Effect of boron on interstitial-related luminescence centers in silicon
S. Charnvanichborikarn, B. J. Villis, B. C. Johnson, J. Wong-Leung, J. C. McCallum, J. S. Williams, and C. Jagadish

Citation: Applied Physics Letters 96, 051906 (2010); doi: 10.1063/1.3300836
View online: http://dx.doi.org/10.1063/1.3300836
View Table of Contents: http://scitation.aip.org/content/aip/journal/apl/96/5?ver=pdfcov
Published by the AIP Publishing

Articles you may be interested in
Dopant effects on the photoluminescence of interstitial-related centers in ion implanted silicon

Impact of oxygen on the permanent deactivation of boron–oxygen-related recombination centers in crystalline silicon
J. Appl. Phys. 107, 123707 (2010); 10.1063/1.3431359

Atomistic analysis of the evolution of boron activation during annealing in crystalline and preamorphized silicon
J. Appl. Phys. 97, 103520 (2005); 10.1063/1.1904159

Effects of boron-interstitial silicon clusters on interstitial supersaturation during postimplantation annealing

Boron-interstitial silicon clusters and their effects on transient enhanced diffusion of boron in silicon
J. Appl. Phys. 88, 4547 (2000); 10.1063/1.1311826
Effect of boron on interstitial-related luminescence centers in silicon

S. Charnvanichborikarn,1,a) B. J. Villis,2 B. C. Johnson,2 J. Wong-Leung,1 J. C. McCallum,2 J. S. Williams,3 and C. Jagadish1
1Department of Electronic Materials Engineering, Research School of Physics and Engineering, The Australian National University, Canberra ACT 0200, Australia
2Centre for Quantum Computing Technology and Micro-Analytical Research Centre, School of Physics, University of Melbourne, Victoria 3010, Australia

(Received 31 October 2009; accepted 6 January 2010; published online 3 February 2010)

Photoluminescence measurements have been used to investigate the optically active defect centers formed by silicon implantation and a subsequent anneal at 275, 400, or 525 °C. The presence of boron in p-type silicon is found to produce deleterious effects on the luminescence of the interstitial-related W- and X-centers as well as a lower energy broad luminescence band. This effect has not been previously reported but it is consistent with the suppression of interstitial-related (311) extended defect formation in the presence of high boron concentrations at higher annealing temperatures. The results presented in this letter provide insight into the role of boron in the initial stages of interstitial cluster formation. © 2010 American Institute of Physics.

[doi:10.1063/1.3300836]

The process of ion implantation commonly creates luminescence centers in silicon. The W-center has been reported after electron,1 neutron,2 and ion3,4 irradiation of crystalline silicon with a zero-phonon emission W-line (or I1) at 1218 nm. It is now widely accepted that the W-center is a tri-interstitial cluster.5–7 Other interstitial-related luminescence lines include a zero-phonon emission line at 1193 nm known as the X-line (or I3) that is thought to consist of four interstitial silicon atoms and is usually observed at higher annealing temperatures.8 The demonstration of a silicon light-emitting diode based on W-center luminescence has renewed interest in the formation mechanisms and properties of this defect.9 This has prompted us to further explore some of the factors which affect the production of several luminescence centers in ion implanted silicon samples. This letter addresses a gap in the literature pertaining to experimental results on Si implanted into a range of boron-doped Si wafers followed by anneals at low temperatures. The interaction of boron and interstitial clusters in this annealing regime is observed using photoluminescence (PL) and important ramifications for modeling the formation mechanisms of boron-related clusters are elucidated.

