Suppressed expansion of single Shockley stacking faults at narrow widths in 4H-SiC

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UV-induced expansion of single Shockley stacking faults (1SSFs) in 4H-SiC was found to be suppressed when the width of 1SSFs \( w \) is narrower than a certain value of \( w_r \). The intensity profiles of 1SSF-originated photoluminescence (PL) show an initial growth with \( w \) followed by an intensity ceiling beyond \( w_r \). The characteristic width \( w_r \) is several tens of \( \mu \text{m} \) at room temperature, which is close to the range of 1SSF PL reduction near the partial dislocations bounding the 1SSF. A qualitative reasoning is discussed for the larger 1SSF expansion threshold in n-type buffer/substrate interfaces than in n-type drift layers. © 2019 The Japan Society of Applied Physics

| Table I. Properties of four samples used. |
| Sample A | Sample B | Sample C | Sample D |
| --- | --- | --- | --- |
| **Conduction-type** | n | n | n | p |
| **Off angle** | 4° | 8° | 8° | 8° |
| **Epi-film thickness** (\( \mu \text{m} \)) | 120 | 36 | 36 | 50 |
| **Dopant concentration** (cm\(^{-3}\)) | 10\(^{15}\) | 5 × 10\(^{13}\) | 1.5 × 10\(^{13}\) | 2 × 10\(^{14}\) |
| **Minority carrier lifetime** (\( \mu \text{s} \)) | 10 | 0.13 | 0.4 | 3.5 |

The degradation due to anomalous expansion of single Shockley stacking faults (1SSFs) in 4H silicon carbide (4H-SiC) induced by forward current injection hampers the reliable usage of high-power bipolar devices based on this material.\(^1,2\) This phenomenon presumably arises from two causes: One is the rise of a driving force for the 1SSF expansion and the other is the enhanced glide of Si-core partial dislocations (PDs) leading to expansion of the stacking faults.\(^3,4\) The driving force for expansion of 1SSF induced by forward current stressing is considered to be owing primarily to the trapping of free electrons in the conduction band to the 1SSF-originated gap levels located at \(-0.3\) eV below the conduction band.\(^5\) The role of holes injected as minority carriers to n-type epi-layers is to efficiently screen the negative charge due to the trapped electrons thereby reducing the electrostatic energy.\(^6,7\) Similarly in p-type layers, the majority carriers (holes) act to screen the negative charge allowing substantial trapping of minority carriers (free electrons) to the 1SSF. Hence, reducing the minority carrier density by intentional introduction of recombination centers would suppress the expansion of 1SSFs.\(^11,12\) In fact, bipolar degradation in 4H-SiC PiN diodes is greatly suppressed by insertion of a recombination-enhanced n\(^+\) buffer layer between the substrate and the upper n\(^−\) drift layer.\(^12,13\)

Nevertheless, the threshold current density necessary for 1SSF expansion from buffer/substrate interfaces is, for unknown reason, nearly one order of magnitude larger than that in the drift layer.\(^14\) This is a basic problem from the scientific viewpoint, and to elucidate its cause is of technological importance for reliability of the devices in such a structure. The present report shows that the velocity of 1SSF expansion, induced by UV light illumination\(^15,16\) instead of bipolar current stressing, depends on the width of 1SSF and is largely reduced at narrow 1SSF widths. The experimental findings could be qualitatively understood in terms of the driving force for expansion of 1SSFs in finite widths, and provide a reasoning for the discrepancy in the threshold hole density between the drift layer and the buffer/substrate interface.

Four samples used were (0001) Si-face 4H-SiC wafers CVD-grown\(^17\) with epi-layers differing in the properties shown in Table I. The off-cut angle toward (1120) direction was 4° in Sample A and 8° in Samples B, C and D. The conduction type was n-type in Samples A, B and C and p-type in Sample D. Sample C was prepared from Sample B by thermal oxidation/annealing processes\(^19\) to reduce the density of lifetime killer \( Z_{1/2} \) centers. The dopant concentrations were deduced from capacitance–voltage characteristics and the minority carrier lifetimes were evaluated by the time-resolved photoluminescence method.\(^12\) Since the 4°-off Sample A contained practically no basal plane dislocations (BPDs) threading the epilayer,\(^20\) its surface was indented by a micro-Vickers diamond stylus with a load of 10 g to intentionally introduce BPD loops.

