pump was used to apply the
force on the chamber.
A 250 bar force (0.27 bar/mm²) was applied onto the sample (area 33 mm x 28 mm) for one minute. PVDF cantilevers with the designed shape were punched out in different orientations ranging from 0° to 90° between the cantilever axis and the PVDF stretch direction (described in Chapter 3). The quality of punching depends on the insert material and the orientation of the polymer. Table 4.6 lists some of these materials and their function in the punching experiment. Among the tested insert materials, which were polycarbonate polymer, paper, rubber, and aluminium foil, the latter proved to be the best.

It turned out that even without any insert materials, PVDF can be punched out at an orientation angle of 45 degree. As we aimed to punch out the PVDF cantilever at the stretch direction (orientation angle 0°), different insert materials were tested mainly at an orientation angle of 0°. In this configuration, it showed that the PVDF cantilever was punched out properly only when an aluminium insert was applied.
Two typical cantilever beams are shown in Figure 4.22. The crossed line pattern seen in the middle of the punched beam surface in Figure 4.22 (a) is the stretch direction of PVDF. During the punching process PVDF cantilevers with an absolute orientation angle of more or less than 0° are very easily punched out as shown in Figure 4.22 (a). However we prefer to punch out the cantilever along the stretch direction as shown in Figure 4.22 (b). The reason is that the tip deflection of the PVDF composite cantilever mainly depends on the piezoelectric strain coefficient ($d_{31}$) along the stretch direction. When an electrical field actuates the cantilever it will elongate in the stretch direction, thus causing the maximum tip deflection when aligned in this direction. The effect of the orientation angle of the beam on the tip deflection of the cantilever is shown in Figure 4.22. It can be observed that the maximum beam deflection was achieved at the orientation angle of 0°. With the increase of the absolute angle of orientation the deflection decreases harmonically to zero at the orientation angle of 90°. This also proved that a PVDF cantilever can generate maximum deflection when the beam axis is aligned along the stretch direction. The dimensions of the punched cantilever shown in Figure 4.22 were 6 mm x 1 mm, with a measured edge roughness of 10-20 μm.

(a) Punched PVDF at 45° orientation.  (b) Punched PVDF at 0° orientation.

Figure 4.22: Punched PVDF cantilevers at different orientations.

(Orientation refers to the angle between the cantilever axis and the stretch direction of polymer).
Figure 4.23: The effect of orientation on the tip deflection of PVDF composite cantilever at a beam length of 6 mm.

The above results and the analysis thereof clearly showed that the best punching conditions were obtained with an aluminium foil as insert material, using a 0° orientation angle.

4.4.4 Electroplating Permalloy on the Metallised PVDF

As the composite cantilever requires a non-piezo layer on the PVDF cantilever structure, the next logical step would be to metallise the PVDF cantilever to form the required bi-layer. Permalloy was chosen for this purpose as discussed in Section 4.3.3. As the end goal of this project is to build a hybrid actuator combining piezoelectric and electromagnetic principles. In such a case, the permalloy will serve the purpose of a soft magnetic layer, which can assist in providing additional force. It is deposited by employing electroplating techniques. The bath composition used for this purpose is presented in Table 4.7. A basic sulphate bath with a pH of 3.5 was used. The electroplating was carried out at room temperature (25°C) at a current density of 5 mA/cm². With a plating rate of about 6 μm/hour, it takes less than an hour to plate 5 μm. In order to limit the electroplating of the permalloy to only one side of the PVDF cantilever, the patterned polymer was attached to a small printed circuit board (PCB) and the copper-nickel alloy layer originally present on the commercial PVDF sheet was used as the seed layer for this plating. The residual stress present in the electroplated layer caused some bending (or slight curling) of the composite cantilever, whose magnitude varied depending on the permalloy film thickness and plating conditions. Another reason for the observed bending of the composite cantilever could be the weight of the plated ma-
material on the thin polymer substrate. Figure 4.24 shows a cross sectional view (over thickness) of the electroplated permalloy layer on the surface of the PVDF.

Table 4.7: Chemical composition of the electroplating bath for permalloy.

<table>
<thead>
<tr>
<th>Compound</th>
<th>Concentration(g/l)</th>
</tr>
</thead>
<tbody>
<tr>
<td>NiSO4.6H2O</td>
<td>200</td>
</tr>
<tr>
<td>FeSO4.7H2O</td>
<td>8</td>
</tr>
<tr>
<td>NiCl2.6H2O</td>
<td>5</td>
</tr>
<tr>
<td>HBO3</td>
<td>25</td>
</tr>
<tr>
<td>Saccharin</td>
<td>3</td>
</tr>
</tbody>
</table>

Figure 4.24: Electroplated cantilever beam.

### 4.4.5 Imprinting of a Micro Pattern on PVDF Cantilevers

As discussed in Section 4.3.4, the simulation results indicated that the microstructuring of the PVDF surface in different patterns appears to enhance the deflection. This prompted further research in this direction on imprinting the punched cantilever surface with different micro patterns using a low temperature hot embossing method following a process similar to that used for punching the PVDF cantilever.

This process mainly involved the fabrication of a mould in a given substrate, electroforming of a shim (master) and finally imprinting this pattern on to the PVDF cantilever. This shim is electroformed on a laser micromachined polycarbonate substrate mould and is then separated for use in the microembossing system, following the same procedure as discussed in Section 4.4.3.

The embossing system used in this experiment is the same one used for punching the PVDF at room temperature. As shown in Figure 4.21, the system consists of two
stages, with the top stage sliding in vertical direction on four guiding posts, while the bottom stage is fixed. Both top and bottom parts of the embossing tool have three 400 W heating elements. The temperature is controlled by a digital control panel. Cooling is achieved by circulating compressed air. The vacuum pump and hydraulic systems are the same as were used in the punching process described in Section 4.4.3.

PVDF polymers, like most other thermoplastic materials, can be patterned by the hot embossing method. The most favourable hot embossing temperature for PVDF ranges from 175°C to 185°C, and the demoulding temperature is 140°C (Ruprecht, 1996). However, considering the risk of depolarizing the PVDF polymer, the hot embossing of PVDF has to be performed at considerably lower temperatures.

After fabrication of the shim, it was mounted in the embossing system together with the PVDF polymer sheet. Both were heated separately in a vacuum chamber to 45°C. The vacuum is necessary in this process to prevent the formation of air bubbles at the surface of the softened polymer, due to the entrapment of air in small cavities. It also allows water vapour (which is driven out of the polymer substrate) to be removed. In addition, it increases the lifetime of nickel tools, as it minimizes corrosion of nickel at these elevated temperatures. The shim is brought into contact with the substrate and then pressed at typical hydrostatic (pressure) forces in the range of 0.5-2 kN/cm². The tool is then cooled down to 30°C.

To minimise imprinting reproducibility errors due to thermal stresses originating from the differential thermal expansion of the shim and the substrate, the thermal cycle should be kept as small as possible. After cooling down to a temperature of much lower than 30°C, the shim was mechanically separated from the substrate, which was now imprinted with the desired features/patterns. The microstructured polymer wafer could then be processed further.

In the hot embossing process, the three important parameters are embossing temperature, force and time, which determine the quality of the replicated pattern on the PVDF. In order to test the hot embossing capability of PVDF at low temperatures, the hot embossing temperature was limited under 50°C. Higher pressures and longer times were applied during this process. Table 4.8 lists the detailed experimental data for five identical samples.
Table 4.8: Process parameters used in hot embossing experiments with PVDF.

<table>
<thead>
<tr>
<th>Sample number</th>
<th>Heating T (top/bot plate) (°C)</th>
<th>Cooling to T (°C)</th>
<th>Pressure (bar)</th>
<th>Heating time (min)</th>
<th>Cooling time (min)</th>
<th>Depth of feature (µm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>46/40</td>
<td>30/30</td>
<td>300</td>
<td>5</td>
<td>20</td>
<td>6-12</td>
</tr>
<tr>
<td>2</td>
<td>45/40</td>
<td>26/24</td>
<td>300</td>
<td>5</td>
<td>20</td>
<td>11-16</td>
</tr>
<tr>
<td>3</td>
<td>41/40</td>
<td>25/23</td>
<td>420</td>
<td>5</td>
<td>17</td>
<td>10-15</td>
</tr>
<tr>
<td>4</td>
<td>40/40</td>
<td>25/23</td>
<td>500</td>
<td>5</td>
<td>18</td>
<td>11-15</td>
</tr>
<tr>
<td>5</td>
<td>40/40</td>
<td>25/23</td>
<td>500</td>
<td>10</td>
<td>24</td>
<td>12-18</td>
</tr>
</tbody>
</table>

### 4.4.6 Profiling and Analysis of the Embossed Feature

The profiles of the embossed structures were examined using a laser scanning confocal microscope (OSL1100, Olympus Pty. Ltd.). The principle of confocal microscope is described in Section 6.3.6. This microscope allows the measurement of the depth of microstructures with a resolution of 0.01 µm. Figure 4.25 (a) and (b) show SEM images of the nickel shim and embossed metallised PVDF polymer respectively. The confocal image of the embossed PVDF shown in Figure 4.25 (c) provides the height profile of the features across its length and width. It was found to vary from 6-12 µm for the embossed feature at different positions. The depth of the embossed structure at different points essentially depends on the roughness and profile of the electroformed shim surface. The profile of embossed PVDF is not as good as that of its master shim, because the PVDF is too flexible and the surface tension from the metal layer might also have caused the PVDF polymer deformation. However, the average depth of the embossed features in this case was around 10 µm. The picture on the left side in Figure 4.25 (c) shows the (top view) 2D image of the embossed structure. The table on the right side shows the measured depth of the feature at different spots (as indicated on the 2D image in the left side) of the surface. The right side bottom part of the same Figure gives a typical profile of the cross section of the embossed feature.
4.5 Testing and Evaluation of Cantilevers

The testing and evaluation of the fabricated cantilevers consisted of three main parts. The first part of the testing used a bimorph piezo cantilever to determine the piezo coefficient, which ensured that the value used in this simulation is realistic for the PVDF used in these investigations. The second part of testing mainly compared the deflection obtained by the analytical and numerical (FEA simulation) methods with those obtained experimentally using a unimorph composite cantilever fabricated following the procedures explained earlier in this Chapter. Finally, the deflection of the patterned or
microstructured cantilever was evaluated experimentally and compared with the values obtained by numerical simulation.

4.5.1 Determination of Piezo Coefficient of PVDF Using a Bimorph Cantilever

The piezo coefficient of the PVDF polymer was verified using a bimorph cantilever having a length of 6 mm and a width of 1 mm. The bimorph constitutes two PVDF punched cantilevers following the procedure described in Section 4.4.3. from a 28 µm thick PVDF sheet and attached together. When an AC voltage was applied to this test structure, the bimorph vibrated like a fan. The measured resonance frequency was found to be about 600 Hz. The tip deflections of the cantilever were measured under an optical microscope. The cantilever was excited by an oscillator. The variation of tip deflection with the applied voltage as measured in this experiment is shown in Figure 4.26. The bottom curve gives the tip deflection of the cantilever as a function of the applied voltage at 50 Hz, while the upper pink curve indicates the deflection when exciting at its resonance frequency. It may be noted that the deflection at 50 Hz excitation is similar to the values obtained with pure DC excitation. Due to a Q-value larger than 1, the amplitude at the resonance frequency is about five times higher for small voltages. At high voltages the amplitude does not show a linear dependence any more, which may be due to a shift of the resonance frequency for high deflections. When using the linear dependence of the deflection on the voltage in the low frequency case, the piezo strain coefficient $d_{31}$ of the PVDF can be calculated using the following equation:

$$\delta = \frac{3}{4} d_{31} \frac{l^2}{t^2} V$$

(4-8)

Where $l$ is the cantilever length, $t$ is the thickness of a single PVDF sheet and $V$ is the applied voltage. By substituting the deflection observed in the above equation, $d_{31}$ was obtained by equation (4-8) as $25 \times 10^{-12}$ m/V, which is exactly the same value as the one used in the simulation.
Figure 4.26: Bimorph cantilever deflection as a function of applied voltage for different frequencies.

4.5.2 Testing of Unimorph Cantilever

The dimensions of the unimorph cantilever used in this experiment were 6 mm x 1 mm with a PVDF sheet thickness of 28 µm having a 5 µm thick electroplated permalloy layer on one side. The cantilever was actuated by a DC voltage in the range from 60 V to 180 V. The tip deflections of the cantilevers were observed under an optical microscope mounted with a micrometer. Three samples with the same nominal dimensions were measured. The deflections observed with each of these beams are shown in Table 4.9.

Table 4.9: Measurement of tip deflections of a composite cantilever (µm).

<table>
<thead>
<tr>
<th>Potential (V)</th>
<th>Beam1</th>
<th>Beam2</th>
<th>Beam3</th>
</tr>
</thead>
<tbody>
<tr>
<td>60V</td>
<td>35-40</td>
<td>40-45</td>
<td>40-45</td>
</tr>
<tr>
<td>100V</td>
<td>90-100</td>
<td>85-95</td>
<td>90-95</td>
</tr>
<tr>
<td>120V</td>
<td>105-115</td>
<td>100-110</td>
<td>105-115</td>
</tr>
<tr>
<td>150V</td>
<td>130-135</td>
<td>130-145</td>
<td>135-140</td>
</tr>
<tr>
<td>180V</td>
<td>145-155</td>
<td>150-160</td>
<td>150-160</td>
</tr>
</tbody>
</table>

To ensure the reproducibility of the readings deflections were measured in each case at least twice (switching the voltage off and on) and the range of the values is provided in Table 4.9. It may be noted that the observed deflection increases four times
when the applied voltage is tripled. Also the values from beam to beam were very consistent.

The variation of the average tip deflection as a function of the applied voltage is plotted in Figure 4.27. In general, the deflection of the cantilever is proportional to the applied voltage. These results showed that the values of the deflection obtained through analytical calculations are in excellent agreement with the numerical values obtained through CoventorWare simulation using finite element methods. However, the deflections observed experimentally were 20% less than the values obtained through analytical numerical computations. This difference between the experimental and computed values may be attributed to a combination of the uncertainty in the thickness measurement, non-uniformity of the electroplated permalloy layer, residual stresses within the electroplated permalloy film and a difference in the Young’s modulus of the electroplated permalloy compared to the bulk value which is used in the simulation.

Figure 4.27: Comparison of experiment and simulation.

Figure 4.27 shows a comparison of the experimentally observed variation of the beam deflection with simulated values at a beam length of 6 mm, width of 1 mm, and thicknesses of PVDF and permalloy of 28 µm and 5 µm respectively.

As discussed above, the residual stresses developed within the electroformed permalloy layer might also have contributed to the difference in deflection between the simulated and experimental values. Both the simulation and the analytical calculations assumed a stress free metallic layer. The electroplated layers are, in general, known to contain residual stress essentially due to the electrochemical kinematic processes occurring during the plating process (Stein, 1996). The plating parameters such as current
density, bath concentration, pH and temperature are known to contribute to the residual stress developed during the deposition process. In addition, residual stress in electroplated permalloy films is also sensitive to their iron content, beyond certain values of the nickel to iron ratio. Different techniques have been used to measure the internal stress during electroplating (Hyoung and Cho, 2001; Stein, 1996). However, it is hard to find a process variable that does not influence internal stresses of the deposited layers. In this work, we found that current density is a critical parameter with respect to the reduction of residual stress. As the current density increased the plating rate also increased at the same time increasing the surface internal stress. Therefore, in order to minimize the stresses a lower current density (5mA/cm$^2$) was used during the electroplating of the permalloy layer.

The Young’s modulus of the non-piezo layer used in the simulation might be another possible cause for the difference in deflection observed in the experiment. The Young’s modulus of the non-piezo layer used in the simulation is mainly a bulk value for permalloy with a nominal composition of 81% Ni and 19% Iron. The Young’s modulus of the electroplated permalloy is expected to be different from the bulk value reported in the literature. All of these factors might have together contributed to the deviation of the experimental cantilever deflection from the simulation. This certainly requires further investigations to determine and identify the reasons for such a large difference.

4.6 Summary

A piezoelectric polymer composite unimorph cantilever was designed and optimized by finite element method modelling using software packages by CoventorWare and ANSYS. The unimorph cantilever consists of a piezoelectric polymer PVDF and a non-piezo elastic layer. The effect of various parameters on the tip deflection of the cantilever was analysed. These studies showed that an increase in the thickness of the piezoelectric layer reduced the tip deflections of the composite cantilever. Thickness of the non-piezo layer affected the tip deflection dramatically, while the material property Young’s modulus had only a marginal effect on the beam deflection. In order to apply this unimorph cantilever as a component of a later hybrid actuator, which combines
electromagnetic actuation along with the piezoelectric cantilever, permalloy was chosen as the material for the non-piezo layer of the unimorph cantilever. Considering the above results and the different aspects of fabrication, a 28 µm thick PVDF layer with a 5 µm permalloy has been selected for future work. The tip deflection of the cantilever is found to be proportional to the square of its length.

