Effect of arsenic doping on {311} defect dissolution in silicon

Richard Brindos,[a] Patrick Keys, and Kevin S. Jones
Department of Materials Science and Engineering, University of Florida, Gainesville, Florida 32611

Mark E. Law
Department of Electrical and Computer Engineering, University of Florida, Gainesville, Florida 32611

Si^+ ions were implanted into silicon wafers with background concentrations of arsenic ranging from 1×10^{17} to 3×10^{19} cm^{-3} to study the interaction between arsenic atoms and excess self-interstitials. Samples were then annealed at 750 °C for a range of times between 15 and 60 min to nucleate and dissolve {311} defects. The concentration of trapped interstitials in these defects was measured using quantitative plan-view transmission electron microscopy. It is shown that, as the arsenic concentration increases, there is a reduction in the number and size of the {311} defects. This decrease in the {311} defect density with increasing arsenic well concentration is believed to be the result of interstitial trapping by the arsenic. Upon annealing, the trapped interstitial concentration in the {311} defects decreases as the defects dissolve. The time constant for the dissolution was calculated to be 33 ± 5 min at 750 °C, and was independent of background concentration. This suggests that the arsenic traps some of the interstitials, and these traps are sufficiently stable that they do not affect the subsequent {311} dissolution at 750 °C. © *1999 American Institute of Physics.* [S0003-6951(99)04628-8]

Arsenic is the most common *n*-type dopant used in silicon-based microelectronic device fabrication today. Arsenic is desirable due to its high mass, high solubility, high activation, and low diffusivity, which are all important in an attempt to decrease junction depths. Arsenic, however, also exhibits transient enhanced diffusion (TED).[1,2] Previous experiments have shown the {311} defect to be partially responsible for TED in Si^+ implants[3] and B^+ implants.[4] Knowledge of the effect of arsenic on {311} defect formation and dissolution is a crucial step in understanding TED in arsenic implanted samples. This knowledge is also useful in developing physically based process simulators such as (SUPREM) and (FLOOPS).

Recently, a new approach to explain the interstitial trapping by impurities was used by Haynes[5] to study boron in silicon. This involved the formation of boron wells, and subsequent quantitative transmission electron microscopy (TEM) of {311} defects from a self-implant and anneal. It was shown that boron traps silicon interstitials for boron concentrations above 1×10^{18} cm^{-3}.[6] In order to understand how arsenic affects excess interstitial evolution this same experimental approach was taken. Arsenic doped wells of concentrations ranging from 1×10^{17} to 3×10^{19} cm^{-3} were created and subsequently implanted with Si^+. The formation and dissolution of {311} defects that form upon low temperature annealing were monitored as a function of arsenic concentration. This letter presents the results of this experiment and discusses the possible reasons for the observed decrease in {311} formation with increasing arsenic concentration.

Arsenic-doped wells were used to establish the effect of arsenic on excess self-interstitials. The arsenic wells were fabricated using the following process. Six *p*-type epi-silicon wafers were amorphized with Si^+ at energies of 200 and 70

keV at doses of 2×10^{15} and 1×10^{15} cm^{-2}, respectively. Arsenic was implanted into the amorphized region at energies of 200 and 70 keV at varying doses. All six wafers were then annealed at 550 °C for 60 min to regrow the amorphized layer. A 45 min anneal at 1050 °C was used to form a fairly constant arsenic concentration to a depth in excess of 1600 Å. Figure 1 shows the results from the secondary ion mass spectroscopy (SIMS) analysis, following the 1050 °C well anneal. The total arsenic implant doses used were 2.5×10^{12}, 7.3×10^{12}, 2.5×10^{13}, 7.3×10^{13}, 2.5×10^{14}, 7.3×10^{14} cm^{-2}, which formed wells with concentrations of 2.0×10^{17}, 4.0×10^{17}, 1.1×10^{18}, 3.5×10^{18}, 1.1×10^{19}, 3.0×10^{19} cm^{-3}, respectively.

Following the well anneals, the wafers were sectioned and implanted with silicon at an energy of 40 keV and dose
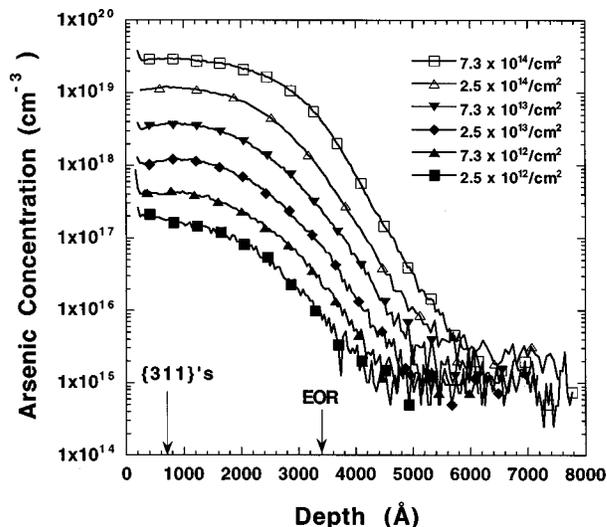