Photoluminescence (PL) imaging\(^21\) was conducted at room temperature by using an optical microscope installed with an electrically cooled CCD camera (PIXIS 2048BR). A short wavelength cut filter (<370 nm) was used for panchromatic imaging, a band pass filter (425 ± 15 nm) for imaging 1SSFs and a band pass filter (700 ± 6 nm) for occasionally imaging PDs. For photo-exciting the samples to generate luminescence for PL imaging and simultaneously to induce expansion of 1SSFs, an unexpanded beam of 355 nm laser was guided from a cw diode-pumped solid-state laser (Titan Infinity) to the sample surface with an incident angle of 60° inclined from the sample normal. The light intensity was adjusted to \( 6 \times 10^6 \) or \( 2 \times 10^7 \) W m\(^{-2} \) on the sample surface. The velocity of 1SSF expansion was evaluated by dividing the increment of 1SSF width \( w \) as defined in Figs. 1(a) and 1(b) with the time interval between the successive PL imaging. The intensity profiles across 1SSFs were analyzed...
along the stripe areas as shown in Figs. 1(c) and 1(d) by averaging the PL pixel signals along the short side of the rectangle. To extract PL intensity profiles due to 1SSFs, a background PL baseline was subtracted from the raw PL signals. The exposure time for each PL imaging was adjusted to maintain the linearity of the CCD signals.

To measure the threshold current density at which bar-shaped 1SSFs initiated to expand from the n⁺-buffer/sub interface at temperatures around 90 °C, the electroluminescence signal was monitored while changing the current density of the PiN diodes having a patterned electrode and an implanted p⁺ contact layer (Al: $2.0 \times 10^{20}$ cm$^{-3}$, 0.3 μm thick) as a p-type anode instead of p-type epilayer anodes doped with various Al concentrations used in a similar study previously reported. In a wider range of temperatures, the same samples were subjected to measurements of the threshold current for the expansion of 1SSFs in the n− drift layer which had been already widely expanded beyond 100 μm. These experiments were conducted for three PiN diode chips doped with N concentration of $1 \times 10^{16}$ cm$^{-3}$ in the n− drift layer and $4 \times 10^{17}$ cm$^{-3}$ in the n⁺ buffer layer. The hole concentration within the PiN diode under the certain temperature and current density was numerically calculated using a device simulator.

Figure 2 shows the dependences of 1SSF expansion velocity on the width of 1SSFs measured for the four samples. In all the samples, the velocity initially increased with 1SSF width $w$ and reached terminal values. These terminal values varied for the four samples due to differences in the sample properties and the illumination intensity, but were almost identical within the same sample as far as the tracked Si-core PDs were oriented at an angle of 30° to the

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**Fig. 1.** (Color online) Typical PL images. (a) 700 nm monochromatic image (Sample A), (b) panchromatic image (Sample B), (c) 425 nm image of the same area as (a), and (d) 425 nm image of the same area as (b). The step flow direction is downward in (a) and (c) and upward in (b) and (d). The distance $w$ defines the width of a 1SSF and the rectangles indicate regions of interest used for analyzing profiles of 1SSF PL intensity.
Burgers vector and with a length longer than about 200 μm.
Hereafter we give a term of “run-up width” for the 1SSF width $w_r$ beyond which the velocity reaches a ceiling level. We noted that $w_r$ was, without significant variations within the same sample, commonly about 30 μm in Samples A, B and D, but about 50 μm in Sample C.