A microstructured surface of a PVDF unimorph cantilever was created and simulated. Simulation results showed that the surface microstructure reduces the thickness of the solid part in the PVDF layer, thus increasing the tip deflection of the cantilever.

The details of the fabrication routes followed in making the PVDF cantilevers are described. Two types of cantilevers, unimorph and bimorph, were fabricated and tested. The cantilevers were punched using electroformed nickel shims fabricated on a polycarbonate mould, which was laser micromachined. The bimorph cantilevers were formed by attaching two PVDF cantilever together, whereas the unimorph cantilevers constituted a single PVDF cantilever with one side having a 5 µm thick electroformed permalloy layer. The effect of microstructures on the deflection of cantilever beams was also investigated by fabricating them using microembossing techniques. The unimorph composite cantilever has generated a 75 µm tip deflection at an excitation voltage of 100 V. The measured results of the cantilever have shown reasonable agreement with the values obtained by analytical and FEA simulation.

Punching is a promising way to shape and fabricate polymer films, which are flexible and sensitive to temperature. Furthermore, it can be used favourably to shape a surface microstructure on a PVDF polymer film.
Chapter 5  Design, Simulation and Optimization of Hybrid Milliactuators and Microactuators

5.1  Introduction

The design, simulation and analysis of piezoelectric polymer actuators based on the PVDF cantilevers as described in the last Chapter, has provided enough background information required to move forward towards the design of a hybrid actuator, which is the final goal of this thesis. This Chapter presents the details of the analytical and numerical methods adopted in the design of hybrid actuator, which is a basic combination of two different actuation mechanisms, i.e., the piezoelectric actuation and electromagnetic actuation. Section 5.3 describes the procedure followed in the ANSYS simulation of the hybrid actuator; following is the discussion of the analytical approach to calculate different forces on the cantilever. Section 5.4 provides results of the ANSYS simulation to determine the effect of different design parameters on the deflection and forces of the actuators. The design of the hybrid actuator is divided into two major parts. The first part deals with the design of a hybrid actuator, which may be classified as a milli-actuator rather than a micro-actuator. The aim of this part of the work is to find an optimal layout of the hybrid actuator based on FEA simulations performed with ANSYS. This will be useful to test the concept by fabricating a prototype device using macro fabrication technologies. The simulation results led to the design of a hybrid microactuator with a planar microstructure described in Section 5.5.
5.2 **Principle Setup of the Hybrid Actuator**

The schematic configuration of the hybrid actuator is illustrated in Figure 5.1. This actuator mainly requires a piezoelectric polymer PVDF cantilever with an electro-plated permalloy thin layer structure on one side. The copper coil wound around a permalloy core is assembled on a silicon substrate along with a permanent magnet at the bottom.

![Figure 5.1: Schematic diagram showing the hybrid actuator.](image)

When the electromagnetic coil is energized by a current, it generates an electromagnetic force, which attracts the cantilever towards the permalloy core. However, this magnetic force is not sufficient to attract the beam down to the top surface of the permalloy core at low currents, as the air gap is larger than the maximum possible deflection. Additional deflection is achieved by actuating the piezoelectric polymer PVDF cantilever. The simultaneous stimulation of both actuators brings the tip of the cantilever to the top surface of the permalloy core. The cantilever acts as a switch. Once the switch is in its closed position it can be held by the magnetic field alone. When the direction of the current flow is reversed, it generates an electromagnetic force in the opposite direction, bringing the switch to its open position.
5.3 Analysis of Forces Acting on the Beam

In the hybrid actuator the magnetic field generates forces acting on the beam. A minimum required magnetic force $F_{RMF}$ can be defined that must be achieved or surpassed by the actuating magnetic force $F_{mag}$, in order to bend the beam with large enough deflection for closing the switch.

![Force model of the cantilever beam.](image)

The magnetic force generated by the electromagnetic coil and the permanent magnet can be expressed by

$$F_z = M_z \int_V \frac{dH_z}{dz} dV,$$

(5-1)

where $M_z$ is the magnetization of the permanent magnet, $V$ the volume of the permanent magnet, and $H_z$ is the vertical component of the magnetic field produced by the electromagnetic coil. The expression for $H_z$ produced by a current loop can be obtained by integration of the Biot-Savart Law. $H_z$ depends on the applied current. In this design, the electromagnetic force was simulated by finite element analysis of the magnetic system using the low frequency electromagnetic analysis solver of the software package ANSYS.

The magnetic force required for bending the beam to a certain displacement position is analysed using 2D static magnetic analysis as described in the following Section.
5.3.1 2D Static Magnetic Analysis

ANSYS provides ‘PREP7’ commands allowing the user to edit the program for the FEA simulation, which is used in this project. It also has a graphics user interface (GUI) menu allowing the user to do the simulation step by step. A 2D static model was used in this simulation as the proposed device exhibits axial symmetry. The geometrical dimensions of the system can be optimised by changing the parameters of the magnetic components. The procedure for doing a static magnetic analysis consists of six main steps:

(1) Define the element

In this simulation, the 2D element PLANE13 shown in Figure 5.3 was applied to all interior regions of the model, including permeable magnetic regions, current conducting regions, permanent magnetic regions, and air (free space). The 2D elements use a vector potential formulation. Because the elements are two dimensional, each node has only one vector potential degree of freedom AZ (vector potential in Z direction). The element has non-linear magnetic capabilities for modelling B-H curves or permanent magnet demagnetization curves. When used in a structural analysis it has large deflection, large strain and stress stiffening capabilities.

Figure 5.3: Element PLANE13 - 2D coupled field solid.

(2) Build a 2D model

The model of the electromagnetic system is shown in Figure 5.4. The outer large square area A1 represents the air surrounding the magnetic field. The area A7 is the sili-
con substrate, which acts as a spacer to separate the permanent magnet from the electromagnetic components. A6 is the permanent magnet, A4, and A5 are the coils, A3 is the central permalloy core, and A2 is the permalloy layer of the cantilever beam.

![Figure 5.4: 2D hybrid actuator model used for static analysis.](image)

### (3) Material properties

In static magnetic analysis the properties of all materials used in this actuator must be specified. Table 5.1 lists all these properties for the different regions existing within a 2-D magnetic model.

<table>
<thead>
<tr>
<th>Material</th>
<th>Properties</th>
</tr>
</thead>
<tbody>
<tr>
<td>Air</td>
<td>$\mu R = 1.0$ (X vector of relative permeability) $\mu_0 = 4\pi \times 10^{-7}$ N/A²</td>
</tr>
<tr>
<td>Permalloy</td>
<td>$\mu R$ or B-H curve</td>
</tr>
<tr>
<td>Permanent magnet</td>
<td>$\mu R$ or B-H curve, $H_c$ (coercive force in terms of vector components, $MG_{XX}$, $MG_{YY}$)</td>
</tr>
<tr>
<td>Current-fed stranded coil</td>
<td>Apply source current density, $JS = nI/A$ (where $n$ is turns of coil, $I$ current per turn, $A$ area of cross section)</td>
</tr>
</tbody>
</table>
The relative permittivity of air and copper is 1, that of permalloy is between 500 and 1000. If the nonlinear B-H curve and the relative permeability are specified for the same material, then the relative permeability will be used. In order to invoke the usage of a B-H curve along one of the axes, the relative permeability for that axis must be explicitly set to zero. The demagnetization B-H curve, which normally lies in the second quadrant, must be defined in the first quadrant. To do this, a constant shift is needed to be added to all H values. The shift is given by:

\[
H_c = \sqrt{MGXX^2 + MGYY^2 + MGZZ^2}
\]

(5-2)

\(H_c\) represents the magnitude of the coercive force. MGXX, MGYY, MGZZ are coercive force vectors along X, Y, and Z axes. The coercive force components are used to align the magnetization axis of the magnet with the element coordinate system. For example, the permanent magnet used in this design has a coercive force of 12 kOe and a residual induction \(B_r\) of 1.32 Tesla. The B-H curve in the second quadrant is shown in Figure 5.5. It has to be moved to the first quadrant in order to define the material properties as a table.

![Figure 5.5: Actual and shifted H-B curve.](image)

The coercive force \(H_c\) can be divided by 6 yielding 7 points (H, B) as shown in Table 5.2, which are input as a table in ANSYS PREP7 command as below

```
/PREP7
! B-H CURVE:
Hc=12000
Br=1.32
TB,BH,6
```
TBPT,DEFI,(-12000+Hc)*1000/4/3.14159,0
TBPT,DEFI,(-10000+Hc)*1000/4/3.14159,0.22
TBPT,DEFI,(-8000+Hc)*1000/4/3.14159,0.44
TBPT,DEFI,(-6000+Hc)*1000/4/3.14159,0.66
TBPT,DEFI,(-4000+Hc)*1000/4/3.14159,0.88
TBPT,DEFI,(-2000+Hc)*1000/4/3.14159,1.1
TBPT,DEFI,Hc*1000/4/3.14159,1.32

Table 5.2: Coercive force of the permanent magnet.

<table>
<thead>
<tr>
<th>H(Oe)</th>
<th>0</th>
<th>10000+Hc</th>
<th>8000+Hc</th>
<th>6000+Hc</th>
<th>4000+Hc</th>
<th>2000+Hc</th>
<th>Hc</th>
</tr>
</thead>
<tbody>
<tr>
<td>B(Tesla)</td>
<td>0</td>
<td>0.22</td>
<td>0.44</td>
<td>0.66</td>
<td>0.88</td>
<td>1.1</td>
<td>1.32</td>
</tr>
</tbody>
</table>

(4) Assign physical attributes to each region within the model and mesh the model

Meshing is an important step for finite element analysis. The dimensions of the elements determine the precision of the result. Smaller dimension of the elements yield more precise simulation results, but require a longer time to perform the simulation. Therefore, suitable dimensions of the elements need to be chosen for different models. Before meshing, the physical attributes of material properties have to be assigned to the corresponding areas. In this design, material properties are assigned to the regions of air, permalloy, copper coil, and permanent magnet. All above areas are meshed using the same finite element PLANE13.

(5) Apply boundary conditions and loads (excitation)

All the boundary conditions are applied to the model at this stage. The Source Current Density (Js) specifies the applied current to the coil A4 and A5. The unit of JS is ampere/meter2 (A/m^2) in the MKS system. For a 2D analysis, only the Z component (perpendicular to the surface of the layout) of JS is valid; a positive value of the current density indicates current flowing in the +Z direction (pointing to the reader) in the planar case and the -Z direction on the other side in the case of axial symmetry. Either the sparse solver or the frontal solver is employed for obtaining a 2-D solution.
(6) Review the results

An ANSYS macro, FMAGBC, is used to identify a body or component for force and torque calculations. In this simulation, the cantilever beam is identified as the body. The macro automates applying virtual displacements and the Maxwell surface flag (it will be discussed later). The body (beam) must be surrounded by at least one layer of air elements. The elements in the body on which forces or displacements are to be calculated into a component are simply grouped.

Maxwell surfaces force (MXWF) are not really loads. They indicate the surfaces on which the magnetic force distribution is to be calculated. Typically, MXWF is specified on the surfaces of air elements adjacent to an air-iron interface. ANSYS calculates forces acting at the air-iron interface (by the Maxwell stress tensor approach) and stores them in the air element. The forces can be reviewed and summed in the POST1 post-processor to obtain the global forces acting on the beam. These forces can then be used as loads in a structural analysis.

Magnetic virtual displacements (MVDI) initiate the calculation of forces on a body (beam) in the model. The MVDI method provides an alternative to the Maxwell force method. The ANSYS program calculates the forces as it processes the solution, using the virtual work approach.

The flux line distribution of this magnetic system is shown in Figure 5.6. It yields a 2D model of the hybrid actuator and the flux lines (PLF2D) of the electromagnetic system at the applied current density. Also, Maxwell and virtual work forces are summarised briefly for element component (cantilever beam) on which those forces were specified as boundary conditions (FMAGSUM).

The magnetic circuit with the lines of flux along the length of the core appears to extend nicely on to the cantilever (with permalloy layer), which generates a force that helps in moving the cantilever in either direction, depending on the sign of the drive current in the coil. In this design, the targeted air gap between the cantilever and the top surface of permalloy core is 400 µm. It may be noted that the magnetic flux line distribution shown in Figure 5.6 is at the middle position (200 µm) for an air gap of 400 µm. The discontinuity at the top results from the change of the permeability between the per-
malloy layer and the air. In this Figure, it may also be observed that the plotted field distribution originated from the bottom, as this is the permanent magnet.

![Figure 5.6: Flux line distribution of the hybrid actuator.](image)

The results of the 2D static magnetic analysis of the hybrid actuator (Figure 5.4) are presented in Table 5.3 below. The magnetic forces acting on the cantilever beam at an air gap of 200 µm are calculated by the virtual work and by the Maxwell stress tensor methods while all other parameters and dimensions of the magnetic components are kept constant.

<table>
<thead>
<tr>
<th>Summary of force by Virtual work (N/m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Component</td>
</tr>
<tr>
<td>BEAM</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Summary of force by Maxwell stress tensor (N/m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Component</td>
</tr>
<tr>
<td>BEAM</td>
</tr>
</tbody>
</table>
It can be seen that the x-component of the magnetic force is much smaller than its y-component. In this application only the y-component was considered. As this is a 2D simulation, the magnetic force listed above is the force per unit width. The total magnetic force (N) can be obtained by multiplying the listed value (N/m) with the width of the cantilever beam (m).

### 5.3.2 Distribution of the Actual Magnetic Force on the Cantilever

In the 2D simulation of electromagnetic components, the permalloy layer on the cantilever beam was considered as the body for calculating the magnetic force. The cantilever beam (6 mm long and 1 mm wide) was meshed into 60 rectangular elements from 1 to 60. There are 122 nodes on the beam as shown in Figure 5.7.

A 2D simulation of a hybrid actuator was performed for an air gap of 400 µm. The induced magnetic force distribution along the length of the beam is shown in Figure 5.8 (a). It shows that the magnetic forces mainly concentrate near the tip of the beam. It may be noted that the length of the beam used in this simulation was 6 mm. However, the x-axis shows the number of elements, which the maximum force was found to be 10 mN/meter. The forces, which act on elements from No.2 to No. 40, are so small that they can be neglected.

The magnetic force distribution along the cantilever width is shown in Figure 5.8 (b). It shows that the force distribution has a symmetric parabolic shape. The maximum force at the point on the cantilever, which is almost facing the centre of the permalloy core can be attributed to the shape of the circular core placed exactly beneath the cantilever at the edge.
5.3.3 Analytical Determination of Magnetic Force on Cantilever

Based on the simulation results of the magnetic force distribution, four kinds of potential force distribution models are considered, as indicated in Figure 5.9 to determine the required magnetic forces for bending the beam to a certain displacement.

In case (a), a point force $F$ is exerted at the end of the cantilever. The tip deflection of the cantilever is given by

$$\delta_{tip} = \frac{FL^3}{3EI}$$  \hspace{1cm} (5-3)

where $I$ represents the moment of inertia of the entire cross sectional area about the neutral axis. $E$ is the equivalent Young’s modulus of the composite beam. In all these four cases under consideration, $EI$ has the same value, which is discussed in the next Section.
In case (b), the force distribution along the beam is assumed to be a surface force exerted at the end 1 mm (length) section of the beam. In this assumption, the beam length is $L = 6$ mm, the length with the surface load is $b = 1$ mm; $a = L - b = 5$ mm. If the force intensity along $b$ is $q$, then the tip deflection $\delta$ for the cantilever beam with the surface load can be expressed as (Timoshenko, 1987)

$$\delta_{tip} = \frac{q}{24EI} (3L^4 - 4a^3L + a^4)$$  \hspace{1cm} (5-4)

In case (c), a surface force is applied along the whole length of the cantilever with a triangular force density distribution. The tip deflection of the cantilever is

$$\delta_{tip} = \frac{11qL^4}{120EI}$$  \hspace{1cm} (5-5)
Assumption (d) is the closest approximation to the real force distribution. In order to simplify the calculation, the triangular force density distribution can be approximated by a point force acting at the middle of the beam segment of length $b$. The tip deflection is then given by

$$\delta_{tip} = \frac{F(a + b/2)^3}{3EI} + \frac{F(a + b/2)^2b}{4EI}$$  \hspace{1cm} (5-6)$$

To compare the force distribution in these four cases, the required magnetic forces (called RMF in the following) for generating the same tip deflection were calculated using these equations (5-3) – (5-6) and are listed in Table 5.4. The units used in these calculations conform to the SI system, i.e., Young’s modulus (Pa or N/m$^2$), moment of inertia $I$ (m$^4$), tip deflection $\delta$ (m) and thus the magnetic force in Newton. Since the Young’s modulus and moments of inertia are the same in all the four cases, the total force will be a proportionate number to the given values in the table. It can be seen that assumptions (b) and (d) yield similar results and are more close to the actual force distribution by the simulation. Therefore, assumption b is a simple and reasonable model for the following design.

