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Abstract. Here we introduce the existing fabrication techniques, detection methods, and related techniques for microfluidic sensing, with an emphasis on the detection techniques. A general survey and comparison of the fabrication techniques were given, including prototyping (hot embossing, inject molding, and soft lithography) and direct fabrication (laser micromachining, photolithography, lithography, and x-ray lithography) techniques. This is followed by an in-depth look at detection techniques: optical, electrochemical, mass spectrometry, as well as nuclear magnetic resonance spectroscopy-based sensing approaches and related techniques. In the end, we highlight several of the most important issues for future work on microfluidic sensing. This article aims at providing a tutorial review with both introductory materials and inspiring information on microfluidic fabrication and sensing for nonspecialists. © 2011 Society of Photo-Optical Instrumentation Engineers (SPIE). [DOI: 10.1117/1.3607430]

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1 Introduction

With microfluidic/nanofluidic technology it is possible to operate on microscale or nanoscale liquids for controlling or sensing purposes. With the microfabrication techniques initially rooted from the microelectromechanical systems (MEMS) technology, this field will gradually develop into a discipline itself.¹⁻³ The fundamental techniques for microfluidic or optofluidic device fabrication originate from the semiconductor industry and are based on silicon or glass materials. With the development of polymer-based fabrication techniques, polymer-based microfluidic devices become more prevalent with the advantages of being economic and easy to fabricate, and having material versatility and good system compatibility.

The early designs of the microfluidic controlling systems were mostly monolithic miniaturized components such as microvalves, micropumps, and micromixers.⁴⁻⁶ With further development, whole microfluidic systems were realized, which were made up of multiple elements to achieve certain functions. These parts comprise either of the monolithic microfluidic components⁷ or of the microfluidic components with the external components/devices.⁸ Designs of those microfluidic devices, such as geometries and scales, have been modified and improved according to the applications for better performance.⁹⁻¹⁶ Further development requires more components to be coupled with the microfluidic system for increased system functionality. Optical components seem ideal, with the benefits of noncontact, fast response, compactness, high sensitivity, multiplex operation possibility, and so on. Self-contained microfluidic devices have generated impact in the point-of-care and global health.^{17,18} However, in order to achieve real self-contained miniature

devices, it is ultimately required to have highly integrated systems. This means lowering or even eradicating the dependence on macro, bulky, external devices to perform control, detection, or analysis functions, by the development and integration of the necessary functional microcomponents. Examples recently demonstrated are the implementation of lensless microscopes of sub-pixel resolving ability on microfluidic platforms for on-chip imaging or diagnosis.^{12,13,19}

The term optofluidics was coined in 2003 at the California Institute of Technology in Pasadena to describe systems that combine optics and microfluidics/nanofluidics (or to say, optical microfluidics).^{20,21} The interaction between light and fluid provides possibilities of both versatile microsystems and a wide spectrum of applications.^{9,22-26} In the past decade, there has been a growing interest and development of optical microfluidics (optofluidics) and an explosion of publications in the field. Actually, we can classify all microfluidic devices to either controllers or sensors. Here, we would like to emphasize on the microfluidic sensors. After the review of fabrication techniques in Sec. 2, we will have a brief introduction of the existing microfluidic detection methods and techniques in Secs. 3 and 4. This is followed by a review of optofluidic sensing techniques in Sec. 5.

2 Fabrication Methods

In the early days, the fabrication of microfluidic devices mainly relied on techniques transferred from the conventional two-dimensional integrated circuit (IC) and silicon-based two- or three-dimensional MEMS processes. This includes photolithography, thin film metallization, and chemical etching. Later, glass based, glass-silicon, glass-polymer mixed microfluidic fabrication techniques, and devices started to garner more

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interest.^{6,27-39} The glass materials were preferred partly for the biocompatibility toward the biomedical related applications⁴⁰⁻⁴⁴ and the ideal surface characteristics where high temperature or strong solvents should appear⁴⁵⁻⁵³ (e.g., on-chip capillary electrophoresis-based operations). However, lack of optical transparency at interested wavelengths (for silicon), micromachining difficulties, and comparably high expenses for both silicon and glass materials have hampered their wider applications in microfluidics. Tremendous effort has been made to find alternative materials that are more cost-effective and easier for micromachining. With the development of related fabrication techniques in recent years, the polymer/plastic-based microfluidic systems has garnered more interest than its conventional competitors.⁵⁴ In spite of comparatively weak bonding and structure deformation during device packaging processes, polymer materials still seem attractive due to the facts that: they are more economic compared with silicon and glasses, easier to be fabricated in/on, avoidance of high-temperature annealing and stringent cleaning, more system integration friendly (e.g., interconnections), and there exists a wider range of materials to be chosen for characteristics that are required for each specific application, such as good optical transparency, biocompatibility, and chemical or mechanical properties. Another important reason for the interest from both academia and industry on polymer microfluidic devices is the possibility of disposable microfluidic chips toward biomedical and clinical applications. These devices usually require low cost of fabrication, high volume production, good reproducibility, and versatility in design for a wide spectrum of specific applications.

