Energy dependence of transient enhanced diffusion and defect kinetics

Hugo Saleh and Mark E. Law[a)]
Department of Electrical and Computer Engineering, University of Florida, Gainesville, Florida 32611

Sushil Bharatan, Kevin S. Jones, and Viswanath Krishnamoorthy
Department of Material Science and Engineering, University of Florida, Gainesville, Florida 32611

Temel Buyuklimanli
Evans East, Hightstown, New Jersey 08520

(Received 1 February 2000; accepted for publication 16 May 2000)

Boron, a *p*-type dopant, experiences transient enhanced diffusion (TED) via interstitials. The boron TED and {311} dissolution rates are explored as a function of implant energy dependence. Silicon implants of $10^{14}/cm^2$ at various energies were used to damage the surface of a wafer with an epitaxially grown boron marker layer. Samples were annealed at 750 °C for 15–135 min to observe the diffusion exhibited by the marker layer and to correlate this with the dissolution of {311} type defects. The diffusion enhancement depends strongly on implant energy but the {311} dissolution rate is weakly dependent. © *2000 American Institute of Physics.* [S0003-6951(00)04727-6]

Transient enhanced diffusion (TED) of boron is caused by the release of interstitials from implantation damage. TED is well known to exhibit an energy dependence; as the implant energy is increased so does the enhanced diffusion.[1,2] Lim and Rafferty showed that TED depends on the distance to the surface by using surface polishing with a fixed implant dose and energy.[3] These effects are thought to be correlated, since an increase in implant energy moves the damage farther from the surface. The surface is thought to control TED.

Below the implant amorphization threshold dose, most of the damage recombines quickly. An excess of interstitials remains from the implanted ions, and these condense into {311} defects. This is known as the ''plus one'' dose of interstitials.[4] The {311} defects dissolve and release interstitials. Eaglesham *et al.*, first proposed that these {311} defects are the source of interstitials for TED.[5]

Since TED depends on the distance to the surface, it has been assumed that the dissolution of {311} defects should be dependent on the distance to the surface. However, there have been some experiments that have suggested that this may not be true. Agarwal *et al.*, showed that some {311} defects could be very long lived just 40 Å from the surface.[6] Moller *et al.*, showed that the width of the {311} layer is almost constant during dissolution, and that the {311} defects do not dissolve faster closer to the surface.[7] This study investigates simultaneously the energy dependence of TED and {311} dissolution.

Si+ was implanted at 20, 40, 80, and 160 keV to a dose of $1\times10^{14}/cm^2$ into a ⟨100⟩ Czochralski wafer to introduce damage above a chemical vapor deposition (CVD) grown buried boron marker layer about 5600 Å deep. These implants were then annealed at 750 °C for a range of times from 15 to 135 min in a N_2 ambient. Plan-view transmission electron microscopy (TEM) samples were prepared and the pictures were then used to measure the average length of {311}s, atomic concentration of trapped interstitials, and areal density of the {311}s. After highlighting the defects and scanning the images, NIH image processing software was used to perform counts and measurements. Counts assume 26 interstitials per nanometer of {311} length assuming a constant width of seven interstitials for the {311} defects.[5,8] Secondary ion mass spectrometry (SIMS) analysis was used to measure the diffusion exhibited by the marker layer.

Figure 1 shows the interstitials trapped in {311}s with respect to anneal time for the four implant energies. A good quality exponential fit is also shown to all of the 20, 40, and 80 keV implant data. Decay rate constants for these energies ranged from 19 to 27 min. The 160 keV data show a pronounced delay before the onset of dissolution. The data points up to 75 min are relatively flat. A good quality exponential fit is obtained considering only the data from 75 min and longer. This decay constant is 43 min when extracted this way. The dose of interstitials contained in the defects at

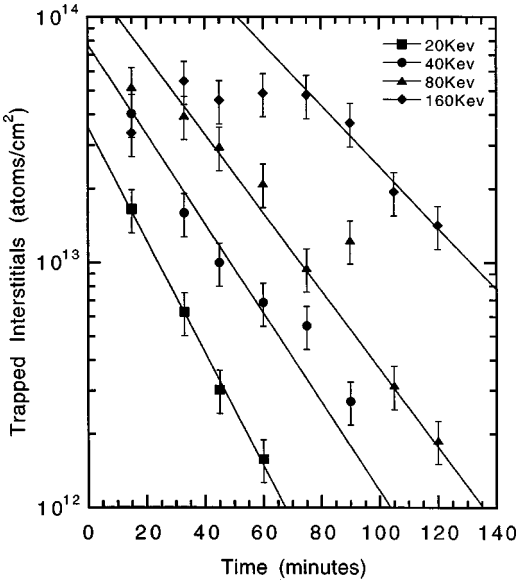

FIG. 1. {311} interstitial dose as a function of anneal time at 750 °C. Best fit exponential decays are also shown.

