CONF-8211109--51

LBL-15489

Lawrence Berkeley Laboratory

UNIVERSITY OF CALIFORNIA

Materials & Molecular Research Division

Presented at the Materials Research Society
Conference on Defects in Semiconductors
Boston, MA, November 1-4, 1982

DAMAGE AND IN-SITU ANNEALING DURING ION IMPLANTATION

D.K. Sadana, J. Washburn, P.F. Byrne,
and N.W. Cheung

November 1982

DISCLAIMER

This report was prepared as an account of work sponsored by an agency of the United States Government. Neither the United States Government nor any agency thereof, nor any of their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof.

LEGAL NOTICE

This book was prepared as an account of work sponsored by an agency of the United States Government. Neither the United States Government nor any agency thereof, nor any of their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise, does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof.

Lawrence Berkeley Laboratory is an equal opportunity employer.

NOTICE

PORTIONS OF THIS REPORT ARE ILLEGIBLE. It has been reproduced from the best available copy to permit the broadest possible availability.

DAMAGE AND IN-SITU ANNEALING DURING ION IMPLANTATION

LBL--15489

DE83 008394

D. K. SADANA AND J. WASHBURN
Lawrence Berkeley Laboratory and
Department of Materials Science and
Mineral Engineering,
University of California, Berkeley, CA 94720

P. F. BYRNE AND N. W. CHEUNG
Department of Electrical Engineering and
Computer Sciences,
University of California, Berkeley, CA 94720

ABSTRACT

Formation of amorphous (α) layers in Si during ion implantation in the energy range 100 KeV-11 MeV and temperature range liquid nitrogen (LN)-100°C has been investigated. Cross-sectional transmission electron microscopy (XTEM) shows that buried amorphous layers can be created for both room temperature (RT) and LN temperature implants, with a wider 100 percent amorphous region for the LN cooled case. The relative narrowing of the α layer during RT implantation is attributed to in situ annealing. Implantation to the same fluence at temperatures above 100°C does not produce α layers. To further investigate in situ annealing effects, specimens already containing buried α layers were further irradiated with ion beams in the temperature range RT-400°C. It was found that isolated small α zones ($\leq$ 50 Å diameter) embedded in the crystalline matrix near the two α/c interfaces dissolved into the crystal but the thickness of the 100 percent α layer was not appreciably affected by further implantation at 200°C. A model for in situ annealing during implantation is presented.

INTRODUCTION

Although doping of semiconductors by ion implantation has been utilized extensively over the last two decades, the damage structures created during

DISTRIBUTION OF THIS DOCUMENT IS UNLIMITED

the implantation and annealing are not yet fully characterized. Neither are the mechanisms by which crystalline (c) materials transform into the amorphous (α) state by radiation damage understood. For most ion implants, the dose routinely used by device manufacturing industry is sufficient to form a continuous α layer in silicon if the implant temperature is at room temperature (RT) or below. However, non-uniform heating due to poor thermal contact of the wafer to the substrate holder has been shown to cause unanticipated defect distributions in the implanted region [1]. In this paper the effect of wafer heating on the formation and regrowth of amorphous layers and in situ annealing of amorphous regions by the ion beams has been investigated.

The experiments for this work were designed such that controlled heating of wafers occurred during implantation. The mechanisms of in situ annealing suggested by Washburn et al. [2] have been further classified. Two step implantations were also performed to investigate in-situ annealing effects. For example, some wafers were first implanted at LN temperature followed by another implantation at high temperature. Ion beam induced annealing studies have been reported earlier in the literature, but the emphasis was on the annealing of already existing amorphous layers [3]. No serious attempt was made to understand the in situ annealing effects during implantation.

High energy (MeVs) ion implantations have also been carried out here to investigate the electronic contribution on the formation of amorphous layers and accompanying in situ annealing.

EXPERIMENTAL

(100) and (111) oriented Si wafers were implanted with P, Si or As at 120, 700 or 11000 keV in the temperature range LN-100°C. The doses used in the three cases were 3×10^{14}, 5×10^{14} and 1.9×10^{15} cm^{-2}, respectively.

Details of 11000 keV As implantations have been described elsewhere [4]. Some of the wafers implanted at LN with P and Si were subsequently implanted in the temperature range RT-400°C. Cross-sectional transmission electron microscopy (XTEM) was utilized to obtain the widths of damage regions and study the in situ annealing effects.