Boron is a common p-type dopant in silicon. There has been speculation that the formation of a boron-related cluster namely Y-center or I2 with an emission line at 1149 nm (1.080 eV) competes with the W-center.10 However, the effect of boron on the W-center has not yet been systematically studied. Theoretical calculations indicate that self-interstitials can be bound in immobile silicon-rich boron interstitial clusters (BICs) in the initial stages of an anneal but more stable clusters with a higher boron-to-silicon interstitial ratio of about 3:1 or 4:1 are expected after an extended anneal.11,12 This latter process is thought to involve the trapping of interstitial boron and the release of silicon interstitials. According to other calculations, optically inactive centers with single or multiple boron atoms and multiple self-interstitials form with increasing boron concentration.13 Although formation of boron clusters such as the B2I6V complexes14,15 (a six-member ring configuration containing three split-interstitials, two being B atoms) is predicted to be favorable, they are also predicted to be nonradiative recombination centers and hence have not been experimentally observed. However, the preferential formation of these centers would be expected to have a profound effect on the formation of the smaller interstitial clusters.

Our experiments were performed on three commercially available Cz-grown boron-doped p-type (100) silicon wafers with different resistivities of 14, 0.18, and 0.018 Ω cm. These values correspond to boron doping concentrations of $9.4 \times 10^{13}$, $1.1 \times 10^{14}$, and $3.2 \times 10^{14}$ cm$^{-3}$, respectively, and were determined using capacitance-voltage (C-V) and four-point probe measurements on unprocessed wafers. The distribution of boron is uniform throughout the sample.

All the wafers were irradiated at room temperature with 300 keV Si$^+$ ions to doses ranging from $10^{10}$ to $10^{14}$ cm$^{-2}$, where the ion flux was adjusted to keep the time for each implantation fluence reasonable. However, predominantly the PL spectra of the samples with a dose of $10^{12}$ cm$^{-2}$ and an average flux of around $5.5 \times 10^{10}$ cm$^{-2}$ s$^{-1}$ are presented in this letter. It should be noted that such an implanted fluence is well below the amorphization threshold. During the implant, the samples were tilted by 7° from normal incidence of the ion beam to minimize channeling. Following implantation, a rapid thermal anneal (RTA) was performed in an Ar ambient at temperatures of 275, 400, or 525 °C for 2 min. The specimens were thereafter mounted on a cryostat holder and cooled to 13 K where they were optically excited by a 532 nm line from a solid state laser with an excitation power of $\sim 15$ mW. The PL spectra were collected and analyzed by a SpectraPro-2500i triple grating monochromator equipped with a temperature-controlled InGaAs infrared photodetector.

Figure 1 illustrates the PL spectra recorded in the wavelength range of 1100 to 1600 nm at 13 K from silicon-implanted samples with the three different boron doping concentrations after a 2 min RTA at 275 °C. Clearly shown in the PL spectra from both low (9.4 $\times 10^{14}$ cm$^{-3}$) and interme-

a)Electronic mail: spc109@physics.anu.edu.au.

This article is copyrighted as indicated in the article. Reuse of AIP content is subject to the terms at: http://scitation.aip.org/termsconditions. Downloaded to IP: This article is copyrighted as indicated in the article. Reuse of AIP content is subject to the terms at: http://scitation.aip.org/termsconditions. Downloaded to IP: 150.203.176.45 On: Fri, 20 Jun 2014 03:39:19
This article is copyrighted as indicated in the article. Reuse of AIP content is subject to the terms at: http://scitation.aip.org/termsconditions. Downloaded to IP:
150.203.176.45 On: Fri, 20 Jun 2014 03:39:19

Charnvanichborikarn et al.

FIG. 1. PL spectra from p-type silicon wafers with different boron concentrations after 300 keV silicon implantation to a dose of $10^{12}$ cm$^{-2}$ and a subsequent RTA at 275 °C for 2 min. $F_{E_{TO}}$, $B_{TO}$, and $Y$ denote the luminescence peaks from the free exciton radiative recombination associated with the TO phonon or silicon band-edge emission, the TO phonon replica of the boron-bound exciton, and BICs, respectively. The inset shows the PL intensity of the W-line for different fluences, where the lines are guides for the eye.

