Chapter 7

Summary and Conclusion

A solid bombarded with heavy ions suffers local transport of atoms, which in crystalline materials may induce structural defects and structural transformation. With low energy ions, atomic displacements due to elastic collisions produce a continuous network of displaced atoms (Displacement Cascade). Single ion cascades overlap at higher doses to produce continuous amorphous layers. At higher energies, however, the nuclear collision cross-section becomes insignificant and a major part of energy dissipates in the solid through electronic excitations (ionization). This energy is momentarily stored in the electric field of the ionised target atoms and also as the kinetic energy of scattered electrons. It eventually transfers into the lattice through ionization and thermal spikes respectively. It has been observed that a material becomes sensitive to electronic energy loss if the deposited energy density exceeds a certain threshold. Atomic transport and lattice damage have been observed in various systems (including metals) above such a threshold. Below the threshold, the heat content of the thermal spike diffuse into the surrounding which may cause annealing of the pre-existing disorder.

In semiconductors, the primary interest in conventional surface implants is to alter the electrical properties by impurity substitution. Of late, however, there has been a growing interest in the defect engineered semiconductor devices. By introducing defects in a controlled way, properties of semiconductors can be suitably tailored for a variety of applications like photorefractive waveguides and bandgap tuning in quantum well structures among others. In this context, the significance of high energy ions is their capability of deep implantation in the crystals. While the implant takes place several micrometers below the surface, the near surface region undergoes only structural modifications by the process of energy transfer. Deep implants may also find applications in the form of buried conducting layers, but of paramount importance is the three dimensional defect network, the full potential of which is yet to be investigated and understood.

In this thesis, an attempt has been made to understand the structural disorder in Si and
GaAs semiconductors induced by high energy ions in comparison to the near-surface damage following low energy implants. Irradiation using ions of different energies has been employed to understand the dependence of structural damage and accompanying lattice strains on single ion disorder and total deposited energy density. Using the techniques of X-ray diffraction topography it has been found that the strain fields in the irradiated lattice have a complex depthwise distribution strongly dependent on the nature of single ion disorder, the total deposited energy density and the properties of the target material. The GaAs crystals show sensitivity to electronic excitations above a deposited energy density of 12 MeV/\(\mu\)m, while in the Si crystals no such threshold is encountered. However, some structural changes do take place even below the threshold which enforce a lateral expansion in the irradiated lattice. An important finding is the existence of a strained wall, extending from the surface up to the implanted sheet, termed as the distortion interface. The irradiated lattice undergoes structural modifications causing a large strain gradient at its boundary with the unirradiated lattice. The distortion interface defines this boundary in the bulk of the crystal up to the projected range of ions. Interestingly, below the surface it deviates from the interface between the irradiated and the unirradiated regions. In this work, apart from the study of structural disorder induced by electronic energy loss, we have also examined in detail the strain fields surrounding the implanted sheet following lattice damage by elastic nuclear collisions. In low energy implants the implanted sheet lies on the surface and is free to expand. In high energy implants, on the other hand, it is buried several micrometers below the surface and the structural modifications associated with volumetric changes are restricted. The nature of lattice distortion has indeed been found to depend upon the depth of the sheet below the surface.

In an attempt to generate artificial defect patterns, irradiation was performed through a two dimensional impenetrable grid network. The configuration also mimics the realistic conditions of selected area implantation. A 5 mm circular region of large crystals was exposed to the ions. The ions were made to pass through a thick impenetrable metal grid so that the irradiated disc contained a network of 40 \(\mu\)m wide unirradiated stripes with a relative spacing of 760 \(\mu\)m. Equivalently, the exposed sample region contained 760 \(\times\) 760 \(\mu\)m\(^2\) irradiated blocks separated from the adjacent ones by 40 \(\mu\)m. Si samples were irradiated with three different energy ions. Irradiation with 100 MeV Ti\(^{7+}\) and 200 MeV Ag\(^{14+}\) ions was performed with the 15 UD Pelletron at NSC, Delhi, while conventional surface implant with 200 KeV Ar\(^+\) ions was carried out at SSPL, Delhi. GaAs samples were irradiated only with 200 MeV Ag\(^{14+}\) ions.

The strain fields accompanying irradiation induced structural disorder have been analysed using the techniques of X-ray diffraction topography (XRT). Anisotropic etching, SEM and stylus measurements have been employed to supplement partially the information obtained from topographic analysis. In all the samples a common observation is the expansion of the
irradiated lattice. This indicates disordering of the lattice as Si and GaAs lattices are known to expand with the introduction of defects. Hence, the topographic mapping of strain fields is directly related to the depthwise distribution of structural disorder. Investigation of lattice defects through anisotropic etching is based on the difference in the etch rates of perfect and disordered lattices. This technique has been used to identify the structurally disordered regions in an otherwise perfect crystal. SEM and stylus measurements have been used to investigate respectively the topography of the irradiated surface and the physical lift of the irradiated region in the form of surface steps.

