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RADIATION DAMAGE AND ANNEALING EFFECTS STUDIES OF SILICON-IMPLA--ETC(U)
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Radiation damage and low temperature (200°-600°C) annealing behavior of 120 keV silicon and selenium ion implants into gallium arsenide have been investigated by Rutherford Backscattering-Channeling and Transmission Electron Microscopy techniques. Lattice location studies of Si implants after high temperature annealing (850° and 950°C) have been conducted using Proton Induced X-Ray Emission method.

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RADIATION DAMAGE AND ANNEALING EFFECTS STUDIES OF SILICON-IMPLANTED GALLIUM ARSENIDE

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RADIATION DAMAGE AND ANNELING EFFECTS STUDIES OF SILICON-IMPLANTED GALLIUM ARSENIDE

by

Samuel C. Ling

ABSTRACT

The lattice damage in GaAs due to ion implantation of Si ions is analyzed by the techniques of Rutherford Backscattering-Chaneling (RBS-C), Particle-Induced x-Ray Emission (PIXE), and Transmission Electron Microscopy (TEM). The RBS-C and PIXE data are obtained by using a 350 keV proton beam, and the TEM studies are performed by a Hitachi H-600 machine operated at 100 kV.

The annealing behavior of GaAs layers implanted at room temperature by 120 keV Si ions to the doses of 5E13 - 3E15 per square cm is investigated in the temperature range of 200 - 600 C using the capless, proximity annealing procedure. Preliminary results indicate that the solid phase epitaxial regrowth process of the damage layers is very complicated depending on the implant dosage as well as the annealing history.

Residual damage and location of implanted Si atoms in Cr-doped GaAs with multiple implant energies (50 - 400 keV) are also studied. The samples are annealed at 850 and 950 C

with silicon nitride encapsulation. Results show that at 950 C, most of the damage is removed and that the Si atoms are 75% substitutional.

Due to the fact that Si-implanted samples were not available until the beginning of September, 1981 whereas the bulk of the research time of the principal investigator for this research project was spent in July and August, 1981, the data analysis of the low temperature anneal of Si-implanted GaAs is still proceeding as part of a student thesis for master degree in physics. Upon the completion of this thesis, it will be appended to this report.

During the summer of 1981, the principal investigator collaborated with other scientists at the Electronic Research Branch, AFAL/AFWAL, on the study of low temperature annealing of Selenium-implanted GaAs. Extensive work on this subject has led to much better understanding of the solid phase epitexial regrowth of damage layers due to ion implantation, and two published papers plus another paper submitted to scientific journal for publication. These papers are included in this report.

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He thanks, also, his many scientific collabortors: Drs. R. S. Bhattacharya, P. P. Pronko, and A. K. Rai of Universal Energy Systems, Inc.; Dr. S. R. Wilson of Motorola, Inc.; Dr. J. Narayan of Oak Ridge National Laboratory; and S. Babkair, master degree student in Physics at Wright State University. Preparation of Si-implanted samples by J. Ehret, AADR/Avionics laboratory, AFWAL; and technical assistance provided by D. Hurley and A. Smith, Universal Energy Systems, Inc., are greatly appreciated.

I. Introduction

Because of its ability to control dose level and profile of implants, ion implantation has been used widely as a means of doping to produced useful semiconductor devices. However, in order to obtain good elecrical performance, the radiation damage to the crystal lattice must be removed. In the case of GaAs, currently being developed as microwave devices, the usual anneling procedure at high temperature for damage removal is complicated by the requirement of suitable prior encapsulation to prevent the out-diffusion of As atoms from the surface. The main purpose of this project is to study the damage caused by Si implantation into GaAs and its subsequent annealing behavior at low temperature without encapsulation.

Various analytical techniques are used in this project: Rutherford Backscattering-channeling (RBS-C) and Transmission Electron Microscopy (TEM) for damage study, and Particle-Induced X-Ray Emission (PIXE) for lattice location of implanted atoms. A beam of 330 keV protons from the 400-keV van de Graaff accelerator is used for the RBS-C and PIXE studies, and the TEM work is done on a Hitachi H-600 machine operated at 100 kV.