Current methods for fabrication of microfluidic devices include prototyping techniques (includes hot embossing,^{55,56} injection molding,^{57,58} and soft lithography⁵⁹) and direct fabrication techniques such as laser photoablation or laser micromachining,⁶⁰ photolithography/optical lithography⁶¹ and x-ray lithography⁶² (Figs. 1 and 2). Table 1 presents the advantages and disadvantages of those techniques. Note that “photolithography” in this table refers to conventional photolithography that is mostly employed in IC industry for micrometer scale patterning. In fact, during the past decade photolithography techniques have progressed to achieve smaller feature patterning ability and have been coupled to various plastic/polymer-based techniques to better suit lab-on-a-chip applications. To date, most of the current soft lithography processes still rely on mod-

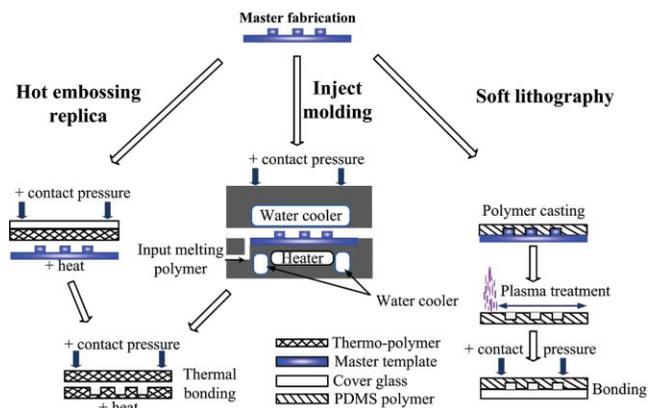


Fig. 1 Illustrations of the typical fabrication procedures by the prototyping techniques (hot embossing, inject molding, and soft lithography).

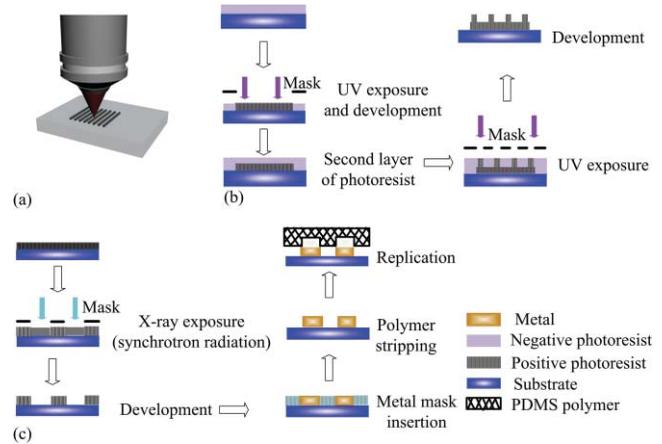


Fig. 2 Illustrations of the typical fabrication procedures by the direct fabrication techniques: (a) laser micromachining, (b) photolithography/optical lithography, and (c) x-ray lithography. The “metal mask insertion” step in x-ray lithography is usually realized by electroplating.

ern photolithography techniques for master template/mask fabrication. Consequently, the low resolution ability of soft lithography can be gradually improved with the high quality masks by modern photolithography. Sub-100-nm fabrication resolution can also be achieved by composite layers of stamps.⁶³ Other techniques were also used to obtain the soft lithography masters with nanometer scale features below 5 nm: such as to replicate those features from single-walled carbon nanotubes⁶⁴ or from crystal fractures⁶⁵ as soft lithography masters. For photolithography made masters for the soft lithography process, the recently reported resolution limit has been pushed to around 20 nm by Li et al.⁶⁶

3 Detection Methods

Integrated microfluidic devices involve the large-scale integration of various microfluidic components, such as microvalves, microchannels, micropumps, microfluidic mixers, and other elements to handle and control fluids at the microscale.⁶⁷ They are frequently used for biological, chemical, and biomedical analysis. There has already been a considerable amount of insightful review articles on related topics.⁶⁷⁻⁷² Various detection methods exist in the field of chemical, biological diagnosis, or analysis on microfluidic platforms.