RESULTS

Figure 1 illustrates the effect of implantation temperature on the formation of an amorphous layer in (111) Si. Phosphorus ions of 120 keV energy were implanted at LN, RT and 100°C, respectively, to a dose of 3×10^{14} cm^{-2} in each case. The dark bands (Figs. 1a and 1b) that represent α or heavily damaged regions appeared in LN and RT implanted cases while no such band was present for 100°C implant. It is well known that solid phase regrowth of implantation induced α Si does not occur until temperatures $\geq$ 500°C are reached. However, in Fig. 1c, a substrate temperature of only 100°C was enough for annealing out of any small α zones that were created during the implantation. This radiation assisted annealing has been referred to as in situ annealing earlier in the text.

Figure 2 shows a series of micrographs corresponding to two step implantations. The reference sample (Fig. 2a, first step implantation) is the same as shown in Fig. 1a. The LN implanted reference samples were subsequently further implanted with equal doses ($3 \times 10^{14} cm^{-2}$) of P at RT, 100, 200 and 400°C, respectively. Figure 2b shows that additional RT implantation produced more damage as is evident from the width of the α layer from LN+RT sample is 2100 Å as compared with 1425 Å of the reference sample. However, LN + 100°C and LN + 200°C implantations produced α layers of widths 1650 and 1380 Å (Fig. 2c and 2d), respectively. Also the upper and lower α/c interfaces became

much more sharply defined in the LN+200°C case (Fig. 2d). The α layer did not completely recrystallize even when the second implantation was carried out at 400°C (Fig. 2e).

In situ annealing was also sutided in (100) Si using the two step implantation procedure. (100) Si samples were self implanted at 700 keV to a dose of $5x10^{14}cm^{-2}$ at LN followed by further implantations of equal doses ($5x10^{14}cm^{-2}$) at elevated temperatures (RT-200°C). The results from these samples were qualitatively similar to those discussed above in that the initial damage structure did contain a buried α layer, the small α zones in crystalline matrix near that α/c interface dissolved and the width of the α layer remained almost unchanged after subsequent implantation at 200°C.

Figure 3 shows the XTEM micrographs from (100) Si implanted with As at LN and RT, respectively, to a dose of $1.9x10^{15}cm^{-2}$. Buried α layers were created in both cases with mean widths of 3.5 μm and 1.5 μm, respectively (Fig. 3a and 3b). A large reduction in the width of the RT implanted sample occurred which was strikingly different from the low energy implantation results (Figs. 1a and 1b). Rapid recrystallization of α zones in crystalline matrix near the α/c interfaces and slow regorwth of 100 percent α layer was also observed when a 1.2 MeV electron beam was placed near the two interfaces.

DISCUSSION

From the results of Figs. 1, 2 and 3 it is clear that the formation of α layers is inhibited drastically when the implantation temperature is increased. However, once an α layer is formed, its regrowth during further ion damage even at high temperature is not significant. The following correlates the experimental observations made so far.

Each ion during implantation is expected to create a damage cascade containing interstitials and vacancies along its track in the crystalline (c) matrix. Small α zones are eventually formed either directly near the end of a heavy ion track or by nucleation within heavily damaged regions [5]. The boundaries between the α zones and surrounding crystal have been found to be sharp within two to three atomic distances [3]. The position of the boundary of the α zone therefore probably corresponds to the surface inside of which the critical concentration of point defects necessary for damaged crystal to transform into an amorphous state has been exceeded. If point defects are mobile, a small α zone surrounded by crystal is inherently unstable. At LN temperature or below where the mobility of the point defects created by energetic ions is limited, a buried α layer will be created when the dose is such that the α zones overlap either due to continuous formation of new α zones or due to their growth as perhaps the point defects concentrations in remaining crystalline volumes exceed the critical level of 10-15 percent necessary for c ⟶ α transformation [6]. This mechanism is believed to account for the α layer of Fig. 1a. In Fig. 1b intense interpenetratin of α and c regions occurs near the two α/c interfaces indicating that elimination of the interpenetrating crystalline volumes becomes more difficult.

In the case of high energy As implantation broad regions of interpenetration occurred at the upper α/c interface even for LN implants. This can be understood from the energy deposition vs depth curve which shows only a slow rise in the amount of energy deposited from the surface to 2.5 μm (Fig. 3). The α/c interface was located in the center of this slow rising region. Furthermore, at 11 MeV, electronic stopping may also contribute to in situ annealing by excitation of atoms at the α/c interface near to the surface.

