

Surface recombination velocities for n-type 4H-SiC treated by various processes

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The carrier lifetime influences the performance of SiC bipolar devices, and the surface recombination is one of the limiting factors of the carrier lifetime. In this work, we measured carrier lifetimes in 4H-SiC treated by various processes to evaluate surface recombination velocities. We found that the surface recombination velocities for the C-face are larger than those for the Si-face for all the samples. In addition, the surface recombination velocity seems to be increased after the reactive ion etching. Increase of the surface area does not show significant effects on the surface recombination velocity.

1. Introduction

4H-SiC is a promising material for high voltage power devices. 4H-SiC unipolar devices, such as Schottky barrier diodes (SBDs) and metal-oxide-semiconductor field effect transistors (MOSFETs), have already been commercially available. On the other hand, 4H-SiC bipolar devices are suitable for higher voltage range than the unipolar devices, but they have never been widely used. For SiC bipolar devices, control of the carrier lifetime is a crucial issue, because the carrier lifetime influences the device performance. Therefore, various studies for the carrier lifetime in 4H-SiC have been reported.¹⁻⁴⁾ A point defect called the $Z_{1/2}$ center has been identified as a dominant recombination center in n-type 4H-SiC, and several methods have been proposed to reduce the concentration of the $Z_{1/2}$ center.⁵⁻⁹⁾ Because the carrier lifetime depends on surface recombination as well as bulk recombination,¹⁰⁻¹⁴⁾ evaluation of the surface recombination velocity S is also important to control the carrier lifetime. Although some experimental results of the surface recombination velocity have been reported so far^{12, 13)}, factors affecting S have not been clarified yet. In addition, fabrication of SiC bipolar devices generally requires processes such as reactive ion etching (RIE), which will introduce defects in SiC surfaces.¹⁵⁾ We have reported preliminary results for S on n-type 4H-SiC whose surfaces were treated by various processes.¹⁶⁾ In that report, we have not discussed effects of the surface area on S and inaccuracies of S due to difficulty of estimation of the bulk carrier lifetime in epilayers τ_{epi} . Moreover, the results could have been affected by the high-level injection of excess carriers. In this work, we measured the carrier lifetime in n-type 4H-SiC samples with a more appropriate experimental condition and discussed effects of surface areas of the samples. Then we estimated S by comparison of the observed carrier decay curves with numerical calculations and discussed accuracy of the estimation.

2. Experimental methods

The samples were cut from a free-standing n-type 4H-SiC epilayer with a nominal doping concentration of $1.0 \times 10^{15} \text{ cm}^{-3}$, and the sample sizes were approximately $1 \text{ cm} \times 1 \text{ cm}$. We prepared the samples with various surface treatments. One of the sample sets was treated by a chemical-mechanical polishing (CMP) both on the Si- and C-faces, and we named them CMP samples. Thicknesses of the CMP samples were 43, 63 and 83 μm . For another sample sets, we etched their surfaces by NaOH at 500°C, and we named them NaOH etch samples (with 31, 60 and 81 μm thickness). We also performed RIE in $\text{SF}_6 + \text{O}_2$ under a pressure of 20 Pa with 150 W for 30 min to two sample sets. RIE was performed on the Si-face for one set of samples, and was performed on the C-face for the other set. We named the former RIE (Si-face) samples (with 29, 57 and 84 μm thickness) and the latter RIE (C-face) samples (with 20, 41 and 69 μm thickness). Carrier lifetimes in all the samples were measured by the microwave photoconductivity decay (μ -PCD) method. In the μ -PCD method, we used 266 or 355 nm pulsed YAG lasers (the penetration depths in 4H-SiC are

1.2 and 48 μm for 266 and 355 nm, respectively¹⁷⁾) as an excitation source, and microwave of 10 GHz as a probe. We measured the carrier lifetime for the all samples with the injected photon densities of $1.8\text{--}4.0 \times 10^{13} \text{ cm}^{-2}$, which were smaller than those used in our previous report.¹⁸⁾ Because the signal peak obtained by $\mu\text{-PCD}$ measurements are not proportional to the injected photon densities in the high injection condition¹⁹⁾, we adopted those relatively small photon densities. We defined the $1/e$ lifetime as the excess carrier decay time from a peak to $1/e$. When the sample is thick enough, the surface recombination at the excited surface and the bulk recombination are dominant factors in the excess carrier decay, because excited carriers hardly diffuse to the other surface. With decreasing thickness, the recombination at the other surface becomes more significant and consequently the lifetime decreases. Therefore, we can evaluate S by observation of thickness dependence of the carrier lifetime, as detailed in Sec.4.