The detection methods in microfluidics can be classified into three major types: optical methods,^{9,73-89} electrochemical methods,⁹⁰⁻¹⁰² and mass spectrometry methods.¹⁰³⁻¹¹³ Among these methods, optical and electrochemical methods are the most frequently utilized due to their selectivity and sensitivity. Other than the above major methods, approaches such as nuclear magnetic resonance (NMR) spectroscopy,¹¹⁴⁻¹¹⁸ magnetoresistive,¹¹⁹ and acoustical^{120,121} are also coupled to microfluidics for sensing application.

As demonstrated in Fig. 3, typical optical detection methods comprise the direct detection by monitoring the light properties including fluorescence,^{74,81-83} absorbance,⁸⁴⁻⁸⁶ and luminescence-based⁸⁷⁻⁸⁹ methods, and the light property modulation detections such as surface plasmon

Table 1 Microfluidic fabrication techniques.

Methods	Advantages	Disadvantages	Ref.
Hot embossing	Cost-effective, precise, and rapid replication of microstructures, mass production	Restricted to thermoplastics, difficult to fabricate complex 3D structures	56
Injection molding	Easy to fabricate complex geometry, fine features, and 3D geometries, low cycle time, mass production, highly automated	Restricted to thermoplastics, high cost mold, difficult to form large undercut geometries	58
Soft lithography	Cost-effective, able to fabricate 3D geometries, high resolution (down to a few nm)	Pattern deformation, vulnerable to defect	59,63–66
Laser photoablation	Rapid, large format production	Multiple treatment sessions, limited materials	60
Conventional photolithography/optical lithography	High wafer throughputs, ideal for microscale features	Usually requires a flat surface to start with, chemical post-treatment needed	61
X-ray lithography	High resolution to fabricate nano-patterns, absorption without spurious scattering, able to produce straight smooth walls	Difficulties in master fabrication process, time consuming, high cost	62

resonance (SPR) detection.^{76,80,122} These methods usually involve techniques such as evanescent waves,¹⁰ SPR,^{76,80,122,123} interferometry,^{75,124–128} Raman spectrometry,^{77,129–131} fiber optics,⁷⁸ and optical waveguides.^{79,132} Photonic crystals, optical cavity structures, and several optical techniques have also been reported to be integrated with the microfluidic system for sensing purposes, using one- and two-dimensional surface PCs (guided mode resonance filters),^{133–136} or three-dimensional photonic crystals,^{137,138} optical cavities,^{139,140} whispering gallery mode

resonators,^{141–147} and optical tweezers for cell related monitoring or fluidic rheological measurements^{148–150} (Fig. 4).

Electrochemical measurements are based on electrical property modulations of the analyte species that undergo redox reactions, and are usually employed for the detection of the electroactive species. They can be assigned to three categories: amperometries,^{90–94} potentiometries^{95–97} and conductometry^{98–102} measurements. The principles of these methods are demonstrated in Fig. 5. Amperometric detection

