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Photoluminescence Study of Oxidation-Induced Stacking Faults in 4H-SiC Epilayers

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Abstract. We have investigated the effect of thermal oxidation on stacking faults (SFs) in 4H-SiC epilayers using photoluminescence imaging. We found that a comb-shaped dislocation array was deformed by thermal oxidation and that SFs were formed on both sides of the comb-shaped dislocation array by a laser irradiation. Transmission electron microscopy has been performed in the comb-shaped dislocation array to observe the stacking pattern of SF near the dislocation. As a result, the SF turned out to be a single Shockley SF (1SSF). We also found that line-shaped faults perpendicular to the off-cut direction were formed during oxidation and were stretched with oxidation time. Moreover, triangle-shaped SFs were formed/expanded from the line-shaped faults by a laser irradiation. The characteristics of these line-shaped faults were discussed.

Introduction

SiC semiconductor is an attractive material for developing high-power, high-temperature, and high-frequency devices, owing to its superior physical properties. However, stacking faults (SFs) are easily incorporated in SiC epitaxial layers and they may cause a severe degradation of SiC power device performances [1,2]. By the way, thermal oxidation is often used in fabrication processes of SiC devices because SiO_2 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_2 film changes in quality after thermal oxidation. For example, Hiyoshi and Kimoto have reported that carbon vacancies present in an as-grown epilayer are filled with carbon interstitials emitted to the SiC layer during thermal oxidation [3]. On the other hand, according to the report from Okojie *et al.* [4], thermal oxidation of highly doped (10^{19} cm^{-3} order) 4H-SiC epilayer induces the formation of multiple SFs having 3C structure. We previously investigated the effect of thermal oxidation on the SFs in 4H-SiC epitaxial layer using micro-photoluminescence (micro-PL) [5]. In the work, we found that SFs (emission wavelength: 425.5 nm) were formed/expanded by thermal oxidation. However, because a micro-focusing excitation laser beam widely and complicatedly expands the SFs, detailed observation of the SFs cannot be performed. In this study, we have investigated the effect of thermal oxidation on SFs using PL imaging. According to the PL imaging, the power density and irradiation time of excitation laser light can be remarkably reduced, and dislocations can also be observed by using near-infrared-band emission [6]. In addition to the PL imaging, we performed transmission electron microscopy (TEM) to observe the SFs with atomic scale.

Experiments

Commercial *n*-type 4H-SiC (0001) substrates with a carrier concentration of 1×10^{16} cm^{-3}, 8° off-orientation towards [11–20], and epilayer thickness of 10 μm were used in this study. A He-Cd laser (λ=325 nm) was used as the excitation source for PL imaging measurements. PL images were magnified by objective lens and captured by a CCD camera through a long pass optical filter (> 700 nm) or band pass optical filter (438±12 nm). PL imaging was performed at room temperature.

First, we performed PL imaging, and observed a comb-shaped dislocation array along the [11–20] direction. Before oxidation of the sample, a laser irradiation in the vicinity of the comb-shaped dislocation array was performed and we observed PL images before and after the laser irradiation. A Q-switched ultraviolet laser (λ=266 nm) with a spot diameter of 0.7 μm and irradiation power of 160 μW (power density is about 4×10^4 W/cm^2) was used as an irradiation source. Then, Ar annealing was carried out at 1000 °C for 1 h. Thermal oxidation was carried out at 1100 °C in a dry oxygen flow of 1 slm for 10 h. We observed the stacking pattern of the oxidation-expanded SF using a TEM.

We also investigated the effect of thermal oxidation in another comb-shaped dislocation array in the case without laser irradiation before oxidation. We performed two times thermal oxidation to the sample. The first time was carried out at 1100 °C in a dry oxygen flow of 1slm for 10 h, and the second time was carried out at the same temperature and same atmosphere for 12 h. We observed PL images before and after each thermal oxidation. After all oxidation of the sample, a laser irradiation was performed. A He-Cd laser (λ=325 nm) was used as an irradiation source.