3. Results

3.1 Decay curves

The decay curves for the CMP samples with 355 nm excitation are shown in figure 1. All the decay curves were nearly exponential, and they became slower with increasing the sample thickness.

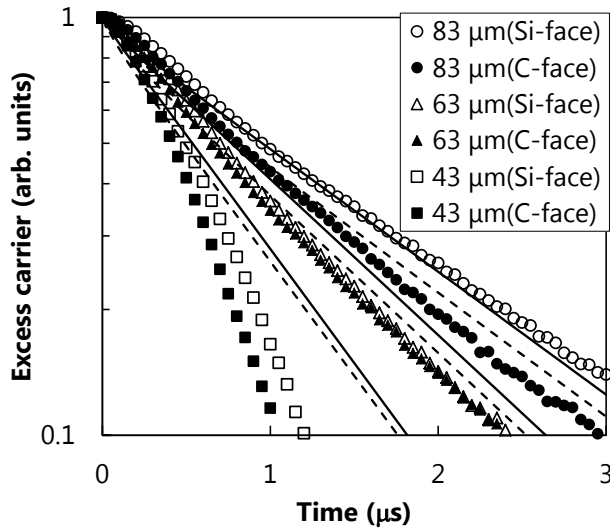


Figure 1. The decay curves for the CMP samples with 355 nm excitation. The solid lines are calculated decay curves for the Si-face, while the dashed lines are those for the C-face. The three curves for each line correspond to the calculation using the thickness of the samples: the slopes becomes more gradual with the thickness. The solid and dashed lines in figures 2-4 also illustrate calculation for the Si- and C-faces with the sample thicknesses, respectively. The detail of the calculation is described in Sec. 4.2.

The decay curves for the NaOH etch samples with 355 nm excitation are shown in figure 2. The decays became slower with the thickness and they were similar to those obtained from the CMP samples.

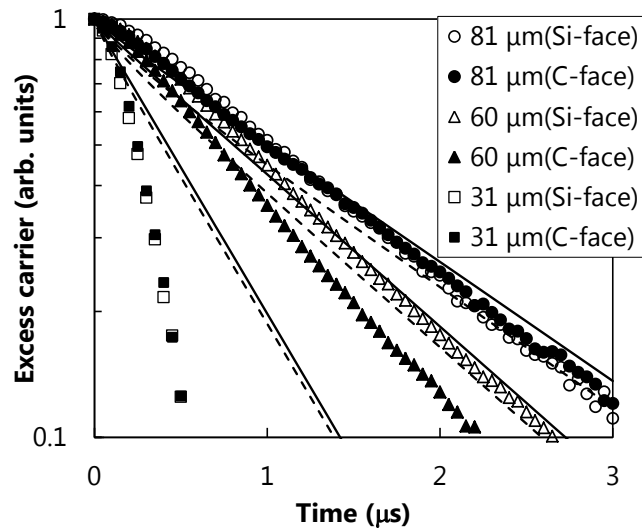


Figure 2. The decay curves for the NaOH etch samples with 355 nm excitation.

The decay curves for the RIE (Si-face) samples with 355 nm excitation are shown in figure 3. The decay became slower with the sample thickness. All the curves for the RIE (Si-face) samples show faster decay than those for the CMP and NaOH etch samples.

