Ultrafast Carrier Trapping in High Energy Ion Implanted Indium Phosphide

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We report on the results of ion implanted and annealed InP for ultrafast optoelectronic applications. MeV ions (P^+, As^+, In^{2+}, and Ga^+) were implanted into semi-insulating InP at 200°C to a dose of 1×10^{16} cm^{-2}. The samples were then annealed at 400, 500, 600 and 700°C for 30 seconds and Hall effect, time resolved photoluminescence, and double crystal X-ray diffractometry (DCXRD) measurements were performed on them. Generally, carrier trapping times decreased for lower annealing temperatures and larger ion mass, however the gallium implanted samples exhibited the shortest trapping times (less than 1 ps) even though the mass of gallium is similar to that of arsenic. At annealing temperaturesof 600 and 700°C, it is presumed that the creation of shallow donor levels has caused the maximum sheet resistivities to drop to ~300 ohm/square from the as implanted values of ~ 2×10^5 ohm/square. DCXRD spectra were similar for the P^+ and As^+ implanted samples, while the Ga^+ and In^{2+} implanted samples exhibited different types of structural evolution as a function of annealing temperature. While these materials have resistivities that are too low for use in ultrafast photodetectors, they are ideal as saturable absorbers for the mode locking of solid state lasers.

A. Introduction

Non stoichiometric III-V compounds have drawn considerable interest in recent years due to their unique properties such as high resistivity, good carrier mobility and short carrier lifetime. Both low temperature (200°C) grown GaAs and ion implanted GaAs after annealing [1-6] have these properties, which are ideal for ultrafast photodetector applications. Recently, these materials have also been used as saturable absorbers for the mode locking of solid state lasers to create femtosecond and picosecond laser pulses [7]. LT grown InP has also shown its suitability for ultrafast optoelectronic applications [8]. In this work we investigate the effect of implanting different ions into semi insulating InP.

B. Experimental

Semi insulating Fe doped InP samples were implanted with P^+, As^+, Ga^+ and In^{2+} at energies of 1, 2, 2.1 and 3.3 MeV respectively, at a dose of 1×10^{16} cm^{-2}, and a substrate temperature of 200°C. The implantation energies were calculated using TRIM (Transport of Ions in Matter) to place the maximum damage at a depth of ~ 1 μm from the surface.

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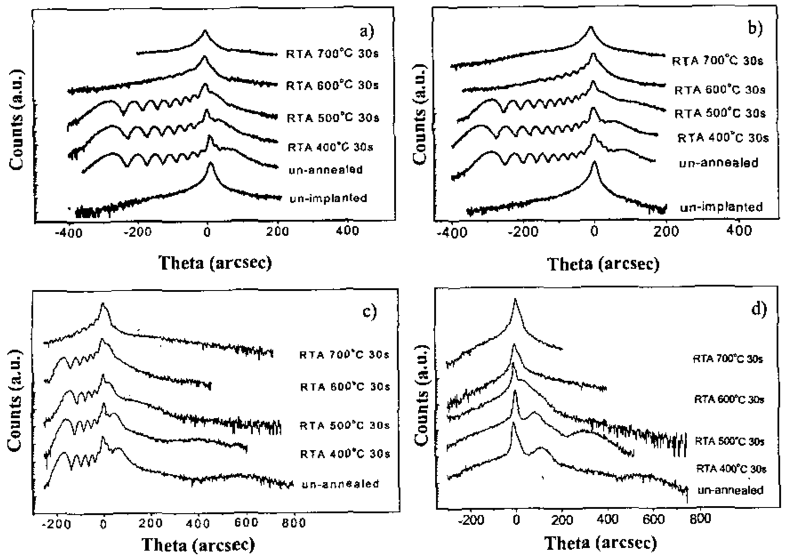

Fig 1: X-ray rocking curves from InP implanted at 200°C with a dose of 1×10^{16} cm^{-2}. 1 MeV P^{+} (a), 2MeV As^{+} (b), 2.1 MeV Ga^{+} (c) and 3.3 MeV In^{2+} (d). Spectra vertically shifted for clarity.

