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Swift heavy ion induced structural evolution in InP

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ABSTRACT

This article reports a comprehensive study on damage evolution in undoped InP due to 100 MeV silver (Ag^{7+}) ion irradiation. Raman and Rutherford back scattering channeling (c-RBS) measurements are employed to bring out two different aspects of disorder in the system. While Raman spectroscopy revealed a monotonic increase in sub-surface strain due to ion irradiation, the later detected heavy damage in the wafer at high fluences. Furthermore, we have estimated the lattice temperature under above irradiation conditions in InP using a unified thermal spike model. The model includes both inelastic thermal spike and elastic collision spike along with the effect of latent heat. This model explains the observed damage evolution of the target. Above experimental techniques in conjunction with the simulation model provides a qualitative explanation of the damage accumulation leading to structural modification in the Ag ion-irradiated InP wafer.

1. Introduction

Ion irradiation is a well-established technique to modify various physical, electrical, optical and mechanical properties of semiconducting materials [1–10]. Modern technology, related to various optoelectronic and microwave devices, exploits the unique characteristics of ion-irradiated Group III–V semiconductors like GaAs and InP. There are quite a few reports in the literature, which discussed the structural evolution in InP on swift heavy ion (SHI) irradiation. Formation of highly resistive thick buried layers [2] and tensile strained layers [3] were observed on high energy ion irradiation in InP. Damage and formation of amorphized tracks in InP for swift Xe ions was first reported by Herre et al. [4]. Amorphous tracks were further observed for other heavy ions like Au, Pb, and Bi [5–9]. Damage annealing could be achieved in pre-damaged InP by SHI irradiation [1,10].

Above reports motivated us to carry out a combined study probing different aspects of structural modification of the system on swift ion irradiation. In this article, we have investigated the damage evolution in 100 MeV silver (Ag^{7+}) ion irradiated InP by Raman and Rutherford back scattering channeling (c-RBS) measurements. Raman scattering is sensitive to small concentrations of defects. On the other hand, c-RBS measurement is effectively used to study high concentrations of interstitial type defects. Furthermore, Raman spectroscopy can detect short-range (atomic scale) disorder, like lattice strain, in the system. Hence, in a broad sense, these two techniques are complementary to each other.

In the literature, the various models have been proposed to explain the damage and track formation in the target materials by high energy ion irradiation [1,5–7,9,11–21]. In this article we have used the thermal spike model (TSM) to explain the observed the structural modification of high energy Ag^{7+} ion irradiated InP. However, we need to keep in mind that the model is based on few critical assumptions [22]. Below we discuss the major concerns in brief. The heat diffusion equation in the TSM model assumes electron-phonon coupling to be the only mechanism of heat transfer between the electronic and the atomic subsystems [1,6,9,17–19]. It does not take into account the consequence of electron–electron scattering of the dense electronic excitations on the evolution of the lattice temperature [22,23]. The model also neglects the fluctuation of the charge state of the projectile ions near the surface of the target. The TSM includes equilibrium values and functional forms for various thermo-physical parameters, like, thermal conductivity, specific heat, heat of fusion, various temperature coefficients etc [1,6,9,17–19]. The estimated lattice temperature is extremely sensitive to choice of these parameters. Furthermore, for the temperature evolution of the electronic system, free electron model is considered while determining the electronic specific heat and thermal conductivity [6]. It is assumed that these parameters are independent of time and are same

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throughout the region of interest. It is also to be noted that the model does not take into account the temperature evolution on ion irradiation in a pre-damaged material as it is difficult to obtain the thermal properties of such a material. Hence, fluence dependence studies are not possible using this model. We demonstrate that despite all above assumptions in the model, it qualitatively explains the observed structural evolution of high energy Ag ion irradiated InP fairly well.

2. Experimental details

We used commercial undoped semi-insulating InP (SI-InP) single crystal wafers (orientation (001) and thickness 500 μm) grown by liquid encapsulated Czochralski (LEC) technique for our irradiation studies. Using the 15UD Pelletron at IUAC, New Delhi, the wafers were irradiated with 100 MeV Ag^{7+} ions in the fluence range of 6×10^{11}–6×10^{13} ions/cm^2. These wafers were characterized by c-RBS measurements and room temperature Raman spectroscopy. The c-RBS measurements were performed using the 1.7 MV Pelletron at IUAC, New Delhi. For c-RBS experiment, backscattered helium (He) ions from a 2 MeV He source were detected at an angle of 160°. The crystals were aligned to the collimated incoming He ions using a four-axis goniometer. To avoid damage in the target by the probing He ion beam, after aligning the crystal along the channeling direction, the beam was slightly shifted to a new position for recording the spectra.

Room temperature micro-Raman spectra were measured using 488 nm argon ion laser as an excitation source in backscattering geometry. The Raman spectrometer was equipped with a single monochromator (model TRIAX 550, make JY, France) with an edge filter and a charge coupled device (CCD) detector. The laser power ~10 mW was used in all measurements. The laser beam was focused on the sample using a 50× objective lens to a spot size ~2 μm diameter.

