

## Micro-Photoluminescence Study on the Influence of Oxidation on Stacking Faults in 4H-SiC Epilayers

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We have investigated the influence of thermal oxidation on stacking faults (SFs) in 4H-SiC epilayers by performing micro-photoluminescence measurements for 4H-SiC substrates before and after thermal oxidation. We found that SF (emission wavelength:  $\sim 425.5$  nm) thought to be a single Shockley stacking fault was expanded by thermal oxidation. In addition, as a result of comparison between before and after Ar annealing, the SF was not extended after Ar annealing. We also found that only the SFs extended by laser irradiation is eliminated by oxidation.

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**S**ilicon carbide (SiC) semiconductor is expected to realize lower-loss and higher-speed power devices than conventional ones because it has values of physical property such as wide band gap, high breakdown field, and high thermal conductivity. However, stacking faults (SFs) are easily incorporated in the SiC epitaxial layer<sup>1-4</sup> and they may cause a degradation of SiC power device performances, e.g., forward current–voltage characteristic degradation.<sup>5,6</sup> By the way, thermal oxidation is often used for fabrication processes of SiC devices because the SiO<sub>2</sub> film grown by it is utilized as a metal–oxide–semiconductor (MOS) junction or a surface passivation film. However, it has been reported that the SiC layer just under the SiO<sub>2</sub> film changes in quality after thermal oxidation. For example, according to the report from Hiyoshi and Kimoto,<sup>7</sup> carbon vacancies present in an as-grown epilayer are filled with carbon interstitials emitted to the SiC layer during thermal oxidation and, in turn, density of deep level states can be reduced. On the other hand, Okojie *et al.* have reported that thermal oxidation of highly doped ( $10^{19}$  cm<sup>-3</sup> order) 4H-SiC epilayer induces the formation of multiple SFs having 3C structure.<sup>8</sup> In this study, aiming to obtain knowledge on the influence of oxidation on SFs in 4H-SiC epilayers, we performed micro-photoluminescence (micro-PL) measurements. We examined the influence of thermal oxidation on SFs in 4H-SiC epilayers by comparing the PL spectra and PL images obtained before with those after thermal oxidation.

We used commercial n-type 4H-SiC(0001) substrates with carrier concentration of  $1 \times 10^{16}$  cm<sup>-3</sup>, 8° off-orientation towards [11 $\bar{2}$ 0], and epilayer thickness of 10  $\mu$ m. Thermal oxidation was carried out at 1100 °C in a dry oxygen flow of 1 slm for 10 h, resulting in oxide thickness of 43 nm. A Q-switched ultraviolet laser ( $\lambda = 266$  nm) with a spot diameter of 0.7  $\mu$ m and irradiation power of 160  $\mu$ W was used as the excitation source for micro-PL spectroscopy and PL intensity mapping. PL measurements were performed at room temperature. The sample was mounted on the XYZ stage with a spatial resolution of 0.1  $\mu$ m, and PL intensity mapping was performed with 20  $\mu$ m scanning step and an irradiation duration of 0.2 s. We previously confirmed that this irradiation energy condition for PL measurements is the upper limit not to extend/form a SF.

Figure 1 shows the PL intensity mapping image obtained at the emission wavelength of 425.5 nm before (a) and after

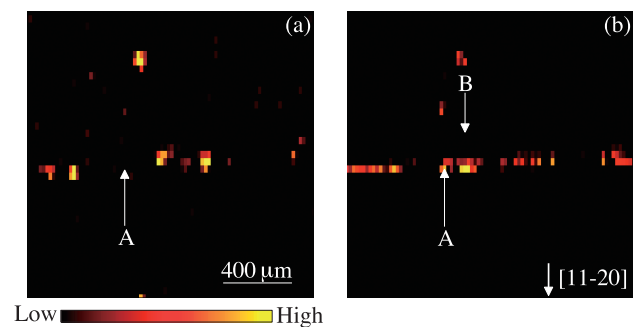


Fig. 1. PL intensity mapping image obtained at the emission wavelength of 425.5 nm (a) before and (b) after thermal oxidation of 4H-SiC epilayer.

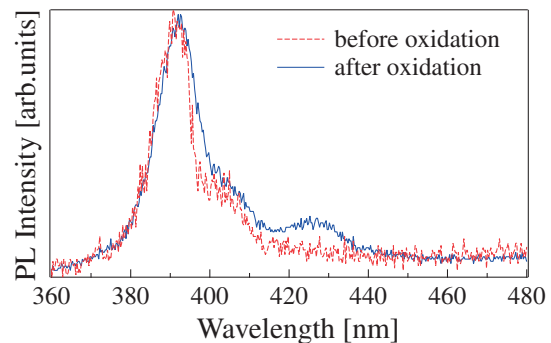


Fig. 2. PL spectra at point A (Fig. 1).