Gray curves in Figs. 3(a) and 3(b) indicate the development of 1SSF-PL intensity profiles acquired for Samples A and B. The open circles recite for comparison the 1SSF width dependence of the 1SSF expansion velocity already shown in Fig. 2. The abcissa for the gray curves represents the distance from the immobile C-core PD and that for the circles is interpreted as the width of 1SSF. With increasing 1SSF width $w$, the 1SSF PL profiles developed with the maximum intensity which grew to reach a saturation level after the 1SSF width exceeded the run-up width $w_r$. As a consequence, the $w$-dependence of expansion velocity appears to roughly follow the peaks of the PL profiles.

Another notable fact in PL profiles is that the PL intensity shows a distinct decrease near the PDs bounding the 1SSF. As shown in Fig. 3(c), the range of PL intensity reduction was almost the same regardless of the PD type, C-core or Si-core, and was common to the four samples differing in electronic properties.

Figure 4 shows the threshold hole densities for initiation of current-induced 1SSF expansion from the $n^2$-buffer/substrate interfaces and for expansion of 1SSFs in widths $w \gg w_r$. A pronounced fact common in the three PiN diodes is that the threshold hole density in the $n^2$ drift layers is systematically almost one order of magnitude smaller than in the $n^2$-buffer/substrate interfaces.

Since the mobile Si-core PD and the counterpart immobile C-core PD interact elastically with a force inversely proportional to the 1SSF width separating the two PDs, one may imagine that the run-up width is of this mechanical origin. In fact, the elastic interaction is attractive in Sample A in which the counting PDs have the same Burgers vector. However, the interaction is repulsive in Samples B, C and D where the two PDs have different Burgers vectors, which would predict enhancement, in contrary to the experimentally observed suppression, of 1SSF expansion in small $w$. Therefore, the run-up width is not of such a mechanical origin.

The origin of the driving force for 1SSF expansion induced by UV light illumination and electron-beam irradiation should be essentially the same as that induced by forward current stressing. The reduction of 1SSF formation energy $\Delta \gamma_{1SSF}$ is primarily owing to the trapping of electrons at the gap level associated with 1SSF that is enhanced by efficient screening of the built-up negative charge by free holes. Meanwhile, the local intensity $I_{1SSF}$ of 1SSF- originated PL should be proportional to the local density of electrons trapped at the 1SSF. Experimentally, as shown in Fig. 3, the intensity of $I_{1SSF}$ is reduced near the PDs at the periphery of the 1SSF, which suggests that a part of the electrons occupying the 1SSF gap states recombine with holes at the PDs. Assuming that electrons trapped at a planar 1SSF diffuse along the 1SSF until they are annihilated at the PDs, we could consider a diffusion length $\lambda$ given by the diffusion constant of free electrons two-dimensionally confined in the 1SSF band states and the electron emission/recombination rate from the 1SSF band, both of which have properties intrinsic for the 1SSF. The profile of $I_{1SSF}$ would exhibit a decrease near the two PDs within the same range of $\lambda$, explaining the experimental feature that the extent of PL intensity reduction is similar between C-core and Si-core PDs independent of electronic properties of the epilayers such as minority carrier lifetime, doping concentrations and even conduction type.

For the driving force for 1SSF expansion, the contribution of $\Delta \gamma_{1SSF}$ to the effective formation energy of 1SSF in a finite width $w$ is affected by this recombination at PDs, because the reduction of 1SSF-trapped electron density would decrease $\Delta \gamma_{1SSF}$. Solid and dashed curves in Fig. 5(a)
illustrate the schematic profiles of local \( \Delta \gamma_{\text{ISSF}}(x; w) \) and \( \Delta \gamma_{\text{ISSF}}(x; w + \delta w) \), respectively, drawn as a function of the distance \( x \) from the immobile C-core PD across the 1SSF. The three curves represent the profiles for 1SSFs in widths \( w < \lambda, \ w \approx 2\lambda \) and \( w \gg \lambda \). The \( \Delta \gamma_{\text{ISSF}}(x; w) \) values at C-core PD and Si-core PD may be different due to the reported difference in the recombination efficiency between the two PD types,\(^{28}\) though this does not affect the result as pointed out below. Since the contribution of \( \Delta \gamma_{\text{ISSF}}(x; w) \) to the total energy of 1SSF in a width \( w \) is given by the area under the respective profile, the driving force to expand the 1SSF in width \( w \) is provided not by the local \( \Delta \gamma_{\text{ISSF}}(x; w) \) but by the derivative of this area with respect to the 1SSF width \( w \):

\[
\Delta \gamma_{\text{ISSF}}(w) = \frac{d}{dw} \int_{0}^{w} \Delta \gamma_{\text{ISSF}}(x; w) dx.
\]