FIG. 1. SIMS profiles of the arsenic wells after a well anneal at 1050 °C and before the Si implant was performed.
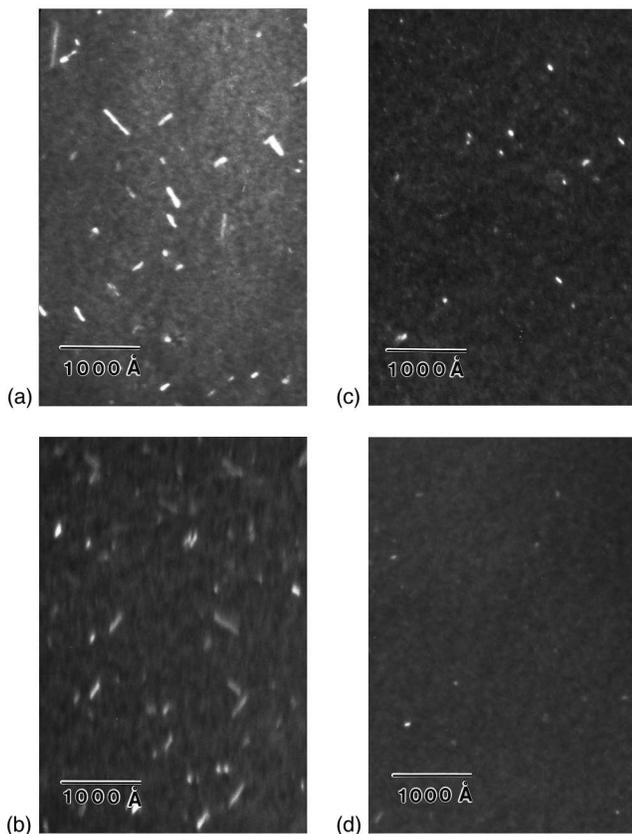
[a]Electronic mail: rich@tec.ufl.edu

FIG. 2. $\mathbf{g}_{220}$ weak beam dark field plan-view TEM micrographs of samples with arsenic background concentrations of (a) $2\times10^{17}\,\mathrm{cm}^{-3}$, (b) 1.1 $\times10^{18}\,\mathrm{cm}^{-3}$, (c) $1.1\times10^{19}\,\mathrm{cm}^{-3}$, and (d) $3.0\times10^{19}\,\mathrm{cm}^{-3}$. The samples also had a 40 keV Si implant at a dose of $1\times10^{14}\,\mathrm{cm}^{-2}$ and were annealed in nitrogen at 750 °C for 30 min.
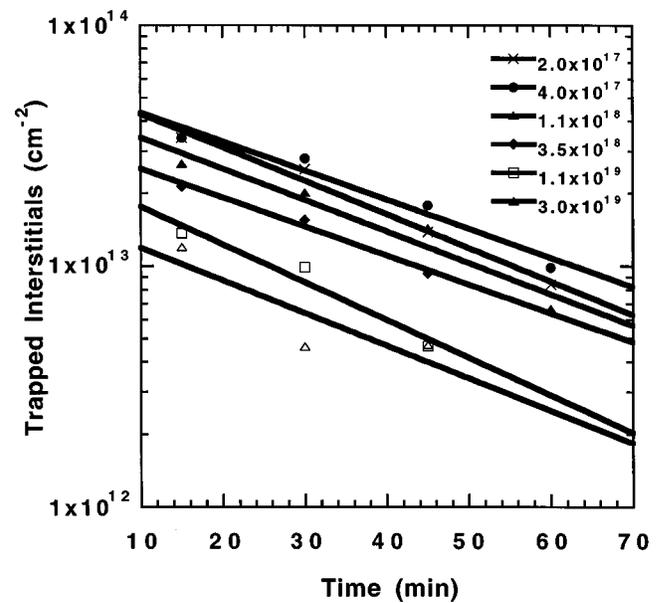

FIG. 3. Total number of trapped interstitials in {311} defects as a function of annealing time. The solid lines are a best line fit assuming an exponential dependence.