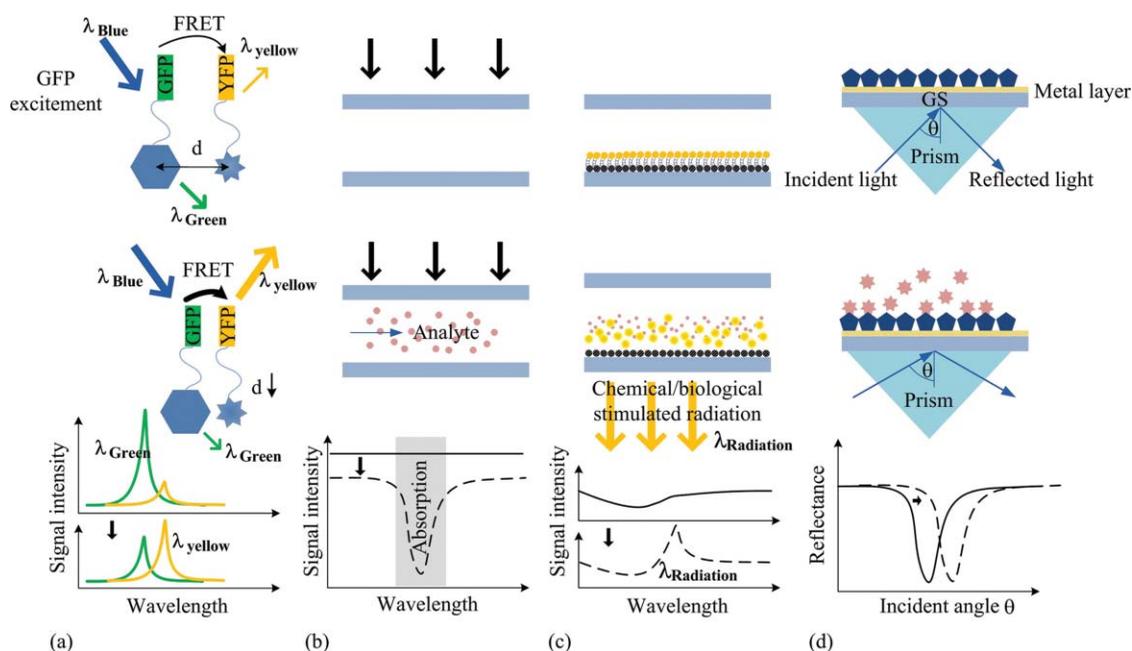


Fig. 3 Typical optical methods. (a) Fluorescence (in this case, fluorescent resonance energy transfer/FRET), (b) absorbance, (c) luminescence, and (d) surface plasmon resonance-based optical detection methods. GFP: green fluorescent protein; YFP: yellow fluorescent protein; GS: glass substrate.

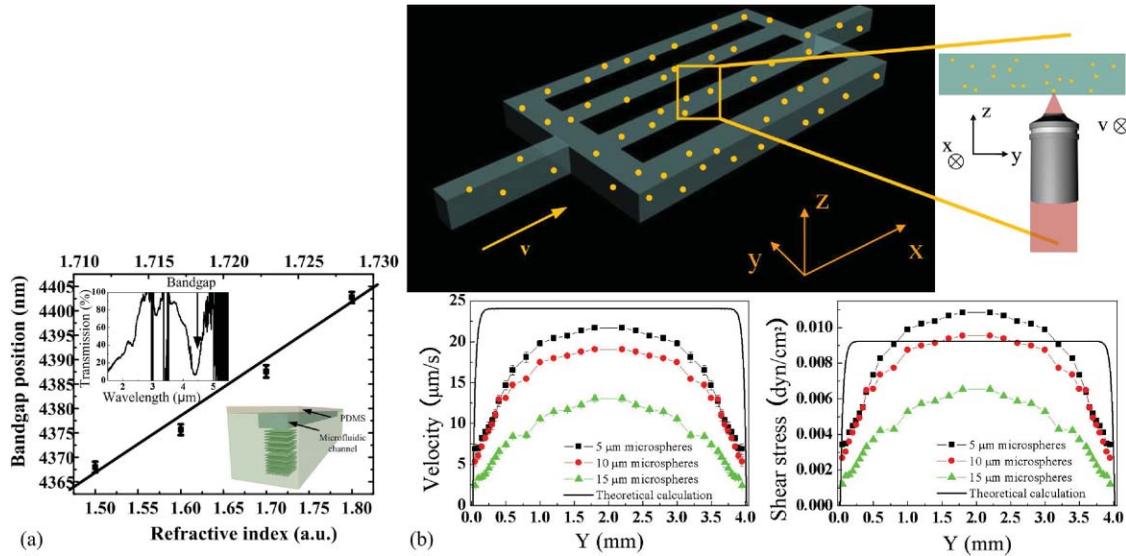


Fig. 4 (a) Result of a three-dimensional photonic crystal optofluidic sensor for refractive index detection. The fluid refractive index in the microchannel above the photonic crystal was detected by the bandgap position shift. Transmittance spectrum of the whole system that reveals a bandgap around $4.3 \mu\text{m}$ (left inset). An illustration of the sensor (right inset and see Ref. 138). (b) Demonstration of the shear stress mapping inside a microfluidic device by optical tweezers (top sketch). Theoretical calculated results by the pure fluidic model and the experimental measured results of the fluid velocity and shear stress along y direction in the microfluidic device (bottom and see Ref. 150).

is based on the fact that an applied voltammetric potential between a reference and a working electrode would cause the oxidation or reduction of the electroactive species in the vicinity, and an electrical current will be induced. Sensitive detection of the analyte(s) can be realized by the cyclic voltammogram(s) and current versus time curves of the electrode. In potentiometric detection, analyte detection is realized by monitoring the potential of an ion-selective electrode (usually a membrane) against a reference electrode. When selective ions pass through the membrane and a local equilibrium is established at the sensing interface, the resulting charge separation causes a potential between the working electrode and the reference electrode in

relation to the species type and concentration. The principle of conductometric detection is that the conductivity of a zone is affected by the charged species in the zone. Different types of species would have their specific conductivity responses, which would also vary with different concentrations. It is the most commonly employed method in electrochemical measurements since it, in principle, can deal with all charged species of interest. The detection involves measuring the conductivity at a series of frequencies, both in conventional contacted conductivity detection¹⁰¹ and capacitively coupled contactless conductivity detection (C^4D) methods such as potential gradient detection.¹⁰² Electrochemical detections are often used together with (capillary) electrophoresis operations (such as capillary electrophoresis separation) or in electrophoresis systems. Considering this, in this review the “electrochemical methods” actually include electrophoresis related work.^{92,99,101,102}