Results and discussion

Figure 1 shows the PL image of before (a) and after (b) laser irradiation and after Ar annealing (c). We found that SFs formed on both sides of the comb-shaped dislocation array by the laser irradiation. Then, only SFs formed by laser irradiation vanish after Ar annealing. It is suggested that these new SFs are single Shockley SFs (1SSFs) because the emission wavelength of these SFs is about 426 nm [1].

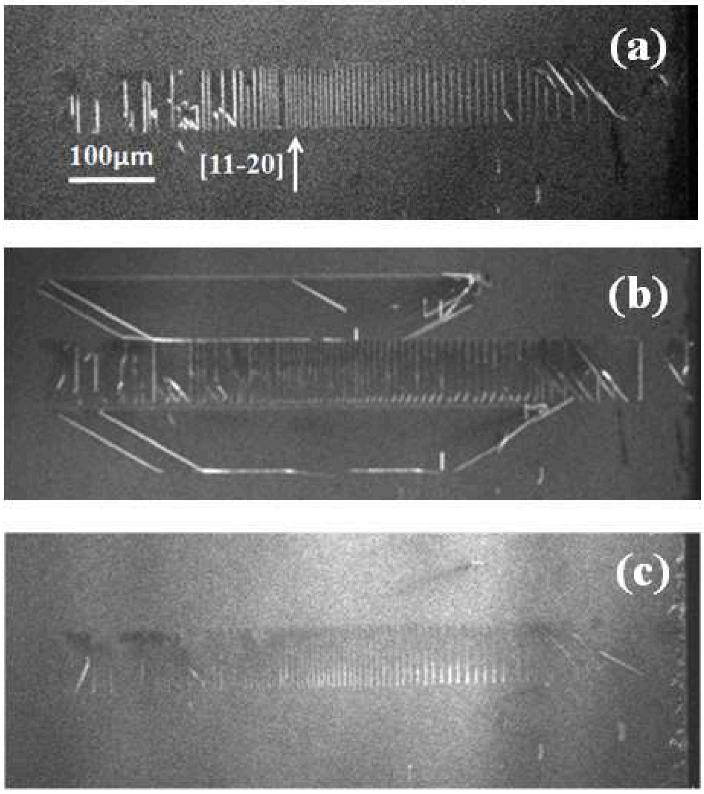

Fig.1 PL image with a long-pass filter (>700nm).
(a) before and (b) after irradiation
(c) after Ar annealing.

Figure 2 shows the PL image of the sample after thermal oxidation. We found that the dislocation is deformed toward [1–100] or [–1100] direction by thermal oxidation.

Figure 3 shows the high-resolution TEM image in the vicinity of comb-shaped dislocation array deformed by oxidation. The stacking sequence of the SF was (1,3) in the Zhdanov's notation. Therefore, these SFs are found to be a 1SSF.

Both of the irradiation-induced SF and the oxidation-induced SF were 1SSF. According to the report from Miyanagi *et al.* [7], 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 by laser irradiation is the looped-type 1SSF and the SF deformed by thermal oxidation is the propagated-type 1SSF.

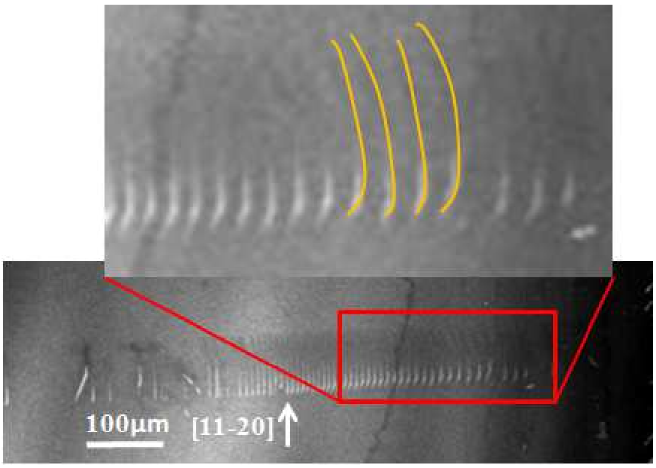

Fig.2 PL image with a long-pass filter (>700nm) after thermal oxidation.