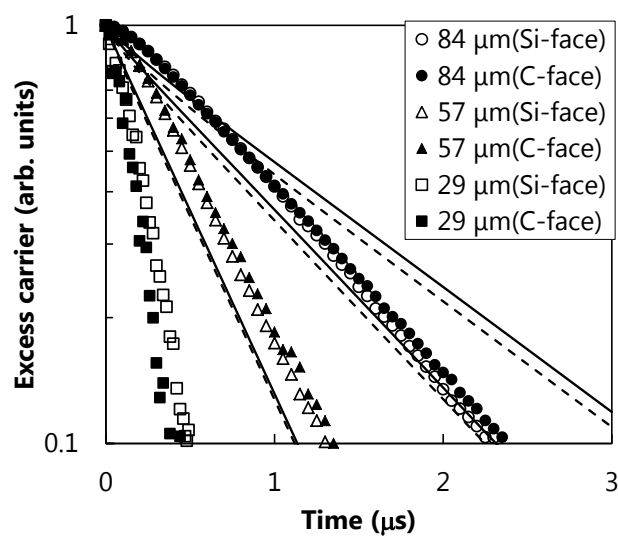


Figure 3. The decay curves for the RIE (Si-face) samples with 355 nm excitation.

The decay curves for the RIE (C-face) samples with 355 nm excitation are shown in figure 4. As for the RIE (Si-face) sample, the decay was faster than for the CMP and NaOH etch samples.

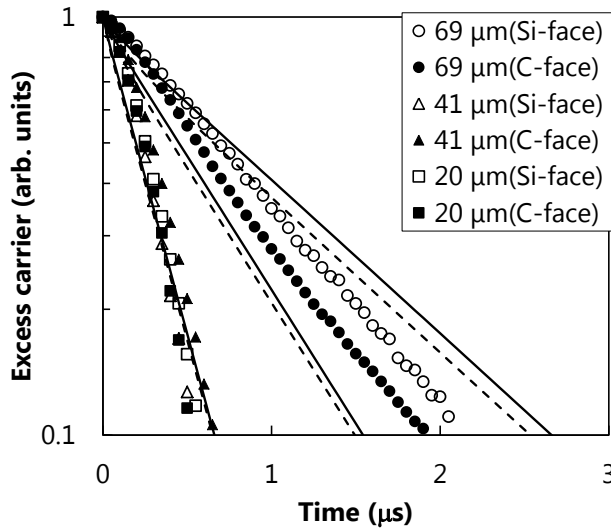


Figure 4. The decay curves for the RIE (C-face) samples with 355 nm excitation.

With 266 nm excitation, as in the case with 355 nm excitation, the decays for the all the samples became slow with the thickness, but the decays were faster than those for the same sample observed with the 355 nm excitation. In addition, the decays for the C-face for all the samples and the Si-face of the RIE samples showed non-exponential curves.

3.2 Surface area

S may depend on the surface area as well as defect concentration. Therefore, we measured the ratio of the surface area to the plane by the laser microscope (LMS) and the atomic force microscope (AFM) for all the samples. Observed areas are $25\ \mu\text{m} \times 25\ \mu\text{m}$ and $97\ \mu\text{m} \times 73\ \mu\text{m}$ for AFM and LMS, respectively. For both the measurements, the ratios of the surface area to the plane are between 1 and 1.04 except for the C-face of the NaOH etch sample which show the ratio from 1.34 to 1.72. Root mean square roughnesses for the CMP, RIE (Si-face) and RIE (C-face) samples range from 10 to 45 nm, while those for the NaOH sample are ~100 and ~500 nm for the Si- and C-faces, respectively. Therefore, only the the NaOH etch sample has a large surface area compared with the other samples.

4. Discussion

4.1 1/e lifetimes

Some decays of observed by μ -PCD with 266 nm excitation are not exponential. The non-exponential decay may be due to presence of minority carrier traps as discussed for SiC and other materials,²⁰⁻²²⁾ and such decay introduces errors in estimation of S ¹⁸⁾. However, the decay curves are nearly exponential up to decay to 1/e and have no slow decay components, and thus by using 1/e lifetimes, we evaluated contribution of the surface recombination.

Figures 5 and 6 show the 1/e lifetimes with 355 nm excitation as a function of the sample thickness for the Si-face and the C-face excitation, respectively. The 1/e lifetimes obtained from the C-faces are slightly smaller than those obtained from the Si-face. In addition, the RIE samples shows smaller 1/e lifetimes compared with the other samples. Even though the surface areas are large on the NaOH etch samples, the 1/e lifetimes are not small compared with other samples. Therefore, increase in the surface area has minor influences on the 1/e lifetime and the surface recombination velocity.