Mass spectrometry¹⁰³ (MS) is able to perform highly selective detection by monitoring the trajectory of ions in electric and/or magnetic fields, which elucidate the mass and charge of the ions. Its most important application is in proteomic studies for protein separation and further identification from the fragmentation pattern of proteins. Identification after separation can be carried out in two ways. One is direct detection by combing through the database using the individual types of obtained protein(s). The more sophisticated way is carrying out tandem MS (Ref. 151) to get protein fragments/ions for sequence tagging. To date, several MS configurations have already been developed to be integrated with microfluidic devices for this application, for instance, electrospray ionization (ESI)-MS (Refs. 104–106) and matrix-assisted laser desorption ionization (MALDI)-MS.^{107–109} In 2006, another paradigm is ion trap mass spectrometry integrated with microfluidics for protein identification by Hardouin et al.¹¹¹ Other systems were also reported, such as a chip-liquid chromatography (LC)-MS system for label-free profiling of human serum¹¹³ and a LC-ESI-MS system for

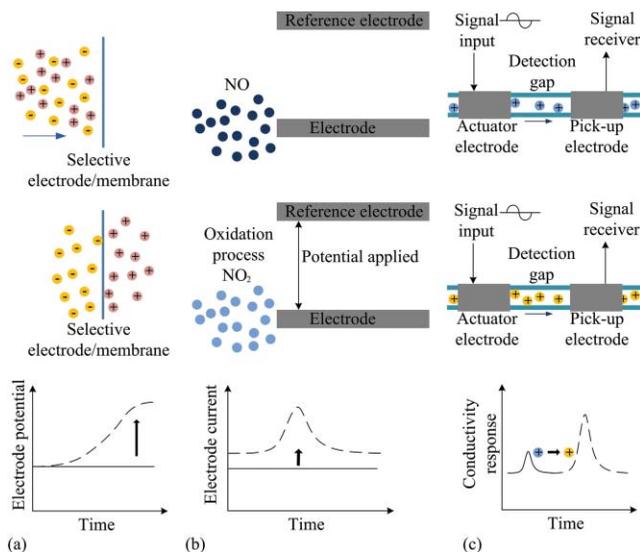


Fig. 5 Three types of electrochemical detection methods for microfluidics: (a) amperometric, (b) potentiometric, and (c) conductometric (capacitively coupled conductivity detector) detection.