While waiting for Si-implanted samples to be made available, the principal investigator of this project spent the bulk of his alloted research time including the months of July and August of 1981 collaborating with other scientists at the project research location in a related study of low temperature annealing of Selenium-implanted GaAs. When the Si-implanted samples were obtained in the beginning of September 1981, the study of the low temperature annealing behavior was initiated and carried on, in part, as a thesis project for a master degree canditdate in physics at the Wright State University. All the RBS-C data for this study have been collected, but the analysis is not yet complete. In addition, the principal investigator participated in a collaborated study of high temperature annealing behavior of Si-implanted GaAs sample and the lattice location of the Si implants.

Thus, this report will consist of detail analysis of the low temperature anneling behavior of Se-implanted GaAs; preliminary results of the low temperature annealing behavior of Si-implanted GaAs; and the summary results of the study of high temperature annealing behavior and lattice location of the implanted atoms of one Si-implanted GaAs sample.

II. Low Temperature Annealing of Se-Implanted GaAs

High depth resolution RBS-C analysis are carried out on Cr-doped and high purity semi-insulating GaAs of (100) orientation implanted at room temperature and liquid nitrogen temperature with 120 keV Se ions. The dosage of the implants varies from 1E13 to 1E15 per square cm. RBS-C with 330 keV protons along <110> direction is used to determine the damage after implantation as well as the annealing behavior of the samples. Both isothermal and isochronal annealing are done from 200 C to 600 C employing the capless, proximity process.

Two distinct annealing stages are observed: first one at 250 C and the other between 400 C to 500 C. TEM studies indicate that the former is associated with amorphous zone annihilation and/or onset of solid phase epitaxial growth, and the latter can be related to dissociation of microtwins. With 600 C annealing, all samples show good recovery of crystalline order; although, for samples with implant dose level beyond 1E14 per square cm, there are higher residual damages than the virgin crystal. TEM analysis shows that these are primarily dislocation loops and precipitates, The calculated number of atoms associated with the precipitates has been found to correspond closely with the number of implanted atoms. This implication of 100% precipitation of implanted Se ions could explain why

Se-Implanted GaAs shows no electrical activation after low temperature anneal (at about 600 C) despite good recovery of crystalline order as evidenced by RBS-C data. Furthermore, these results are obtained on both Cr-doped and high purity samples, thus, eliminating the speculation about involvement of Cr in the nucleation of microtwins.

Detailed study of the level of residual damage after annealing at 400 C, indicates that it increases sharply at a dose just above that required to amorphize the surface layer and, then, reaches a saturation level. Once the saturation level is reached, the level of residual damage depends almost linearly on the thickness of the amorphous layer, confirming results of similar studies of implantation into GaAs with other ion species and implant energies.

Complete ananysis of these results and the discussion of various mechanism that could be responsible for the formation of twins in low temperature annealed GaAs are presented in two published papers and one mauscript submitted for publication. These are included in the Appendix Section of this report:

Appendix A -- "Low Temperature Annealing Behavior of Se-Implanted GaAs Studied by High Resolution RBS-Channeling", by R. S. Bhattacharya, P. P. Pronko, and S. C. Ling, J. Appl. Phys. 53, 1803 (1982).

Appendix B -- "dose Dependence of Epitaxial Regrowth of Se-Implanted GaAs", by R. S Bhattacharya, P. P. Pronko, S. C. Ling, and S. R. Wilson, Appl. Phys. Lett. 40, 502 (1982).

Appendix C -- "Damage Annealing Behavior of Se-Implanted GaAs", by R. S. Bhattacharya, A. K. Rai, P. P. Pronko, J. Narayan, S. C, Ling, and S. R. Wilson, submitted to Journal of Physics and Chemistry of Solids for publication.