Small α zones in crystalline matrix should be metastable so long as the point defect concentration in the surrounding crystal stays below the critical level (10-15 percent) of c ⟶ α transformation. Furthermore, α/c interfacial energy favors a reduction in the size of the α zone. Therefore, α zones should tend to shrink by a net transfer of atoms across the interface from the α side to the crystalline side. Concomitant with the formation of amorphous zones, however, interstitials and vacancies will be continuously created in the crystalline material. All the previously formed α-c interfaces should act as sinks for these defects because they are mobile at room temperature. Their recombination at the interface and other radiation induced transfers of energy to atoms at the interface could provide the necessary activation energy for continuous shrinkage of all existing amorphous zones. It has been shown that MeV electron irradiation at slightly above RT causes regrowth of α zones.[7,11]

In the case of the 100°C implantation, it is believed that the point defect concentration never exceeded the critical 10-15 percent and the α zones that may have been formed directly at the end of the ion tracks shrank and disappeared faster than new ones were being formed due to high mobility of the surrounding point defects. As a result, an α layer was never formed.

The results of two step implantation can also be explained by the above model. The regions above and below the α/c interfaces where α and c zones co-existed initially were strongly affected by the second higher temperature implant. For the 200°C second implant small α zones surrounded by crystal shrank and disappeared leaving sharper α/c interfaces. There was therefore some shrinkage of the previously formed amorphous volume. However, the width of the fully amorphous layer remained almost unchanged. A minimum rate of migration of the α/c interface sufficient to eliminate small α zones of the

order of 50 Å in diameter within the time of the second irradiation would cause only an insignificant reduction in thickness of the 100 percent amorphous layer.

CONCLUSIONS

In conclusion, the details of the formation of an amorphous layer are sensitively dependent on implantation temperature. It is suggested that this happens because small amorphous zones surrounded by crystalline matrix can undergo radiation induced shrinkage at temperatures $\geq$ 100°C where elementary point defects are mobile. At very high implant energies, electronic stopping may also contribute to in situ annealing by excitation of atoms at α/c interfaces.

ACKNOWLEDGEMENTS

The authors would like to thank the Heavy Ion Linear Accelerator staff of Lawrence Berkeley Laboratory for 11 MeV As implantations and Ilka Suni of Caltech, Pasadena, CA, for 700 keV Si implantation. One of us (DKS) would also like to acknowledge useful discussions with Simon Prussin of TRW, Lawndale, CA. This work was supported by the Director, Office of Energy Research, Office of Basic Energy Sciences, Material Science Division of the U.S. Department of Energy under Contract No. DE-AC03-76SF00098.

REFERENCES

1. D. K. Sadana, M. Strathman, J. Washburn and G. R. Booker, J. Appl. Phys. 51 5718 (1980).

2. J. Washburn, C. S. Murty, D. Sadana, P. Byrne, R. Gronsky, N. Cheung and R. Kilaas, Nucl. Inst. Meths. (in press).

3. I. Golecki, G. E. Chapman, S. S. Lau, B. Y. Tsaur and J. W. Mayer, Phys. Lett. 71A 267 (1979).

4. P. F. Byrne, N. W. Cheung and D. K. Sadana, App. Phys. Lett. 41 537 (1982).

5. F. F. Morehead Jr. and B. L. Crowder, Rad. Eff. 6 27 (1970).

6. L. A. Christel, J. F. Gibbons and T. W. Sigmon, J. App. Phys. 52 7143 (1981).

FIGURE LEGENDS

Fig. 1. The effect of implantation temperature on the formation of an amorphous layer in P implanted (111) Si. Dose: 3×10^{14} cm^{-2}; Energy: 120 keV; Implantation Temperature: a) LN, b) RT and c) 100°C.

Fig. 2. Further implantation of the sample of Fig. 1a at higher temperature: a) LN only, b) LN+RT, c) LN+100°C, d) LN+200°C and e) LN+400°C. Additional dose: $3\times10^{14}cm^{-2}$; Energy: 120 keV.

Fig. 3. Comparison of XTEM measured α-c interface depths with calculated displacement energy absorption vs. depth at LN and RT.

