

Evolution of {311} type defects in boron-doped structures: Experimental evidence of boron–interstitial cluster formation

A. D. Lilak, S. K. Earles, M. E. Law,^{a)} and K. S. Jones

Department of Electrical Engineering, SWAMP Center, University of Florida, Gainesville, Florida 32611

(Received 4 May 1998; accepted for publication 13 January 1999)

Boron-doped well structures formed in Czochralski silicon are subjected to a self-implant and various anneals to form a population of type {311} defects. Quantitative transmission electron microscopy is then used to measure the residual interstitials trapped in the {311} defects as a function of boron concentration and anneal temperature. We have found a strong tendency for increased dissolution rates of {311} type defects at boron concentrations above 10^{18} cm^{-3} , providing direct evidence for the formation of boron–interstitial clusters. By profiling the samples with secondary ion mass spectroscopy and comparing the results to spreading resistance measurements the degree of deactivation can be determined. © 1999 American Institute of Physics.

[S0003-6951(99)04810-X]

Modern device technologies require the formation of very shallow $p+n$ junctions. This is complicated by the fact that boron, at high concentrations, interacts with the interstitials resulting from implant-induced Frenkel pairs to form stable boron interstitial clusters (BICs).^{1–3} These clusters are relatively immobile,^{2,4} and the boron which they contain is held in an electrically inactive state or a fractionally active state.

Previous studies have shown that for short times, the transient enhanced diffusion of boron is mediated by the release of interstitials from type {311} defects.⁵ At higher boron concentrations, the {311} defects and BICs form a competitive system for the available interstitials.^{1,2,6} Since the {311} defects are observable and quantifiable with transmission electron microscopy,^{7,8} it is possible to use them to gauge the level of boron clustering.

In order to accomplish this, four boron-doped wells were formed by the ion implantation of boron at 400 keV through 100 Å screen oxide into (100) Czochralski silicon with doses varying from 1×10^{13} to $2 \times 10^{14} \text{ cm}^{-2}$ followed by a 330 min anneal at 1100 °C. This resulted in the formation of four boron-doped wells with concentrations of roughly 5.5×10^{16} , 3×10^{17} , 5×10^{17} , and $1.2 \times 10^{18} \text{ cm}^{-3}$ to a depth in excess of 1 μm. The boron profile in these well structures was later verified with both secondary ion mass spectroscopy (SIMS) and spreading resistance measurements. The boron-doped wells were then subjected to a silicon self-implant at 40 keV of 1×10^{14} – $2 \times 10^{14} \text{ cm}^{-2}$ dose followed by anneals of 10–30 min at 740 °C, 15–35 s at 815 °C, and 30 min to 6 h at 670 °C in order to nucleate and grow populations of both {311} defects and BICs. The number of residual interstitials trapped in the {311} defects following the anneals was then determined by quantitative transmission electron microscopy.

Figure 1 shows a series of transmission electron microscopy (TEM) micrographs of the residual {311} defects for

two of the samples from the 740 °C study with the $1 \times 10^{14} \text{ cm}^{-2}$ implanted silicon dose which clearly illustrate the trend towards fewer and smaller {311} defects at higher boron concentrations for the same anneal conditions. Experimental measurements of those samples annealed at 740 °C are plotted in Fig. 2. These results follow the same trend as a previous study which utilized floating zone material,⁶ however, we note significant degradation of the residual interstitial concentration in the {311} defects at boron concentrations roughly an order of magnitude lower than the previous study. For the 740 °C anneals, no quantifiable population of {311} defects was observed for the 30 min anneals for all boron concentrations.

Results from the 670 °C study are less clear. For anneal times of 30 min to 6 h, very few {311} defects were observed regardless of boron concentration. It is possible that the boron is influencing the nucleation of the {311} defects at these lower temperatures, or that the silicon interstitials are diffus-