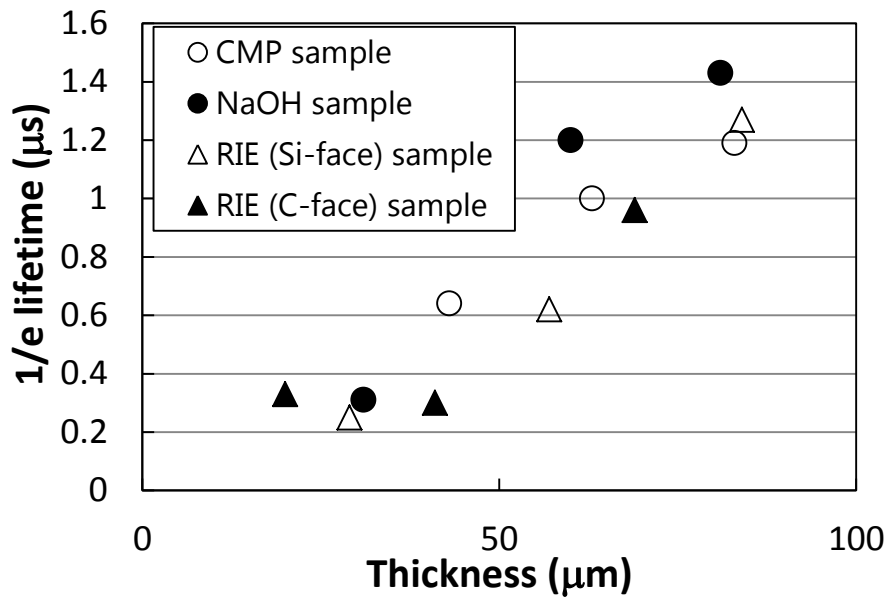


Figure 5. Thickness dependence of the 1/e lifetime for the Si-face in 355 nm excitation.

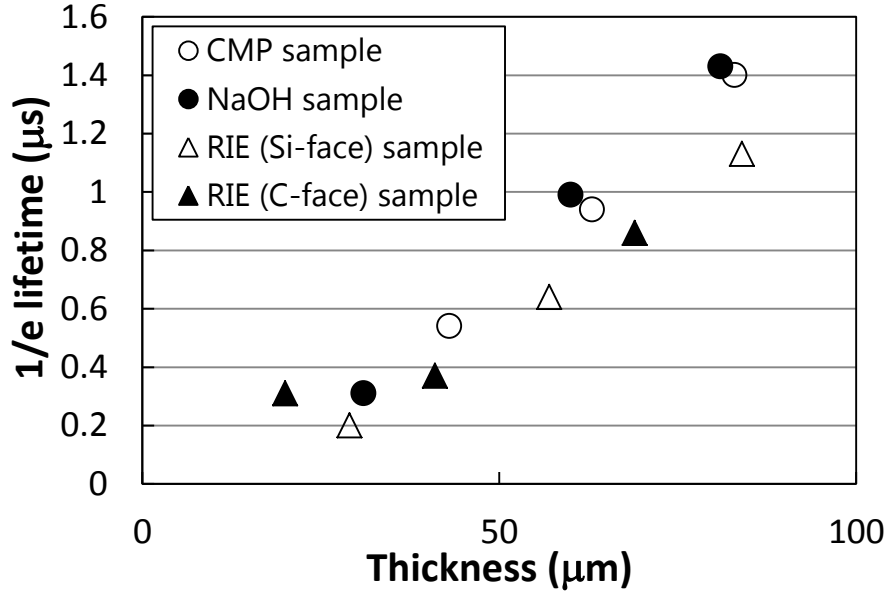


Figure 6. Thickness dependence of the 1/e lifetime for the C-face in 355 nm excitation.

