AN INVESTIGATION OF LIGHT ION IMPLANTATION DAMAGE AND ITS ANNEALING IN P-TYPE SILICON

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A thesis submitted to the

INDIAN INSTITUTE OF TECHNOLOGY, DELHI

for the degree of

DOCTOR OF PHILOSOPHY

1977

ACKNOWLEDGEMENTS

I am deeply indebted to my supervisors, Dr. J. Stephen and Professor A.B. Bhattacharyya, for their keen interest and kind encouragement. I am grateful to Dr. J. Stephen and Dr. B.J. Smith for suggesting the problem and for their advice during the work. Dr. B.J. Smith read the whole manuscript and made valuable comments.

I should like to thank my many colleagues at the Atomic Energy Research Establishment, Harwell and at the Indian Institute of Technology, Delhi for stimulating interaction and technical support.

I am grateful to Mr. K. Kandiah, Drs. A.B. Lidiard, W. Marshall and M.S. Sodha for their kind support to the research programme.

I am grateful to Drs. J.A. Grimshaw, A.H. Harker, C. Ramasastry and A.M. Stoneham for conceptual discussions of various parts of the work; to Drs. K.L. Chopra and G. Dearnaley for helpful comments on the experimental results, to Dr. D.W. Palmer and his 1976 research group for their stimulus and a helpful discussion; to Dr. D.H.J. Totterdell for critical comments and help with the literature survey and to Dr. M.D. Matthews for discussion on and help with calculation of range and damage distributions.

I acknowledge the financial support given to me by A.E.R.E. during my stay at Harwell and the National Science Talent Search scholarship awarded by N.C.E.R.T. (India).

ABSTRACT

The study of damage accompanying ion implantation is of great technological importance. In the present study the damage caused by hydrogen or helium implantation into p-type silicon and its annealing behaviour are investigated. Previous studies similar to the present one concentrated almost entirely on n-type silicon and it appears that the dopant atoms play a determining role in the type of defects formed on implantation in these studies. It is of further interest, therefore, to investigate damage in p-type silicon.

Range distributions of hydrogen and helium ions implanted into silicon are calculated. The calculations reveal errors in some of the previously published results. The distribution of lattice damage created by the incoming ions is also calculated. Theoretical considerations of the macroscopic nature of this damage are made. Semiempirical and theoretical data on specific energy loss of the ions used in these calculations are obtained using the methods available in the literature.

Research in the past fifteen years using EPR and IR spectroscopy and other techniques has yielded a wealth of data on radiation-induced defects. The structure and properties of a number of defects are well understood while there is conflicting data for a few others. A review of the defects which have a bearing on the present work is given.

Capacitance-voltage measurements on n^+ on p mesa diodes in reverse bias have been made in order to study hydrogen and helium ion implantation damage in boron-doped low oxygen content silicon before and after annealing. The implants were made at room temperature in a non-channeling direction at an energy of 400 KeV. The range is such that the damage lies on the p side and one may deplete through the damaged region. Hydrogen was implanted to doses of 5×10^{11}, 1×10^{12} and 5×10^{12} ions/cm^2 and helium to doses of 5×10^{11}

and 5×10^{12} ions/cm^2. Measurements were made at room temperature before and after annealing the specimens in steps of $50^{o}C$ from $50^{o}C$ to $700^{o}C$. A Boonton 75D capacitance-conductance bridge which has a measurement signal frequency of 1 MHz was used for these measurements. The measurements were used to calculate the majority carrier profile in the damaged region.

Some measurements were made at $132^{o}K$. A cryostat in which measurements could be made by probing unbonded mesa diodes was required for this purpose. Existing cryostats were designed for measurements on die bonded and wire-bonded diodes only. These were unsuitable since annealing takes place during the bonding process and interferes with the annealing programme described in the last paragraph. The construction of a suitable cryostat for the present work is described.

If the position of a defect in the crystal lattice is different in two different charge states, alternating between these two charge states would result in the defect taking a random walk through the crystal. This is known as the Bourgoin mechanism. It is shown how a p-n junction may be used to alternate the charge between the two desired states in certain cases and to demonstrate any movement of defects by the Bourgoin mechanism.