Table 5.4: Required magnetic force as a function of tip deflection.

<table>
<thead>
<tr>
<th>Case</th>
<th>a</th>
<th>b</th>
<th>c</th>
<th>d</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total force (N)</td>
<td>1.389 x 10^7 E I $\delta$</td>
<td>1.586 x 10^7 E I $\delta$</td>
<td>2.525 x 10^7 E I $\delta$</td>
<td>1.587 x 10^7 E I $\delta$</td>
</tr>
</tbody>
</table>

The equivalent Young’s modulus and the moment of inertia of the composite cantilever beam are calculated as follows. The cross section of the composite piezoelectric cantilever beam along with the electroplated permalloy layer is shown in Figure 5.10. The top part (1) represents the piezoelectric polymer PVDF and the bottom part (2) represents the permalloy layer. The thicknesses of these layers are $h_p$ and $h_m$ respectively. The distance between the top surface of the beam and the position of the neutral axis of the composite beam is denoted by $h_{neu}$. 
Assuming that the materials behave in a linear elastic manner, Hooke’s law for uniaxial stress is valid. Then the stresses in both the materials can be represented by the equations,

\[ \sigma_{x1} = -E_1 ky \quad \sigma_{x2} = -E_2 ky \]  
(5-7)

Where \( \sigma_{x1} \) is the stress in the PVDF layer and \( \sigma_{x2} \) is the stress within the permalloy layer. \( E_1 \) and \( E_2 \) are the Young’s moduli of PVDF and permalloy respectively. The position of the neutral axis can be found by using the condition that the resultant axial force acting on the cross section is zero; therefore,

\[ \int_1 \sigma_{x1} dA + \int_2 \sigma_{x2} dA = 0 \]

(5-8)

where it is understood that the first integral is evaluated over the cross sectional area of PVDF and the second integral is evaluated over the cross sectional area of permalloy. Replacing \( \sigma_{x1}, \sigma_{x2} \) in the preceding equation by their expressions from Equation (5-7), we get the location of the neutral axis of the composite beam,

\[ h_{neu} = \frac{E_1 h_p^2 + E_2 (h_p + h_m/2) h_m}{E_1 h_p + E_2 h_m} \]

(5-9)

Furthermore, the inertia about the neutral axis of cross sectional area 1 and 2 can be calculated by
\[ I_1 = \frac{wh_p^3}{12} + wh_p\left(h_{\text{neu}} - h_p/2\right)^2 \]
\[ I_2 = \frac{wh_m^3}{12} + wh_m\left(h_p + h_m/2 - h_{\text{neu}}\right)^2 \]

(5-10)

The Young’s modulus of these materials can be related to the bending moment \( M \) and the curvature \( \rho \) of the bending beam by (Koch, 2000)

\[ k = \frac{1}{\rho} = \frac{M}{E_1 I_1 + E_2 I_2} = \frac{-M}{EI} \]

(5-11)

\( I_1 \) and \( I_2 \) are the moments of inertia about the neutral axis of cross sectional area 1 and 2 respectively. \( E_1 \) and \( E_2 \) are Young’s moduli of PVDF and permalloy. \( I \) represents the moment of inertia of the entire cross sectional area about the neutral axis. \( E \) is the equivalent Young’s modulus of the composite beam.

In the present design, \( E_1 = 2.8 \times 10^9 \) Pa, \( E_2 = 150 \times 10^9 \) Pa, \( h_p = 28 \times 10^{-6} \) m, and \( h_m = 5 \times 10^{-6} \) m, the width of the beam is 1 mm. According to Equation (5-9), the value for \( h_{\text{neu}} \) is found to be 28.9 \( \mu \)m; \( I_1 \) and \( I_2 \) are \( 8.08 \times 10^{-18} \) \( \text{m}^4 \) and \( 2.26 \times 10^{-20} \) \( \text{m}^4 \). Therefore, the equivalent \( EI \) is \( 2.60 \times 10^{-8} \) Pa.m\(^4\).

From Table 5.4, the required magnetic force for beam bending is \( F = 1.586 \, EI \delta = 0.4124 \, \delta \) (N), where \( \delta \) is the tip deflection of the composite cantilever. If the air gap is 400 \( \mu \)m, the required maximum magnetic force to close the actuator would be \( F = 165 \) \( \mu \)N.

5.3.4 Hybrid Actuation - Forces on the Composite Cantilever

Figure 5.11 illustrates the basic relationship between the force and deflection underlying the actuation principle of the hybrid actuator. Two linear lines (RMF and RMFP) represent the required magnetic force of the beam without and with the external stimulation of the piezoelectric effect on the cantilever, while the other two curves correspond to the electromagnetic force generated by the magnetic system for opposite stimulation currents. In order to determining the magnetic force required for bending the cantilever when an additional piezoelectric actuation is included, the latter is assumed to
cause a base deflection of 120 µm. To achieve a 400 µm tip deflection on the cantilever with a 5 µm thick permalloy layer, the maximum RMF without piezoelectric actuation should be 165 µN as calculated above. The value reduces to 115.5 µN (RMFP) with the assistance of piezoelectric actuation. The two curves F(+) and F(-) representing the magnetic forces were obtained when the current was applied in opposite directions.

(RMF = required magnetic force without piezoelectric actuation; RMFP = required magnetic force with piezoelectric actuation; F(+) = induced magnetic force under a positive current; F(-) = induced magnetic force under a negative current).

Figure 5.11: Simulation of the beam deflection of a hybrid actuator.

As shown in Figure 5.11, when a positive current is applied to the coil, the generated electromagnetic force is smaller than the required magnetic force RMF. With the assistance of the piezoelectric effect, the required magnetic force decreases to RMFP so that the in situ magnetic forces F (+) are larger than the RMFP force at all tip positions during the switching operation. This brings the actuator to its closed position. When removing the current and voltage applied to the device, the cantilever is held by the permanent magnet. When a negative current is applied on the coil the magnetic force F (-) becomes smaller than the RMF force, and the actuator opens. The curve F (+) has two intersections with the line indicating the required maximum magnetic force RMF. These two intersections A and B are expected to be in the middle of the line so that the magnetic force on the left end of the curve F (+) is much larger than the required force.
Thus, the cantilever can latch on top of the permalloy firmly. The optimized dimensions of the system can be achieved by adjusting the curves with the desired characteristics.

The simulations shown in Figure 5.11 led to the design of a functional hybrid actuator device described in Chapter 7. The design parameters include the diameter of the drive coil (50 µm diameter copper wire) total number of coil turns (100) and coil input current (80 mA). The permalloy core diameter and height are 500 µm and 2115 µm respectively, while the thickness of the silicon substrate is 345 µm and the dimensions of the permanent magnet are 600 µm x 600 µm x 300 µm. The thicknesses of the PVDF and permalloy layers used in this analysis are 28 µm and 5 µm respectively. In order to achieve an ideal magnetic force distribution within the air gap between the cantilever beam and the top of the permalloy core during beam bending, a thorough analysis was carried out for optimising the above mentioned parameters.

5.4 Optimization of Design Parameters

The process of optimizing different design parameters primarily involved the use of ANSYS simulation. The range of design parameters used in the following simulation and their symbols are listed in Table 5.5. It should be noted from the Table that some of the parameters are fixed. This is mainly necessitated based on their commercial availability, for example, 2” diameter wafers are available in a standard thickness of 300 µm and similarly, the Sm-Co permanent magnets are available in the dimensions 300 x 600 x 600 µm only. The length and width of the silicon wafer have no influence on the generated magnetic field, thus the dimension is fixed as in Table 5.5.

The dimension of the coil is mainly determined by the current density required for producing an electromagnetic field and this is calculated using the following equation

\[ JS = nI / A \]  

(5-12)

where \( n \) is the number of turns of the coil, \( I \) is the current going through the coil, and \( A \) is the cross sectional area of the coil. This is also helped in fixing the diameter of the coil wire (50 µm) as well as the number of turns (100). The usable range of current to achieve the required current density is found to be 50 mA to 90 mA. Therefore the
important parameters in this design are the diameter and height of the permalloy core, the current applied, and the air gap between the tip of the cantilever and the top of the permalloy core.

Table 5.5: Parameters of the hybrid actuator.

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Values [reference value]</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Permalloy core</strong></td>
<td></td>
</tr>
<tr>
<td>Diameter $L_3$</td>
<td>150-1000 [500] µm</td>
</tr>
<tr>
<td>Height $H_3$</td>
<td>2000-3000 [3000] µm</td>
</tr>
<tr>
<td>Permeability MURX</td>
<td>500</td>
</tr>
<tr>
<td><strong>Copper coil</strong> (cross section)</td>
<td></td>
</tr>
<tr>
<td>Width $L_4$</td>
<td>200 (100 turn, 50 µm in diameter)</td>
</tr>
<tr>
<td>Height $H_4$</td>
<td>1250 µm</td>
</tr>
<tr>
<td><strong>Silicon wafer</strong></td>
<td></td>
</tr>
<tr>
<td>Area $L_7 x W_7$</td>
<td>10000 x 5000 µm$^2$</td>
</tr>
<tr>
<td>Thickness $H_7$</td>
<td>300±30[300] µm</td>
</tr>
<tr>
<td><strong>Permanent magnet</strong></td>
<td></td>
</tr>
<tr>
<td>$L_6 x H_6 x W_6$</td>
<td>600 x 600 x 600 [300] µm$^3$</td>
</tr>
<tr>
<td>Coercivity $H_c$</td>
<td>12 kOe</td>
</tr>
<tr>
<td>Magnetic field $B_r$</td>
<td>1.32 Tesla</td>
</tr>
<tr>
<td><strong>Ranges of design variables:</strong></td>
<td></td>
</tr>
<tr>
<td>Current $I$</td>
<td>50-90 mA, 100 turn</td>
</tr>
<tr>
<td>Magnetic force $F$</td>
<td>up to 165 µN</td>
</tr>
<tr>
<td>Air gap</td>
<td>300-450 [400] µm</td>
</tr>
<tr>
<td>Applied voltage on beam</td>
<td>100-180 [100] V</td>
</tr>
<tr>
<td>Beam deflection</td>
<td>300-450 [400] µm</td>
</tr>
<tr>
<td>Piezoelectric deflection</td>
<td>70-130 [120] µm</td>
</tr>
<tr>
<td>Electromagnetic force induced displacement</td>
<td>80-130 µm</td>
</tr>
<tr>
<td>Permanent magnet force induced displacement</td>
<td>~150 µm</td>
</tr>
</tbody>
</table>
5.4.1 Optimizing the Diameter of the Permalloy Core

The diameter of the permalloy core was identified as one of the important parameters that needed optimization. As permalloy is commercially available in three different diameters, i.e. 250 µm, 500 µm and 1000 µm, the simulation was conducted in the range from 150 µm to 1000 µm. Figure 5.12 shows the simulation results under the above mentioned conditions. The blue dashed line represents the force simulated by virtual work (F/V) and the purple solid line is the force calculated by the Maxwell stress tensor (F/M). As the diameter of permalloy core increased, initially there was an increase in magnetic force by around 10 µN. The maximum magnetic force was generated for a permalloy core diameter in the range of 250 µm to 500 µm. In this work, a 500 µm diameter permalloy core was selected as it was easy to handle larger size materials, at the same time providing the maximum magnetic force. From the diagram it can be seen that the induced magnetic force was considerably lower for a 1000 µm diameter permalloy core. This is due to the fact that the flux leakage is larger when the aspect ratio of the permalloy (height to diameter) becomes smaller than 3.

![Figure 5.12: Magnetic force as a function of the diameter of the permalloy core.](image)

5.4.2 Choosing the Permanent Magnet

The dimensions of the permanent magnet can potentially impact the generated magnetic force. The magnetic force is proportional to the volume of the permanent magnet as described in Chapter 3. Figure 5.13 gives the magnetic forces as a function of the diameter of the permalloy core for two different permanent magnet blocks with di-
dimensions of 600 x 600 x 600 µm$^3$ and 300 x 600 x 600 µm$^3$ respectively. Among the four curves in the graph, the top two curves represent the magnetic force generated by the 600 x 600 x 600 µm$^3$ permanent magnet using the Maxwell stress tensor and virtual work methods respectively. The bottom two curves represent the magnetic force generated by the 300 x 600 x 600 µm$^3$ permanent magnet. As can be seen, when the volume of the permanent magnet doubles the magnetic force increases by more than three times. So a careful selection of the dimensions of the permanent magnet is necessary. This design proposes to use the 300 x 600 x 600 µm$^3$ permanent magnet. For a given volume of permanent magnet block, the magnetic force is determined by the dimensions of the permalloy core. As shown in Figure 5.13, the magnetic force seems to change by 15 ~ 35% as the permalloy core diameter is increased from 250 to 1000 µm. Interestingly, the change in magnetic force is minimal in response to an increase in permalloy core diameter from 250 to 500 µm (in agreement with the results shown in Figure 5.12). However, increasing the permalloy core diameter further resulted in a decrease of the magnetic force in all cases. Therefore, it confirms the selection of a permalloy core diameter of 500 µm in the previous Section.

![Figure 5.13: Parameter effects on the magnetic force.](image)

(PM1 refers to the permanent magnet with cross section area of 600 µm x 300 µm, PM2 for 600 µm x 600 µm).

### 5.4.3 The Effect of the Height of the Permalloy Core

As mentioned above in Section 5.4.1, the height and diameter of the permalloy core together decides the aspect ratio of the core structure and in turn the magnetic force
applied on the beam. Figure 5.14 shows the graph drawn between the magnetic force and the height of the permalloy core. It can be seen from this Figure that the induced magnetic force decreases exponentially with the increase of the core height, when a current is applied in the electromagnetic coil. This indicates that the shorter the permalloy core, the larger the magnetic force. However, choosing a permalloy core which is too short would cause a leakage of flux lines due to the small aspect ratio. Normally the ratio of height to diameter of the permalloy core should be more than three to avoid flux line leakage. Considering all these aspects, a permalloy core height of 2000 µm to 2500 µm seems to be a reasonable value, which can provide the required magnetic force.

![Graph showing magnetic force vs. height of permalloy core](image)

Figure 5.14: The magnetic force as a function of the height of the permalloy core.

5.4.4 The Effect of the Thickness of the Silicon Wafer

A silicon wafer was used as substrate for the device, which also acts as a spacer separating the permanent magnet and the permalloy core. Thus, an increasing silicon wafer thickness reduces the induced magnetic field, leading to a decrease of magnetic force. Figure 5.15 clearly shows the variation of magnetic force, as the silicon wafer thickness is increased. It may be observed that the magnetic force is computed in two methods using the Maxwell stress tensor and the virtual work principle, as explained in Section 5.3.1. The differences between the two values are almost constant for all thicknesses of silicon wafers. Therefore, either one of them can be used as a reference for selecting parameters. As the silicon wafer thickness is increased from 200 µm to 450 µm, the magnetic force was reduced from 130 µm to around 70 µm, which is close
to half of the original value. A wafer thickness of 300 µm is a good compromise, taking both commercial availability and the required magnetic force into consideration.

Figure 5.15: The magnetic force vs. thickness of the silicon wafer.

5.4.5 The Effect of Current on the Magnetic Force

Current is applied to the coil to produce an electromagnetic field. This is the only boundary condition applied in the 2D static magnetic simulation. In this simulation the effect of current is determined by keeping all other parameters fixed as shown in Table 5.5. The magnetic force acting on the cantilever beam increases linearly with the increase of the current as shown in Figure 5.16. It increases by about 8 µN when going from 3 to 6 Amp-turns, as indicated in the graph. In this case, it is clear that one has to go to the maximum possible current, which is mainly limited by the thermal heat generation.

Figure 5.16: Magnetic force increases with the current.
5.4.6 Optimum Set of Parameters

To achieve an effective actuator, the intersections of the magnetic force curves and linear RMF line A and B are expected to be at the one third positions on the RMF line as shown in Figure 5.11. The optimal parameters for a hybrid actuator based on the above analysis are listed in Table 5.6.

Table 5.6: Optimised set of parameters for the hybrid actuator.