4.2 Fitting to evaluate the surface recombination velocity S

To evaluate S , we compared experimental results with numerical calculations. The model used in this study has been reported in Refs. 16, 18, 23 and 24. The following continuity equation is solved to obtain the excess carrier concentration $\Delta n(z, t)$ at given time t and depth z in a semiconductor layer

$$\frac{\partial \Delta n(z, t)}{\partial t} = D_a \frac{\partial^2 \Delta n(z, t)}{\partial z^2} - \frac{\Delta n(z, t)}{\tau_{epi}}, \quad (1)$$

where D_a is the ambipolar diffusion coefficient. The initial carrier concentration profile with illumination by a light pulse is expressed as

$$\Delta n(z, 0) = g_0 \exp(-\alpha z), \quad (2)$$

where g_0 is the carrier concentration at $z = 0$ and α is the absorption coefficient. Boundary conditions at the excited and other surfaces are given by

$$D \frac{\partial \Delta n(0, t)}{\partial z} = S_0 \Delta n(0, t), \quad (3)$$

$$D \frac{\partial \Delta n(W, t)}{\partial z} = S_w \Delta n(W, t), \quad (4)$$

where S_0 and S_w are surface recombination velocities at the excited and other surfaces, respectively, and W is the thickness of the layer. The solution of $\Delta n(z, t)$ using eqs. (1) to (4) is obtained as

$$\Delta n(z, t) = \sum_{i=1}^{\infty} \Gamma_i \{a_i \cos(a_i z) + S_a \sin(a_i z)\} \exp \left[- \left(\frac{1}{\tau_b} + a_i^2 D \right) t \right]. \quad (5)$$

Γ_i and a_i are determined by

$$\Gamma_i = \frac{2g_0(a_i^2 + S_b^2)[(a_i^2 + S_a^2)(S_b - \alpha)\exp(-\alpha w)\sin(a_i w) + a_i(S_a + S_b)(\alpha + S_a)]}{[(a_i^2 + S_a^2)(a_i^2 + S_b^2)w + (S_a + S_b)(a_i^2 + S_a S_b)][S_a + S_b)(a_i^2 + \alpha^2)]} \quad (6)$$

$$\cot(a_i w) = \frac{a_i^2 - S_a S_b}{a_i(S_a + S_b)}, \quad (7)$$

where $S_a = S_0/D_a$ and $S_b = S_w/D_a$. We can obtain the average carrier concentration $\Delta N(t)$ in the layer by integrating $\Delta n(z, t)$ from 0 to W , and then from $\Delta N(t)$, 1/e lifetimes can be estimated. Here, τ_{epi} , S_0 , S_w , W , and D_a are parameters, and we adopted D_a of 4.2 cm²/s, which is the same as used in Ref.11. In Ref. 24, we employed the samples from the same wafer as in this work, and τ_{epi} was assumed to be 5 or 10 μ s in the calculation. However, the carrier lifetime in Ref. 16 should be overestimated because of measurements in the high injection condition (the photon density was 1.0-3.8 $\times 10^{15}$ cm⁻²) as discussed in Ref. 19. Therefore, actual τ_{epi} is expected to be smaller than 5 μ s and it must be larger than maximum of the experimentally observed lifetimes. By assuming $\tau_{\text{epi}} = 3$ μ s which is an intermediate value between 5 μ s and the experimental 1/e lifetime, we estimated S_0 and S_w with minimum difference in 1/e lifetimes from the experimental values for all the conditions (the Si- or C-faces, and 266 or 355 nm excitation). Comparison of the experimental 1/e lifetimes for the CMP samples with the calculations is shown in figure 7. The experimental results are near to the calculation with $S = 2000$ cm/s for the Si-face and $S = 5500$ cm/s for the C-face.

