Chapter 8

Summary and Conclusions

Ion implantation is a widely used technique for doping of semiconductors and has been used to modify the materials or fabricate new materials with desired properties. MeV ion implantation brings in greater flexibility to the technique, and at the same time enhances the operational characteristics of sub-micron device structures. The typical feature of this technology is that a buried layer with a high concentration of dopants can be created in the region several hundred-nanometers beneath the substrate surface. Together with this process, a buried damaged and/or amorphous layer is also formed near the high-concentration region of implanted impurities. Hence, for ion implantation to be a viable candidate for the development in semiconductor technology, it is important to estimate and characterize this implantation induced damage and also to investigate the annealing behavior of the damage and defects formed. With the development of devices with physical dimensions of order of sub-micron or smaller, it is essential to obtain the two- or three-dimensional details of the dopant and damage profiles, so as to avoid interactions between adjacent implanted logic elements in the integrated circuit. Furthermore, the modifications on the surface due to ion implantation can influence the performance of the devices. This necessitates an understanding of the effect of residual lattice damage and amorphicity on the ultimate surface morphology.

In the present thesis, the structural modifications taking place in Si(100) single crystal due to MeV Sb implantation have been presented. It involves the study of
range parameters and lattice location of the implants, implantation-induced damage and their depth profiles and annealing behavior. The influence of defect production due to high energy ion irradiation (HEII) using carbon ions, on the state of a pre-existing amorphous layer, and dopant (Sb) substitution, distribution and diffusion as a function of annealing temperature have been discussed. Results of annealing treatment prior to HEII are also presented. The structural modifications occurring in bulk and at the surface of single crystal of Si(100) due to MeV Sb implantation have also been investigated. Techniques like Rutherford backscattering spectrometry (RBS/C), Raman spectroscopy and Atomic force microscopy (AFM) have been primarily used to characterize the samples.

Antimony (Sb) is a group V element and is usually preferred as a n-type dopant in Si. Although, there are a number of studies involving Sb implantation in Si, all these have been performed using ions in the keV energy regime. There are no reports on the Sb-range parameters, lattice location, diffusion or damage distribution after MeV Sb implantation in Si. This study has been undertaken as a part of the present thesis work. For this we have implanted 1.5 MeV Sb+ ions into a Si(100) crystal at room temperature at a dose of $5 \times 10^{15}$ atoms/cm$^2$. The implantation was carried out in tilted geometry, in order to confine the implanted atoms to a shallower depth, thus preserving the energy deposition character of high energy implant. The implanted sample was analyzed using combined RBS and channeling techniques. From the simulations of the experimental spectra, range parameters, viz., projected range ($R_p$) and range straggling - both longitudinal straggling ($\Delta R_p$) and transverse straggling ($\Delta R_t$), have been determined and compared with the TRIM predictions. The measured values are in good agreement with the results of TRIM calculation. Channeling measurements reveal the formation of a thick amorphous layer ($\sim 745 \text{nm}$) after implantation. On annealing the implanted sample at $600^\circ$C, solid-phase-epitaxial-growth of the Si lattice takes place. On further annealing at $800^\circ$C, the crystallinity of the Si lattice improves giving rise to a minimum yield ($\chi_{min}$) of 9.0%. Compared to this, the minimum yield for Si obtained from the unimplanted region is 3.8%. These results imply that annealing at $800^\circ$C for 30 mins does not result in complete removal of lattice defects produced by implantation. The estimated Sb-substitution fraction
was calculated to be 89%. The spatial distribution of damage in the lattice has been extracted from the RBS/C data using the multiple scattering formalism developed by Feldman and Rodgers. The damage profile from the 600°C sample indicates the presence of excess of damage in the regions $< R_p$, between $R_p - 2R_p$ and at the a/c interface. These can be attributed to the clusters of vacancies (region $< R_p$), interstitials (region $R_p - 2R_p$) and secondary defects formed at the a/c interface. After an 800°C anneal, recombination of vacancies and interstitials takes place giving rise to a surface region with very little damage. However, increase in damage intensity at the a/c interface region indicates that an anneal at 800°C results in the growth in size and number of secondary defects at the end-of-range region.