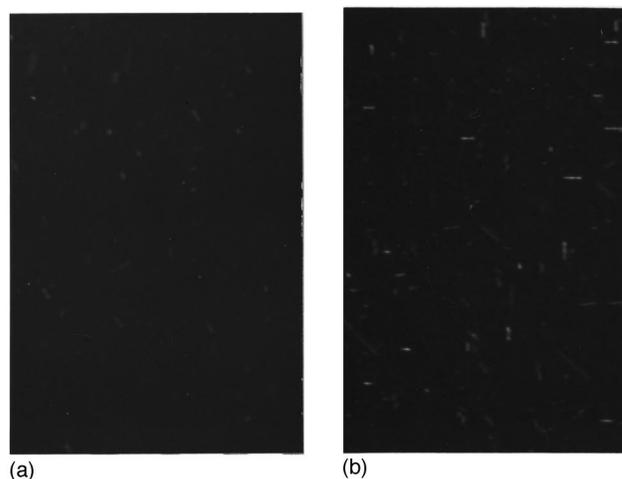


FIG. 1. TEM micrographs of a $1 \times 10^{14} \text{ cm}^{-2}$ silicon implant followed by a 10 min 740 °C anneal into boron-doped wells of concentration 1.0×10^{18} and $5.5 \times 10^{18} \text{ cm}^{-3}$, respectively. Note the reduction of type {311} defects in the higher-doped sample.

^{a)}Electronic mail: law@tec.ufl.edu

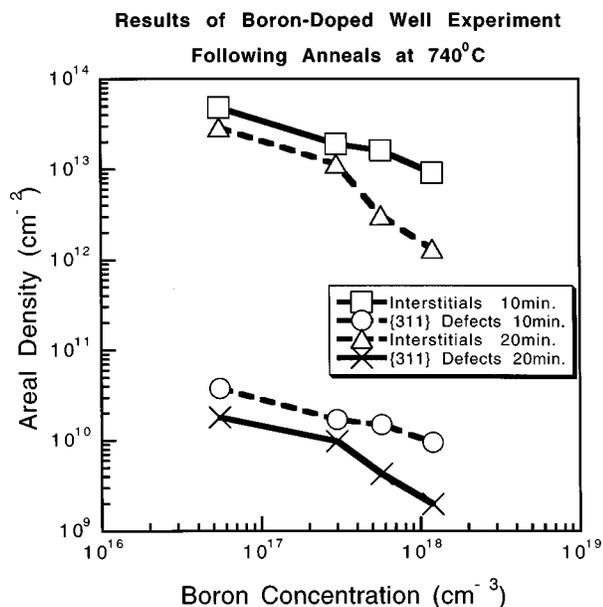


FIG. 2. Plot of residual {311} defect areal density along with residual interstitials trapped in type {311} defects as a function of boron well concentration arising from a $1.0 \times 10^{14} \text{ cm}^{-2}$ silicon implant followed by a 10 or 20 min anneal at 740 °C.

ing away or trapped before the {311}'s can nucleate. A similar self-implant of 40 keV $2 \times 10^{14} \text{ cm}^{-2}$ does show quantifiable populations of {311} defects for these anneal conditions, indicating that the additional $1 \times 10^{14} \text{ cm}^{-2}$ implanted silicon ions quench whatever sink was responsible for the lack of {311} defects at the lower implant dose.

Those samples subjected to 815 °C anneal with the $2 \times 10^{14} \text{ cm}^{-2}$ implanted silicon dose show a population of both {311} type defects and dislocation loops. In addition to the trend towards fewer {311} defects with increasing boron concentration, we also note fewer of the dislocation loops with increasing boron concentration for the higher fluence silicon implants.

These same samples were then analyzed by spreading resistance profiling (SRP) in order to determine the profile of the boron which is electrically active. By then comparing these results to SIMS profiles of the chemical boron, it is possible to determine the inactive boron concentration. By comparing the SIMS and SRP, it is possible to determine the fractional activation which is shown in Fig. 3 for one of the samples.

By utilizing the lightest-doped boron well as a control to gauge the intrinsic bimolecular recombination of interstitials and vacancies and account for the surface recombination of interstitials, it is possible to elucidate some of the kinetics of the BICs. Following the 10 min anneal at 740 °C, the heaviest-doped boron well showed approximately $3.9 \times 10^{13} \text{ cm}^{-2}$ fewer interstitials than the lightest-doped boron well. A comparison of the SIMS and the SRP results indicate that for this same case approximately $3 \times 10^{13} \text{ cm}^{-2}$ boron is deactivated. By attributing all of the missing interstitials to BIC formation, an upper bound of 1.3 can be placed on the ratio of clustered interstitials to inactive boron in the BICs. A similar analysis following a 20 min anneal at 740 °C, leads to an upper bound of .9 for this fraction. This result supports previous work utilizing cluster precursors and the progres-