3. Experimental results

3.1. Rutherford back scattering measurements

Raman and c-RBS scattering measurements have been extensively used for III–V materials to quantify the spatial distribution of defects and to understand the microscopic nature of the defects created due to ion irradiation [24,25]. In (i) and (ix) of Fig. 1(a), we plot the channeled and the random spectra of the un-irradiated wafer. The c-RBS spectra of 100 MeV Ag^{7+} irradiated SI-InP wafer in the fluence range 6×10^{11}–6×10^{13} ions/cm^2 are presented in (ii)–(viii) of Fig. 1(a). The spectra in Fig. 1(a) are shifted along the y-axis only for the clarity; there is no change in the minimum yield of the channeled spectra with fluence. Here, the surface peak (~1692 keV) is observed upto a fluence of 1×10^{13} ions/cm^2 (spectrum (vi) in Fig. 1(a)). We find a slight increase in the background over the fluence range between 6×10^{11} (spectrum (ii) in Fig. 1(a)) and 1×10^{13} ions/cm^2 (spectrum (vi) in Fig. 1(a)). At the fluence of 3×10^{13} ions/cm^2 (spectrum (vii) in Fig. 1(a)), there is a sudden increase in the de-channeling yield suggesting the formation of a damaged layer. A further increase in de-channeling yield is observed at an ion fluence of 6×10^{13} ions/cm^2 (spectrum (viii) of Fig. 1(a)), suggesting the formation of heavily damaged zones in the target.

RBS damage fraction is a measure of the volume fraction of the disordered atoms in an ion irradiated layer. The damage fraction, related to the difference in the minimum yield ($\Delta\chi_{min}$), at a depth (z), is evaluated from the channeled and random RBS spectra of all irradiated samples using the relation, $\Delta\chi_{min}(z) = (Y^{irr}_{aligned}(z) - Y^{pristine}_{aligned}(z))/(Y_{random}(z) - Y^{pristine}_{aligned}(z))$ [6], where $Y^{pristine}_{aligned}(z)$ and $Y^{irr}_{aligned}(z)$ are the RBS yields of the aligned (channeled) spectra for un-irradiated (pristine) and irradiated samples respectively; $Y_{random}(z)$ is the yield measured in the random direction. We have calculated $\Delta\chi_{min}$ for all the samples at an energy of ~1400 keV (energy of He backscattered from indium) and integrated over ~20 channels (refer to Fig. 1(a)). This energy corresponds to a depth of ~0.2 μm. The variation of $\Delta\chi_{min}$ with fluence, as obtained from the above equation, is shown in Fig. 1(b). There is a slight increase in $\Delta\chi_{min}$ upto a fluence of 1×10^{13} ions/cm^2 (inset), however beyond this fluence; $\Delta\chi_{min}$ shows a sudden sharp rise.

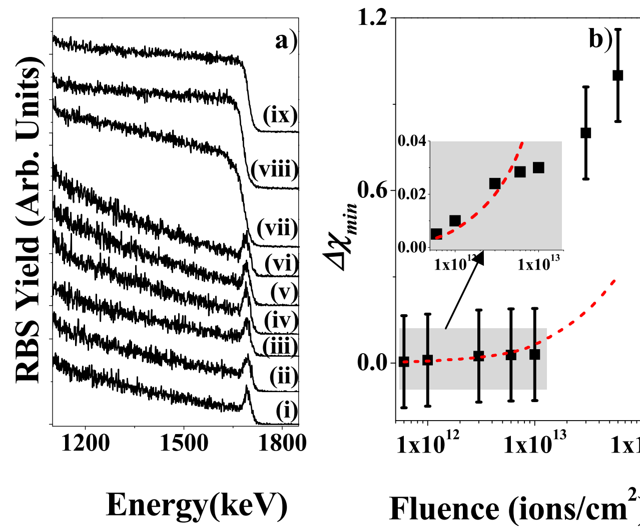

Fig. 1. a) RBS ion channeling spectra of InP (i) un-irradiated and irradiated with 100 MeV Ag^{7+} ions for different fluences [(ii) 6×10^{11} ions/cm^2, (iii) 1×10^{12} ions/cm^2, (iv) 3×10^{12} ions/cm^2, (v) 6×10^{12} ions/cm^2, (vi) 1×10^{13} ions/cm^2, (vii) 3×10^{13} ions/cm^2 and (viii) 6×10^{13} ions/cm^2]. The random spectrum for the un-irradiated sample is shown as (ix). (b) The evolution of c-RBS minimum yield ($\Delta\chi_{min}$ (■)) as a function of fluence. The evolution of $\Delta\chi_{min}$ in the low fluence regime ($\leq 1 \times 10^{13}$ ions/cm^2) is shown separately. The red dashed line is the best fit to the data points in the low fluence regime using the direct impact Gibbons' model. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

In general, the direct impact Gibbons' model is used to discuss the damage evolution in a target by ion irradiation [8,26]. The model explains the formation of amorphous zones in the target by a single projectile ion. In this model, the calculated damage concentration n_{def} is given by, $n_{def} = 1 - \exp(-A_\Phi \Phi)$, where, Φ is the ion fluence and A_Φ is the damage cross-section by a single ion, from which track radius can be calculated [6,8]. We find that the whole range of $\Delta\chi_{min}$, obtained from c-RBS measurements in Fig. 1(b), could not be fitted by the above equation for n_{def} (red dashed line). In the low fluence regime (upto about ~6×10^{12} ions/cm^2), the experimental data points could be reasonably fitted with the direct impact Gibbons' model. A_Φ was kept as a free fitting parameter. The net fitted curve to the data points with $A_\Phi = 0.6 \pm 0.01$ nm^2 is shown by the red dashed line in the inset of Fig. 1(b). The radius of the damaged zone obtained from A_Φ is ~0.44 ± 0.05 nm. It is important to note that the above radius of the damaged area is even less than the lattice constant (0.59 nm [27]) of InP. Thus, we believe that in the low fluence regime only point defects are produced. With the increasing ion fluence ($\geq 1 \times 10^{13}$ ions/cm^2), as more number of high energy projectiles hit the target, the concentration of point defects increases. However, this cannot be described in the framework of the direct impact Gibbons' model (refer to the data points and the dashed line above the fluence 1×10^{13} ions/cm^2 in