III. Low Temperature Annealing of Si-Implanted GaAs

120 keV Si ions are implanted into GaAs of (100) orientation at room temperature. Six implant doses are used: 3E13, 5E13, 1E14, 5E14, 1E15, and 3E15 per square cm. Similar procedures of RBS-C and TEM analysis are employed. Prelimary results show that the damage caused by 120 keV Si implants in GaAs is quite different than by Se implants of the same energy. Whereas the threshold dose for amorphization is much higher for Si than for Se (5E14 vs 5E13 per square cm), the thickness of the damage layers due to Si implants is about double that due to Se implants of the same dose. Below the threshold dose, Si implants do not seem to cause much damage. Fig. 1 shows that RBS-C spectrum in <110> and (110) directions for the dose of 1E14 per square cm. The minium yield behind the damage peak of the as-implanted sample is only 0.08 as compared to the value of about 0.03 for virgin crystal. Isochronal annealing of the sample from 200 C to 600 C reduces the minimum yield to a level very close to that of the virgin crystal.

On the other hand, above the threshold dose, isochronal annealing behavior of Si-implanted GaAs is quite different than the case with Se implants. Fig. 2 illustrates the isochronal annealing results of a sample implanted with a dose of 1E15 per square cm. As can be seen, even after 30-minute annealing at 600 C, extensive damage still remains.