Diode-like $Y$-line and $F_{E_{TO}}$ are observed to originate from the boron concentration specimens, a strong W-line peak at 1218 nm (1.018 eV) and its phonon replicas at longer wavelengths (lower photon energies). For the lowest boron concentration, the W-line luminescence is observed to be brightest, with relatively weak silicon band-edge luminescence ($F_{E_{TO}}$) at 1129 nm (1.098 eV). When the background boron concentration is about two orders of magnitude higher, the W-line intensity drops significantly and the two new luminescence peaks at 1135 nm ($B_{TO}$) and 1148 nm ($Y$ or $I_2$) are observed. This is also true for all other doses, which are plotted in the inset of this figure. The inset also shows that the W-line intensity increases with dose up to $10^{12}$ cm$^{-2}$ consistent with previous studies.17 This optimal fluence condition also appears to be independent of the boron concentration. For higher Si concentrations, the W-line is quenched as the probability of nonradiative recombination channels becomes more likely with an increasing concentration of irradiation damage.17 The W-line luminescence is not observed in the high boron concentration wafer irrespective of Si concentration. The $B_{TO}$ peak is the transverse optical (TO) phonon of the boron-bound exciton transition18 and the shoulder at $\sim$1130 nm is presumed to be $F_{E_{TO}}$. With respect to the Y-line peak, we note that it has previously been observed from a boron-implanted silicon sample3 and this observation was later attributed to BICs.19 Theoretical calculations of this center, called $B_{2}$ (a trigonal tri-interstitial cluster containing two boron atoms and one silicon interstitial), is similar in structure to the tri-interstitial cluster proposed for the W defect.10 A comparison of the spectra in Fig. 1 clearly shows that the intensity of the PL at 1218 nm ($W$ or $I_1$) increases with decreasing boron concentration. The W-line luminescence entirely disappears when the boron concentration is of the order of $3.2 \times 10^{18}$ cm$^{-3}$ for this anneal schedule.

After a 2 min RTA at 400 °C, the W-line and its replicas are still observed to dominate the spectrum of the low boron concentration wafer as shown in Fig. 2. In addition to the W-line and $F_{E_{TO}}$, a relatively weak X peak is clearly seen at 1193 nm. Similar to the samples annealed at 275 °C, the W-line intensity is observed to drop with increasing boron concentration. On the other hand, the Y-line intensity initially increases with boron concentration at least up to a background boron level of about $1.1 \times 10^{17}$ cm$^{-3}$. The sharpness of the $Y$-line indicates that it is relatively unperturbed and electronically isolated from the boron doping band. For the highest boron concentration of $3.2 \times 10^{18}$ cm$^{-3}$, a low intensity $Y$-line appears in the PL spectrum of the wafer. The corresponding high resolution PL is shown in the inset, where we note that the clear red-shift of the $B_{TO}$ is due to the high boron doping level.20

Figure 3 shows the PL spectra measured at 13 K from the different p-type silicon wafers after Si-irradiation and thermal annealing at 525 °C for 2 min in Ar. For the low boron concentration case, the W and $Y$ peaks are annealed out by 525 °C as can be expected from previous published work,3 but the more thermally stable X peak remains at 1193 nm (1.040 eV) with its transverse acoustic phonon replica on an intense broad luminescence band. This broadband luminescence is the brightest feature observed for this spectrum, extending from approximately 1220 nm to over 1600 nm. A similar broad spectral band has previously been reported and attributed to strain surrounding interstitial defect clusters after silicon implantation and annealing at 600 °C for 4 h.21 We believe that the observed broadness arises from the localized strain in the early stages of extended defect formation and/or large clusters involving silicon interstitials.22,23 Like the W-line, the intensities of this broadband and the $X$-line, if observable, decrease with increasing boron concentration.

FIG. 2. PL spectra for boron-doped p-type silicon wafers implanted with 300 keV Si$^+$ to a dose of $10^{12}$ cm$^{-2}$ and subsequently annealed at 400 °C for 2 min. The inset is a high resolution PL spectrum showing a weak $Y$-line luminescence and a $B_{TO}$ peak observed from the wafer with the highest boron concentration (lowest resistivity).