The amount of damage was expected to increase with increasing ion mass. Rapid thermal annealing (RTA) was then performed on the samples at 400, 500, 600 and 700°C for 30 seconds, and in an Ar atmosphere. Carrier lifetimes in the samples were measured by time resolved photoluminescence (TRPL), with a femtosecond self-mode locked Ti:sapphire laser, using a $LiIO_3$ nonlinear crystal. The laser was tunable between 750 and 900 nm, the pulse width was 80 fs, the repetition rate 85 MHz, and the output power was 200 mW at λ=780 nm. Double crystal x-ray diffractometry (DCXRD) and Hall effect measurements (Van de Pauw method) were also performed on these samples.

C. Results and Discussion

Figure 1 shows the DCXRD spectra for implantation with the four different ions. P^{+} and As^{+} implantation produce similar spectra - and presumably similar types of damage - with periodic fringes on the negative angle side of the rocking curves. These fringes have been associated with a sharply defined layer of positive strain (expansion); etching/DCXRD experiments (not shown) have confirmed that these fringes correspond to a region approximately one micron into the sample,that is, where the maximum damage and concentration of interstitials is located. This damage is mostly annealed out at a temperature of 600°C, and the rocking curves become similar to that of the unimplanted sample, except for the larger FWHM caused by residual defects in the material. The spectra for Ga^{+} implantation also show these periodic fringes, but over a narrower angle range, and they are still present

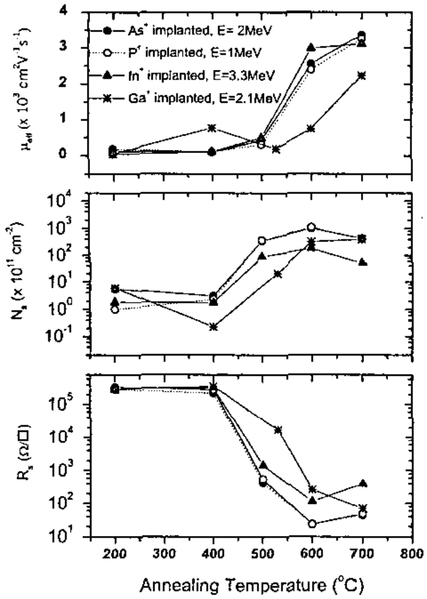

Fig 2: Mobility (a), sheet carrier concentration (b) and sheet resistance (c) as a function of annealing temperature, for P^+, As^+, Ga^+ and In^{2+} implanted s-i InP.

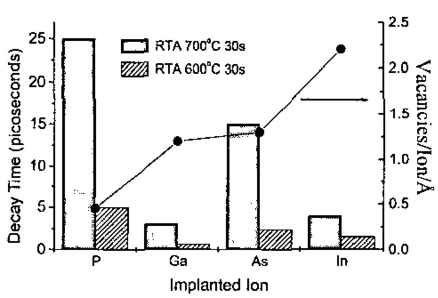

Fig 3 : TRPL decay times measured at 300 K and simulated peak atomic displacements (TRIM) produced for P^+, As^+, Ga^+ and In^{2+} implanted s-i InP.

after annealing at 700°C. We conclude that the implanted Ga atoms are affecting the recrystallization processes during annealing. Further work is necessary to understand this behaviour. In^{2+} implantation does not yield these fringes at all, most likely because the damaged layer is broader and more diffuse (as revealed in TEM images - not shown). Both Ga^+ and In^{2+} implantation also result in broad features at Theta ~ 600 arcsec, which have been proven to be very close to the surface in etching experiments, and probably result from compression of a layer of implantation induced vacancies. At temperatures above 500°C, this layer is annealed out.