In the high energy irradiated Si crystals the near surface region is found to possess in-plane compressive stress, i.e. it expands laterally against the unirradiated region. Strain within the irradiated region is too small to be detected in the present experimental conditions. However, we have been able to deduce such an expansion from the contrast at the boundary separating the disordered and perfect lattices since XRT is quite sensitive to the strain-gradient developed at the boundary due to such an expansion. The irradiated lattice in high energy implants actually extends to a depth $\sim 20 \mu m$. Thus, the boundary separating the disordered and perfect lattices forms a two dimensional interface extending from the surface to the implanted sheet. For convenience it has been termed as the *distortion interface*. Below the surface, the distortion interface has been found to deviate from the experimentally defined irradiation interface (between the irradiated and unirradiated regions), shifting increasingly into the irradiated part of the crystal. A similar behaviour has also been observed following anisotropic etching where the widths of unirradiated stripes increase with the etch. This indicates an effective neutralization of the lattice disorder at the edges of a distorted sheet when it lies below the surface. This effect can possibly be attributed to the effects of relaxation. On the surface, the distorted lattice is free to expand due to which the stress relaxes. In the low energy implant expansion of surface layers has indeed been observed and the contrast at the boundary attributable to lateral stresses has been found to be insignificant. But in the bulk a distorted lattice is not free to expand and the structural modifications leading to the expansion of lattice are quite restricted. The effect being maximum at the edges, neutralization of the structural disorder is quite possible. However, our understanding in this regard is only qualitative and the problem remains yet to be solved analytically. Moreover, the role of some collective excitations and preferential heat dissipation at the edges through non-local transport of energy cannot be overruled. In some other systems such effects have been found to induce phase transformation [78, 79].

The topographic features have been found to depend strongly on the energy loss profiles. In the Ti$^{7+}$ implant, the electronic energy loss remains constant over the entire irradiated range which gives rise to a sharply defined interface contrast. In the Ag$^{14+}$ implant, on the other hand, energy loss has a negative gradient due to which the contrast is diffused. In terms of the
strain field, the curvature of the lattice planes at the interface is larger in Ti7+ irradiation than in Ag14+ implants.

Particular emphasis has been paid while investigating the strain field around the implanted sheet. Of the entire irradiated region maximum damage has been observed in this sheet which can be attributed to the atomic displacements by elastic collisions. A novel technique has been devised to investigate its depth below the surface. Stationary topographs have been recorded in reflection geometry with a narrow (< 10 μm) incident beam. Since the irradiated surface remains almost perfect, the rays diffracted from the surface suffer primary extinction and emanate from a depth usually less than a micrometer. The rays which propagate through the bulk suffering ordinary absorption are also diffracted if they encounter a distorted lattice. The depth of the distorted lattice has been inferred from the spatial separation between rays diffracted from it and those diffracted from surface.

The strain field structure in the GaAs crystals has been found similar to that in Si. The distortion interface shifts into the irradiated part of crystal and the implanted sheet suffers the maximum lattice damage. However, unlike Si, GaAs has been found to be quite sensitive to the electronic energy loss if the deposited energy density exceeds a threshold of 12 MeV/μm. The threshold has been inferred from the stationary topographs analysed in combination with the TRIM profile. The topographs provide the depth upto which the lattice remains sensitive to electronic energy loss while the TRIM profile gives the corresponding electronic energy loss at that depth. The expansion of the irradiated lattice in this case is easily detected using X-ray topography. In the 10^{13} ions/cm^2 implanted crystals the irradiated region rises ~ 200 Å above the surface.

In a novel experiment of water condensation on the irradiated surfaces of Si, GaAs and CdTe, we observed that the adsorption and wetting properties are affected drastically due to irradiation. Our investigations in this regard are only preliminary and require further experimentation for a complete understanding of the entire process. Such effects can possibly be used to generate surface patterns of different adsorption behaviour.

From the point of view of applications, the use of ion irradiation has ramified over the past few years. Interest has grown in the defect engineered semiconductor devices where high energy ions can play a central role [80, 81]. In this regard, this thesis opens up additional possibilities of generating artificial 3-D defect patterns in semiconductor single crystals. Such defects may find application in electronic as well as optical devices. In the quantum well lasers (GaAs/Ga_{1-x}Al_xAs), for example, the waveguiding mechanism is provided by the stripe-geometry insulating (oxide) film deposited on the surface. A high compressive stress in the oxide film produces a strain field beneath the edges of the stripe window, and a photoelastic waveguide is formed by the small variations in the refractive index resulting from the strain
field. The distortion interfaces formed by ion irradiation actually represent 2-D sheets of large strain field. The refractive index variations in these may open up waveguiding possibilities in 3-D optical devices.

In the course of investigations, some new applications of XRT in the study of extended defects were also observed. In the Ti$^{7+}$ irradiated Si samples, for example, the irradiating ion beam was focussed to a small spot whose intensity decreased gradually at the flanges. In the topograph, the flanges appear in the form of broad side bands. Thus, in a way, the ion beam profile gets imprinted on the single crystals which can be mapped through XRT. Another important finding is the depth analysis using stationary topographs in reflection geometry. Using this, the depth of the implanted sheet can be found non-destructively. In fact, we have also employed this technique to investigate the sensitivity of the materials to electronic energy loss.

In conclusion, we have investigated three problems in this thesis related to the high energy ion irradiations— the distribution of structural disorder in semiconductor single crystals in comparison to the surface damage due to conventional low energy implants, its dependence on the deposited energy density and the depth profiles of the energy losses, and the generation of artificial defect patterns with possible applications in semiconductor devices. However, due to the involved experimental and analysis procedures required, our investigations and understanding are still very limited. Experiments with a range of different energy ions need to be performed to understand a complete dependence of the strain-fields on single ion disorder, total deposited energy density and energy loss profiles. Additionally, more systems have to be investigated to understand its crucial dependence on materials properties. This thesis is only a small effort in this direction.