of $1\times10^{14}\,\mathrm{cm}^{-2}$. Undoped control wafers, one with no preamorphization and one preamorphized with the same Si^+ implant were also annealed at 1050 °C and then subjected to the 40 keV $1\times10^{14}\,\mathrm{cm}^{-2}$ silicon implant. TEM specimens (3 mm diameter) were cut and furnace annealed in a nitrogen ambient at 750 °C for times of 15, 30, 45, and 60 min to nucleate and grow the {311} defects. Plan-view TEM specimens (PTEM) were then prepared and analyzed using a $\mathbf{g}_{220}$ weak beam dark field condition on a JEOL 200CX. Cross-sectional TEM images showed that the {311} defects were at a depth centered at 700 Å and the amorphous/crystalline interface for the arsenic well was at 3900 Å. End of range (EOR) dislocation loops from the preamorphization of the silicon substrate remained after the 1050 °C 45 min anneal at a depth of 4000 Å. The size and distribution of the EOR defects was constant for all the specimens. There was no difference in the {311} formation or dissolution for the control sample with no preamorphization and the control with the EOR loops from preamorphization. This implies the EOR defects were sufficiently removed from the self-implanted region and thus had no effect on the {311} formation or dissolution process, which is consistent with previous experiments.[7]

In the analysis of the PTEM micrographs, it was assumed that the {311} defects were on average 40 Å wide and thus there are 26 silicon interstitials per nm of length in the {311} defects under these annealing conditions.[3] TEM images are presented in Fig. 2 of specimens annealed at 750 °C

for 30 min as a function of increasing arsenic background concentration. The {311} defects are the bright rod-shaped defects. These images show that as the background concentration increases, the length and total number of {311} defects decreases. Figure 3 shows the number of interstitials in the {311} defects decreases with increasing anneal time, as expected. The dissolution of {311} defects in the control sample is also presented in Fig. 3. Extrapolation of the dissolution curves shows the initial trapped interstitial concentration in the control sample is $3-4\times10^{13}\,\mathrm{cm}^{-2}$ or 0.3–0.4 of the initial dose. This is less than has been previously reported for self-implants[3] but is consistent with our other observations.[8,9] This {311} dissolution can be modeled by the simple equation $n_i = n_i^0 \exp(-t/\tau)$, where n_i is the number of interstitials in a {311} defect, n_i^0 is the number of interstitials contained in {311} defects at time zero, t is the anneal time at 750 °C, and τ is the dissolution time constant. Figure 3 shows that as the arsenic well concentration increases the value of n_i or the initial concentration of interstitials trapped in {311} defects decreases. Figure 3 also shows that the dissolution rate is unaltered with the addition of arsenic. The time constant, τ_{311}, was calculated to be 33 ± 5 min and, within measurement error, is independent of the arsenic background concentration. The time constant obtained in this experiment is similar to previously reported dissolution times.[9–11]

Figure 4 is a plot of the value of n_i^0 as a function of arsenic concentration. Also included in Fig. 4 is the data on the trapped interstitials in {311} defect for boron-doped wells previously published by Haynes.[5] The silicon implants were the same and the 15 min arsenic data is also shown so direct comparison could be made for the same anneal conditions.

The data presented suggest that introduction of arsenic is having a significant effect on the trapping evolution of excess interstitials. There are several possible mechanisms that might account for this effect. Two of the more likely reasons include formation of arsenic clusters or enhanced diffusivity
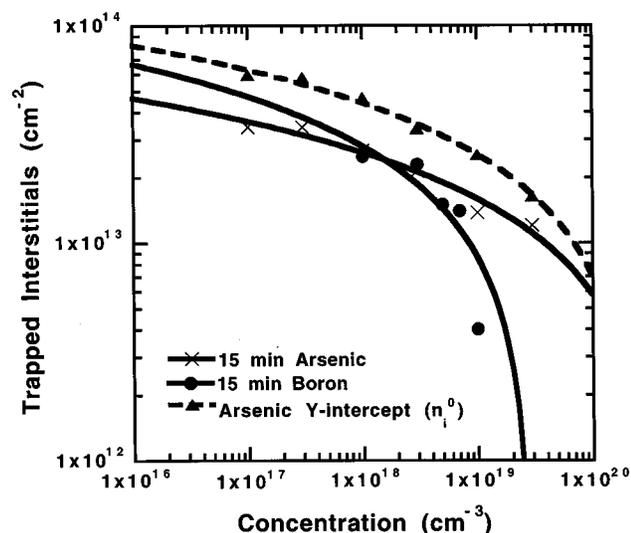
FIG. 4. Comparison of arsenic and boron backgrounds on the total number of trapped interstitials in {311} defects. Extrapolated values from Fig. 3 (n_i^0) are also plotted. The solid lines are a least-squares fit of the data, extrapolated out to the axis.

