Observation Of Track Formation and Track Annealing In Swift Heavy Ion Irradiated InP

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Introduction

Besides the controlled doping of semiconductors by means of conventional ion implantation, energetic ion beams, Swift Heavy Ion (SHI), irradiation offer a much broader range of possibilities to modify the structure and properties of materials, due to the very high local energy density deposited into the solid along the ion path. Ion-track engineering may be developed to a stage allowing controlled fabrication of track-structured nano-components for semiconductor electrical and mechanical devices [1].

Ions with energies ~ E ≥ 1 MeV/amu that penetrate into a solid lose energy at rates ≥ 10 keV/nm. More than 90% of the energy loss of these ions is due to electronic excitations where the incoming ion transfers its energy to the electrons in very short times $t < 10^{-16}$ s within a small cylindrical volume of material surrounding the ion trajectory. Subsequent energy and momentum transfer to the atoms of the target usually creates a trail of permanent material damage (point/cluster defects, phase transformation, amorphization) along the ion's path. The structure and morphology of these ion tracks can shed light on their complex processes of formation. Track registration processes in semiconductor materials are phenomena that are still not well understood.

The purpose of the present investigation is to observe the tracks created in the wake of 200 MeV Au ions and their annealing behaviour in the technologically important III-V semiconductor InP. Previous TEM investigations have shown that tracks are formed in this material upon irradiation with 250 MeV Xe ions at room temperature. There has been some controversy about the conditions for track registration in InP [2,3] by 250 MeV Xe ions. In the present investigation an attempt has been made to clarify some of these issues.

Experimental methods

Single crystals of electron-transparent InP were irradiated with 200 MeV Au ions at normal incidence at a temperature of 300 K in the 14 UD Pelletron of the Australian National University. To reduce the heating effect of the beam, the ion flux was kept around 6.2×10^9 ion/cm^{2}s. The working vacuum inside the irradiation chamber was 10^{-6} Torr. Ion fluences ranged from 5×10^{10} to 1×10^{14} ion/cm^2. To enable accurate dosimetry for low fluences (< 5×10^{12} ion/cm^2), thin crystallites of MoO_3 deposited on standard C coated Cu grids were irradiated simultaneously with the pre-thinned InP samples. The oxide material produces one hole per incident ion and provides an accurate nano-solid state detector exhibiting fluence calibration in the low dose ranges. The fluence can be accurately measured by simply counting the number of the holes observed in the electron micrographs.

Transmission Electron Microscopy (TEM), both in conventional and high-resolution modes, was used to investigate the SHI tracks in InP. The effect of in-situ thermal annealing upon the samples was also examined.

Results and discussion

An example of the observed tracks is shown in figure 1. Most tracks have a regular intermittent beaded structure and the absence of any diffused rings in the selected area electron diffraction pattern indicates that the observed structures may be not amorphous in nature.

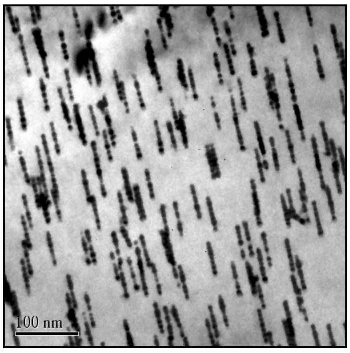
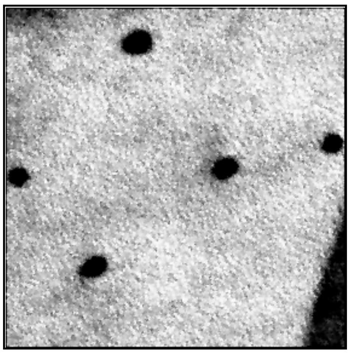


Figure 1. TEM diffraction contrast image of an ensemble of tracks showing uniform intermittent structure. The sides of the figure are of length 600 nm.

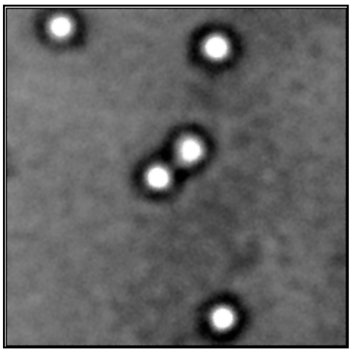
The high rate of electronic energy deposition of 200 MeV Au ions over distances in which InP is electron-transparent can be regarded as almost constant along the length of the track. This suggests that the basic registration phenomenon for explaining the intermittent nature is not dynamic charge fluctuation processes as proposed for track morphology in InP [4]. In this model the inelastic energy loss of the impinging ion fluctuates around the threshold energy due to the effective charge resulting from the capture or loss of electrons. This then gives rise to defect formation or the absence of the defects along the ion path. Atomic defect rearrangement processes are more likely in the aftermath and quench of a complex compound spike mechanism [5] rather than simple melting and recrystallization based on the thermal spike model, while the statistical nature of the charge fluctuation model cannot fully explain the regularity of the defects observed along the tracks.