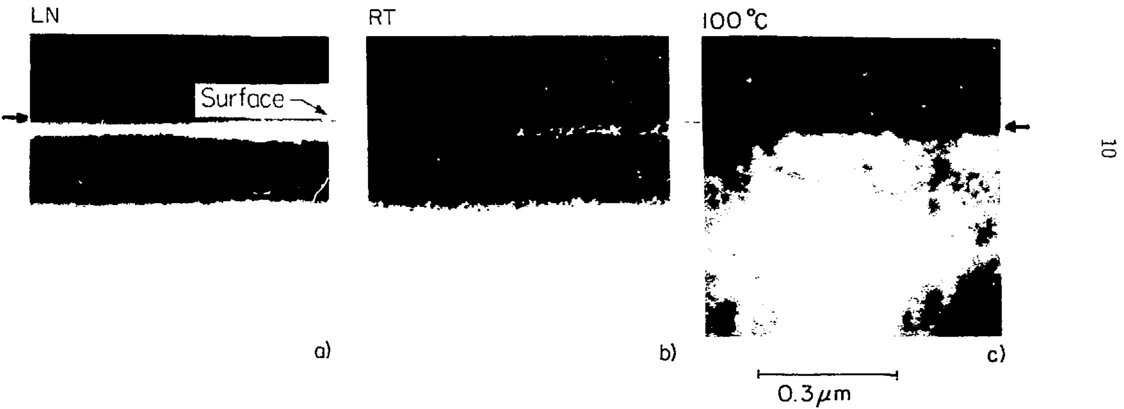

Fig. 1

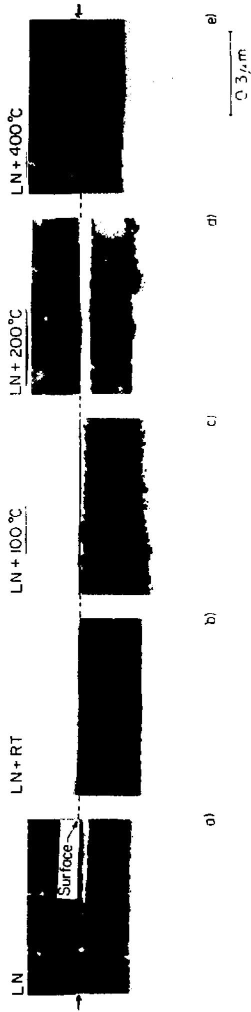

Fig. 2

XBB 820-9450A

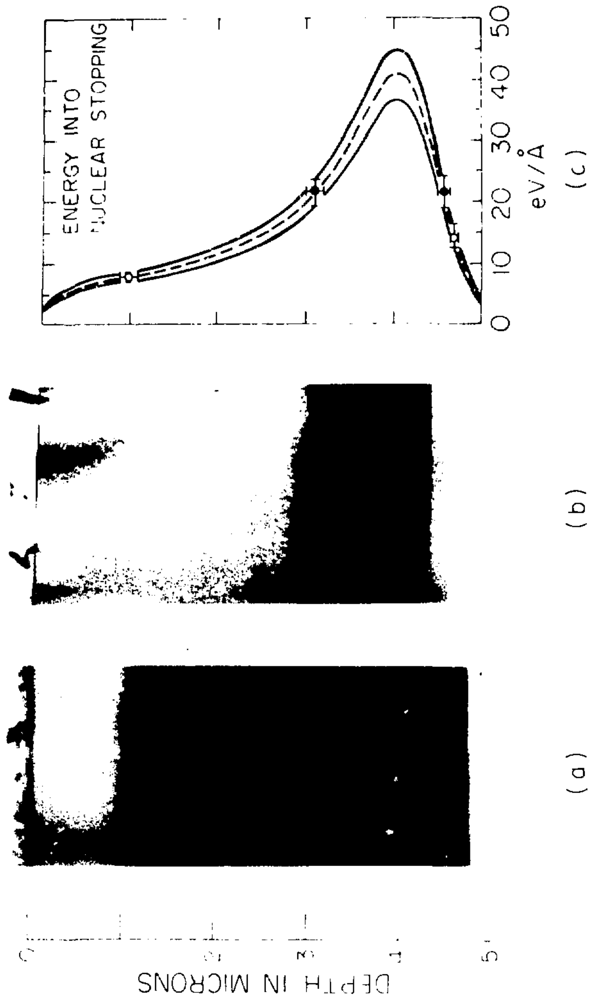

Fig. 3