a)Electronic mail: law@tec.ufl.edu

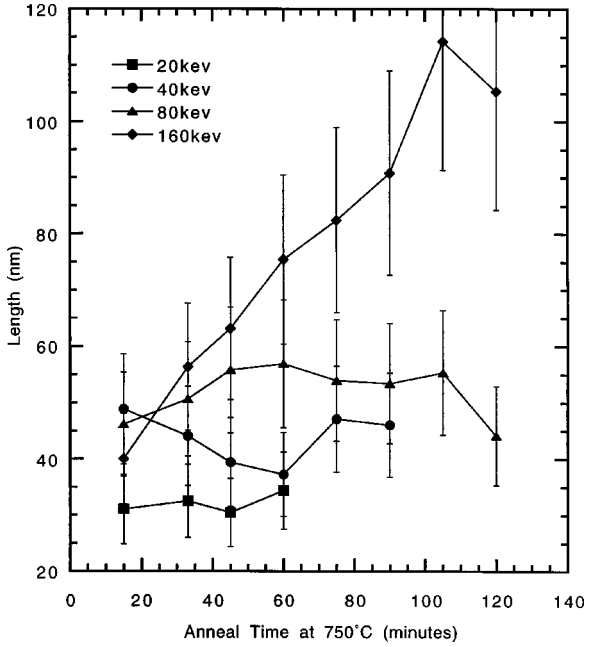

FIG. 2. Average length of {311} defects as a function of anneal time at 750 °C and implant energy.

the shortest time (15 min) is also an increasing function of implant energy.

Figure 2 shows the average size of the defects as a function of anneal time and implant energy. The average size of the {311}s for the 40 and 80 keV are approximately constant and within the error bars of each other. Many small {311}s can be seen in the TEM photograph for the 20 keV implanted samples. The 160 keV implant shows a pronounced increase in size of the {311} defects with increased annealing time that is not present for the lower energy samples.

SIMS was used to measure the broadening of the boron marker layer. Figure 3 shows the junction broadening as a function of time and implant energy. The change in the width of the boron marker layer at a concentration of $5\times10^{16}/\mathrm{cm}^3$ was used to quantify the junction broadening. As previously reported,[1–3] the junction depth broadening increases with increased energy of implant. The fits in Fig. 3 were extracted assuming the diffusivity decays exponentially with time. Decay times can be extracted for the TED process from these fits.

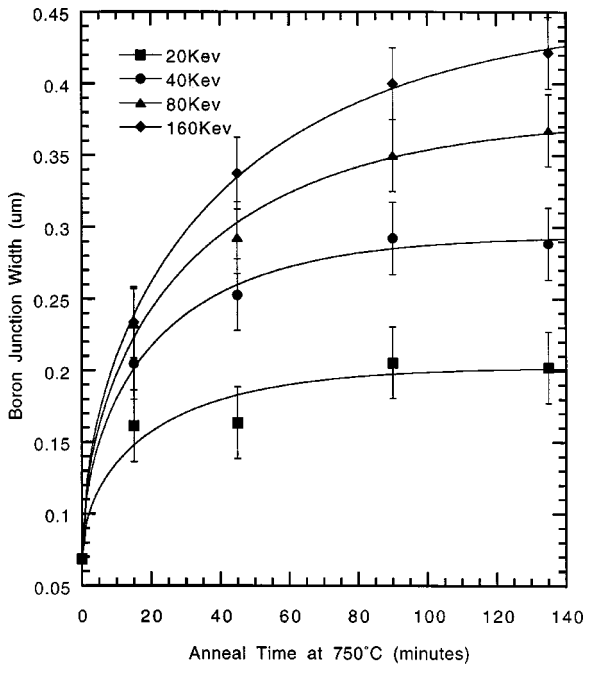

FIG. 3. Junction width of buried boron marker layer as a function of anneal time at 750 °C and implant energy.