FIG. 3. PL spectra for boron-doped p-type silicon wafers implanted with 300 keV Si$^+$ to a dose of $10^{12}$ cm$^{-2}$ followed by an anneal at 525 °C for 2 min.
regardless of Si fluence. The features appearing around 1375 nm are known to result from atmospheric water vapor absorption.\(^{32,33}\) The B\(_{10}\) peak intensity becomes strongest for the intermediate boron concentration sample. Apart from a very weak red-shift B\(_{10}\) band, the sample with the highest boron doping concentration (3.2 \(\times 10^{18}\) cm\(^{-3}\)) has no interesting features.

Our observations of the boron doping effect on defect luminescence need to be interpreted with care. Two possible contributing factors are as follows: (i) competition between formation of optically active silicon-interstitial clusters and BICs and (ii) a process in which the silicon-interstitial clusters are formed but the presence of BICs promotes a non-radiative recombination pathway that acts to quench the luminescence from the W- and X-centers. Silicon interstitials are known to interact strongly with boron as in the transient enhanced diffusion process.\(^{25}\) It is, therefore, rational to expect that more interstitials initially bound in small clusters become trapped in boron clusters with increasing boron concentration. This behavior is consistent with an earlier study on B–Si interstitial interactions, where it was demonstrated by transmission electron microscopy that a high concentration of boron (\(\geq 10^{19}\) cm\(^{-3}\)) was sufficient to prevent the formation of \{311\} rod-like defects (RLDs).\(^{26}\) These results clearly show that the silicon interstitials can become tightly bound in boron-rich clusters which prevent silicon-interstitial related \{311\} RLDs from forming as well as the mass migration of silicon interstitials.\(^{27}\) Such behavior is also consistent with Pelaz’s modeling that indicates that self-interstitials can be bound in immobile silicon-rich BICs in the initial stages of annealing.\(^{27,31}\) The W-center in our case has been postulated to be one of the building blocks of these RLDs.\(^{28}\) The \{311\} RLDs also act as interstitial sources in agglomeration and dissolution processes.\(^{26}\) Thus, it is not surprising to observe in this work that the W-line is completely suppressed with a boron concentration of 3.2 \(\times 10^{18}\) cm\(^{-3}\), which is slightly lower than the concentration required to inhibit the formation of the RLDs in the higher annealing temperature regime.

Given the evidence outlined above, we believe that competition between optically active silicon-interstitial clusters and BICs is the main reason behind the dramatic reduction in the W-line intensity and the intensity of other interstitial-related luminescence centers with increasing boron concentration. Indeed, it is highly possible that the formation of the small interstitial defect clusters giving rise to the W-line, X-line, and broad luminescence band is suppressed by the presence of boron in a similar manner as observed for the RLDs. However, the exact pathway and the nature of the boron-related centers are not well understood. In the samples with the lower boron concentrations, the suppression of the W-line is accompanied by an increase in the Y-line intensity. However, at the highest boron concentration the Y-line intensity is also suppressed. In fact, all interstitial related luminescence is suppressed across the entire spectrum. This cannot necessarily be interpreted as a reduction in the concentration of Y-centers since it appears that there may be other quenching mechanisms at play.

In conclusion, we have shown that boron generally has a detrimental effect on the PL intensity of several interstitial-related luminescence centers including W- and X-centers. For the sample containing the highest boron concentration studied here, the luminescence from these centers is completely suppressed. This is attributed predominantly to the active participation of silicon interstitials in the formation of BICs. A high boron concentration, therefore, results in a higher concentration of silicon interstitials locked up in BICs and thus unavailable for the formation of optically active silicon interstitial clusters. A similar observation whereby boron inhibits the formation of the \{311\} RLDs in a higher Si fluence and higher annealing temperature regime was discussed. The present work shows that the optically active centers that are thought to be the precursors to these extended defects are also affected and are, in fact, more sensitive to the presence of boron.

We thank Professor Bob Jones for fruitful discussions. This work was financially supported by an Australian Research Council Discovery project (DP0985131).

---