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Values</th>
</tr>
</thead>
<tbody>
<tr>
<td>Permalloy core</td>
<td></td>
</tr>
<tr>
<td>Diameter L₃</td>
<td>500 µm</td>
</tr>
<tr>
<td>Height H₃</td>
<td>2000-2500 µm</td>
</tr>
<tr>
<td>Permeability MURX</td>
<td>500</td>
</tr>
<tr>
<td>Copper coil (cross section)</td>
<td></td>
</tr>
<tr>
<td>Width L₄</td>
<td>200 µm</td>
</tr>
<tr>
<td>Height H₄</td>
<td>1250 µm</td>
</tr>
<tr>
<td>Silicon wafer</td>
<td></td>
</tr>
<tr>
<td>Area L₇ x W₇</td>
<td>10000 x 5000 µm</td>
</tr>
<tr>
<td>Thickness H₇</td>
<td>300 µm</td>
</tr>
<tr>
<td>Permanent magnet</td>
<td></td>
</tr>
<tr>
<td>Dimension L₆ x H₆ x W₆</td>
<td>300 x 600 x 600 µm³</td>
</tr>
<tr>
<td>Coercivity H_c</td>
<td>12 KOe</td>
</tr>
<tr>
<td>Magnetic field B_r</td>
<td>1.32 Tesla</td>
</tr>
<tr>
<td>Ranges of design variables:</td>
<td></td>
</tr>
<tr>
<td>Current I</td>
<td>50–90 mA</td>
</tr>
<tr>
<td>Magnetic force F</td>
<td>up to 165 µN</td>
</tr>
<tr>
<td>Air gap</td>
<td>400 µm</td>
</tr>
<tr>
<td>Beam applied voltage</td>
<td>100–180 V</td>
</tr>
<tr>
<td>Beam deflection</td>
<td>400 µm</td>
</tr>
<tr>
<td>Piezoelectric force induced</td>
<td>120 µm</td>
</tr>
<tr>
<td>Electromag. force induced</td>
<td>80–130 µm</td>
</tr>
<tr>
<td>Permanent Magnet force induced</td>
<td>~150 µm</td>
</tr>
</tbody>
</table>
5.4.7 Examples

To verify the optimal parameters, three hybrid actuators were built with different dimensions as listed in Table 5.7. The simulations of these three actuators were carried out as shown below.

Table 5.7: The dimensions of three different hybrid actuators used for testing.

<table>
<thead>
<tr>
<th>Device ID</th>
<th>1</th>
<th>2</th>
<th>3</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cantilv. dimensions</td>
<td>6 mm x 1 mm x (28 µm PVDF+5 µm permalloy)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Permalloy core (µm)</td>
<td>φ500 x 2115</td>
<td>φ500 x 2455</td>
<td>φ500 x 3240</td>
</tr>
<tr>
<td>Copper Coil (µm)</td>
<td>φ50 µm 100turn (1250 x 200)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Si thickness (µm)</td>
<td>345</td>
<td>285</td>
<td>300</td>
</tr>
<tr>
<td>Permanent magnet</td>
<td>600 x 600 x 300 µm³</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

(a) Device 1 with an air gap of 400 µm.
(b) Device 2 with an air gap of 400 µm.

(c) Device 3 with an air gap of 400 µm.
Device 2: Current 60mA, coil 1250x200, 100 turn, permalloy core 500x2455, Si285um, PM600x600x300, air gap 350um

Figure 5.17: Simulation results of the tested devices

As shown in these diagrams, the required bending force varies linearly with the beam deflection in the range from 0 to 400 µm. Lines RMF and RMFP represent the required magnetic forces for beam bending without and with the external piezoelectric stimulation on the cantilever respectively. A deflection of 120 µm was assumed to be obtained when applying the piezoelectric actuation. The other four curves representing the magnetic forces were obtained for both directions of current and for two different simulation methods. F/V (+80) and F/M (+80) represent the magnetic forces obtained by these two different simulation methods (virtual work and Maxwell stress tensor) as described in Section 5.3.1 under a positive current of 80 mA. The other two curves F/V (-80) and F/M (-80) show the results for a reversed current. In order to close the actuator, the applied magnetic force must be larger than the required magnetic force at all beam tip positions.
The results of the simulations clearly showed that

- With the increase of the permalloy height (from device 1 to device 3), the intersection of curves F/V (+) and F/M (+) with RMFP line is closer to the left end of the line. That means the cantilever is difficult to latch on the permalloy core. Therefore higher currents are needed.

- By reducing the air gap in device 2 as shown in Figure 5.17 (b) and (d) from 400 µm to 350 µm, the curves F/V (+) and F/M (+) tend to the desired characteristics.

- The combined use of two different actuation mechanisms (piezoelectric and electromagnetic) ensures that the force achieved is always higher than the required magnetic force during the closing operation.

The simulation results are in good agreement with the theoretical analysis obtained from simulation using finite element method. This design and modelling method can be extended to fabricate a planar hybrid microactuator.

### 5.5 Hybrid Microactuator

The design of the milli-actuator as described above provided input for the design of a simple, planar hybrid microactuator. This work used similar simulation procedures as employed for the milli-actuator. The configuration and the details related to the microactuator are presented in the following Sections.

#### 5.5.1 Design and Simulation

The schematic of the hybrid microactuator is shown in Figure 5.18. A top view and a cross-sectional view of the actuator are shown in Figure 5.18 (a) and (b) respectively. It consists of a PVDF composite cantilever beam, a planar copper microcoil, a permalloy central core electrodeposited on the silicon substrate and a permanent magnet attached to the back side of the silicon wafer to achieve bi-directional actuation. The
microcoil, central core and the permanent magnet are aligned along the centre of the permalloy core as shown in Figure 5.18 (b).

(a) 3D view of the prototype.

(b) Side view of the prototype.

Figure 5.18: Schematic diagram of the hybrid microactuator.

In this design, the cantilever beam is 3 mm long and 1 mm wide. The thicknesses of the PVDF layer and permalloy are 28 µm and 5 µm respectively. When the beam length is to be decreased and the tip deflection is to be kept simultaneously constant, we have to choose a thinner PVDF layer and permalloy layer as explained in Chapter 4. In an alternative design, the cantilever beam was 2 mm long and 1 mm wide with 9 µm thick PVDF and 2 µm thick permalloy.

Taking into account fabrication aspects, the dimensions of the permalloy core were chosen to be 500 µm x 500 µm x (40–60) µm with a permeability of 500. Permeability of permalloy layer can be varied from 500 to 10000 depending on the Ni/Fe ratio of the material. The Ni$_{81}$Fe$_{19}$ composition can have a permeability of 1000 to 2000. In order to keep the design more conservative, a permeability of 500 was used in this
The copper microcoil was designed as a planar microstructure with an equal line width and separation of 25 \( \mu \text{m} \) and a thickness of 25 \( \mu \text{m} \) with a total of 20 turns. The thickness of the silicon wafer was 500 \( \mu \text{m} \) with a tolerance of 10\%. The dimensions of the permanent magnet used are 500 \( \mu \text{m} \times 500 \mu \text{m} \times 200 \mu \text{m} \), with a coercivity force \( (H_c) \) of 10 kOe and a residual induction \( B_r \) of 0.41 Tesla.

The current applied to the microcoils was typically in the range of 30-50 mA, leading to an induced magnetic force of 50 \( \mu \text{N} \). The maximum air gap in this design was around 100 \( \mu \text{m} \). The voltage applied to the piezoelectric cantilever was 100-150 V, leading to a tip deflection of 25-50 \( \mu \text{m} \).

The required magnetic force for the microactuator was calculated by the same force distribution assumption in Figure 5.9 (d). In the microactuator, the cantilever length \( L \) is 3 mm. The maximum required magnetic force (RMF) is \( 1.269 \times 10^8 EI\delta \) (N). Thus, an air gap of 100 \( \mu \text{m} \) leads to a force of 330 \( \mu \text{N} \).

The modelling of the microactuator was based on the same principle as described earlier for the macro hybrid actuator, using the ANSYS 2D static magnetic analysis program. It is well known that the properties of thin film materials are usually different from the respective bulk material value. For example, the magnetic properties of a 200 \( \mu \text{m} \) thick permanent magnetic film have a remnant polarization \( B_r \) of 0.41 Tesla and coercivity \( H_c \) of 10 kOe, which are smaller than those of bulk material of the same composition. As the area and thickness of the permanent magnet determines the achieved maximum magnetic force, it is necessary to work out the relationship between the magnetic field and the volume of the permanent magnet. The 2D static magnetic analysis of the planar microstructure follows the same steps as mentioned before. Figure 5.19 indicates the dependence of the magnetic force on the area of the permanent magnet. The thickness of the permanent magnet was fixed at 200 \( \mu \text{m} \). Because a 2D simulation is used in this project, the free parameter to be considered in this simulation of the permanent magnet is its length. The width was assumed to be equal to the length. The induced magnetic force increases nearly linearly with the length and width of the permanent magnet after exceeding a value of 300 \( \mu \text{m} \).
Figure 5.19: Effect of the size of the permanent magnet on the induced magnetic force.

The magnetic flux line distribution of the micro hybrid actuator is slightly different from that of the macro device. As can be seen from Figure 5.20, the flux lines on the tip of the cantilever are not as dense as for the macro device. This is due to the flux leakage caused by the short permalloy core.

Figure 5.20: Magnetic flux line distribution of a micro hybrid actuator.
Figure 5.21 shows the results of an ANSYS simulation plotting the required forces as a function of beam deflection for the hybrid microactuator. In the plot, the curves marked with F/V (+50) and F/M (+50) represent the magnetic force when 50 mA current are applied to the electromagnetic coil, using virtual work and Maxwell stress tensor methods respectively. The negative sign in the F/V (-50) and F/M (-50) indicate the reversal of the direction of the current in the coil. The induced magnetic force under a positive current is much larger than the force under the negative current. It would be very easy to latch off the cantilever from the permalloy core when a negative current is applied. Comparing this design with an earlier hybrid actuator it shows that the hybrid microactuator has more advantages in the latching off operation. This design aimed for an air gap of 100 µm assuming a 30 µm tip deflection generated by the piezoelectric effect.

The current applied to the microcoil was limited to less than 50 mA, which constrained the current density below the value of 5 Amp turn/mm², taking the associated power dissipation and thermal effects into consideration. The thermal dissipation of the coil will be discussed in the next Section.
5.5.2 Analysis of the Microcoil

Figure 5.22 shows the layout of the microcoil. There is one contact pad (100 µm x 200 µm) on the outer perimeter, a second one near the centre. The material properties of copper are listed in Table 5.8.

![Figure 5.22: Layout of the microcoil.](image)

Table 5.8: Physical and mechanical properties of copper.

<table>
<thead>
<tr>
<th>Property</th>
<th>Copper</th>
<th>Units</th>
</tr>
</thead>
<tbody>
<tr>
<td>Elastic constants-E</td>
<td>1.28e5</td>
<td>MPa</td>
</tr>
<tr>
<td>Poisson ratio-ν</td>
<td>3.6e-1</td>
<td></td>
</tr>
<tr>
<td>Density</td>
<td>8.96e-15</td>
<td>kg/µm³</td>
</tr>
<tr>
<td>Resistivity</td>
<td>1.68e-6</td>
<td>Ω cm</td>
</tr>
<tr>
<td>TCE</td>
<td>9.4e-6(@300K)</td>
<td>1/K</td>
</tr>
<tr>
<td>Specific heat</td>
<td>3.846e14</td>
<td>pJ/kg/K</td>
</tr>
<tr>
<td>Thermal Conductivity</td>
<td>3.98e8 (@300K)</td>
<td>pW/µm/K</td>
</tr>
<tr>
<td>Electrical Conductivity</td>
<td>5.95e13</td>
<td>pS/µm</td>
</tr>
<tr>
<td>Yield strength</td>
<td>100</td>
<td>MPa</td>
</tr>
</tbody>
</table>
The length $L$ of the coil is calculated to be 72.2 mm, its cross section is $6.25 \times 10^{-4} \text{ mm}^2$. With the resistivity of $1.68 \times 10^{-6} \text{ ohm cm}$, the total resistance of the coil is 2.43 ohm.

When a current is applied to the coil, its temperature rises due to the electrical energy dissipated in the resistor. The balance of the thermal energy equation for the microcoil is given by

$$I^2R = Km\Delta T$$  \hspace{1cm} (5-13)

Where $I$ is the current applied on the coil, $K$ is the specific heat, the mass of the coil $m$ is $3.236 \times 10^{-7} \text{ kg}$, the temperature difference $\Delta T$ can be calculated as 48.8 K.

According to the above analysis the temperature of the microcoil increases by 48.8 K when a current of 50 mA is applied. This calculation neglects thermal diffusion and thermal convection to the environment, thus yielding an overestimation of the real value. Hence, the 50 mA current can be considered as a very conservative value of current for this design.

The design of the hybrid microactuator was followed well with a relatively larger prototype actuator. As expected the reduced size resulted in a reduction of force as well as of deflection. Nevertheless, the microactuator design was found to be very efficient, being able to produce a maximum deflection of 100 $\mu\text{m}$ and achieving a force of 330 $\mu\text{N}$.

### 5.6 Summary

This Chapter described the results of simulation and modelling of a hybrid actuator combining the two mechanisms viz, piezoelectric and electromagnetic principles. This device consists of a piezoelectric polymer composite unimorph cantilever as described in Chapter 4 and electromagnetic components, which include a copper coil, a permalloy central core on a silicon substrate and a magnet on the bottom.

The magnetic forces acting on the cantilever were modelled and analysed by FEA simulation. A 2D static magnetic analysis was performed using the ANSYS software...
package. The parameters and dimensions of the device were optimized by these simulations. The design involved two prototype devices, a milliactuator and a microactuator. The design of the planar microactuator has taken into account the intricacies of the fabrication technologies and processes. The parameters and dimensions were optimized by using a similar simulation method. As the material properties are different between the bulk material and its thin film, aspect ratios of the microstructures are different as well; the magnetic flux line of the micro-device is less at the tip of the cantilever than on its macro counterpart. The magnetic force distribution acting on the cantilever is not concentrated at its end due to the flux leakage. Overall, these simulation techniques provided the required answer to understand the effect of different parameters, without embarking on the fabrication of a large number of different versions, keeping the application of expensive processing technologies to a minimum. The realization of these two prototype devices, including fabrication and assembly techniques, are explained in the next Chapter.
Chapter 6  Fabrication of the Hybrid Actuators

6.1  Introduction

After a hybrid milliactuator and a microactuator were designed, modelled, and their expected performance was analysed, as presented in the last Chapter, a demonstration of the proof of concept was required. This Chapter mainly deals with the details of the fabrication and processing methodologies adopted and the assembly of different components. The first part briefly describes the fabrication of the hybrid milliactuator, while the second part mainly concentrates on the planar technologies adopted for the fabrication of the microactuator. The milliactuator was fabricated by using mainly conventional manufacturing technologies and was finally assembled to obtain a working device. The fabrication of the microactuator included the application of planar technology for generating the magnetic components - a copper microcoil, a permalloy central core, and a nickel stand post for suspending the cantilever by lithographically defined patterning of 2-D planar and 3-D high aspect ratio structures, subsequent electroplating of different materials (copper and permalloy), wet etching of seed/under layers and reactive ion etching or cleaning of resist layers as well as the assembly of the hybrid microactuator by different bonding methods. The characterization of these structures using different instruments has also been described at different stages to assert the important aspects of used processing technologies at each of these stages.

6.2  Fabrication of Hybrid Milliactuator

As described in previous Chapters, the hybrid actuators were designed in two different dimensions, millimetre scale and micrometre scale. The main purpose of the first
model was to demonstrate the proof of concept by fabricating the actuator with most of the conventionally used macro technologies. This actuator configuration mainly involves the fabrication of the unimorph composite cantilever, an electromagnetic coil, a small permanent magnet and a permalloy core. The composite PVDF cantilever has dimensions of 6 mm (length) x 1 mm (width) x 28 µm (thickness) with a 5 µm thick permalloy (Ni$_{81}$Fe$_{19}$) layer on one sides of the PVDF polymer. The fabrication of the cantilever follows the procedures described in the previous Chapter. The Cu-Ni alloy on one side of the PVDF polymer and permalloy layers on the other side act as the electrode for providing voltage to the cantilever for achieving piezoelectric actuation. The permalloy core is made out of commercially available 0.5 mm diameter permalloy wire (99.9% pure alloy wire from Goodfellow, UK). This wire is cut to around 2.5 mm length and is stuck on to the silicon wafer substrate (5 mm x 5 mm x 0.3 mm) using a thin layer of epoxy. An electromagnetic coil was manually wound around the permalloy core. The copper wire, having a diameter of 50 µm, is wound up to 100 turns. The coils are soldered to a thick copper wire to facilitate external power connections to this drive coil. A Sm-Co permanent magnet with dimensions of 600 (length) x 600 (width) x 300 (thickness) µm$^3$ is attached beneath the silicon substrate exactly below the position where the permalloy core is fixed, so that these two components follow the same centre line. The picture of the assembled milliactuators is shown in Figure 6.1. The cantilever is bent down due to the stress in the electroformed permalloy layer imposed on the PVDF cantilever. Though this stress was minimised by optimising the conditions, as discussed in Section 4.5.2, it could not be eliminated completely. The procedures followed for testing the actuator are presented in the next Chapter.