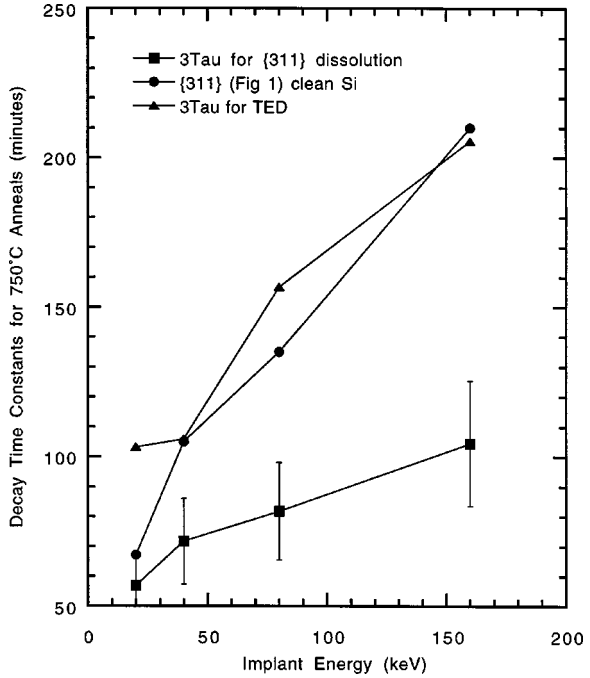

FIG. 4. Comparison of the time to remove {311} defects, TED saturation time, and decay rates of {311} defects as a function of energy.

Figure 4 shows three times the decay constants as a function of energy. For the TED, three times the decay constant of the diffusivity can be thought of as the time for TED to disappear. As expected the TED shows a strong energy dependence, increasing with a rough square root dependence on energy. Figure 4 also shows three times the {311} dissolution rate constant. The {311} rate constant has a weaker dependence on energy and is almost constant within error bars. Finally, the clean silicon line is defined as the point where no visible {311} defects are observed. This is the x intercept in Fig. 1 which corresponds to a dose of 1×10^{12} interstitials/cm^2. The time to clean silicon is larger than the {311} dissolution rate for the higher energy implants due to the increase in the initial number of trapped interstitials.

The time to clean silicon is similar to the TED decay rate. {311} defects are indeed the source of interstitials for TED. However, this is due to a more complex interaction than previously expected. TED stopped when no {311} defects were visible. Even though there was no change in the number of trapped interstitials in {311} defects for 0–75 min, the {311} defects will maintain a supersaturation of interstitials about them. These interstitials will contribute to TED. Cowern *et al.* showed that during early annealing, small interstitial clusters with low binding energy give rise to a large interstitial supersaturation.[9] These interstitials could be contributing to the TED for the 160 keV implants and could prevent {311} dissolution until they are all dissolved. The decay rate of the {311} defects does not correlate well with

the energy dependence of TED. However, the implant energy dependence also changes the ''plus one'' [4] value of interstitials and the onset of {311} defect dissolution. Combined, these effects are responsible for a strong energy dependence of the time to dissolve all {311} defects that match the observed energy dependence of TED.

[1] P. A. Packan and J. D. Plummer, Appl. Phys. Lett. **56**, 1787 (1990).
[2] P. A. Packan, Ph.D. thesis, Stanford University, 1991.
[3] D. R. Lim, C. S. Rafferty, and F. P. Klemens, Appl. Phys. Lett. **67**, 2302 (1995).
[4] M. D. Giles, J. Electrochem. Soc. **138**, 1160 (1991).
[5] D. J. Eaglesham, P. A. Stolk, H.-J. Gossmann, and J. M. Poate, Appl. Phys. Lett. **65**, 2305 (1994).
[6] A. Agarwal, T. E. Haynes, D. J. Eaglesham, H.-J. Gossmann, D. C. Johnson, J. M. Poate, and Y. E. Erokhin, Appl. Phys. Lett. **70**, 3332 (1997).
[7] K. Moller, K. S. Jones, and M. E. Law, Appl. Phys. Lett. **72**, 2547 (1998).
[8] S. Takeda and M. Kohyama, Inst. Phys. Conf. Ser. 33 (1993).
[9] N. E. B. Cowern, M. Jaraiz, F. Cristiano, A. Claverie, and G. Mannino, IEDM Tech. Dig. 333 (1999).