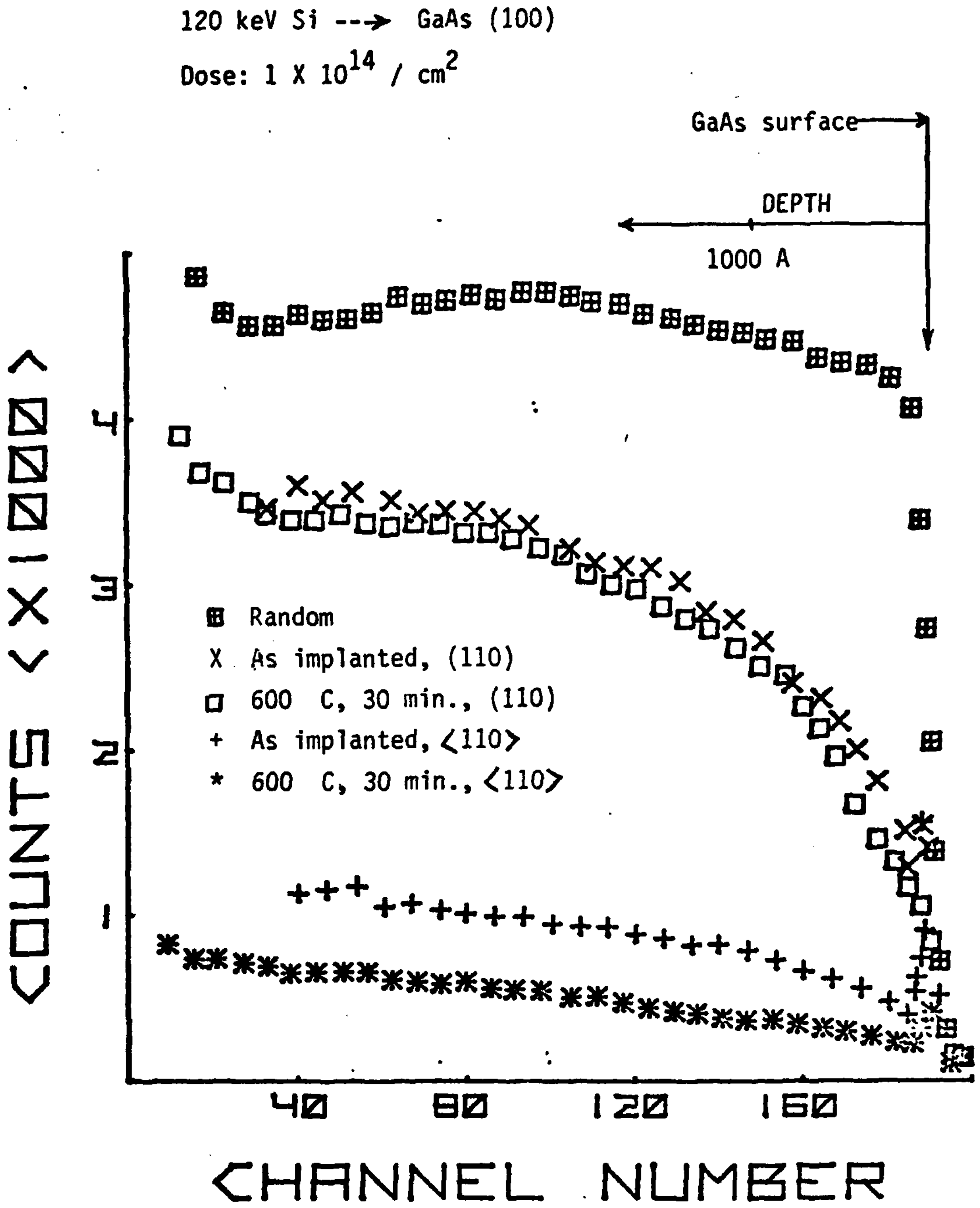

Fig. 1 ⟨100⟩ axial and (110) planar channeling spectra of a GaAs sample implanted with 120 keV Si at a dose of $1X10^{14}/cm^2$. The annealing is done sequentially on the same sample with the following steps (temperature in C and time in minutes): 200,10; 200,20; 250,30; 250,30; 300,30; 350,30; 450,30; 550,30; 600,30. As the damage is slight, only the results after the final step is shown.