The results are interpreted in the light of the calculations and the review mentioned above. This leads to an explanation of various observed effects in terms of specific defects and to a possible model for light ion implantation damage in silicon and its annealing behaviour.

The hydrogen ion-damaged samples show a majority carrier removal in the region of damage. Various possible causes for this effect are examined and capture of majority carriers in states at the edges of interstitial clusters appears to be the most likely cause. The clusters could be formed by freely migrating interstitials created during implantation. After annealing at $100^{o}C$ this effect begins to anneal out and a peak associated with a deep acceptor level appears in the carrier profile. This peak is seen to anneal in the range 250 - 350°C. This annealing behaviour suggests that the defect responsible may be the divacancy. The energy level of the deep acceptors is estimated from the displacement of the above peak from the true position of damage and found to be E_c - 0.6 eV. This agrees with the known divancy acceptor level at E_c - 0.54 eV within the errors of the method. The absence of the effect, in the profile measured at room temperature, of the known donor level of the divacancy is explained by the fact that the Fermi level for the present doping concentration would be above this level.

In order to examine the last suggestion further, the samples were cooled down to 132°K. At this reduced temperature, the Fermi level would have fallen below the divacancy donor level and on measuring the profiles at this reduced temperature its effect should be seen. It is predicted that the effect at this reduced temperature will depend on the direction of bias scan during measurement. On measurement it is found that when the reverse bias is monotonically increased from zero to each measurement value before taking the reading, the result is a profile with a dip which is truly representative of the effect of donors in decreasing hole concentration. On the other hand making measurements as the reverse bias is reduced gives rise to an anomalous peak in the profile just further from the surface than the dip. These effects are completely explained in terms of the emission or capture of holes at the donor level during the two different experiments.

The changes on annealing to 100°C mentioned above are possibly due to the beak up of electrically inactive vacancy clusters on annealing. The clusters would be formed by the agglomeration of vacancies created by the incoming ions. On annealing the released vacancies would diminish the size of interstitial clusters and, also, devacancies would form.

The growth of a defect having an acceptor level less deep than the one mentioned above accompanies the decay of the divacancy peak in the range 250 - 350^{o}C. Annealing above 350^{o}C gives rise to decay of this defect and formation of shallow acceptor levels. Possible causes for these effects are discussed. By about 650^{o}C all radiation effects anneal out and the profile is restored to the flat, pre-implanting shape. The dose dependence of the above effects is also discussed.

Conclusions are also drawn about the nature of the electronic levels of defects responsible for the various annealing stages that were observed in helium ion-damaged silicon. There are significant differences between the results for hydrogen and helium ion-damage and the possible reasons for these differences are discussed.

LIST OF PRINCIPLE SYMBOLS

A	Diode junction area.
A_1	Incident ion atomic weight.
A_2	Target atomic weight.
C	High frequency junction capacitance.
c_n	Capture constant for electrons at defect level.
c_p	Capture constant for holes at defect level.
$d\sigma_n$	Differential elastic scattering cross section for energy transfer T_n.
D	Depth from target surface.
Δ	Distance moved by defect in one step when migrating by the Bourgoin mechanism.
e_n	Emission rate of electrons from defect level.
e_p	Emission rate of holes from defect level.
E	Ion energy.
E_c	Conduction band edge.
E_d	Displacement energy for atom at lattice site.
E_f	Fermi level.
E_g	Band gap.
E_i	Intrinsic Fermi level.
E_p	Energy level of the p-type dopant.
E_t	Defect energy level.
E_v	Valence band edge.
ε	Dielectric constant.
ε_0	Permittivity of free space.
f	Frequency.
$\hbar$	Planck's constant divided by 2π.
I	Average excitation energy of electrons in the target.
k	Boltzman constant.
L_D	Debye length.

m	Electronic mass.
M_H	Mass of hydrogen atom.
M_{Si}	Mass of silicon atom.
n_i	Intrinsic carrier concentration at temperature T.
p_p	Hole concentration in p-type semiconductor.
q	Electronic charge.
r	Distance along ion path.
S	Atomic Density.
T	Temperature (^{o}K)
T_m	Maximum possible value of T_n.
T_n	Energy transfer in ion-target atom collision.
v	Ion velocity
V	Reverse bias voltage applied to junction.
Z_1	Incident ion atomic number.
Z_2	Target atomic number.

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