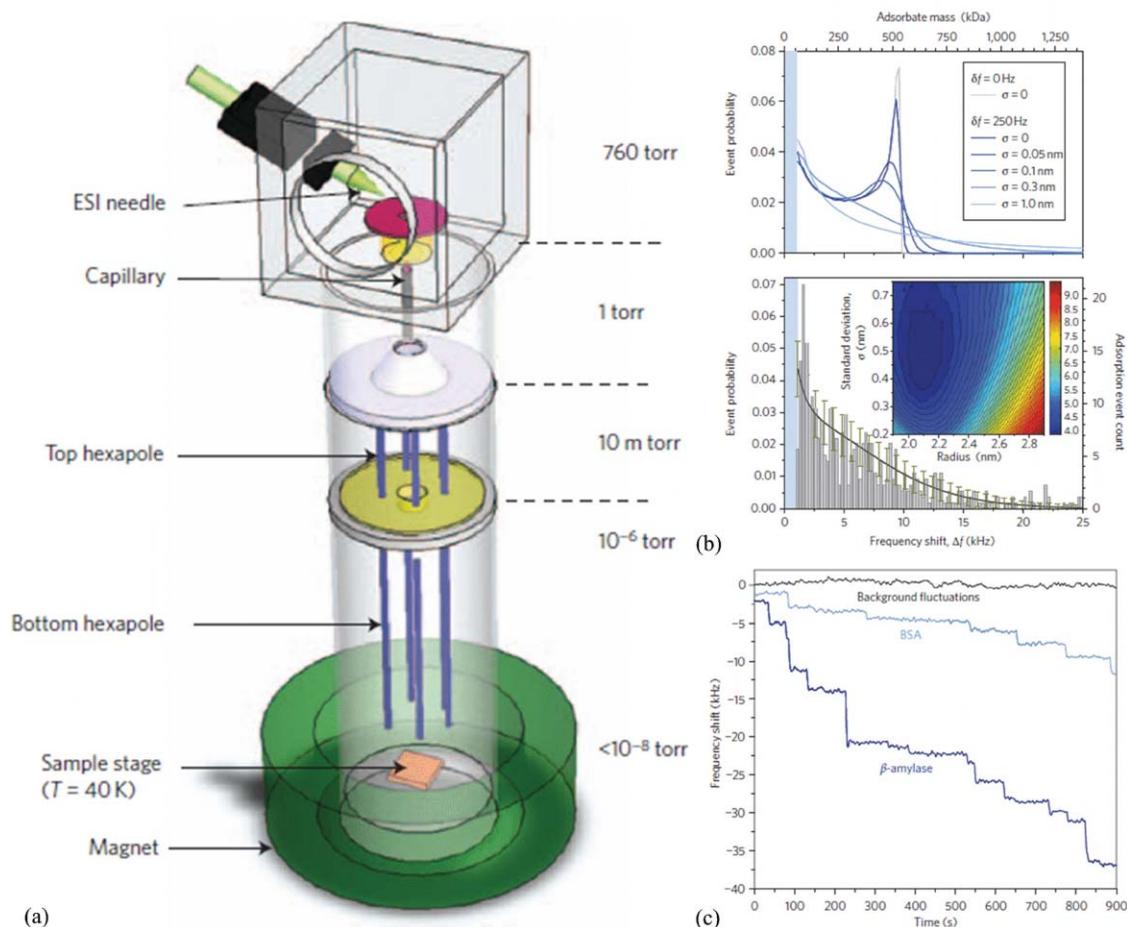


Fig. 6 First generation NEMS-MS system developed by Roukes's group (a), the NEMS mass spectrometry for a gold nanoparticles dispersion (b), and the real-time records of single-molecule adsorption events from their experiments (Ref. 110).

multiple proteins detection from breast cancer cellular extract.¹¹² The resolving ability of MS has recently been pushed down to the detection of a single molecular by Roukes's group in Caltech using a nanoelectromechanical system-based MS (NEMS-MS) (Fig. 6).¹¹⁰ It can be expected that in the future when NEMS-MS meets microfluidics, a much more effective microfluidic-MS platform could be realized to analyze biological or chemical species (e.g., proteins or nanoparticles) at a single molecular level with the ability to operate in multiplexing and parallel modes.

Besides protein separation and identification, MS has also been applied to the quantitative detection in protein expression in various states (especially in disease states). However, the miniaturization and high sensitivity requirements have currently been one of the most significant technological hurdles. Yet, microfluidics seems to hold great promises for the related technological breakthrough: The micrometer scale geometries and smaller platform of microfluidic devices meet the enhanced sensitivity and system miniaturization need; the multi-channel geometries in microfluidics enable high throughput processing and multiplexing ability. Considering these, to couple with microfluidics could be the ultimate lab-on-a-chip solution for MS toward quantitative proteome applications. To our knowledge, there has not been any further report on MS-based microfluidic sensing and yet a lot of interesting research remains to be carried out.

Other than the three major categories, other methods such as the NMR spectroscopy¹¹⁵ have also been explored to be applied to microfluidic detection.⁴³ It is a well-developed detection method in chemistry and life sciences, which employs the magnetic properties of nuclei or the chemical shift Zeeman effect and/or the Knight shift effect for detection purpose. NMR spectroscopy is able to detect biological and chemical analyte species such as proteins and nucleic acids. However, its application in microscale systems has been restricted by the low sensitivity of conventional NMR detection technique. Recently, this problem has been solved by hyperpolarization methods (e.g., to introduce the highly polarized para-hydrogen agent for signal enhancement). High resolution NMR for microfluidic systems was realized in 2007 by Pine's group in UC Berkeley on the study of multi-phase flows and catalyst deactivation (Fig. 7).¹¹⁶ Besides direct detection, the Pines' group also pioneered the remote monitor work of NMR-based microfluidic detections. In 2007, they reported the remote monitoring of spin coherence transfer in chemical transformations¹¹⁷ and a double-phase encoded remote detector of the fluid diffusion through membranes.¹¹⁸ This technique is readily applicable mostly in hydrogenation reaction-related detection and imaging, and might be extended for more applications in microfluidics. However, the limited reaction time scale/polarization lifetimes remains a key technological bottle-neck for NMR-based microfluidic analytical detection. Besides, similar to MS spectroscopy, another key hurdle

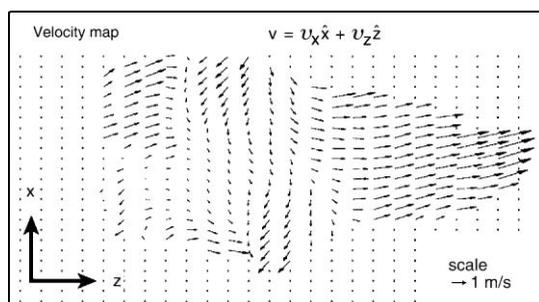


Fig. 7 Density of active catalyst and flow map imaging by the hyperpolarization enhanced NMR spectroscopy reported by Pines' group. MRI images [field of view (FOV) (x to z): 2.3 mm by 7.0 mm; pixel size: 20 μm by 60 μm] of a tightly packed catalyst bed (catalyst layer thickness is ~ 5 mm) are shown. The picture shows the flow map in the xz plane with the use of polarized propane. The orientation of the arrows represents direction of the velocity, and their length represents its magnitude. The SNR of thermally polarized propylene was insufficient to generate a velocity map. The resolution of the flow map is intentionally decreased by retaining only one of every 16 arrows to avoid excessive overlap of the arrows (Ref. 116).