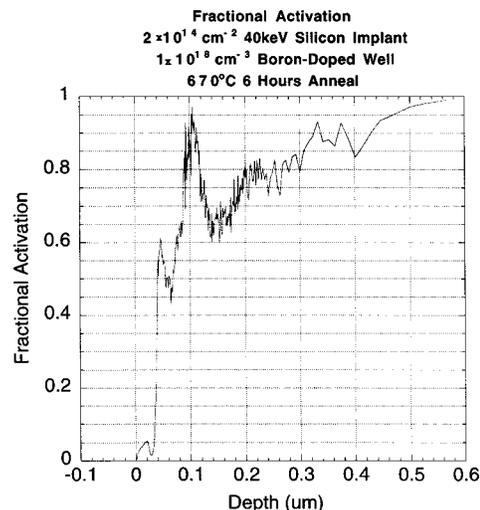


FIG. 3. Fractional activation as a function of depth for a $2.0 \times 10^{14} \text{ cm}^{-2}$ silicon implant into a $1.0 \times 10^{18} \text{ cm}^{-3}$ boron-doped well followed by a 6 h anneal at 670 °C as determined by a series of SIMS and SRP measurements. The SRP measurement is normalized to the SIMS measurement in the bulk.

sion of the clustered boron toward larger more stable clusters. Both of these ratios are likely high due to the fact the diffusion of the boron mediated by the defect gradient from the region subjected to the self-implant is neglected. Assuming boron diffusion dominated by a boron-interstitial pair mechanism, these ratios are reduced to approximately 1 for the 10 min anneal and .6 for the 20 min anneal at 740 °C. Accounting for other mechanisms could further lower these ratios.

Recent work has determined the fractional activation of different boron cluster configurations. These analyses demonstrate support for the assertion that clustering is due to either a B3I mechanism or a B4I mechanism which are shown to have 33% and 50% electrical activation,⁹ respectively. Accounting for the fractional activation of the boron clusters, it is possible to determine the ratio of clustered boron to interstitials trapped. Assuming a cluster with 33% activation as in the case of the B3I complex, the ratio of trapped boron to interstitials is determined to be approximately 2.5 for the 20 min anneal at 740 °C. If a cluster with 50% electrical activation is assumed as in the case of the B4I, this ratio is determined to be approximately 3.33 for the 20 min anneal at 740 °C.

In conclusion, a series of experiments have been described in which the {311} defect is used as a means to quantify the interstitials which take part in the formation of stable boron interstitial clusters. Spreading resistance and SIMS results for these same samples are then used in order to determine the fraction of the boron profile which is inactive. These results support the contention that either a B3I or a B4I complex is responsible for a majority of the boron clustering.

The authors would like to acknowledge material support provided by Intel and Motorola. Fred Stevie and Samir Chaudhry of Lucent Technologies have arranged for SIMS to be performed on several of the samples. Financial support has been provided by the Semiconductor Research Corpora-

tion. Kathryn Moller has aided in the preparation of TEM samples.

¹A. D. Lilak, S. K. Earles, M. E. Law, K. S. Jones, and M. D. Giles, 1997 IEDM.

²M. J. Caturla, J. Zhu, T. Diaz de la Rubia, and M. Johnson (private communication).

³L. Pelaz, M. Jaraiz, G. H. Gilmer, H.-J. Gossman, C. S. Rafferty, D. J. Eaglesham, and J. M. Poate, Appl. Phys. Lett. **70**, 2285 (1997).

⁴N. E. B. Cowern, A. Cacciato, J. S. Custer, F. W. Saris, and W. Vanderhorst, Appl. Phys. Lett. **68**, 1150 (1996).

⁵D. J. Eaglesham, P. A. Stolk, H.-J. Gossman, and J. M. Poate, Appl. Phys. Lett. **65**, 2305 (1994).

⁶T. E. Haynes, D. J. Eaglesham, P. A. Stolk, H.-J. Gossman, D. C. Jacobson, and J. M. Poate, Appl. Phys. Lett. **69**, 1376 (1996).

⁷K. S. Jones, S. Prussin, and E. R. Weber, Appl. Phys. A: Solids Surf. **45**, 1 (1988).

⁸J. L. Benton, S. Libertino, P. Kringhoj, D. J. Eaglesham, J. M. Poate, and S. Coffa, J. Appl. Phys. **82**, 120 (1997).

⁹T. Diaz de la Rubia, M. Caturla, and S. Theiss, 1998 IEDM.