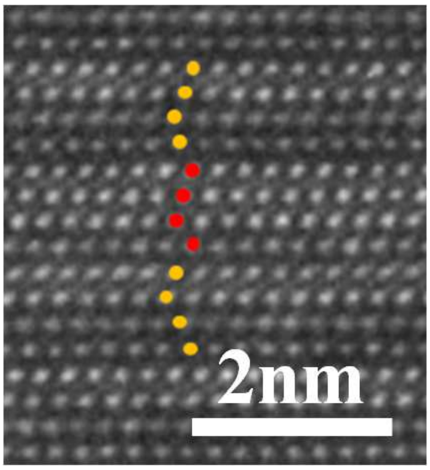

Fig.3 TEM image where SF is deformed by thermal oxidation.

Figure 4 shows the PL images of the another comb-shaped dislocation array through a band-pass filter (438±12 nm) before (a) and after the first time oxidation (b) and after the second time oxidation (c). We found that line-shaped faults perpendicular to the off-cut direction formed after the first time oxidation (marked with arrows in Fig. 4(b)), and they were extended after the second time oxidation. The faults are not seen through a long pass optical filter (> 700 nm) and, hence, they may not be dislocation because any kinds of dislocations have near-IR emission [6]. Triangle-shaped SFs shown in Fig. 4(c) (inside the red rectangular) were formed by the laser irradiation and expanded from the line-shaped faults along the [–1–120] direction, getting wider with irradiation duration. From the expanding direction, they may be extended from the oxidizing interface to epilayer. Figure 5 shows the PL spectrum emitted from the triangle-shaped SFs. These SFs are suggested to be double Shockley SFs (2SSFs) because their emission wavelength (500 nm) corresponds to 2SSF [1]. We have not confirmed the spectrum of line-shaped faults yet, but from the PL image, they may have the 2SSF structure identical to the triangle-shaped SFs.