In figure 2 is shown an electron micrograph of a 100 nm x 100 nm area of an irradiated InP sample and similar area of a MoO_3 sample irradiated simultaneously. There is a one-to-one correspondence between fluence and track density, which precludes any predamaging condition for track formation as suggested by Komarov et al. [2]. In that study the InP was irradiated with 250 MeV Xe ion, and it was found that for doses lower than 5×10^{12} ion/cm^2 no tracks were formed; only small defects and clusters were detected.

A model based upon these observations has been suggested previously [6,7]. It is based on the thermal spike mechanism and considers the nature of the matrix surrounding the melted region along the ion path. Track melting is accompanied by rapid cooling and resolidification of the surrounding matrix and this depends on the crystalline quality of the matrix because the presence of defects impedes perfect epitaxial recrystallization of the melted region and affects the quality of the reconstructed lattice. In the case of imperfect recrystallization, which is affected by the presence of point defects in the solid phase surrounding the melt, this gives rise to the observed track structures and therefore the need for a certain incubation dose to form an imperfect crystal.



(a)



(b)

50 nm

Figure 2(a) Tracks in InP (5 x 10^{10} ion/cm^2) exhibiting strong TEM phase contrast, indicating the sharp boundary between the induced disorder and the surrounding unperturbed matrix. Track widths are ~ 10 nm. **(b)** A similar area of MoO_3 sample, irradiated simultaneously with the InP sample, in which the tracks are simple holes. The lengths of the sides of the figures are 100 nm.

High Resolution TEM (Figure 3) indicates that there is no evidence for amorphization in the cores of the individual tracks. The continuous fringes visible inside the track core point to the crystalline nature of the core, which must be formed by homoepitaxial regrowth and point defect motion during target recovery phase after the compound spike [5]. Further TEM and electron diffraction investigations have revealed that the progression to complete amorphization at doses ~ 5 x 10^{13} ion/cm^2 proceeds through the formation and coalescence of amorphous zones as a result of the overlap of tracks.

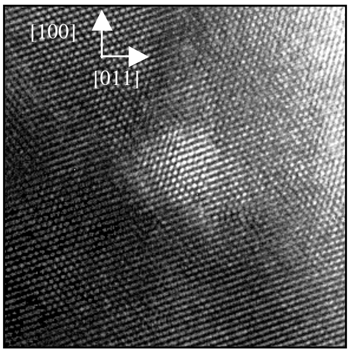


Figure 3. High Resolution TEM phase of a single-track core. The lattice structure (phase grating approximation) appears to continue without any visible distortion across the tracks (the core diameter ~ 5nm). The lengths of the sides of the figure are 20 nm.

The tracks were found to be very sensitive to the imaging electron beam in TEM. They fade and anneal out even under a diffused 200 keV beam at liquid nitrogen temperature and complete crystallinity is restored, as observed by HREM, suggesting a role of point defect motion and rearrangements activated by electron beam induced elastic interactions. In-situ TEM thermal annealing, as shown in Fig. 4, indicates that tracks in InP anneal out almost completely upon heating the sample to ~ 475 K; this might further indicate the point defect nature of the tracks. Similar *in-situ* thermal annealing observations for recovery of cascades produced by 50 keV Si ion bombardment of InP was observed by Zheng et al [8], where complete recovery of the low-energy ion impact induced defects occurred at ~ 500 K.

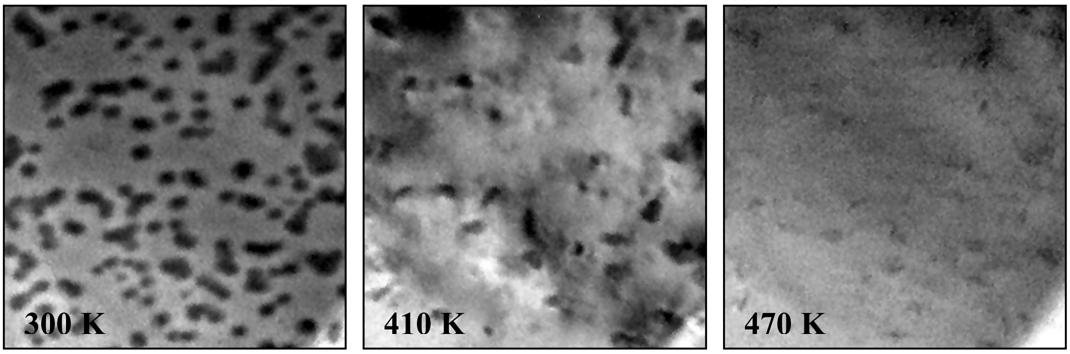


Figure 4. In-situ TEM observation of the progression of thermal-induced recovery of tracks in 200 MeV irradiated InP**;** the tracks disappear upon reaching 475 K. The size of the observed area is 200 x 200 nm^2. The heating stage used was a Gatan Double Tilt Heating Holder, Model 652 with Controller Type 901.

Conclusions

Each 200 MeV Au ion produces a single track in its wake without any need of pre-damage or lattice modification for track registration to occur. The track formation results from a complex process mediated by point defects induced by high electronic deposition by the SHI irradiation. Single tracks do not appear to be amorphous in nature. The tracks are probably an agglomerate of point defects and are sensitive to the imagining electron beam. In-situ thermal annealing leads to complete recovery at T ~ 500 K.

References

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