

# Slow photoconductivity decay in 3C-SiC on Si substrates

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*N*-type 3C-SiC layers grown on *p*-type (001) Si substrates were characterized by the conventional photoconductivity decay method. A N<sub>2</sub> laser (337 nm wavelength) was used as the excitation source. A very slow component with a time constant larger than 1 ms was observed in the photoconductivity decay curves. A numerical simulation considering a trap with a very small capture cross section for electrons ( $<1 \times 10^{-21}$  cm<sup>2</sup>) was able to reproduce main qualitative features of the experimental results. From comparison of the experimental decay curves with the theoretical ones, the following conclusions were drawn about the trap in 3C-SiC. (1) The trap level  $E_t$  is close to the conduction band edge  $E_c$  ( $E_c - E_t = 0.1\text{--}0.15$  eV). (2) The concentration is considered to decrease with increasing donor concentration. © 1998 American Institute of Physics. [S0021-8979(98)07417-9]

## INTRODUCTION

Much effort has been made to understand fundamental properties of SiC, which is a promising material for high-power, high-temperature, and high-frequency devices. Crystal growth techniques have been developed recently, and crystals of three dominant polytypes, 3C, 4H, and 6H, are now available. Many reports have been published on their intrinsic and extrinsic properties and also on characteristics of basic electronic devices. Some recent studies deal with the carrier lifetime (photoconductivity decay) in 6H-, 4H- and 3C-SiC.<sup>1-4</sup> The carrier lifetime critically influences the behavior of minority carriers. Moreover, it includes rich information about defect levels. It is well known that the quality of Si wafers used for LSI is now constantly monitored by the carrier lifetime measurement. In a previous study,<sup>2</sup> we measured carrier lifetime in 3C-SiC on Si at room temperature (RT) by the microwave-photoconductivity decay ( $\mu$ -PCD) method and found that the decay curve of excess carrier concentration consists of a fast component and a slow component ( $>200$   $\mu$ s). From comparison with calculated decay curves, we predicted the presence of a trap with very small electron capture cross section ( $<1 \times 10^{-21}$  cm<sup>2</sup>). However, we could not unambiguously determine the energy level of the trap and only concluded that the level is at least 0.1 eV from the conduction band edge and at least 0.4 eV from the valence band edge. The slow decay of excess carriers (or persistent photoconductivity) has also been observed for other polytypes,<sup>3-5</sup> but its mechanism has not been fully understood.

In this study, we measure the carrier lifetime in 3C-SiC/Si by the conventional photoconductivity decay method at various temperatures below RT. Simulation of the decay process is also performed considering a recombination center and a trap. From the temperature dependence of the decay curves, the traps which cause the slow carrier decay are characterized in more detail than in the previous study.

## EXPERIMENTAL PROCEDURE

The samples used are *n*-type 3C-SiC grown on a *p*-type (001) Si substrate by atmospheric-pressure chemical vapor deposition without intentional doping. The thickness and the carrier concentration of the SiC layer are 4–9  $\mu$ m and  $0.15\text{--}1 \times 10^{17}$  cm<sup>-3</sup>, respectively. The carrier concentration was determined by the Hall measurement.

For the photoconductivity measurement, two ohmic contacts were made on the SiC surface by evaporating Al. The distance between the two contacts is about 1 cm. The sample was set in a liquid nitrogen cryostat with an optical window, and the temperature was varied between about 90 K and room temperature. The sample was irradiated with a N<sub>2</sub> laser pulse (337 nm wavelength, 1 ns pulse width, and 20 Hz repetition frequency). The penetration depth of the N<sub>2</sub> laser light is about 2.5  $\mu$ m for 3C-SiC,<sup>6</sup> and thus the photons are mainly absorbed in the SiC layer. The photon flux at the sample surface is estimated to be of the order of  $10^{13}$  cm<sup>-2</sup>, except for measurement of the excitation power dependence. A constant-voltage source and a series resistance at least 20 times larger than the sample resistance were connected, so that change in the current due to the laser irradiation is negligible. Change in the voltage drop across the sample after the laser pulse irradiation was monitored by an oscilloscope

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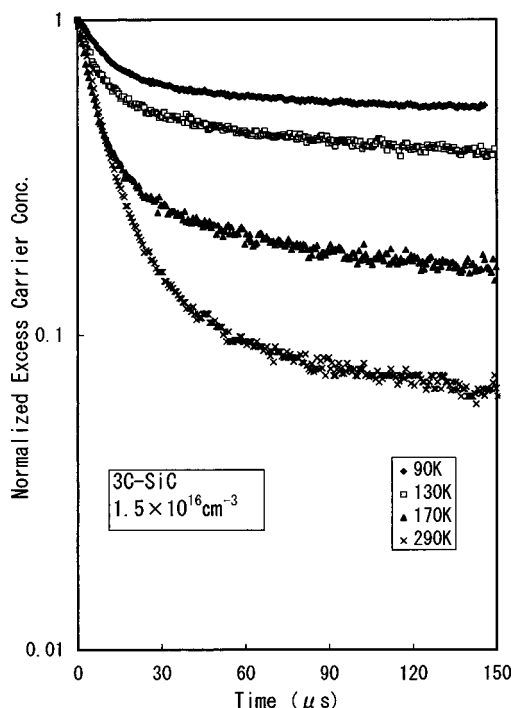


FIG. 1. Photoconductivity decay curves of 3C-SiC ( $n = 1.5 \times 10^{16} \text{ cm}^{-3}$ ) at three different temperatures.

and recorded by a computer. The voltage across the sample in the dark was kept about 0.5 V at any temperature by adjusting the value of the series resistance.