is system miniaturization, in other words, to reduce the comparably large detector for better interface into microfluidics. In fact, not many related publications were reported afterward on NMR-based microfluidic detection. In spite of the technological challenges, NMR is still a competitive technique for microfluidic applications compared to optical or electrochemical methods: It does not have the optical accessibility issue for the region of interest (ROI) and the data acquisition time is much shorter, which makes time-resolved studies much easier; it has better detection pervasiveness than electrochemical methods that are limited to electroactive species. Hence, the solution to the weak NMR signal issue in microsystems, either by further signal enhancement or better detection instrumentations, will trigger a wider spectrum of lab-on-a-chip applications of NMR.

4 Sensing Techniques

In Sec. 3 we discussed general detection methods in microfluidics. Here, we would like to emphasize the microfluidics/optofluidics sensing techniques. A general review is presented in Table 2. From Table 2 we can see that the different methods have corresponding advantages and limitations. Some of them can be coupled with each other either to achieve certain phenomena for detection or to enhance sensor ability. For instance, evanescent waves are utilized with interferometers, optical fibers, fluorescence induction, and optical waveguides, in order to further enhance the detection sensitivity (e.g., in the form of a fiber-optic evanescent-wave approach¹⁵² or a fiber-optic localized plasmon resonance sensor¹⁵³). They are also widely used to induce surface plasmon resonance, which is essential in surface-enhanced Raman scattering.¹⁵⁴ Cavities structures are used in localized plasmon resonance detections to improve sensing performance.¹⁵⁵ Other detection methods were also actively studied for microfluidics, such as integrated optics components that can accommodate large arrays of compact optical channels and devices. One example is the laser induced fluorescence (LIF) detection, which is extensively used in microchip separations.¹⁵⁶

5 Outlook

The past decade has witnessed the progresses in microfluidics: more microfluidic system prototypes, increased device complexity, and more fabrication and sensing techniques have been developed or improved. However, microfluidics sensors are still in a formative stage and hold tremendous opportunities to be applied to a wider spectrum of fields and applications. We could expect the next drive engine to microfluidics sensors development would be based on:

- (1) Complete integration for compactness and self-contained microsystems

While most of the current microfluidic systems are still based on microfluidic devices that are coupled with external macroscopic detectors or preliminary external detection platforms, it is of great significance to push the microfluidic systems down to a complete microscale level. The development of specific detection components for microfluidics and complete integration techniques would enable real compact and self-contained microfluidic systems.

- (2) New and existing sensing principles and related technological advances

It is essential to explore for new sensing principles, or possible sensing components to be integrated with microfluidics while improving the sophistication of the microfluidic sensing systems. Ideal candidates should be both localized and sensitive (with minimized negative system perturbation), easy to fabricate and integrate, easy to assemble or even without post-fabrication assembly. More materials could also be considered, for instance, functionalized nanoscale particles, such as specialty nanocomposites (e.g., nanomaterials, nanocrystals, nanoparticles, nanocolloids, liquid crystals, quantum dots) and bio-/chemical-functionalized nanoscale materials or particles, could be incorporated with a microfluidic environment for flexible reconfiguration and system tuning for various sensing purposes.

Continuous research investments on optical, electrical, chemical, as well as mechanical, thermal, magnetic, or biological phenomena would open up new possibilities as well. In addition, technological advances in related fields such as electrical/optical/chemical instrumentation, microfabrication techniques, new material development, and processing techniques, would all contribute to the development of microfluidic sensors. Once the major barriers of existing sensing methods are cleared, such as the short life time and low resolution issue in NMR microfluidic sensors, the progress would be rapidly sped up.

- (3) Theoretical work and software development

The study of integrated microfluidic sensors should be extended to more sophisticated simulation methods and elaborate algorithmic models for a deeper understanding at a theoretical level. For instance, a more complex model should be developed for the theoretical understanding of the shear stress acting on the particle in microflows, which includes the effect of the particle size and other parameters such as concentration and temperature. As in a real microfluidic suspension

Table 2 Optofluidic sensing techniques.