![Figure 6.1: A typical assembled hybrid milliactuator.](image)
6.3 Important Tools Used for the Fabrication

This Section describes some of the important tools used in the fabrication of planar hybrid microactuators. The tools used for the fabrication and analysis of the microactuator include a mask aligner (MA 1006, SUSS MicroTec, Germany), a spin coater (RC-8, SUSS MicroTec, Germany), a frequency tripled Nd:YAG laser micromachining system (Coherent Scientific, USA), a wire bonder (West Bond Inc, USA), a laser scanning confocal microscope (OLS-1100, Olympus, Japan), a magnetron sputtering system, and a Plasma ion reactive etching machine.

6.3.1 Mask Aligner

A semi-automatic SUSS MicroTec mask aligner MA 1006 (Figure 6.2) was used in this work for lithographic exposure. This is a double sided mask aligner with an alignment accuracy of ±1 µm. It is equipped with a collimated light optical system and a programmable unit allowing the application of all common printing modes, namely soft contact, hard contact and vacuum contact. Alignment is carried out by means of micrometer screws, the Z axis is motorized. The machine is fitted with a calotte chuck wedge error compensation system. For top side alignment the aligner is equipped with a split field microscope. An upgrade with a CCD camera and monitor is available.

Figure 6.2: SUSS Mask aligner MA1006.
For backside alignment the MA 1006 is equipped with BSA microscopes using a special image storage system. The typical spectral range is 250 nm to 400 nm. The exposure illumination uniformity over a 6” wafer is ±5%. Both the alignment and proximity exposure distance are adjustable in 1 µm steps.

### 6.3.2 Spin Coater

The RC-8 spin coater used in this work is designed to meet the requirements of coating thick resist layers for fabricating high aspect ratio structures uniformly over a 4” diameter substrate. The picture of the system used is shown in Figure 6.3. The Gyrset design allows the top cover along with the substrate holder to rotate at high speeds. It facilitates to set the optimum pressure and air flow conditions on the top of the spinning resist layer, which allows the formation of a uniform film.

![Figure 6.3: RC-8 Suss spin coater.](image)

### 6.3.3 Magnetron Sputtering System

Titanium and copper seed layers for subsequent electroforming were deposited on the silicon substrate by using the magnetron sputtering technique. A home made dual magnetron sputtering system with titanium and copper targets (3” diameter and ¼” thick 99.9% purity targets) were used for this purpose. The system is pumped with a turbomolecular and a rotary pump combination fitted with a 20” diameter stainless steal chamber. Two layers were deposited without breaking the vacuum, so that pure con-
ducting layers were deposited. The substrate holder is maintained at room temperature and was rotated whenever necessary. The picture of the system is shown in Figure 6.4.

![Magnetron Sputtering System](image)

**Figure 6.4: Magnetron Sputtering System.**

### 6.3.4 Wire Bonder

The bonding pads of a chip are commonly connected to the outside world by wire bonding. Using this technique, a thin wire (diameter of 25 µm) is soldered to the bond pad by a combination of pressure, heat and/or ultrasonic energy in a commercial wire bonder. It is a solid phase welding process, where the two metallic materials (wire and pad surface) are brought into contact, leading to a firm electrical and mechanical connection by the inter diffusion of atoms. In this process, the bonding force can lead to a material deformation, breaking up contamination layers and smoothing out surface asperity, which can be enhanced by the application of ultrasonic energy. Heat can accelerate interatomic diffusion, thus the bond formation.

West bond wire bonder, as shown in Figure 6.5 was used for bonding the electrodes on the hybrid microactuator to a substrate PCB board.
6.3.5 Plasma Reactive Ion Etching

The plasma etching equipment used in these experiments was a LFE Barrel Etcher with a 13.56 MHz RF coil around a glass barrel shaped chamber. A conceptual diagram is shown in Figure 6.6. The wafer is positioned on the substrate holder contained within a Faraday cage, in the centre of the chamber. CF$_4$ gas is introduced into the chamber from several inlets throughout the chamber. Due to presence of high electric field, it is excited into plasma state thus forming ions, electrons and chemically active species (radicals and other excited neutrals). Ion bombardment is suppressed since the substrate holder is contained within a Faraday cage. Chemical reaction takes place on the surface to be etched and the resulting volatile product is pumped off.

Base pressure was kept 0.2 Torr in each experiment. RF power, etch time, gas flow rate and working pressure were varied. The reflected power was found to be less than 5W in all the cases, which is less than 5% of the total forward power in all the cases.
6.3.6 Laser Scanning Confocal Microscope

In a laser scanning confocal microscope, a finely focused beam of laser light is scanned across a sample, and the resultant emitted light is passed through a pinhole aperture to exclude any out of focus light. The image thus produced includes only the plane of focus for a given objective lens. By varying the focusing depth a series of sequential images through the thickness of a single sample can be collected and used to project a three-dimensional image of the sample.

This microscope allows the measurement of the depth of a microstructure with high resolution (0.01 µm). It can also be used as a common microscope in order to get 2D surface images. A confocal microscope yields quantitative information on surface roughness, surface reflectivity and on high aspect ratio structures in a contact free way. It is thus superior to other 3D data acquisition systems, such as interferometers, or fringe protection systems. Filtering and levelling operations are available for post processing the generated image data. The quality of these images and the time taken to acquire images is in between a scanning electron microscope and an optical microscope.
6.4 Fabrication of the Planar Hybrid Microactuator

As described in the previous Chapter, the design of the hybrid microactuator also involved the considerations related to the fabrication process. In fact, the dimensional design of the device was closely linked to the process design, which helped in organising the process steps related to the fabrication of different components in parallel, thus reducing the overall duration.

The hybrid microactuator, as shown in Figure 5.18, constitutes three different structures, i.e. the electromagnetic drive coil (thickness of 25 µm), the permalloy core (thickness of 50 µm), and a nickel post (thickness of 150 µm). All the three microstructure layers were fabricated by using a similar photolithography process, based on SU-8 2000 photoresist, which was employed as a mould for subsequent electroplating.

One of the most important aspects of the fabrication of different components for this device is the design of the masks for different features and an integrated fabrication sequence minimising the number of necessary lithography steps. As part of the strategy it was decided to use the negative tone photoresist SU-8 for the lithographic processing of all the components. A negative tone mask pattern was designed using AutoCAD and has been contracted out for fabrication. The mask layout for each of the four patterns constitutes four quarters of a 5” x 5” mask as shown in Figure 6.8.
Figure 6.8: Mask layout for planar microstructures.

In the layout the left bottom pattern is the microcoil, the right bottom is the permalloy central core, and the top two patterns are for the metal post to suspend a 2 mm or 3 mm long cantilever respectively.

As the three different components in the device needed different thicknesses, the chosen photoresist should be capable to adjust for this. The advantage with the chosen SU-8 resist is that its viscosity can be changed by adding a thinner, which allows the deposition of a thin layer, down to 1 µm. The SU-8 2000 can also be adjusted for a thickness of up to 500 µm in a single layer.

The outline of this process is shown in Figure 6.9. The lithography process parameters were varied for obtaining optimal results in each of these three separate lithographic process sequences.
6.4.1 Fabrication of the Microcoil

The fabrication of the microcoils involved the cleaning of the substrate, seed layer deposition, lithographic patterning of the coil in a chosen resist, electroplating of metallic coils, stripping the resist and etching the seed layer. The processing procedures followed in this work are described in detail below.

**Patterning of coils**

In the first stage, the microcoils were fabricated on a 500 µm thick (100) silicon substrate using the process depicted in Figure 6.10. For obtaining the maximum process reliability, the silicon substrates were cleaned using the standard RCA cleaning process as described in Appendix C. These cleaned wafers were deposited with Ti/Cu/Ti seed layer combination with individual layer thicknesses of 50 nm/300 nm/50 nm respectively. The wafers were in situ glow discharge cleaned prior to seed layer deposition in the vacuum chamber at a typical pressure of $6 \times 10^{-2}$ Torr for 60 s to ensure a clean wafer surface at the same time improving adhesion. The 50 nm thick titanium layer was deposited by RF sputtering at $2 \times 10^{-3}$ Torr for 5 min at 300 W, the 300 nm thick copper layer was deposited by DC sputtering at $2 \times 10^{-3}$ Torr for 4.5 min at 400 W, followed by the deposition of a final titanium layer of a thickness of 50 nm as protective layer.

![Figure 6.9: Outline of lithography process flow.](image)
helped in protecting the copper layer from oxidation and other contamination during different lithographic processing steps prior to electroplating of the coil structures. After the seed layer deposition, the adhesion of these layers was tested using the pull test with a commonly used 3M sticky tape. All these seed layers were found to have reasonable adhesion, surviving the pull test.

(a) Sputter deposition of a Ti/Cu/Ti layer (50/300/50 nm) on the silicon wafer.
(b) Spin coating of SU-8 2025 on top of the seed layer.
(c) UV exposure to pattern the photoresist applying a Cr/quartz mask.
(d) Development of SU-8 photoresist to form the microcoil mould.
(e) Electroplating the copper coil with subsequent removal of SU-8.

Figure 6.10: Fabrication steps of the planar Cu microcoil – first layer.

In order to dehydrate the surface of the silicon wafer, it was heated up to 150°C for 15 min to remove any surface moisture. After the substrate cooled down to room temperature, a 40-50 μm thick photoresist SU-8 2025 was spin coated on the seed layered silicon wafer with a spin speed of 1200 rpm for 30 s. The photoresist was pre-baked (or soft baked) for 5 min at 65°C and 15 min at 95°C with a ramp of 250°C per hour on a levelled programmable PMC-732 hot plate (PMC, USA), then cooled down to room temperature with a ramp of 140°C per hour. The photoresist layer is exposed to UV radiation in the mask aligner through the mask with the required coil pattern at a
dose of 250 mJ/cm². The expanded view of the coil mask pattern is shown in Figure 6.11 (a). The yellow lines indicate the microcoil lines, which are covered by chromium on the quartz mask. The UV light was blocked in this opaque chromium region during exposure. Therefore, the SU-8 resist can be removed in these unexposed areas. All other regions on the mask are transparent to the UV light, leading to the cross linking of the SU-8 there, rendering it insoluble in the developer solution.

(a) Quartz chrome mask of microcoil geometry (2” x 2”).
(b) SU-8 mould of microcoil after developing.
(c) Enlarged SEM image of the SU-8 mould.
(d) Wafer segment after removing the top protection Ti layer.

Figure 6.11: View of the microcoil in various processing stages.

The photoresist was subsequently subjected to a post exposure bake (PEB) at a temperature of 95°C for 15 min to remove any solvent present in the resist layer and render it resistant to attack by different aggressive acidic solutions especially during
plating. The PEB also smoothes the sidewalls of the microcoils and therefore helps to obtain coils without shorts, especially at different corners, after copper electroplating. To prevent the resist from thermal shock, the post exposure baked wafer was placed on the hot plate to cool down gradually to ambient temperature as in the soft bake step. After cooling down to room temperature the sample was developed in the SU-8 developer. The microcoil mould was formed after developing as shown in Figure 6.11 (b). The gap between two coil channels is supposed to be 25 µm and so is the coil width. However, the actual coil width turned out to be 23 µm, while the space between two consecutive lines was also approximately 23 µm. Figure 6.11 (c) shows an enlarged scanning electron microscope (SEM) image of the resulting SU-8 mould. The dark regions show the space between the coils, while the light regions are the SU-8 sidewalls. The 3D profile of the microcoil mould can be clearly seen. The depth of the channels is around 30 µm. An array of microcoil patterns was fabricated on a quarter of a 4” silicon wafer as shown in Figure 6.11 (d).

As explained above, a laser scanning confocal microscope (Olympus Pty. Ltd, OSL1200) was employed to examine the profiles of the lithographically patterned features. One of the major advantages of this microscope is that it provides excellent depth resolution down to 0.01 µm. Figure 6.12 shows the data/information that can be obtained using the confocal microscope. Figure 6.12 (a) shows the top view of the two coil lines at 50 X magnification. Figure 6.12 (b) represents the 3D profile of the coils, while Figure 6.12 (c) is the thickness profile on a 2D scale. Finally, Figure 6.12 (d) provides a table which gives a series of precise values of the vertical dimensions of the coils.
Figure 6.12: Information obtained using a confocal microscope.

Figure 6.13 shows two confocal images of a 3D profile of the SU-8 mould resulting from different lithography conditions. The SU-8 layer shown in Figure 6.13 was deposited at a spin speed of 1200 rpm. This measurement provided thickness values around 40-50 µm. The uneven profile in Figure 6.13 (a) could have resulted from the diffraction effects of the proximity exposure carried out under the soft contact mode, which has resulted in a partially developed resist structure between coils. It may be noted that the soft contact mode allows a gap of 50 to 100 µm between the mask and the substrate. In contrast, Figure 6.13 (b) shows the image of the SU-8 mould fabricated using the hard contact exposure mode in the mask aligner. This shows a well developed mould and has vertical side walls to facilitate the plating of uniformly thick coil structures.
It should be mentioned that the soft (pre) bake and the post exposure bake are two very important steps, which decide the quality of the patterned features during this process. Although SU-8 photoresist has been widely employed in MEMS recently, fabrication parameters differ in almost every published reference. As the SU-8 lithography process is not yet standardized, detailed fabrication conditions depend not only on the used experimental equipment, but also on the desired geometries. All parameters used in this process were optimised based on the MicroChem Datasheets. Details of the fabrication recipe are given in Appendix C.

(a) Laser scanning confocal microscope image of SU-8 mould fabricated using soft contact mode.

(b) Laser scanning confocal microscope image of SU-8 mould fabricated using hard contact mode.

Figure 6.13: Confocal images for the SU-8 mould of the microcoils.
Electroplating of copper coils

The next step is the electroplating of copper coils using SU-8 mould patterned in the previous step. As copper plating needs to be performed on the copper seed layer, the top titanium protection layer was etched using 5% HF solution. The electroplating of the copper microcoil was performed using a copper plating bath with a chemical composition as presented in Table 6.1. With a current density of 10 mA/cm², a plating rate of 10-12 µm/h was obtained at room temperature. Thus it took around 2.5 h to plate a 25-30 µm thick copper layer.

Table 6.1: Chemical composition of the Cu electroplating bath.

<table>
<thead>
<tr>
<th>Compound</th>
<th>Concentration (chemicals/DI water)</th>
</tr>
</thead>
<tbody>
<tr>
<td>CuSO₄. 6H₂O</td>
<td>250 g/l</td>
</tr>
<tr>
<td>97%H₂SO₄</td>
<td>25ml/l</td>
</tr>
</tbody>
</table>

After electroplating, the SU-8 resist has to be removed completely. This step turns out to be very tricky as has been stated by many researchers (Ho et al., 2002; Dentinger et al., 2001; Ghantasala et al., 2001; Vora et al., 2003). Most commonly, some residues of SU-8 remain within high aspect ratio gaps. In this work, the SU-8 remover supplied by Microchem was heated up to 80°C and stirred to remove most of the SU-8. Subsequently a CF₄/O₂ plasma etch was performed to remove the residual SU-8 layer completely.

Figure 6.14 shows confocal images of the copper microcoils before and after plasma etch with the photoresist stripped in both cases. The coils show a structural height of about 30 µm. Before plasma ashing, some SU-8 residues are clearly seen between the microcoil channels, as shown in Figure 6.14 (a). The plasma etch process helped in effectively removing the SU-8 residues between the coil lines. Though the picture shown in Figure 6.14 (b) does not exhibit SU-8 residues, one can notice such residues at a few places. It was found difficult to remove the SU-8 completely in all the areas between the coil lines.
(a) Laser scanning confocal microscope image of copper microcoil with some residual SU-8 remaining between the channels.

(b) Laser scanning confocal microscope image of copper microcoil after plasma etch.

Figure 6.14: Confocal images of an electroplated copper microcoil.

This kind of analysis at the end of each fabrication step helped in optimising the parameters for achieving the coil patterns without cracks or shorts (electrical shorts between the lines due to defects in the mould during lithography processing), stresses and non-uniformities (due to edge bead development around the edge of the wafer). The op-
timisation of the lithographic parameters, such as spin speed, relaxation time, soft bake time and temperature, exposure dose, post exposure bake time and temperature, and development time, was carried out during this process and the final parametric values resulting in better microcoils are summarized in Table 6.2.

Table 6.2: Optimized SU-8 lithography conditions.