of charged interstitials when the material becomes extrinsic ($n > n_i$). First, as was suggested for boron, the arsenic could be trapping the excess interstitials in some form of a complex. The complex would have to be more stable than the {311} defect in order to not influence the {311} dissolution rate. In this experiment, the maximum depth of the {311} defect layer was measured to be 750 Å by cross-section TEM. If this value is multiplied by the concentration of arsenic, the dose of arsenic atoms affected by the excess interstitial dose could be estimated. These values range from 1.5×10^{12} As/cm^2 for the 2×10^{17} cm^{-3} well to 2.25×10^{14} As/cm^2 for the 3×10^{19} cm^{-3} well. As previously stated, the dose of the interstitials injected by the Si$^+$ implant was determined to be $3–4 \times 10^{13}$ cm^{-2}. A ''missing'' interstitial dose can be calculated from the difference between the y intercept of the undoped well, and the y intercept of the doped samples in Fig. 3. Comparison of the ''missing'' interstitial dose versus the number of As atoms available over a depth of 750 Å reveals that there is a 2:1 arsenic to interstitial ratio before a saturation of interstitial trapping is reached. Thus, if arsenic trapping were occurring, the cluster might be an As$_2$I. This is a crude estimate and other complexes with higher Si to As ratios might also be possible, because the excess interstitial profile is not constant but instead is approximately gaussian. One final attractive feature to the cluster hypothesis is that boron, which has a significantly smaller tetrahedral covalent radius, would be expected to trap interstitials much more readily than arsenic and this is consistent with Fig. 4.

The Fermi level effect on interstitial diffusivity is also a possible explanation. At 750 °C, the intrinsic carrier concentration is 1.3×10^{18} cm^{-3}. The arsenic concentration has an increasing effect on {311} formation for concentrations above 1×10^{18} cm^{-3}. The self-interstitial diffusivity as a function of charge state has been calculated recently by Zhu.[12] If this model is correct, the neutral interstitial migration energy is about the same as the negatively charged interstitial migration energy, but there could be a large difference in the prefactor of the exponential. Thus, it is possible that the change in Fermi level increased the diffusivity of the silicon interstitials. This increase in diffusivity could result in interstitials leaving the Si$^+$ implanted region before being trapped in a {311} defect. If the increase in diffusivity was a pure Fermi level effect, one would expect arsenic and phosphorus to have the same defect behavior. We have evidence that arsenic and phosphorus behave very differently, suggesting that Fermi level effects cannot fully explain the defect behavior. However, these data are not yet ready to be presented in full and is reserved for a future publication.

In conclusion, we have demonstrated that arsenic retards the formation of {311} defects. Increasing the arsenic background concentration reduced the {311} defect density and density of trapped interstitials in the {311} defects. It is shown that approximately one interstitial is missing from the {311} defects for every two arsenic atoms in the region of interstitial saturation. This data are consistent with the assertion that arsenic is reacting with the excess interstitials to form As$_2$I clusters.

[1] Y. Kim, H. Z. Massoud, and R. B. Fair, J. Electron. Mater. **18**, 143 (1989).
[2] V. Krishnamoorthy, K. Moller, K. S. Jones, D. Venables, J. Jackson, and L. Rubin, J. Appl. Phys. **84**, 5997 (1998).
[3] D. J. Eaglesham, P. A. Stolk, J.-J. Gossmann, and J. M. Poate, Appl. Phys. Lett. **65**, 2305 (1994).
[4] J. Liu, V. Krishnamoorthy, K. S. Jones, M. E. Law, J. Shi, and J. Bennett, *Proceedings of the International Conference on Ion Implantation Technology 1996* (IEEE, Piscataway, NJ, 1996), 96TH8182, pp. 626–629.
[5] T. E. Haynes, D. J. Eaglesham, P. A. Stolk, H.-J. Gossmann, D. C. Jacobson, and J. M. Poate, Appl. Phys. Lett. **69**, 1376 (1996).
[6] P. A. Stolk, H.-J. Gossmann, D. J. Eaglesham, D. C. Jacobson, H. S. Luftman, and J. M. Poate, Mater. Res. Soc. Symp. Proc. **354**, 307 (1995).
[7] R. Raman, M. E. Law, V. Krishnamoorthy, and K. S. Jones, Appl. Phys. Lett. **74**, 700 (1999).
[8] J. Desroches, V. Krishnamoorthy, K. S. Jones, and C. Jasper, Mater. Res. Soc. Symp. Proc. **469**, 283 (1997).
[9] K. Moller, K. S. Jones, and M. E. Law, Appl. Phys. Lett. **72**, 2547 (1998).
[10] C. S. Rafferty, G. H. Gilmer, M. Jaraiz, D. Eaglesham, and H.-J. Gossmann, Appl. Phys. Lett. **68**, 2395 (1996).
[11] D. J. Eaglesham, P. A. Stolk, H.-J. Gossmann, T. E. Haynes, and J. M. Poate, Nucl. Instrum. Methods Phys. Res. B **106**, 191 (1995).
[12] J. Zhu, Mater. Res. Soc. Symp. Proc. **469**, 151 (1997).