Methods	Measurements/Applications	Advantages	Disadvantages	Sensitivity	Reference
Fluorescence	Temperature, cell function, flow velocity, polymer dynamics	High selectivity, sensitivity	High cost, extensive calibration and mathematical corrections, lack of appropriate fluorophores	Down to single DNA level	74, 81–83, 157, and 158
Mach-Zehnder interferometers	Refractive index, fluorescein concentration	High resolution, label free	Compromise between interaction lengths and sensitivity, multiplexing difficulties	Down to a few nano-molar concentration	75, 124–126, and 159
Dual polarization interferometry	Refractive index, conformational change, layer thickness, average density	Label free, simultaneous multiple parameters detection	High cost, alignment difficulties, unsuitable for detection of large numbers of mutations	Down to sub-pico-molar concentration	127, 128, and 160
Surface enhanced plasmon resonance	Refractive index, molecular and chemical reactions, polymer dynamics	Superior sensitivity and selectivity, label free	Low throughput, system alignment difficulties, small penetration depth, large sensing area required, small molecular weight analytes sensing difficulties, specific and nonspecific interactions differentiate difficulties, surface sensitive	Down to nano-molar level, single molecules (e.g., DNA, RNA, proteins)	76, 80, 122, and 123
Localized (surface) plasmon resonance	Refractive index, binding events	Label free, highly localized, real-time monitoring, simple and cost-efficient detection equipments	Instability of the metal nanostructures' morphology and optical properties	Down to pico-molar concentration, single DNA level	153–155, and 161
Surface enhanced Raman spectroscopy	Molecular detection, investigation of the structure and function of large biomolecules, analysis of chemical processes	Superior sensitivity and selectivity, label free	Small penetration depth, surface quality dependence, denaturation problem for biomolecules, overlapping peaks	Down to single molecule level, sub-pico molar concentration	77, 129–131, 154, and 162
Fiber optics	Rotation, acceleration, electric and magnetic field measurement, temperature, pressure, acoustics, vibration, linear and angular position, strain, humidity, viscosity	Superior sensitivity, simultaneous multiple parameters detection, easy for integration, refractive index, chemical measurements, label free, environmental ruggedness, multiplexing ability, dynamic range and resolution	High cost, end-user unfamiliarity	Down to tens of nanometers, pico-molar concentration	78, 153, 163, and 164
Planar waveguides	Refractive index detection, study and detection of particles	High sensitivity, label free, compact configuration	Small penetration depth, limited for processes with diffusing particles	Single viruses and liposomes resolution	79 and 132
photonic crystals	Particle interactions (e.g., protein-protein, antibody-antigen and small molecule-protein interactions), cell-based assays, refractive index, concentration, absorption and conformation of biomolecules on a surface	Potentially high sensitivity, localized confinement, flexibility in sensor structures and related properties	Fabrication difficulties for higher order photonic crystals, related high cost, difficulties in high-throughput screening	Down to single molecule level (e.g., protein), nano-molar concentration	133–138
Micro-ring and microsphere resonators, including those using whisper gallery modes (WGM)	Detection of virus, protein, DNA, or bacteria, detection of concentration, refractive index, binding events of molecules	Multiplexing feasibility for micro-ring resonators, high Q (microsphere resonators: $Q > 10^9$ micro-ring using WGMs: $Q > 10^8$)	Mass produce difficulties, multiplexing difficulties for microsphere resonators, lack robustness	Down to single molecule level	146, 147, and 165

environment, considerable deviations have been observed in the experimental measurement results from the simulation with a pure fluidic system.¹⁵⁰ Modeling of the fluidic dynamic characteristics, such as velocity, heat transfer, and shear stress inside microfluidic devices will also be beneficial.

Microfluidic work from the very beginning has been mainly among physical or more specifically fluid mechanical and lab-on-a-chip communities. However, the most important end-users are usually biological or chemical specialists, to whom the theoretical understanding, numerical simulation skills, and lab-on-a-chip know-how could be a huge hurdle. The accessibility of more user friendly simulation software to nonspecialists could alleviate this problem and allow biologists and chemists to actually get actively involved in the early stage development of the sensors to better suit the actual demands.

Besides, the simulation software provides a more economical and quicker research and development loop by the pre-fabrication numerical tests for various designs or fabrication procedure optimization. In this way, the cost and time frame will be sharply reduced with refined theoretical simulations and modeling work carried out beforehand.

(4) Standard integration interfaces

Another important issue is that most of the current microfluidic sensing platforms are “one-design-one-application” types. It is not easy to modify or upgrade the systems or switch for multi-function operations. Usually the change of applications or the instruction of an additional task would simply mean redesigning a system. Thus, a standard microfluidic interface, that is friendly and flexible for various functional components to be easily integrated to, holds great promises for enhancing the adaptivity of microfluidic sensing systems. This will open up the possibility of dynamic microfluidic systems that support versatile modes of interfacing and operations.

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