<table>
<thead>
<tr>
<th>Process step</th>
<th>Microcoil</th>
<th>Permalloy core</th>
<th>Beam support</th>
</tr>
</thead>
<tbody>
<tr>
<td>Thickness of resist</td>
<td>45-50 µm</td>
<td>~80 µm</td>
<td>~250 µm</td>
</tr>
<tr>
<td>SU-8</td>
<td>2025</td>
<td>2100</td>
<td>2100</td>
</tr>
<tr>
<td>Dehydration bake</td>
<td>15 min.@150°C</td>
<td>20 min @ 95°C</td>
<td>10 min @ 95°C</td>
</tr>
</tbody>
</table>
| Spin coating           | 500 rpm for 5 min
                        | 1200 rpm for 30 s acceleration
                        | 100 rpm/s        | 500 rpm for 5 min
                        | 3000 rpm for 30 s Acceleration
                        | 500 rpm/s        | 1000 rpm for 30 s acceleration
                        | 100 rpm/s        |
| Relaxation             | 10 min          | 10 min         | 10 min       |
| Soft bake              | 5 min @ 65°C    | 5 min @ 65°C   | 20 min @ 65°C|
                        | 15 min @ 95°C   | 18 min @ 95°C  | 2 h @ 95°C    |
| Relaxation             | 30 min above    | 24 h           | 48 h         |
| Exposure               | Dose: 250 mJ/cm²
                        | Hard contact 22 s
                        | Dose: 250 mJ/cm²
                        | Hard contact 22 s
                        | Dose: 250 mJ/cm²
                        | Soft contact 25 s |
| Post exposure bake     | 5 min @ 65°C    | 5 min @ 65°C   | 10 min @ 65°C|
                        | 15 min @ 95°C   | 18 min @ 95°C  | 45 min @ 95°C |
| Relaxation             | >10 min         | >10 min        | >10 min      |
| Develop                | 6 min. Immersion| 6-8 min        | 25 min       |
| Etch Ti                | 5%HF 40 s       | 5%HF 40 s      | 5%HF 40 s    |
| Electroplating         | Cu 10 mA/cm²
                        | 2.5 h           | Permalloy
                        | 5 mA/cm² 10 h   | Ni 10 mA/cm²
                        | 15 h           |
| Removal                | 50°C stir 6 h   | 10 h           | 15 h         |

The microcoil was fabricated both on the polished and on the unpolished side of the silicon substrates. Both approaches have their advantages and drawbacks. The removal of the SU-8 for releasing the microstructure turned out to be easier on the unpol-
ished side. However, in this case it was more difficult to align mask and substrate for the subsequent two layers.

### 6.4.2 Fabrication of the Permalloy Core

The second major step in the fabrication of the hybrid actuator is to build the permalloy core at the centre of the coil. The coil has been designed in such a way that its centre accommodates a permalloy core with dimensions of 500 µm x 500 µm x 60 µm. The fabrication process of the permalloy core (second layer) is shown schematically in Figure 6.15.

![Fabrication of the Permalloy Core](image)

(a) Spin coating of a second SU-8-2100 layer.  
(b) Alignment of this pattern with the coil structures and exposure.  
(c) Developing of SU-8 mould for the core structure.  
(d) Electroplating of permalloy within the SU-8 mould.  
(e) Removing the SU-8 to release the core.

Figure 6.15: Fabrication step sequence for making the permalloy core.

A procedure similar to the one described above for depositing the microcoil is repeated. Before spin coating, the substrate was heated up to 95°C for dehydration. Normally, heating up to 150°C would be preferable to get rid of the moisture in the sample.
However, this would take the risk of hardening any residual SU-8, which would prevent its removal in the final step. SU-8 2100 was spin coated on top of the microcoil to a thickness of 80-100 μm. The mask of the second layer was aligned to the previous structure, as demonstrated in Figure 6.16 and subsequently patterned with UV exposure.

![Figure 6.16: Permalloy core aligned in the centre of the microcoil.](image)

Soft bake and post exposure bake are necessary for this process, as well. Baking time and temperature differed slightly from the microcoil, as the core is much thicker (almost three times the coil thickness). Different parameters used in this process are tabulated in Table 6.2. After developing the second layer, the mould for the central core was formed. Subsequently, the Ti protection layer on the central core was etched away to expose the copper seed layer using 5% HF solution as was done earlier. Permalloy was electroplated in the open copper area, located in the centre of the microcoil. The plating bath composition used for this purpose is same as that used for plating the unimorph cantilever given in Chapter 4. It is worth mentioning that the current density greatly affects the quality of the electroplated permalloy central core. Typically, a small current density yields a better quality. Figure 6.17 (a) and (b) show a very solid electroplated central permalloy core using a current density of 5 mA/cm$^2$ while Figure 6.17 (c) shows an image of a very loosely packed structure obtained with a current density of 10 mA/cm$^2$. After plating the SU-8 mould was removed by immersing the sample into the SU-8 remover again. It was found that the second layer SU-8 could be removed much more easily as the adhesion between SU-8 and the substrate with coil patterns decreased dramatically.
The permalloy core should be aligned well within the centre of the coil. Figure 6.17 shows SEM images of the fabricated permalloy core with microcoils. The dimensions of the core are 500 µm x 500 µm x 60 µm. Figure 6.17 (a) shows a misalignment of the central core with the coils, while it is aligned perfectly in Figure 6.17 (c). All the structures fabricated on the unpolished side as the adhesion between the microstructure and the seed layer was found to be much better than on the polished side of the silicon wafer.

(a) SEM image of permalloy core plated at a current density of 5 mA/cm² (before cleaning of SU-8).

(b) Permalloy central core plated at current density of 5mA/cm² (after cleaning of SU-8).
6.4.3 Fabrication of the Beam Support

For suspending the PVDF composite cantilever, a 250 µm high metallic support post (stand) was required on the silicon substrate. This structure again needs alignment with respect to the microcoil and core structures. The fabrication sequence followed is shown in Figure 6.18. The process is similar to that described for the copper microcoils and permalloy core. Detailed lithographic and plating parameters used in this processing sequence are given in Table 6.2. Nickel has been used for this purpose because of its robustness, strength and ease of plating without any stresses even at thicknesses of 200-250 µm. The plating bath used for this purpose is the same as that described in Chapter 4. After plating nickel for 15 hours at a plating rate of 10 µm/hour at a current density of 10 mA/cm² a nickel post with a height of 150 µm is achieved. The SU-8 mould is then removed as described in the earlier Section. However, some SU-8 still remained on the substrate as shown in Figure 6.19 (a). The remaining SU-8 had to be cleaned completely, before the seed layer could be etched away in all open areas. This is important for electrically isolating the microcoil, the permalloy core, and the support stand from each other.
(a) Spin coating of a 250 µm thick SU-8 2150 on top of coil and core structures.

(b) Alignment and UV exposure to pattern the mould for plating the nickel post to mount the cantilever.

(c) Development of SU-8 structure.

(d) Electroplating of nickel post.

(e) Removing SU-8 to facilitate the seed layer etch.

Figure 6.18: Process sequence for fabrication of nickel post to support the cantilever generating the cantilever support.
Figure 6.19: A top view of all the microstructures before and after plasma etching.
6.4.4 Substrate Cleaning

It is well known that cross linked SU-8 is very difficult to remove from the substrate. Substrate cleaning after patterning and plating different layers was carried out using two techniques namely the excimer laser machining and CF$_4$/O$_2$ plasma etching.

**Excimer laser based cleaning process**

Excimer laser micromachining is a possible way to remove different photoresists, including SU-8 (Ghantasala et al., 2001). The ablation characteristics of the SU-8 photoresist under 248 nm KrF excimer laser (Exitech Limited, UK) radiation have been studied by Ghantasala and Harvey. The threshold fluence for ablation of SU-8 was found to be 0.05 J/cm$^2$ and with the increase of the fluence the etch rate increased. The fluence vs etch rate curve for SU-8 is shown in Figure 6.20. In the same publication it was shown that the bake time and temperatures do not affect the etching rates. Dry film photoresist was removed by laser ablation of localized areas around the (meandering) nickel heater pattern. The fluence and number of shots used for this purpose were 1.0 J/cm$^2$ with 50 pulses respectively.

![Figure 6.20: Variation of SU-8 etch rate with laser fluences (Ghantasala et al.).](image)

Starting with the data provided in these previous publications, a matrix of ablation sites at different fluences and laser shots was machined around on the microcoil arrays with residual SU-8. This helped in finding the near optimal ablation parameters for removing SU-8 with minimal damage to the copper microcoil. The fluences were varied between 0.24 J/cm$^2$ and 2.15 J/cm$^2$, by adjusting an external attenuator. The number of pulses in these patterns ranged between 10 shots and 640 shots.
Figure 6.21 shows images of a segment of the microcoil after laser cleaning, where the microscope is focussed either to the top of the microcoil or to the silicon substrate surface at the bottom. These three patterns were ablated by an excimer laser at a constant energy density of 1.0 J/cm\(^2\) with 20, 40, and 80 shots, respectively. With the increase of the number of laser shots the SU-8 was removed more and more while the surface of the copper coil was gradually affected due to laser induced damage. Therefore, the optimisation of the laser ablation parameters is very critical.

Figure 6.21: Part of the microcoil pattern subjected to excimer laser removal with varying numbers of shots at a constant energy density of 1.0 J/cm\(^2\). (Microscope images are focused on (a) Top copper coil surface, (b) Bottom silicon substrate base respectively)
From these pictures it is apparent that residual SU-8 can be removed only with severely damaging the copper microcoils, when using 40-80 shots at a fluence of 1 J/cm². Even with a careful setting of the laser parameters, some visible damage on the copper coil still occurred, which could not be tolerated. Therefore, an alternative cleaning technique was needed.

**Plasma etch using CF₄**

Plasma etch based removal of SU-8 has been reported by Dentinger in 2001. Although it is a slow process compared to wet remover based etching or laser micro-machining, this is useful especially for removing residue layers of SU-8. More recently carbon tetrafluoride (CF₄) based plasma etching was demonstrated to be a simple and feasible way to remove small quantities of SU-8 (Vora et al., 2003). Etch rates of 1 μm/min have been achieved on SU-8 using O₂/CF₄ mixtures approaching a 1:1 ratio at high plasma powers of 2500 W. The plasma etching equipment used in these experiments was an LFE barrel etcher with a 13.56 MHz RF coil around a glass barrel chamber. Samples were placed on the top of the holder in the centre of the barrel. It took around 60 min to strip off the residual SU-8 completely. Figure 6.19 (b) showed the structure after cleaning with this process, which demonstrated the usefulness of this method for final cleaning of the residual SU-8 on the substrate.

### 6.4.5 Removing the Seed Layer

After finishing all fabrication steps and cleaning processes mentioned above, the seed layer must be removed in order to electrically isolate the microcoil, the central permalloy core, and the cantilever stand from each other. The exposed titanium protection layer was etched away by using a 5% hydrofluoric acid solution (HF). It takes about 40 s to etch the 50 nm thick titanium layer. The middle copper seed layer was removed by a 25% NH₄OH solution. It takes 65 minutes to etch away the 300 nm copper seed layer. This etching step could possibly etch the surface of the copper coils as well. As the etched thickness of the coils is also similar to the copper seed layer thickness, this does not alter the structure of the coils dramatically. This is followed by another etching step, which is mainly meant for etching the titanium adhesive.
6.4.6 Dicing the Chips

In order to separate the individual devices fabricated on a single wafer, conventionally dicing is used. In this work, two different methods, conventional dicing and laser cutting were successfully used for this purpose.

The conventional dicing was carried out using a dicing machine PFS/PDF/PDS-501 made by LFE Corp., USA. This machine allows the positioning of the dicing line by a microscope to an accuracy of a few microns. However, the cleaning water necessary for dicing has resulted in peeling the coils in an extreme case, resulting in the failure of some devices.

Nd:YAG laser based cutting has been the alternative technique tried in this work. This method is less aggressive in the sense that the samples are cut and separated by purely dry methods. However, the machine that was available for this work only allowed a manual control of the cutting line, thus yielding less precise alignment. Furthermore, debris from the removed silicon material was found in the vicinity of the cutting line. Therefore, laser machining is ideal, provided the space between the devices can be maintained at few mm, so that debris will not affect the device. Both these methods were successfully employed in this work.

6.5 Assembly of the Hybrid Microactuator

The assembly of the microactuator mainly involves the patterning of electrical contacts on a printed circuit board and wire bonding. Finally, it was necessary to mount the cantilever on the nickel post.

6.5.1 Mounting the Hybrid Microactuator on a Printed Circuit Board (PCB)

The footprint area of the microactuator is about 5 mm x 3 mm. In order to connect the bonding pads of the microcoil and the piezoelectric cantilever to the power supply, a special electrode PCB connection board was designed, which is shown in Figure 6.22. It was fabricated by photolithography on a bare PCB substrate.
In order to align the permanent magnet with the permalloy core, a cubic cutout with the dimensions of 500 x 500 x 200 µm$^3$ was machined into the exact centre of the top side of the electrode board by a micromilling machine. The permanent magnet block with dimensions equal to the cutout was attached inside this cavity, as indicated in Figure 6.23. The silicon substrate, with microcoil, permalloy core and nickel post on it, was placed on the top of the permanent magnet block and aligned with the marked line.

6.5.2 Wire Bonding

An ultrasonic wedge bonding system (West Bond Inc., USA) with a 25 µm gold wire was used in this project. Figure 6.24 shows the wire bonding of the microcoil. The electrode pads are wedge bonded.
6.5.3 Assembling the PVDF Cantilever on the Nickel Support

The last step in the assembly of the hybrid microactuator is the mounting of the unimorph PVDF cantilever on the nickel post. Most of the bonding techniques are based on heating the substrate which can cause depoling of PVDF polymer, thus irreversibly destroying its piezoelectric structure at temperatures exceeding 70°C. A UV curable acrylic adhesive (Webster and Binnie, 1995) was successfully used to bond the metal-lised PVDF onto the substrate metal post at room temperature even though there is a 40 nm thick nickel copper alloy on the surface of PVDF. Finally, the electrode layers of the cantilever were connected to the electrode pad on the PCB board, yielding devices of the hybrid microactuator, as shown in Figure 6.25.
6.6 Summary

This Chapter described the fabrication of the planar hybrid microactuator with three different metallic microstructures having different dimensions and aspect ratios on a single substrate layer by using a photolithography process with the negative photoresist SU-8 2000. A copper microcoil, a permalloy core and a nickel metal post for suspending a cantilever beam were electroplated on the same seed layer with aspect ratios varying from 1:1, 5:1 to 10:1, and the dimensions of the features ranging from 25 µm to 500 µm. The three different features were fabricated separately in three layers. Different viscosity of SU-8 2000 was used in three layers. 50 µm, 80 µm and 200 µm thick SU-8 photoresist were used to pattern the moulds for electroplating three different features. 25 µm thick copper microcoils with an aspect ratio of 1:1 were first electroplated on the Ti/Cu/Ti seed layer. This was followed by electroplating of a 50 µm thick permalloy layer with an aspect ratio of 10:1 on the same seed layer. A 150 µm thick nickel post with an aspect ratio of 5:1 was then electroplated in the next step. The respective SU-8 resist mould was removed between each of these layers. In a final step, the residual SU-8 was cleaned using a CF4 based plasma etching process. The coils have 20 turns with a footprint area of 10 mm².
The microactuator was assembled on a PCB board with connecting pads. To align the magnet to the centre of the permalloy core, a cutout with the dimension of 500 µmx500 µmx200 µm was fabricated by using a micro-miller machine, and the magnetic block was fixed in it. Then the microstructures on the silicon wafer were assembled on the top of the PCB. Finally the piezoelectric polymer unimorph cantilever was bonded onto the top of the nickel metal post. The testing and performance evaluation of the device is described in the following Chapter.
Chapter 7  Testing and Performance
Evaluation of a Hybrid Actuator

7.1  Introduction

The design and fabrication of hybrid actuators has so far been dealt with in detail in previous Chapters. The relevant concepts, design methodologies and fabrication techniques were all presented there. This Chapter provides the results of testing and evaluation of their performance. It describes the set-up used for testing different models of the hybrid actuators. Subsequently, the test procedures and experimental results are discussed. Analysis of these results and their comparison with the simulated values forms the final Section of this Chapter. Overall, this Chapter describes the proof of concept of a hybrid actuator and demonstrates a working microactuator.

7.2  Proof of Concept

7.2.1  Experimental Set-up

The experimental set-up built for testing the proof of concept of the hybrid actuator is shown in Figure 7.1. As shown in the picture the PVDF composite unimorph cantilever is suspended and adjusted to the desired air gap between the cantilever and the top of the permalloy core by a 3-axis micrometer stage. The close-up view of the magnetic components including copper coil, permalloy core and permanent magnet bonded on the silicon substrate are shown in Figure 7.1 (b). A 50 μm diameter copper wire with polymer insulation coating is wound around a 500 μm diameter permalloy core to form a coil with 100 turns. The height of the permalloy core is around 2 to 3 mm. The permalloy core with the coil is bonded on the silicon substrate using epoxy. The permanent
magnet with dimensions of 600 x 600 x 300 μm$^3$ is attached to the other side of the silicon wafer and aligned in the centre of the permalloy core using a jig.

Figure 7.1 (b) shows the opened and closed position of the actuator with the current applied to the coil and the voltage across the piezoelectric cantilever.