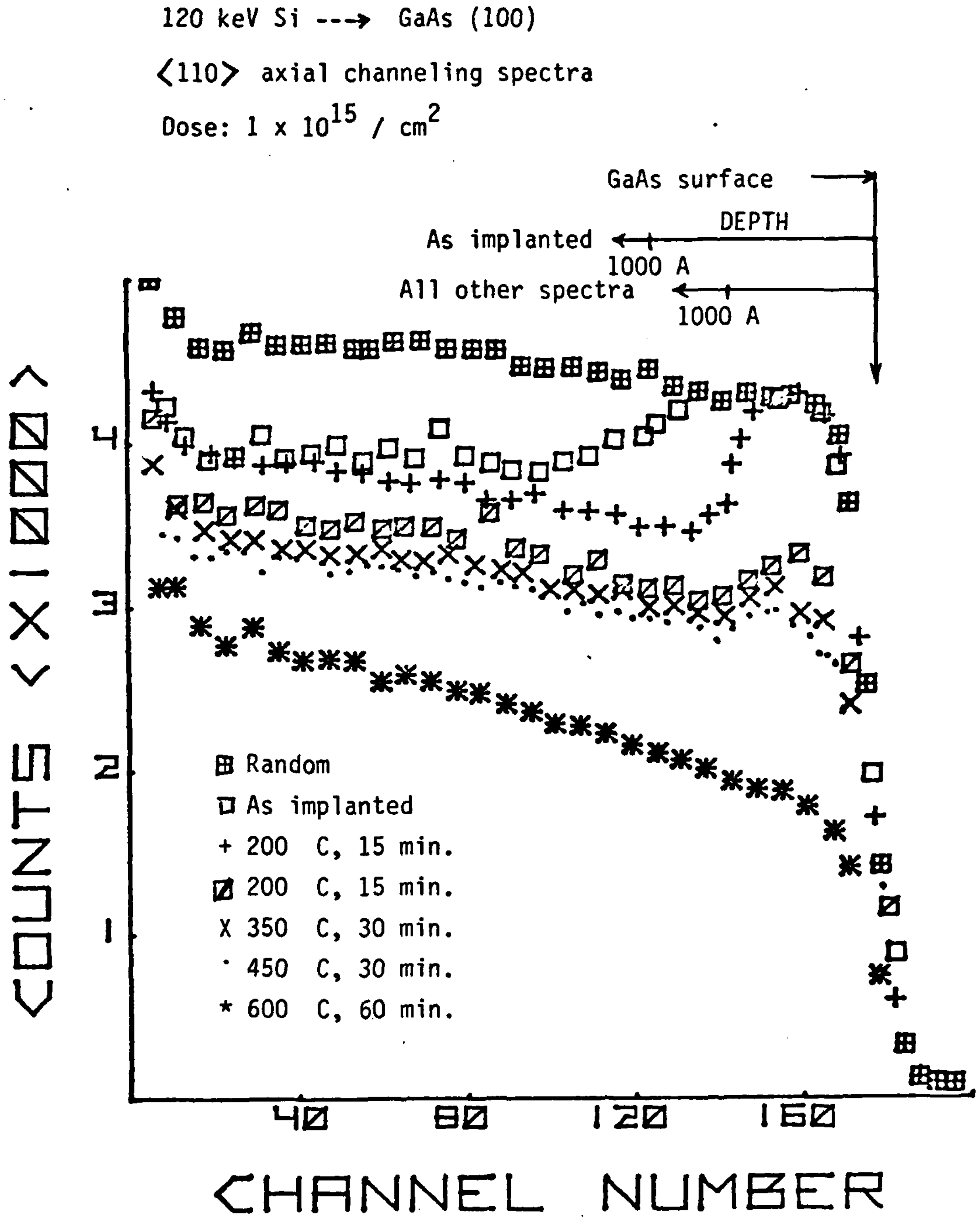

Fig. 2 ⟨110⟩ axial channeling spectra showing isochronal annealing of GaAs (100) sample implanted with 120 keV Si ions at a dose of $1 \times 10^{15}/\text{cm}^2$. The annealing is done sequentially on the same sample with the following steps (temperature in C, time in minutes): 200,15; 200,15; 200,30; 250,30; 350,30; 400,30; 450,30; 550,30; 600,30; 600,60.

TEM results reveal some very large twin structure extending to thousands of angstroms, much larger than the damage thickness or the range of the implants. However, one-step annealing of 30 min. at 600 C of a sample subjected to the same dose results in considerably less residual damage. Detail analysis on the collected RBS-C data and TEM analysis are still in progress.

In view of the qualitatively different results of Se and Si implants on GaAs, it would be interesting to study S implants, which have atomic masses close to Si, and Si implants with less energy so that they would have approximately the same range in GaAs as that of the Se implants we have studied.

IV. High Temperature Annealing and Lattice Location Study of Si-implanted GaAs

RBS-C, TEM, and PIXE techniques are used to study residual damage and location of implanted Si atoms in the Si-implanted Cr-doped GaAs. The purpose of this study is to investigate the reason why, in contrast to the case of low dose implants, the electrical activation for high dose (>1E15 per square cm) Si-implanted GaAs is very poor even after high temperature annealing which should result in good recovery of crystalline order.

Multiple energies (50-400 keV) and doses totaling 5E15 per square cm of Si were implanted in the same sample in order to achieve a flat concentration profile. High depth resolution channeling spectra in the <110> direction reveal that the sample has recovered completely its crystallinity up to about 1300 angstroms from the surface after annealing at 850 C. Yet, a disordered region remains between 1300 - 3760 angstroms. Further annealing at 950 C removes most of this damage. After 850 C annealing, angular scans across <110> and <100> directions show 65% attenuation of Si K-x-ray and a dip curve with narrower width as compared to the K x-rays from the host lattice. The attenuation is 75% after 950 C annealing with the width the same as that of the host lattice.

While RBS-C results points to good recovery of crystallinity and PIXE indicates substantial substitutionality of the implanted Si ions, TEM reveals no precipitates. The combination of these data tend to rule out extensive damage to the crystal, or precipitation and nonsubstitutionality of Si implants as the main reasons for poor electrical activation of Si-implanted GaAs. They are in agreement with the suggestion by Masuyama et.al. that Si implants may occupy neighboring Ga and As sites forming neutral pairs. (A. Masuyama, M. A. Nicolet, I. Golecki, J. L. Tandon, D. K. Sadana, and J. Washburn, Appl. Phys. Lett. 36, 749 (1980)).

These results have been reported at the Dallas Meeting of the American Physical Society, 8-12 March 1982. An abstract sent to the meeting is included in this report as Appendix D.