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MELTING BY PULSED LASER IRRADIATION*

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The phenomenon of melting produced by pulsed ruby-laser ($\lambda = 0.694\mu\text{m}$) irradiation has been investigated. Removal of dopant precipitates, dislocations, and loops during laser irradiation provides clear evidence of melting. The depth of melting can be determined as a function of laser parameters (energy density and pulse duration) from the thickness of defect-free regions and lengths of reoriented dislocation segments.

I. INTRODUCTION

High power laser pulses have been successfully used to anneal displacement damage in ion-implanted semiconductors (1), transform amorphous into single crystalline layers (2-3), diffuse dopants into semiconductors deposited with thin layers of dopants (4), and to investigate growth of dislocations during laser annealing (5). These effects have been interpreted on the basis of a melting model. It has been suggested as an alternate possibility that annealing is achieved in the presence of an electron-hole plasma while the lattice remains close to ambient temperature (6). The purpose of this paper is to discuss microstructural evidence which clearly suggests that the laser pulses in this regime cause melting. In addition, two techniques to measure the melt depth are described.

II. EXPERIMENTAL

Silicon single-crystal wafers (5-8 $\Omega\text{-cm}$), 0.5 mm thick, with (100) and (111) surfaces were used in this investigation. To produce precipitates and/or dislocation loops, diffusion (at 1100°C) of boron or phosphorous was carried out using B_2O_3 or PH_3 sources in an argon atmosphere, followed by slow cooling. Dislocations were generated by ion implantation

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followed by thermal annealing. For laser annealing, the Q-switched output of a ruby laser (20×10^{-9} sec pulse duration time) was used with energy densities ranging from 1 to 3 J cm^{-2} .

III. RESULTS AND DISCUSSION

Fig. 1 shows results of laser annealing a phosphorous-diffused specimen. One pulse of energy density 2.0 J cm^{-2} produced an annealed, defect-free region $\sim 0.57 \mu\text{m}$ deep containing no phosphorous precipitates or loops (7). Phosphorous, originally associated with the precipitates, was dissolved as a result of the laser pulse and incorporated into solid solution. Electrical measurements on companion samples indicated an increase in carrier concentration equal to the number of phosphorous atoms in the precipitates. Depth of the annealed region was measured by stereomicroscopy and could also be estimated directly from the number of thickness fringes because the sample near the edge was wedge-shaped. When the pulse energy density was increased from 2.0 to 3.0 J cm^{-2} , the depth of the annealed region increased from $0.57 \mu\text{m}$ to $0.95 \mu\text{m}$, (Fig. 1b) the increase being approximately proportional to the pulse energy density.

FIGURE 1. Bright-field electron micrographs of phosphorous diffused Si crystals after one laser pulse. Samples were back-thinned with the upper surface being the original crystal surface. (a) $E = 2.0 \text{ J cm}^{-2}$, (b) $E = 3.0 \text{ J cm}^{-2}$.

The times involved in the removal of dislocation loops and precipitates in phosphorous-diffused specimens by solid state diffusion close to melting point were calculated to be of the order of minutes and measured (from "in situ" experiments) to be 4 min. at 1100°C . However, if melting is

assumed then the time for the removal of precipitates in the liquid is estimated to be ~ 20 nsec and the loops instantaneously lose their identity because they represent an extra layer of self interstitials. The calculated melt lifetime as a function of depth was found to be consistent with the observed thicknesses of defect-free regions and the nature of microstructure at the transition between the defect-free and original structure (7). Therefore, it is concluded that melting is necessary to remove precipitates and loops during pulsed laser irradiation.

Another technique to investigate the thickness of the melted zone is based upon the reorientation of dislocation segments emerging in the surface (5). By measuring the length of projected segments and from the angle of these segments with respect to the surface normal, the thickness of the laser melted zone can be determined accurately. This study was carried out in arsenic implanted (100 keV, 1.0×10^{16} /cm²), thermally annealed specimens. After the thermal treatment, (001) specimens contained a cross grid of dislocation with $a/2[110]$ and $a/2[1\bar{1}0]$ Burgers vectors in $[1\bar{1}0]$ and $[110]$ directions respectively. Fig. 2 shows the $a/2[110]$ set of dislocations under $\bar{g} = [220]$. These dislocations were arcs lying approximately in (110) planes and extending from the surface to 0.6 μ m deep. The dislocation segments near the surface were approximately normal to the surface, while longer segments were approximately in the $[1\bar{1}0]$ direction with deviations up to 25°. Hence, these dislocations were of edge type, the amount of deviation from the $[1\bar{1}0]$ direction being a measure of the amount of screw character.

FIGURE 2. Bright-field electron micrograph showing dislocations in ⁷⁵As (100 keV, 1×10^{16} /cm²) implanted silicon after annealing at 1100°C for 30 min. Most of the lines lie along $[110]$, with variations up to 25° .

When these specimens containing dislocations were irradiated with laser pulses, the dislocations in the laser melted region were found to lie approximately $25^\circ \pm 2^\circ$ (close to $\langle 113 \rangle$

directions) from the surface normal. The depth of melting was determined to be 600 Å after a 0.9 J cm^{-2} pulse (Fig. 3a). The depth increased to 4000 Å after a 1.5 J cm^{-2} pulse (Fig. 3b). At 2.2 J cm^{-2} , the depth of melting exceeded the depth boundaries of dislocations ($\sim 6000 \text{ Å}$), and dislocations were completely removed (Fig. 3c). These depths of melting were found to be in a good agreement with calculations (8).

FIGURE 3. Electron micrographs of edge dislocations, $b = a/2[111]$ in the laser-melted region as a function of pulse energy density: (a) $E = 0.9 \text{ J cm}^{-2}$, (b) 1.5 J cm^{-2} and (c) 2.2 J cm^{-2} .

Some of the phosphorous-diffused specimens contained dislocations in addition to loops and precipitates, as shown in Fig. 1. After laser-irradiation, of these specimens it was possible directly to compare the thickness of the defect-free (free from loops and precipitates) region with the thickness of the region in which dislocations had reoriented, as shown in a stereopair in Fig. 4. The two methods of measuring melt depth are in good agreement.

The reorientation of dislocations after the laser irradiation would involve climb distances of the order of microns in the solid state. Measurements (9) of solid state climb rates show them to be very small ($\sim 1 \text{ Å/sec}$) leading to climb distances of $< 1 \text{ Å}$ during times comparable to the pulse duration even if the lattice was near the melting point. There have been observations of optically-induced fast glide in

gallium arsenide heterostructures (9), but such effects have not been observed in pure materials. Our results can only be explained by melting followed by growth of dislocations from the melt depth while underlying dislocations act as sources.

FIGURE 4. Stereopair (20° , $g = [220]$) of a phosphorous-diffused laser-annealed specimen showing the growth of a near-edge dislocation in the laser-melted region. The arrow indicates the exit position of the dislocation at the back surface.

In conclusion, removal of dislocation loops and precipitates and the reorientation and removal of dislocations by pulsed laser irradiation can be satisfactorily explained on the basis of a melting model. The results provide a straightforward technique to determine the depth of melting as a function of laser parameters.

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