(a) Experimental set-up used for testing the hybrid actuator.

(b) Close-up view of hybrid actuator (open and close position).

Figure 7.1: Experimental set-up for testing actuator along with a close-up view of different positions.

Figure 7.2 shows the schematic of the experimental set-up. The current for driving the electromagnetic coil was supplied by a Bipotentiostat Model AF CBP1 power supply (Pine Instruments, USA) and was varied in the range from 50 mA to 90 mA. A lo-
cally made high voltage power supply was used for energizing the PVDF cantilever within the range from 60 V to 150 V.

![Diagram of experimental set-up for testing the concept of hybrid actuation.](image)

Figure 7.2: Schematic of experimental set-up for testing the concept of hybrid actuation.

When the electromagnetic coil (wound around the permalloy core) is energized by applying a current, it generates an electromagnetic force, which attracts the cantilever towards the core. The deflection produced by the magnetic force is in the range from 230 µm to 280 µm depending on the current applied. However, this force is not sufficient for closing the switch, as the air gap is larger than the maximum possible deflection. Based on the piezoelectric actuation using the PVDF composite cantilever, an additional deflection of 70 µm to 130 µm was achieved. This brings the actuator to its ON (closed) position. Once the switch is closed it is only held by the external permanent magnetic field, obviating the need for additional power to keep it in that position. The configuration saves the power otherwise required to keep the actuator in closed position. When the direction of current was reversed, an electromagnetic force in the opposite direction was generated, bringing the switch into its OFF (open) position.
7.2.2 Testing of Hybrid Actuation

The deflection generated by the magnetic and piezoelectric forces is measured by the following method.

The air gap between the tip of the cantilever and the top of the permalloy core was set to an initial value of 400 µm by adjusting the position of the micrometer stage. While decreasing the air gap until the beam suddenly latches to the top of the permalloy core, the micrometer value at which the latching action occurs is recorded. At this stage the permanent magnet is removed, which causes the cantilever tip to recover to the balanced position. Decreasing the air gap until the tip of the cantilever touches the top of the permalloy core, record this as value 2 of the micrometer stage. The difference between the two values on the stage is the tip deflection generated by the permanent magnet, which was found to be 150 µm.

A predetermined current in the range from 50 mA to 90 mA is then applied to the driving coil, the air gap at which the tip of the cantilever latches on the top of the permalloy core is noted. This is recorded as the maximum tip deflection generated by the applied current due to the electromagnetic effect. This is found to be 80 µm to 130 µm, corresponding to the excitation current from 50 mA to 90 mA as listed in Table 7.2.

The additional deflection achieved by using the piezoelectric polymer actuator was 90 µm to 140 µm when the applied voltage varied from 100 V to 150 V, which was also measured following the same method. The cantilever actuator used for this test had a length of 6 mm, a width of 1 mm and the thickness of the PVDF polymer was 28 µm with a permalloy layer thickness of 5 µm. As the breakdown voltage of the piezoelectric cantilever is 200 V, the applied voltage in the testing was limited to 150 V.

In the next stage of testing, three different prototype devices with different silicon wafer thickness (285 µm to 345 µm) and permalloy core length (2115 µm to 3240 µm) were used to understand the influence of these parameters, while keeping the cantilever dimensions constant. Table 7.1 presents the dimensions of these three devices tested. The results are summarized in Table 7.2. These results showed that a tip deflection of 400 µm can be achieved by applying a current of 90 mA and a voltage of 150 V.
Table 7.1: The dimensions of three different hybrid actuators used for testing.

<table>
<thead>
<tr>
<th>Device ID</th>
<th>1</th>
<th>2</th>
<th>3</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cantilev dimensions</td>
<td>6 mm x 1 mm x (28 µm PVDF+5 µm permalloy)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Permalloy core (µm)</td>
<td>φ500 x 2115</td>
<td>φ500 x 2455</td>
<td>φ500 x 3240</td>
</tr>
<tr>
<td>Copper coil (µm)</td>
<td>φ50 µm 100 turn (1250 x 200)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Si thickness (µm)</td>
<td>345</td>
<td>285</td>
<td>300</td>
</tr>
<tr>
<td>Permanent magnet</td>
<td>600 x 600 x 300 µm³</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Table 7.2: Test results of hybrid actuator.

<table>
<thead>
<tr>
<th>Device ID</th>
<th>1</th>
<th>2</th>
<th>3</th>
</tr>
</thead>
<tbody>
<tr>
<td>Applied voltage</td>
<td>Piezoelectrically induced tip deflection</td>
<td></td>
<td></td>
</tr>
<tr>
<td>100 V</td>
<td>90-100 µm</td>
<td>80-95 µm</td>
<td>90-95 µm</td>
</tr>
<tr>
<td>120 V</td>
<td>105-115 µm</td>
<td>100-110 µm</td>
<td>105-115 µm</td>
</tr>
<tr>
<td>150 V</td>
<td>130-135 µm</td>
<td>130-145 µm</td>
<td>135-140 µm</td>
</tr>
<tr>
<td>Applied current</td>
<td>Magnetically induced tip deflection</td>
<td></td>
<td></td>
</tr>
<tr>
<td>50 mA</td>
<td>235 µm</td>
<td></td>
<td></td>
</tr>
<tr>
<td>60 mA</td>
<td>240 µm</td>
<td>230-240 µm</td>
<td>200-225 µm</td>
</tr>
<tr>
<td>70 mA</td>
<td>250 µm</td>
<td>250 µm</td>
<td>230-235 µm</td>
</tr>
<tr>
<td>80 mA</td>
<td>265 µm</td>
<td>260-270 µm</td>
<td>230-240 µm</td>
</tr>
<tr>
<td>90 mA</td>
<td>265-270 µm</td>
<td>255-260 µm</td>
<td></td>
</tr>
<tr>
<td>Parameters to achieve an air gap of 400 µm</td>
<td>Current</td>
<td>80 mA</td>
<td>90 mA</td>
</tr>
<tr>
<td>Voltage</td>
<td>150 V</td>
<td>150 V</td>
<td>150 V</td>
</tr>
</tbody>
</table>

These results are in good agreement with the simulation results presented in Section 5.4. It may be noted that all dimensional parameters used in the simulation were the same as those of the tested devices presented in Figure 5.7. Hence, it is easy to compare the simulation results with those obtained in the actuator testing and evaluation process and to understand its operation characteristics. In the simulation results shown in Figure 5.17, when a positive current is applied to the coil, the generated electromagnetic force is smaller than the required magnetic force (RMF) at some points of the beam during
bending. With the assistance of the piezoelectric effect, the required magnetic force decreases to RMFP so that the magnetic forces are larger than the RMFP at all tip positions during the latching operation. This brings the actuator to its closed position. This explains the reason for the actuator not closing until the air gap reduces below the combined total deflection achievable by both actuation principles. When a negative current is applied to the coil, the magnetic force becomes smaller than RMF, the actuator opens. The optimised parameters of the system were obtained by adjusting the curves F/V (+) and F/M (+) with the desired characteristics, as discussed in Section 5.3.4.

The switch on and off characteristics of the device has been tested using an oscilloscope. It shows that the switch-on time at the cantilever tip depends on the air gap between the tip of the cantilever and the top of the permalloy core, as well as the excitation current and voltage, which is in good agreement with modelling analysis of a typical microswitch (Schmid and Adamschik). For an air gap of 400 µm, the switch on time of this device is measured in the range from 50 µs to 100 µs.

The switch-off characteristic is important since the energy stored in the deflected cantilever for a closed switch may lead to a repeated contact after opening the switch.

It is well known that all mechanical switches can generate some mechanical bouncing (Pico Technology Limited; Walter). Mechanical bouncing is the back and forth movement of the cantilever tip before it completely closes with respect to the top of the permalloy core. This effect may vary from a single to several bounces depending on the stability of operation of the actuator. For normal switches, this can last from as little as a fraction of a millisecond (ms), to as long as 50 ms. High quality switches generate little or no bouncing. The mechanical bouncing was tested in this device using an oscilloscope by operating the actuator several times. It was found to be in the range of a few milliseconds.
7.3 Characterization and Testing of the Hybrid Microactuator

7.3.1 Characterization of the Resistance of the Microcoil

As described in the previous Chapter, it was very difficult to remove the SU-8 layer completely. In such circumstances, the seed layer used for electroplating of the coils and other structures may not be etched away completely in all the open areas, especially between subsequent coil windings. The resistance of the electroplated copper planar microcoil was tested using the standard current – voltage measurements. The change in voltage was measured at increasing currents and the resulting coil resistance was calculated. Three different coils were tested following this procedure. The average test results of these three coils are presented in Figure 7.3.

\[
R = \frac{U}{I} = 3.71\,\Omega
\]  

(7-1)

Comparing this with the theoretical calculation in Section 5.5.2, the measured resistance of the microcoil turned out to be larger. The main reason for this is that the resistivity of electrodeposited copper is larger than its bulk value. Furthermore, the microcoil has a spiral shape. Both the rectangular cross section of the microcoil and the
spiral layout reduce the area of current to go through. Therefore, the total resistance increases. Another practical reason is that the thickness of the electroplated copper coil is not constant along the length of the coil. The uniformity of the electroplated microcoil is in the range of ±5%.

It is well known that the resistivity of copper increases with its temperature. This particular study showed that the resistance of the microcoil is constant irrespective of the current applied. The coil current was increased from 5 mA to 50 mA. As the coil current increases, the temperature of the coil is expected to increase above a certain point, which again is expected to induce an increase in its resistance. However, in this particular case, no visible change of resistance was observed, even when the coil current was increased from 5 mA to 50 mA, as shown in Figure 7.3. It indicates that the temperature in the microcoil does not change significantly when the excitation current is raised up to 50 mA. This is identical with the estimated calculation in the thermal analysis in Chapter 5.

7.3.2 Characterization of the Magnetic Properties of the Permalloy Core

The magnetic properties of the permalloy layer are important to know since both the unimorph cantilever as well as the core were fabricated by electroplating. These two components together determine the deflection and force of the actuator. Simulation studies presented in Chapter 5 require input such as permeability, magnetization etc., before being able to predict the force. Hence, this study helps in obtaining the realistic magnetic values of these magnetic inputs. These can be conventionally obtained from the magnetic hysteresis loop of the material. Figure 7.4 shows a typical demagnetization hysteresis loop of the permalloy measured by the Reciprocating Sample Option (RSO) measurement.

Superconducting quantum interference devices (SQUID) have two measurement modes: RSO and DC. Unlike DC measurements where the sample is moved through the coils in discrete steps the RSO measurements are performed using a servo motor which rapidly oscillates the sample. The sensitivity that can be achieved is 1x10-8 EMU. It appears that the RSO mode measurement is quicker than the DC mode, both yielding they give very similar results. A shaft encoder on the servo motor records the position.
of the sample synchronous with the SQUID signal. The data received are fitted to an ideal dipole moment response. The RSO reduces the effects of environmental magnetic fields and SQUID "drifts" allowing measurements of higher sensitivity to be performed in less time. The RSO also reduces the effects of field inhomogeneity.

Although there was a variation in magnetic properties from one to another; different samples did not show much difference in characteristics. The coercive force $H_c$ is 12 Oe. The maximum residual induction $B_r$ is around 0.15 EMU. The permeability of the permalloy is calculated to be in excess of 1000 from the measured data.

![Figure 7.4: Hysteresis loop of permalloy obtained using reciprocate sample option (RSO) method.](image)

7.3.3 Testing of the Hybrid Microactuator

After verifying the resistance of the microcoil the piezoelectric composite cantilever was assembled on a PCB board with electrode connections. A similar testing method to the one applied for the macro scale hybrid actuator was also used for this test, as shown in Figure 7.5. The current for driving the microcoil was supplied by a bipotentiostat model AF CBP1 power supply (Pine Instruments, USA) and was varied in the range from 5 mA to 50 mA. A model PS35/5000 V-25 W high voltage power supply...
(Stanford Research System Inc.) was used for energizing the PVDF cantilever within the range from 0 V to 120 V.

![Experimental set up for testing the hybrid microactuator.](image)

As the dimensions of the micro device are much smaller than in the macro case, it needed to be viewed under an optical microscope. It was difficult to measure the deflection of the cantilever accurately due to the difficulty in operating the high voltage device under the microscope objective. Therefore, a simple test based on the latching ability of the cantilever was conducted. A 120 V voltage was applied to a 3 mm long piezoelectric unimorph cantilever while a 50 mA current was employed on the microcoil at the same time. The air gap between the tip of the cantilever and the top of the permalloy core was set at 100 µm. The tip of the cantilever was latched to the top of the permalloy. Removing the applied voltage and current, the cantilever stayed in its closed position. When a reversed voltage and current were applied to the device, the cantilever released and lifted up from the permalloy core. This test verified that the hybrid microactuator operated in a similar manner to the macroactuator.

### 7.4 Summary

This work demonstrated the principle of a hybrid actuator, which for the first time combined piezoelectric and electromagnetic actuation mechanisms in a single device. This enabled deflection over a larger air gap than any of the single actuators could cover. The device consists of a punched piezoelectric cantilever with an electroplated
permalloy layer on the top and a copper coil wound around a permalloy core assembled on a silicon substrate with a permanent magnet at the bottom. The tip deflection of the cantilever to a closed position is achieved by the combined forces of the piezoelectric and the electromagnetic effects. The permanent magnet helped in holding the cantilever in its closed position, even when the current and voltage were removed, which in turn resulted in significant power saving in the use of this actuator. The application of a current in the opposite direction through the coil unlatched the cantilever to an open position. Again, once switched to its open position, no power is necessary to keep it there. The switch on and off characteristics were tested and very little mechanical bouncing was found during switching operation. These actuators may be useful in applications where the frequency of operation (number of on-off cycles) is small and larger forces or displacements are required. Additionally, the latching behaviour of the actuator means that power is not required to hold the switch in its closed position.

The results of the simulation clearly showed that the combined use of two different actuation mechanisms (piezoelectric and electromagnetic) ensures that the force achieved is always higher than the mechanical restoring force during the closing operation. The experimental results were in good agreement with the theoretical analysis obtained from simulation using finite element packages.

Overall, two different prototypes of the actuators in macro and micro (planar) configuration were successfully tested and demonstrated. The performance of the hybrid actuators was satisfactory and was in good agreement with the simulated results in both cases.
Chapter 8  Conclusions

8.1 Summary

This thesis reported for the first time the concept of a hybrid actuator employing two commonly used mechanisms viz., electromagnetic and piezoelectric actuation together in a single device, providing increased force and larger deflection. Power is required only during the switching operation from one state to the other. No power is required to keep it continuously in either of its two states (closed or open positions), and this is the second major advantage of this actuator. This thesis has successfully demonstrated the concept of hybrid microactuation.

The first key component of the actuator is a shaped unimorph piezoelectric cantilever with an electroplated permalloy layer deposited on its top. The second important component is a planar copper microcoil wound around a permalloy core fabricated on a silicon substrate with a permanent magnet at the bottom. The cantilever operates as a switch, opening or closing the gap with respect to the centrally placed permalloy core. The concept of this hybrid actuation was first validated by simulation and was later fabricated and tested.

The permalloy layer takes over a two-fold function: under piezoelectric operation it serves as the passive layer, converting the longitudinal contraction of the active foil into bending moment. Under electromagnetic operation it serves as an active layer, being attracted or repelled in accordance with the induced magnetic field. Simulations predicted that a maximum tip deflection of this composite cantilever can be achieved when using an optimal thickness of permalloy between 1~5 μm on a 28 μm thick PVDF layer. The latter thickness was chosen for reasons of practical availability. The tip deflection of this cantilever with dimensions of 6 mm x 1 mm (length and width) was found to attain 100 μm under an actuation voltage of 100 V.
The modelling and simulation of the composite piezoelectric polymer cantilever with both planar and microstructured surfaces was performed using the commercially available FEA software tool - CoventorWare. The main goal was the optimization of the design parameters in order to achieve the largest possible tip deflection. The simulation results indicated that a microstructured cantilever could produce more than 25% higher deflection compared to a simple planar cantilever surface. The improvements in deflection may be attributed to the reduced stiffness and increased compliance of the foil when microstructures are inserted by a low temperature hot embossing process.

The piezoelectric composite cantilevers were fabricated by laser micromachining, electroplating and micro punching techniques. Punching is a promising way to shape and fabricate polymer films, which are flexible and sensitive to elevated process temperatures. This includes the shaping of a surface microstructure on a PVDF polymer. The non-piezoelectric permalloy layer was electroplated on one side of the pre-metallised PVDF polymer, thus forming a composite bilayer structure described above. The experimental results are in good agreement with the numerical simulation performed using finite element analysis. The small differences in the results observed in the experiment compared to those obtained from FEA simulation can be attributed to the induced stresses in the electroplated permalloy layer on the PVDF cantilever. The magnetic forces acting on the cantilever were modelled and analysed by FEA simulation, as well. A 2D static magnetic analysis was performed by using the low frequency electromagnetic analysis solver in the ANSYS software package, leading to an optimization of parameters and dimensions of the device.