In order to investigate the effect of high energy ion irradiation (HEII), on the implantation induced damage and the dopant (Sb) behavior, we have irradiated the Sb implanted Si(100) sample with a carbon beam of 8 MeV at a dose of $5 \times 10^{16} \text{ions/cm}^2$ at room temperature. Irradiation alone did not produce any change in the implantation induced damage or amorphisation. However, the V supersaturation created during irradiation stimulates the recrystallization in Si and induces a high dopant substitution on annealing at 400°C. Annealing at 600 and 800°C leads to some precipitate formation of Sb. Inward diffusion of Sb towards the a/c interface is also observed. It is suggested here that the V released during early stages of precipitation are promoting dopant diffusion. We have also studied the effect of low-temperature annealing prior to irradiation (HEII) on the implantation induced damage in Si and the dopant behavior. HEII of the pre-annealed sample at 600°C resulted in an increase in damage at the surface and sub-surface region. The increase in damage could be due to production of Si and Sb recoils. However, a further anneal at 800°C leads to an Sb substitution of 94%. Moreover, the damage profiles indicate large reduction in overall lattice damage. The removal of point defects during pre-annealing maybe suppressing the formation of secondary defects during annealing at 800°C. The excess of vacancies introduced into the system during HEII can also play a crucial role during dopant relocation and damage removal.

In order to investigate the radiation damage and amorphisation process caused by ion-solid interactions and to study the structural modifications that occur in the
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Si lattice with the introduction of dopants, single crystals of Si(100) have been implanted with 1.5 MeV Sb at fluences varying from $1 \times 10^{12}$ to $5 \times 10^{15}$ ions/cm$^2$. RBS/C and Raman spectroscopy have been utilized to evaluate the crystallinity and damage of the Si lattice as a function of dose and annealing temperature. Multiple scattering formalism has been applied to extract the damage distributions in Si(100) from the RBS/C data, as a function of depth for several fluences. Investigations were performed at several annealing temperatures. The results have been compared with the MC simulations performed using SRIM'97. Though the damage peak position of as-implanted sample compares well with the simulation results, it is shallow compared to the peak of Sb ion distribution. Recombination of point defects as well as the role of surface may be significant in surface-region. The total damage accumulated as a function of implantation dose demonstrates two types of behavior. For low doses, a small damage accompanied by a slow damage accumulation rate is observed. This region is characterized by small defects consisting of simple point defects. However, this trend changes and a faster rate of accumulation of damage is observed for fluences higher than $1 \times 10^{13}$ ions/cm$^2$. During this later stage, defect-zones formed previously enlarge in size by accumulation of defects. Studies indicate that Raman spectroscopy is more sensitive than channeling in detecting small volume defects and amorphous zones formed during the early stages of crystalline/amorphous (c/a) transition. Raman spectroscopy indicates the presence of undamaged crystalline zones of nanometer sizes in the Si lattice at a dose of $1 \times 10^{13}$ and $1 \times 10^{14}$ cm$^{-2}$; i.e. regime where undamaged and amorphous regions coexist. Thus implantation can be used to provide nano-structures/crystals of desired dimensions by tuning the dose or energy. The depth dependent measurements of shifts of c-Si peak using Raman spectroscopy show a transition in the nature of stress. The crossover from tensile stress in near implantation depth to compressive stress in surface layers is significant at a fluence of $1 \times 10^{12}$ ions/cm$^2$ which is characterized by a maximum strained lattice. At increased fluences the stress is relieved due to the development of the amorphous areas.

Using a combination of AFM and RBS/C techniques, we have also studied the surface evolution in conjunction with the surface disorder, bulk-lattice damage and amorphicity. The surface roughness due to implantation has a 1:1 correspondence
with the net bulk damage accumulation. The surface displays formation of ellipse-like nano-sized features after a critical dose where the amorphisation in the lattice sets in, i.e. at a dose of $1 \times 10^{13} \text{ions/cm}^2$. The inequivalent surface stress on Si(100) seems to influence the shape of the defect zones. With increase in fluence the size of these defected zones inflate. A shape transformation from ellipsoidal to deformed circular-like structures are observed at a dose when complete amorphisation sets-in. Stress relaxation at this stage can be responsible for the shape transition.
LIFE AT THE ACCELERATOR IS ALL PEANUTS

The experimenter sets up his apparatus.

The experimenter detects the particles and radiation given off.

The Accelerator hurls the projectiles at the chosen target.

SOME CASES ARE RELATIVELY SIMPLE.

Often the experiments must run to the wee hours of the morning.

The data must be analyzed, presented at meetings, and finally written as an article for publication.

There is the satisfaction and joy of making a contribution to mankind's knowledge.

discussed with collaborators.