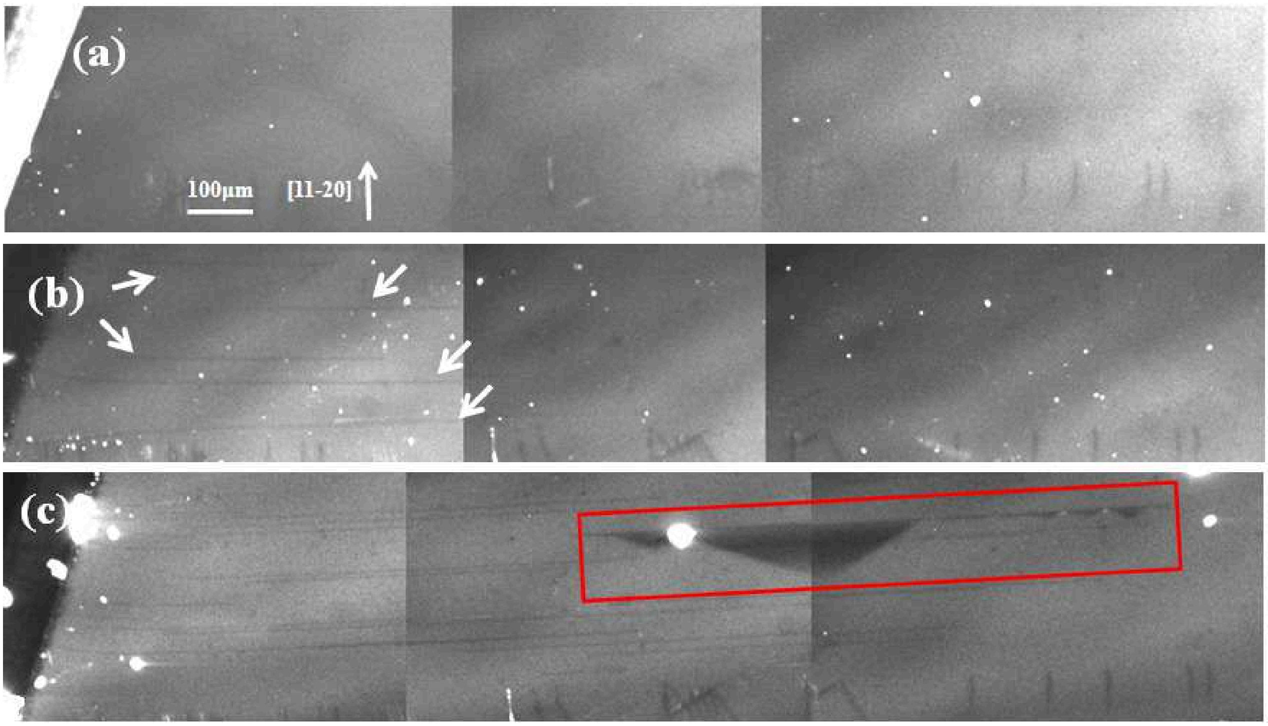

Fig.4 PL image with a band-pass filter (438±12 nm):
(a) before oxidation (b) after the first oxidation, and (c) after the second oxidation.

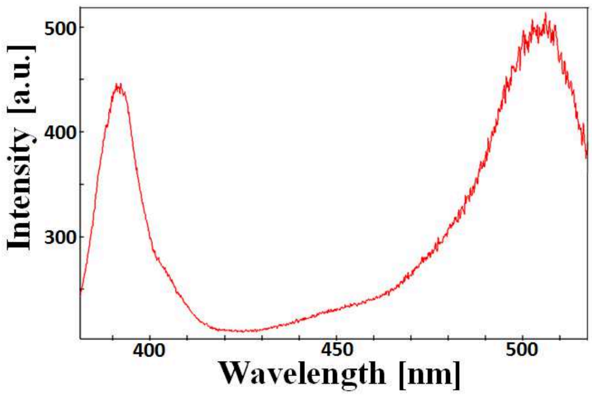

Fig.5 PL spectrum of triangle-shaped SFs

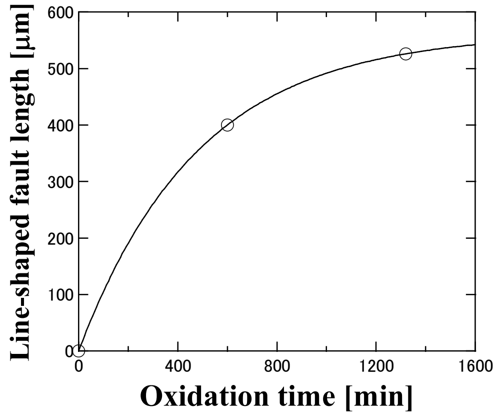

Fig.6 Line-shaped fault length vs oxidation time at 1100 °C in dry O_2.

Figure 6 shows the relationship between average length of line-shaped faults and oxidation time. As seen in the figure, the line-shaped fault length logarithmically increases with oxidation time. In the case of Si oxidation at 1150 °C in wet O_2 (wafer thickness is over 80 μm), oxidation-induced stacking faults (OSF) length is less than 10 μm [8]. Thus, the OSF length of SiC appears to be longer, compared with Si. The cause of this result may be that the stress around oxide–SiC interface is stronger than that of Si because the interatomic distance of SiC is smaller than that of Si and this enhances the misfit against SiO_2. Since such an interfacial stress gives rise to an interstitial emission during oxidation [3,8–9], the emission rate of interstitials in SiC oxidation may be larger than that of Si. In addition, the reason for logarithmically increase in the line-shaped faults length can be explained by considering that Si and/or C interstitials logarithmically increase with oxidation time.

Summary

We performed PL imaging to investigate the effect of thermal oxidation on SFs in 4H-SiC epilayers. We found that a comb-shaped dislocation array was deformed by thermal oxidation. TEM has determined the kind of SF for the comb-shaped dislocation array, and this SF turned out to be a 1SSF. We regarded this SF as a propagated type 1SSF because of its annealing characteristic and shape. We also found line-shaped faults perpendicular to the off-cut direction and they were extended more with oxidation time. In addition, 2SSFs were formed from the line-shaped faults as the starting point by a laser irradiation.

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