The proof of concept was demonstrated by fabricating a macro hybrid actuator with a footprint size of 6 mm x 8 mm using mostly conventional machining and assembly techniques. The cantilever was actuated as a switch, bringing it from its off position to its on position by closing the gap between the tip of the cantilever and the top of the permalloy core. The tip deflection of the cantilever is achieved by the combined forces of piezoelectric and electromagnetic effects. This is implemented in the device by supplying power to the piezoelectric cantilever as well as to the electromagnetic coil at the same time using two different power supplies. The bistable operation of the switch was tested by varying the air gap as well as the electromagnetic driving current and piezoelectric voltage. This not only demonstrated the successful demonstration of the con-
cept, but also provided an opportunity to verify the simulation results in an experimental device. This device was shown to give a maximum deflection of 400 μm with a maximum force of 165 μN. Thus the switch is bistable, making it attractive for a number of applications, such as in optical switches, microarrays and telecommunication.

In the next stage, a hybrid planar microactuator was designed and fabricated using conventional lithography based techniques. The parameters and dimensions were optimized using the same simulation methods. As the material properties of thin films are different from bulk values and since the aspect ratios of the microstructures also differ from those of the macro device (the permalloy core has an aspect ratio of 1:10 compared to 1:3 for the macro-device), the density of magnetic flux lines of the microdevice is smaller at the tip of the cantilever than on the corresponding macro device due to the flux leakage of the permalloy core. The effect of dimensional changes of different elements, for example, the length of the permanent magnet, thickness of the silicon substrate and the height of the permalloy core, on the induced magnetic force was analysed and optimized.

The planar microstructures including the copper microcoil, its central permalloy core and a nickel post for suspending the cantilever were fabricated using lithography and surface micromachining techniques. The microcoil was designed to have 20 turns with a line width and spacing of 20 μm and a thickness of 20 μm to 30 μm. The permalloy core dimensions were fixed at 500 μm x 500 μm x 60 μm. The nickel post has dimensions of 500 μm x 1000 μm x 150 μm. These three microstructures with different dimensions and different aspect ratios were fabricated on the silicon substrate using the same seed layer but in three different steps. The fabricated microcoil was tested for any possible short or open circuit by passing a driving current of up to 50 mA thus estimating its resistance. Similarly, the magnetic properties of the electroplated permalloy layers were also characterized and found to have a permeability of 1000. The hybrid microactuator was assembled and tested by applying a potential of 100 V on the cantilever and a current of 50 mA through the microcoil. The composite cantilever latched on and off the permalloy core as expected. The maximum deflection and force demonstrated in this device were 100 μm and 330 μN, respectively.
8.2 Suggestions for Future Work

The major advantage of using a piezoelectric polymer PVDF for actuation is its flexibility, its light weight and its relatively low Young’s modulus. Another benefit using PVDF is that it can also both be used as a sensor as well as an actuator, if required in a given application. However, the biggest disadvantage is that it can not be integrated completely with other components of the device due to fabrication restrictions. This can be overcome using the copolymer PVDF-TrFE of PVDF. Rashidian and Allen (1993) have done work on spin coating and polarizing this material, integrating it directly with MEMS structures. Its use allows the direct integration of the microactuator on a silicon wafer, thus avoiding tricky micro assembly techniques. Even though the fabrication of an integrated micro device will involve multiple layers and more complicated fabrication techniques, the use of PVDF copolymers is an interesting aspect, which would help in integrating the cantilever processing along with the electromagnetic device. This work also open-up the potential for the development of a hybrid microactuator based on materials other than piezoelectric and electromagnetic concepts used in the present work.

A more detailed simulation study of the surface microstructure effects on the PVDF cantilever force/deflection would help to improve its performance further in achieving either high deflection or large force. Surface microstructures on PVDF polymers could be fabricated by low temperature micro embossing techniques, using longer process times. More comprehensive work is required in modelling and fabrication of complex surface microstructures on these cantilevers and studying their effects.
References


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Appendix A  List of Publications


A2  International Conference Publications


A3 Local Publications


Appendix B  Programs of Simulation

B1  Piezoelectric Composite Cantilever

/ PREP7
!! Units: Length=meters (m), Force=Newton (N), Time=Second (S)
!! Charge=Coulomb, Voltage=Volt

!! Materials
!!! 1. Base: Permalloy
!!! 2. Piezo: PVDF

!! Material properties
! Material #1 is permalloy
MP,EX ,1,150e9 ! Young modulus [Pa]
MP,Nuxy,1,0.25 ! Poisson's ratio
MP,DENS,1,8688 ! Density [kg/m^3]
MP,damp,1,1e-6 ! approx 2% damping using 1st mode 46.6kHz

!! Material #2 is Piezoelectric material
TB,PIEZ,2 ! piezo matrix [C/m^2]
!! x    y    z
TBDATA,1, 0, 0, 70E-3 ! e11,e12,e13 - X
TBDATA,4, 0, 0, 6.16E-3 ! e21,e22,e23 - y
TBDATA,7, 0, 0, -95.2E-3 ! e31,e32,e33 - z
TBDATA,10, 0, 0, 0 ! e41,e42,e43 - xy
TBDATA,13, 0, -70E-3, 0 ! e51,e52,e53 - yz
TBDATA,16, -56E-3, 0, 0 ! e61,e62,e63 - xz

MP,DENS,2,1.78E3 ! density [kg/m^3]
!! # permitivity [F/m]
MP,PERX,2,105E-12
MP,PERY,2,105E-12
MP,PERZ,2,105E-12
MP,EX,2,2.8E9
MP,NUXY,2,0.3
FINISH
!! END CREATION OF MATERIAL LIBRARY ENTRY

! Dimensional parameters [m]
length=6000e-6 ! 2500-5000 microns
width=1000e-6 ! 500 - 1000 microns
thick2=28e-6 ! Thickness of PVDF
thick1=5e-6 ! Thickness of permalloy
! Load
Vload=100 ! voltage input

/PREP7
ET,2,SOLID5,3 ! for piezo element - Ux,Uy,Uz and Volt
ET,1,SOLID45 ! for substrate

! Beam geometry
BLOCK,0,length,0,thick1,0,width,
BLOCK,0,length,thick1,thick1+thick2,0,width,

/VIEW,1,1,1,1
vglue,all

local,11
local,13,,,,,-45 ! Orient material axis with geometry
csys,11
esys,13 ! Rotate material axis to geometry

! Mesh controls
KSEL,S,LOC,X,0
KSEL,R,LOC,Z,0
LSLK,,1
LESIZE,ALL,,,,3
ESIZE,LENGTH/20
TYPE,2 $ MAT,2 $ REAL,1
VMESH,3
TYPE,1 $ MAT,1 $ REAL,1
VMESH,1
finish

/SOLU
NSEL,S,LOC,X,0
D,ALL,ALL,0
NSEL,S,LOC,Y,THICK1
D,ALL,VOLT,0
!/EOF
NSEL,S,LOC,Y,THICK1+THICK2
D,ALL,VOLT,100

ALLSEL,ALL
FINISH

/SOLU
SOLVE
FINISH
/POST1
/EFACE,1
AVPRIN,0,0,
PLNSOL,U,Y,2,1
FINISH
/EOF
/POST1
PLDISP,2
ANDSCL,10,0.5
!/EOF
/SOLUTION
ANTYPE,MODAL
EQSLV,SPARSE
MODOPT,LANB,3
MXPAND,3
SOLVE
FINI
/POST1/DSCALE
SET,FIRST
PLDISP,2
/VIEW,1,1
/ANG,1,-10,YS,1
/ANG,1,10,XS,1
/REPLOT

! display animation of deformed shape
! produce a sequence of animation of deformed shape
B2  2D Simulation of Magnetic System

!/BATCH,LST
/TITLE,2D HYBRID SWITCH STATIC ANALYSIS
/ PREP7
ET,1,PLANE13
KEYOPT,1,1,0
KEYOPT,1,2,0
KEYOPT,1,3,0
KEYOPT,1,4,0
KEYOPT,1,5,0

! MATERIAL PROPERTIES

MP,MURX,1,1 !AIR
MP,MURX,2,500 ! PERMALLOY, BEAM 100~1000
MP,MURX,3,500 ! PERMALLOY, YOKE 100~1000
MP,MURX,4,1 ! COPPER LEFT COIL
MP,MURX,5,1 ! COPPER RIGHT COIL
!Mp,MURX,6,1
MP,MURX,7,1 ! Si SUBSTRATE

Hc=12000 ! Coercive FORCE OF PMS [OERSTEDS]
MP,MGYY,6,Hc*1000/4/3.14259 ! PM[A/M]

! B-H CURVE:

TB,BH,6
TBPT,DEFL,(-12000+Hc)*1000/4/3.14159,0
TBPT,DEFL,(-10000+Hc)*1000/4/3.14159,0.22
TBPT,DEFL,(-8000+Hc)*1000/4/3.14159,0.44
TBPT,DEFL,(-6000+Hc)*1000/4/3.14159,0.66
TBPT,DEFL,(-4000+Hc)*1000/4/3.14159,0.88
TBPT,DEFL,(-2000+Hc)*1000/4/3.14159,1.1
TBPT,DEFL,Hc*1000/4/3.14159,1.32

!/COM  ! SET PARAMETER'S VALUE FOR ANALYSIS
CURRENT=8
n=5
THETA=0.382255*n
!THETA=0.5071059*n

!THETA=3.72685

! GEOMETRY DIMENSION
GAP=400
X0=0
Y0=0, X1=12000, Y1=12000

L3=500
L2=6000
L4=200, L5=L4
L6=300, L7=10000
H0=5000, H3=2115
H4=1250, H5=H4
H6=600, H7=345
XM=(X0+X1)/2
XA=XM+L3/2-L2
YA=H0+H6+H7+H3+GAP
XD=XA
YD=YA+5

*AFUN,DEG
XB=XA+L2*COS(THETA)
YB=YA-L2*SIN(THETA)
XC=XB
YC=YB+5
A=L4*H4
JDL=CURRENT/A
JDR=-CURRENT/A
/PNUM,AREA,1 ! Area number on

RECTNG,XM-L3/2,XM+L3/2,H0+H6+H7,H0+H6+H7+H3
RECTNG,XM-L3/2-L4,XM-L3/2,H0+H6+H7,H0+H6+H7+H4
RECTNG,XM+L3/2,XM+L3/2+L5,H0+H6+H7,H0+H6+H7+H5
RECTNG,XM-L6/2,XM+L6/2,H0,H0+H6
RECTNG,XM-L7/2-1000,XM+1000,H0+H6,H0+H6+H6+H7

AOVLAP,ALL ! Overlaps area
NUMCMP,AREA !compresses the numbering of defined items
APLOT
!/EOF

ASEL,S,AREA,7 ! Assign attribute to air
AATT,1,1,1,0

ASEL,S,AREA,1
AATT,2,1,1,0
ASEL,S,AREA,5
AATT,3,1,1,0
ASEL,S,AREA,4
AATT,4,1,1,0
ASEL,S,AREA,3
AATT,5,1,1,0
ASEL,S,AREA, .2
AATT,6,1,1,0
ASEL,S,AREA, .6
AATT,7,1,1,0

/PNUM,MAT,1  ! TURN MATERIAL NUMBER ON

ALLSEL,ALL
APLOT

!SMARTSIZE,4
!AMESH,ALL
ESIZE,100,0,
MSHAPE,0,2D
AMESH,ALL
!/EOF
ESEL,S,MAT, 2
CM, BEAM, ELEM
FMAGBC,'BEAM'
ALLSEL,ALL
ARSCAL,ALL,,1E-6,1E-6,1, ,0,1
FINISH

/SOLU
ESEL,S,MAT,,4
BFE,ALL,JS,1,,JDL/1e-12
!ESEL,S,MAT,,5
!BFE,ALL,JS,1,,JDR/1e-12
ESEL,ALL
NSEL,EXT
D,ALL,AZ,0
ALLSEL,ALL
FINISH

/SOLU
MAGSOLV
SAVE
FINISH

/POST1
PLF2D
FMAGSUM

FINISH
/EOF
Appendix C  Fabrication of Microstructures

C1  RCA wafer cleaning process

1. Rinse the wafer in DI water for 5 min;
2. Put the wafer into the solution with the components 3 H$_2$SO$_4$ (98%) + 1 H$_2$O$_2$ +6H$_2$O at 80°C for 10 min;
3. Rinse the wafer in DI water for 5 min;
4. Put the wafer in 10% HF solution for 10 min;
5. Rinse the wafer in DI water for 5 min;
6. Apply the wafer in the solution with the component 1 HCL +1H$_2$O$_2$ + 5H$_2$O at 80°C for 10 min;
7. Rinse the wafer in DI water for 10 min;
8. Finally dry it using nitrogen gas.

C2  Electromagnetic Microcoil Fabrication

This part contains the detailed process steps for fabricating the electromagnetic microcoil.

1. Substrate: a quarter of 4 inch <100> single side polished silicon wafers. The thickness of the silicon wafer is 500±50 μm;
2. RCA clean of the silicon wafer;
3. Sputtering Deposition of Ti/Cu/Ti for 50 nm/300 nm/50 nm on the polished or unpolished side;
4. Prebake: 15 min at 150°C on hot plate then cool down to room temperature with gradient;
5. Spin coat SU-8 2025 photoresist (5 s at 500 rpm, 30 s at 1200 rpm) to achieve 40 μm thick patterns;
6. Soft bake: 5 min at 65°C then 15 min at 95°C on hot plate. Cool down to the room temperature gradually. Let the sample sit at room temperature for more than 30 min for relaxing;
7. UV exposure: Exposure time is 22 s, hard contact between substrate and mask;
8. After exposure bake: same as soft bake;
9. Develop the sample for 5 min in SU-8 developer and 15 s in ultrasonic DI water bath;
10. Etch Ti: rinse the sample in 5% HF solution for 50 s, and carefully move it to DI water, then dry it using nitrogen gas;
11. After develop check: check the SU-8 microcoil pattern under the optical microscope and laser scanning confocal microscope;
12. Electroplating copper microcoil in the prepared copper electroplating bath, set current density to 10 mA/cm² for 2.5 hours;
13. Remove photoresist using SU-8 remover for few hours, then clean it using DI water and dry it using nitrogen gas.

**C3 Permalloy Core Fabrication**

This part contains the detailed process steps for fabricating the permalloy core on top of the electromagnetic microcoil.

1. Preheat the sample with fabricated microcoil to 95°C for 20 min on the hot plate, cool down to room temperature;
2. Spin coat SU-8 2100 photoresist (5 s at 500 rpm, then 30 s at 3000 rpm) for 100 μm thick patterns;
3. Soft bake: 5 min at 65°C then 20 min at 95°C on hot plate. Cool down to the room temperature gradually. Let the sample sit at room temperature for more than 30 min;
4. Align and UV exposure: align the core pattern in the centre of the micro coil and then exposure. Exposure time is 22 s, hard contact between substrate and mask;
5. After exposure bake: same as soft bake;
6. Developing the sample for 8 min in SU-8 developer;
7. Etch Ti: rinse the sample in 5% HF solution for 50 s, and carefully move it to DI water, then dry it using nitrogen gas;
8. Electroplating permalloy in the prepared permalloy electroplating bath, Current density is 5 mA/cm² for 5 hours at room temperature;
9. Remove photoresist using SU-8 remover for few hours, then clean it using DI water, and finally dry it using nitrogen gas.

**C4 Cantilever Support Fabrication**

This part contains the detailed process steps for fabricating the cantilever support on top of the electromagnetic microcoil and permalloy core.

1. Preheat the sample with fabricated microcoil and permalloy core to 95°C for 20 min on the hot plate, cool down to room temperature;
2. Spin coat SU-8 2100 photoresist (5 s at 500 rpm, then 30 s at 1000 rpm) for 250 μm thick patterns;
3. Soft bake: 20 min at 65°C then 120 min at 95°C RAMP 140°C/h on hot plate. Cool down to the room temperature at rate 70°C/h. Let the sample sit at room temperature for over night for relaxing;
4. Align and UV exposure: align the support pattern with the first two layers by marks on mask and substrate and then exposure. Exposure time is 23 s, hard contact between substrate and mask;
5. After exposure bake: same as soft bake;
6. Develop the sample for 25 min in SU-8 developer;
7. Etch Ti: rinse the sample in 5% HF solution for 50 s, and carefully move it to DI water, then dry it using nitrogen gas;
8. Electroplating nickel in the prepared nickel electroplating bath, Current density is 10 mA/cm$^2$ for 5 hours at 50°C;
9. Remove photoresist using SU-8 remover for few hours, then clean it using DI water and dry it using nitrogen gas.