An unimplanted, semi insulating InP wafer has a mobility μ_{eff}, of approximately 2000 $cm^2V^{-1}s^{-1}$, sheet carrier concentration n_s of 10^7 cm^{-2} and sheet resistance R_s of 3×10^8 Ω/ζ. Figure 2 shows the post implantation evolution of these values as a function of annealing temperature, as determined from Hall effect measurements. The sheet resistance is reduced to ~4×10^5 Ω/ζ by implantation with all four ions, and further reduced to tens or hundreds of Ω/ζ as more shallow donors [8-10] are created upon annealing at temperatures above 400°C. The carrier concentrations become very small, but annealing above 500°C can create materials with $n_s > 10^{13}$ cm^{-2}. The mobility is reduced to 180, 40, 45 and 113 $cm^2V^{-1}s^{-1}$ respectively for implantation with P^+, As^+, In^{2+} and Ga^+. Annealing at temperatures above 600°C will generally increase mobilities to ~1.5 times the unimplanted value, with the exception of Ga^+ implantation. Similarly to the DCXRD results, P^+ and As^+ implanted samples have practically identical electrical behaviour as a function of annealing temperature. Annealing at 600 and 700°C, for Ga^+ and In^{2+} implantation, yields materials with higher sheet resistances and lower carrier concentrations than for P^+ and As^+ implantation.

Figure 3 shows the dependence of the carrier lifetimes on ion mass, as measured using TRPL. Generally, there is a trend of decreasing lifetime with increasing ion mass, which would be expected from the known dependence of damage on the mass of the implanted ion. The decay times are larger for RTA at 700°C, as more defects are annealed out and consequently there are fewer trapping centres. Interestingly, implantation with Ga^+ produces the shortest decay times (0.66 ps at RTA 600°C), even though the mass of this ion is similar to As^+. The shorter decay time is consistent with the evidence of greater structural damage in the DCXRD spectra at these annealing temperatures, and the corresponding fact that the mobility at the same annealing temperatures does not reach the high values that it does for the other samples.

D. Conclusion

Implantation of s-i InP with P^+, As^+, Ga^+ or In^{2+} and annealing at 600°C will result in materials with response times below 5 ps, mobilities comparable to the unimplanted material, and low sheet resistivities. As such they would be ideal as materials for saturable absorbers, for the mode locking of solid state lasers.

References

[1] F. W. Smith, A. R. Calawa, C.-L. Chen, M. J. Manfra, and L. J. Mahooney, IEEE Electron Device Lett. **9**, (1988) 77.

[2] S. Gupta and J. F. Whitaker, IEEE J. Quantum Electron. **28** (1992) 2464.

[3] M. Kaminska and E. R. Weber, Mater. Sci. Forum **83-87** (1992) 1033.

[4] A. Claverie, F. Namavar, and Z. Lilienthal-Weber, Appl. Phys. Lett. **62** 1271 (1993).

[5] A. Krotkus, S. Marcinkevicius, J. Jasinski, M. Kaminska, H. H. Tan and C. Jagadish, Appl. Phys. Lett **66** (1995) 3304.

[6] C. Jagadish, H. H. Tan, A. Krotkus, S. Marcinkevicius, K. P. Korona, and M. Kaminska, Appl. Phys. Lett **68** (1996) 2225.

[7] M. J. Lederer, M. Hildebrandt, V. Z. Kolev, B. Luther-Davies, B. Taylor, J. Dawes, P. Dekker, J. Piper, H. H. Tan and C. Jagadish, Optics Lett **27** (2002) 436.

[8] S. Radautsan, I. Tiginyanu, and N. Pyshnaya, Phys. Stat. Sol. (a), **108** (1988) K59.

[9] K. Kuriyama, S. Satoh, K. Sakai and K. Yokoyama, Nucl. Instr. And Meth. in Phys. Res. B **127/128** (1997) 456.