(b) thermal oxidation of 4H-SiC epilayer. It can be seen that the emission spots, which originate from SFs,<sup>9</sup> expanded and/or formed to the directions of [1 $\bar{1}$ 00] and [1100] from the SFs present before the thermal oxidation (i.e., as-grown SFs). Figure 2 shows the PL spectra at point A in Fig. 1. The expansion of SFs is confirmed also from the fact that the intensity of SFs-induced emission (425.5 nm) increases.

Next, we irradiated around the SFs in the center of Fig. 1(b) to observe the effects of laser irradiation to these SFs. The irradiation power was 640  $\mu$ W, i.e., 4 times higher than that of PL intensity mapping measurements, by giving 4 times scanning steps. Figure 3 shows the PL intensity mapping image after laser irradiation. In the comparison Fig. 1(b) with Fig. 3, it is clearly seen that SFs are significantly expanded/formed by the laser irradiation. In addition,

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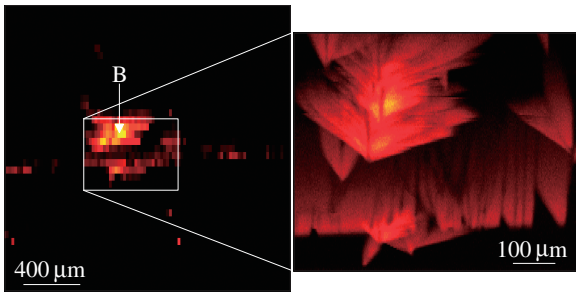


Fig. 3. PL intensity mapping image at  $\lambda = 425.5$  nm after laser irradiation.

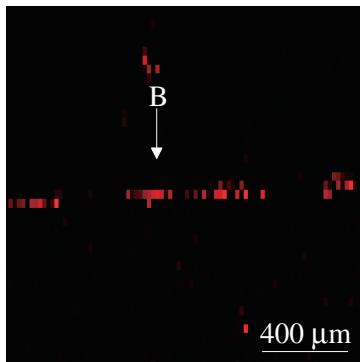


Fig. 4. PL intensity mapping image at  $\lambda = 425.5$  nm after re-oxidation for the laser irradiated sample.

it can be seen from the inset in Fig. 3 ( $1\ \mu\text{m}$  scanning step) that the main expansion direction is  $[1\bar{1}20]$ , however, the expansion to other directions can also be seen. We again carried out oxidation of this irradiated sample for 13 h, resulting in total oxide thickness of 77 nm. Figure 4 shows the PL intensity mapping image after re-oxidation for the laser-irradiated sample. In comparison Fig. 3 with Fig. 4, it is found that the SFs expanded/formed by the laser irradiation vanish by re-oxidation, whereas, as-grown SFs and expanded/formed by the first thermal oxidation do not vanish. It is also confirmed from the comparison of PL spectra in Fig. 5 at point B [see Figs. 1(b), 3, and 4] that the SFs expanded/formed by the laser irradiation vanish after re-oxidation. It is believed that the vanish of SFs by re-oxidation is due to the effect of heating accompanied with thermal oxidation because the SF extended by laser irradiation can be shrank/removed by heating (annealing), as has been reported by Miyanagi *et al.*<sup>10)</sup>

In order to examine the difference in the effect of annealing and thermal oxidation, micro-PL measurements were carried out also for before and after Ar annealing. For making a comparison with thermal oxidation, Ar annealing was conducted with the same temperature and time as those of thermal oxidation. As a result, no expansion/formation of SFs due to Ar annealing was observed. Therefore, oxidation has somewhat particular affection that cannot be obtained with Ar annealing.

As SFs with the emission wavelength near 425.5 nm, single Shockley SF (1SSF,  $\sim 420$  nm) and extrinsic Frank-type SF ( $\sim 424$  nm) have been previously reported. It has been reported that an 1SSF is induced and expanded by the

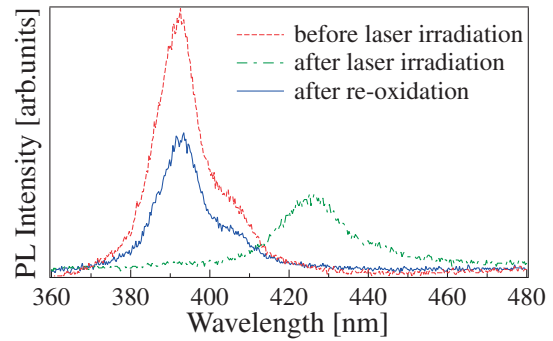


Fig. 5. Comparison of PL spectra at point B [Figs. 1(b), 3, and 4].

high-intensity laser beam scanning and shrunk by annealing,<sup>10,11)</sup> while an extrinsic Frank-type SF cannot be expanded by the high-intensity laser beam scanning.<sup>2)</sup> Therefore, we believe that the SFs observed in this study originate from 1SSF.