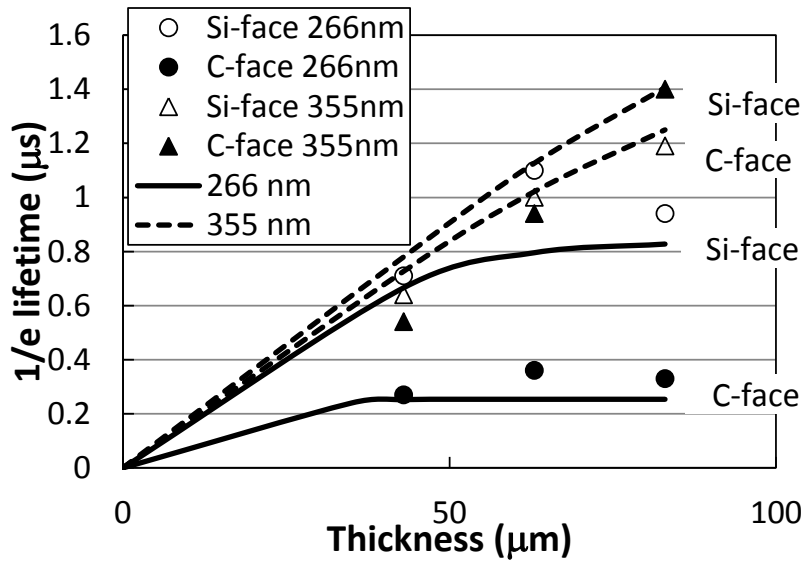


Figure 7. 1/e lifetimes for the CMP samples. The lines are calculation with $\tau_{\text{epi}} = 3$ μ s, $S = 2000$ and 5500 cm/s for the Si- and C-faces, respectively.

Obtained S are summarized in Table 1, and we also illustrated the calculated decay curves with $\tau_{\text{epi}} = 3 \mu\text{s}$ and the obtained S by the lines in figures 1-4. The calculation almost reproduced the experimental curves other than those for the thinnest one of all the sample sets and the Si-face of the RIE samples. If we adopted larger τ_{epi} than $3 \mu\text{s}$, reproduction of exponential curves became difficult, while with smaller τ_{epi} than $3 \mu\text{s}$, decay curves with long $1/e$ lifetimes were not able to be reproduced. Therefore, we consider that τ_{epi} of $3 \mu\text{s}$ is preferable even though some decay curves are not be reproduced.

The obtained S would include errors with ± 500 for the Si-face ± 1500 for the C-face because of imperfect fitting of calculation to experimental results. Even considering the errors, S in this work are larger than those for the CMP samples in Ref. 16 (1300-2000 cm/s) and in Ref. 18 (1000-2000 cm/s), because, as described above, the carrier lifetimes in Refs. 16 and 18 are overestimated. We also found that S for the C-face is larger than those for the Si-face for all the samples as reported in Refs. 16 and 18. Atomic structures on the surface and/or depth of damaged layers after CMP or etching should be different between the Si- and C-faces, because the chemical reactivity is different.^{25, 26)} In addition, we found that S for the Si-face of RIE samples are larger than those for the CMP and NaOH etch samples, and S for the C-face of RIE (C-face) samples is larger than those for the other samples. From these results, defects introduced by RIE would increase S . However, the calculated decay curves considerably deviate from the experimental curves for the Si-face of the RIE treated samples observed by 266 nm excitation. This indicates that RIE will not simply increase S but have other effects, which should be investigated further.

Table 1. Estimated surface recombination velocities S [cm/s]

	Si-face	C-face
CMP sample	2000	5500
NaOH etch sample	1500	5000
RIE (Si-face) sample	2500	5000
RIE (C-face) sample	2500	7500

Finally we compared our results with S reported by other groups.^{12, 13, 27)} S for the as-grown epitaxial sample has been reported as 5000 cm/s in Ref. 12, 400-7000 cm/s in Ref. 13, and 2000-6000 cm/s in Ref. 27. In this work, S for the CMP sample is 1500-5500 cm/s, close to those reported in Refs. 12, 13 and 27. For dry etched 4H-SiC, S for the sample treated by standard electron

cyclotron resonance etching and HF cleaning has been reported to be 50000 cm/s.¹²⁾ On the other hand, our dry etched (RIE) samples show S of 2000-7500 cm/s, which is much smaller than S reported in Ref. 12. We considered that the dry etching process used in Ref. 12 was not optimized and resulted in large S . Our RIE is included in a typical recipe of device fabrication, and S obtained here would be useful for design of 4H-SiC bipolar devices.

5. Conclusions

We evaluated the carrier lifetime and estimated surface recombination velocities S for 4H-SiC whose surfaces were treated by various processes. We found that S for the C-face is larger than those for the Si-face for all the samples, and S for the surface treated by RIE seems to be larger than S for the other samples. In addition, increase of the surface area does not change S significantly. The obtained S values will be useful in the design of bipolar 4H-SiC devices.

Acknowledgments

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