The dotted curve in Fig. 5(a) illustrates the \( w \)-dependence of \( \Delta \gamma_{\text{ISSF}}(w) \) which is characterized by a substantial drop for \( w \) falling below the diffusion length \( \lambda \). It should be pointed out that exactly the same driving force for 1SSF expansion acts on the C-core PD and the Si-core PD. In the present experiments, the minority carrier injection level is considered to be high enough for \( \Delta \gamma_{\text{ISSF}}(w) \) to dominate the driving force for 1SSF expansion. Under this condition, we carried out simple model calculations assuming one-dimensional diffusion of 1SSF-trapped electrons with annihilation sinks at the PDs bounding the 1SSF and the proportional relationship between \( \Delta \gamma_{\text{ISSF}}(x; w) \) and the local density of trapped electrons. The calculation shows that the run-up width \( w_r \) is \( \sim 3\lambda \) when the 1SSF expansion velocity \( V \) is linearly dependent on the driving force \( \Delta \gamma_{\text{ISSF}}(w) \), which quantitatively explains the experimental results for Samples A, B, and D. If \( V \) is supralinearly dependent on \( \Delta \gamma_{\text{ISSF}}(w) \), the same calculation shows that the run-up width becomes larger, which may explain the relatively large \( w_r \) value exceptionally observed in the sample C.

For the systematic discrepancy in the threshold hole density for 1SSF expansion shown in Fig. 4, a similar result was previously reported for the threshold current density in PiN diodes fabricated in the same structure.
diodes for the current-induced formation of 1SSFs in different shapes.\textsuperscript{14)} It was found that the threshold current for 1SSF formation from BPDs beneath epi-layer/substrate interfaces is roughly one order of magnitude larger than that from BPDs in epilayers. Also in the present study, since 1SSF expansion near buffer/substrate interfaces takes place, as shown by TEM observations,\textsuperscript{14)} near the points of conversion from BPDs to threading edge dislocations (TEDs) as illustrated in Fig. 5(b), the 1SSF widths should be close to the thermal equilibrium separation of $w \approx 50$ nm,\textsuperscript{29)} far narrower than $\lambda \approx 10$ $\mu$m. In such extremely narrow 1SSFs, the driving force for 1SSF expansion is so reduced that the 1SSF expansion should become difficult, which must provide a reason for the higher threshold near the buffer/substrate interfaces than in the drift layers where 1SSFs are already expanded to $w \gg w_i$ as in Fig. 5(c). Quantitative analysis based on a simplified model is now in progress.

In conclusion, the photo-induced expansion of 1SSFs in 4H-SiC epilayers was found to be suppressed when the width of 1SSFs is narrower than a characteristic width of several tens of $\mu$m. The intensity of 1SSF-originated photoluminescence is reduced in a similar range near the PDs bounding the 1SSF. These results are qualitatively explained by a simple model assuming that electrons two-dimensionally bound in the 1SSF band, which yield the reduction of 1SSF formation energy as well as 1SSF-originated photoluminescence, diffuse along the 1SSF band and are annihilated at the PDs. The expected reduction of expansion velocity in very narrow 1SSFs near BPD/TED conversion points at buffer/substrate interfaces provides a reason for the considerable difference of experimental threshold for 1SSF expansion between $n^-$ drift layers and $n^-$-buffer/substrate interfaces. The present knowledge will also supply a guideline for a refined design of the buffer layer to suppress bipolar device degradation.

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