The SFs expanded/formed by thermal oxidation are perhaps different from those expanded/formed by laser irradiation because there is a significant difference in which the former does not vanish but the latter vanish after re-oxidation (or heating). According to the report from Miyanagi *et al.*,<sup>10)</sup> there are two types of 1SSF, i.e., isosceles triangle (looped basal-plane dislocation, BPD) and right-angled triangle (propagated BPD). They also reported that the looped-type shrinks and vanishes easily by annealing, whereas, the propagated-type is hard to shrink. Therefore, we consider that the SF expanded/formed by laser irradiation is the looped-type 1SSF and the SF expanded/formed by thermal oxidation is the propagated-type 1SSF. However, it is also probable that the influence of thermal oxidation (or laser irradiation) is different in accordance with stacking sequence such as SSF(13) and SSF(31), or that this SF is an unknown SF which has not been reported.

Consider why the SFs were expanded/formed by thermal oxidation. Since the interatomic distance of Si is different between SiC and SiO<sub>2</sub>, strain arises at the SiC–SiO<sub>2</sub> interface during thermal oxidation.<sup>12)</sup> A SF has in general two partial dislocations at the both end of it, the partial dislocations are strongly affected from a strain because they are boundaries between normal crystal and the crystal slid, and, hence, they are easily moved. That is, partial dislocations relax the strain at the SiC–SiO<sub>2</sub> interface accompanied with thermal oxidation by moving the partial dislocations toward the normal crystal side and, as a result, SFs were extended. On the other hand, since naturally Ar annealing does not form an oxide film, strain does not arise. Therefore, it is considered that Ar annealing never expands/forms SF even if it reduces/removes SFs.

In conclusion, we observed the influence of thermal oxidation on SFs in 4H-SiC epilayers with micro-PL measurements. By comparing the images and the spectra between before and after thermal oxidation, we found that, after thermal oxidation, SFs (425.5 nm) thought to be 1SSFs were expanded toward the  $[1\bar{1}00]$  and  $[\bar{1}100]$ . In addition, as a result of comparison between before and after Ar annealing, we confirmed that SF was not expanded at all after Ar annealing. These results suggest that the expansion of SF

attributed to thermal oxidation is caused by strain near the SiC–SiO<sub>2</sub> interface during oxidation. We also found that the SFs expanded by laser irradiation is shrunk by oxidation, in contrast, those of as-grown type and oxidation-induced type are not shrunk. This suggests that, despite same emission wavelength, the oxidation-induced SF is different type from the laser irradiation-induced SSF.

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- 1) H. Tsuchida, I. Kamata, and M. Nagano: *J. Cryst. Growth* **310** (2008) 757.
- 2) I. Kamata, X. Zhang, and H. Tsuchida: *Appl. Phys. Lett.* **97** (2010) 172107.

- 3) G. Feng, J. Suda, and T. Kimoto: *Appl. Phys. Lett.* **92** (2008) 221906.
- 4) G. Feng, J. Suda, and T. Kimoto: *Appl. Phys. Lett.* **94** (2009) 091910.
- 5) H. Lendenmann, F. Dahlquist, N. Johansson, R. Söderholm, P. A. Nilsson, J. P. Bergman, and P. Skytt: *Mater. Sci. Forum* **353–356** (2001) 727.
- 6) H. Fujiwara, T. Kimoto, T. Tojo, and H. Matsunami: *Appl. Phys. Lett.* **87** (2005) 051912.
- 7) T. Hiyoshi and T. Kimoto: *Appl. Phys. Express* **2** (2009) 091101.
- 8) R. S. Okojie, M. Xhang, P. Pirouz, S. Tumakha, G. Jessen, and L. J. Brillson: *Appl. Phys. Lett.* **79** (2001) 3056.
- 9) S. G. Sridhara, F. H. C. Carlsson, J. P. Bergman, and E. Janzén: *Appl. Phys. Lett.* **79** (2001) 3944.
- 10) T. Miyanagi, H. Tsuchida, I. Kamata, and T. Nakamura: *Appl. Phys. Lett.* **89** (2006) 062104.
- 11) N. Hoshino, M. Tajima, M. Naitoh, E. Okuno, and S. Onda: *Mater. Sci. Forum* **600–603** (2009) 349.
- 12) Y. Hijikata, H. Yaguchi, and S. Yoshida: *Appl. Phys. Express* **2** (2009) 021203.