## EXPERIMENTAL RESULTS

Figure 1 shows photoconductivity decay curves at various temperatures. Each decay curve has a fast component with a time constant of about  $15 \mu\text{s}$  and a very slow component with a time constant  $> 1 \text{ ms}$ . The slow component tends to dominate as the temperature is lowered. As discussed in the previous paper, the slow component is attributed to some defects in the SiC layer and not in the Si substrate, because it does not appear when a laser with photon energy smaller than the band gap of 3C-SiC is used as the excitation source.<sup>2</sup> The time constant of the fast component does not strongly depend on temperature in the temperature range above 150 K. It apparently increases with decreasing temperature below 150 K, but the increase seems mainly due to the overlap of the slow component. Figure 2 shows the decay curves for the same sample over a larger time scale. The time constant of the slow component is about 4 ms and seems independent of temperature. The absolute signal intensity is about 0.05 V at the peak. The amount of the slow component is 1/10–1/2 of the peak intensity, i.e., 1%–5% of the total voltage drop across the sample. The carrier concentration of this sample is  $1.5 \times 10^{16} \text{ cm}^{-3}$  at room temperature. The resistance of the sample  $R$  is 2.3 k $\Omega$  at room temperature and decreases to about 1.5 k $\Omega$  as the temperature is reduced to 150 K. It then begins to increase with a further reduction in temperature because of freeze out of carriers.  $R$  at 90 K is about 5 k $\Omega$ , still sufficiently low for the photoconductivity measurement.

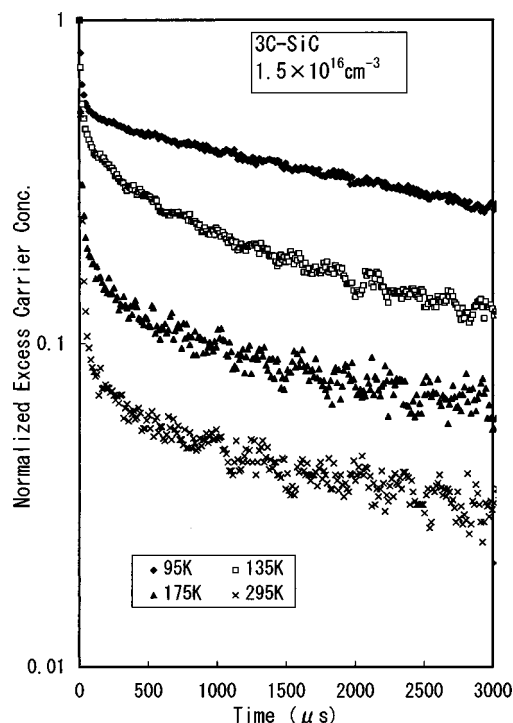


FIG. 2. Photoconductivity decay curves for the sample of  $n = 1.5 \times 10^{16} \text{ cm}^{-3}$  in a longer time scale.

Figure 3 shows the photoconductivity decay curves at 83 K for various excitation strengths. The laser power was increased or decreased by a factor shown in Fig. 3 compared with the data in the other figures. As shown in Fig. 3, the relative amount of the slow component is larger for a weaker excitation. The same tendency was observed by  $\mu$ -PCD at RT in the previous study.

Figure 4 shows the decay curves for a sample with a higher carrier concentration ( $1 \times 10^{17} \text{ cm}^{-3}$ ). The results are similar to Fig. 1, but the slow component is less dominant. For example, at about 90 K, the normalized signal intensity decreases to about 0.2 before the slow component appears in Fig. 4, but the slow component begins to appear at a signal intensity of about 0.6 in Fig. 1. The time constant of the

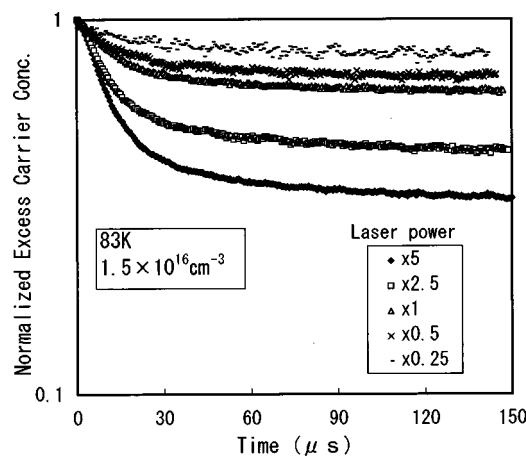


FIG. 3. Photoconductivity decay curves for the sample of  $n = 1.5 \times 10^{16} \text{ cm}^{-3}$  at 83 K under various excitation strengths.

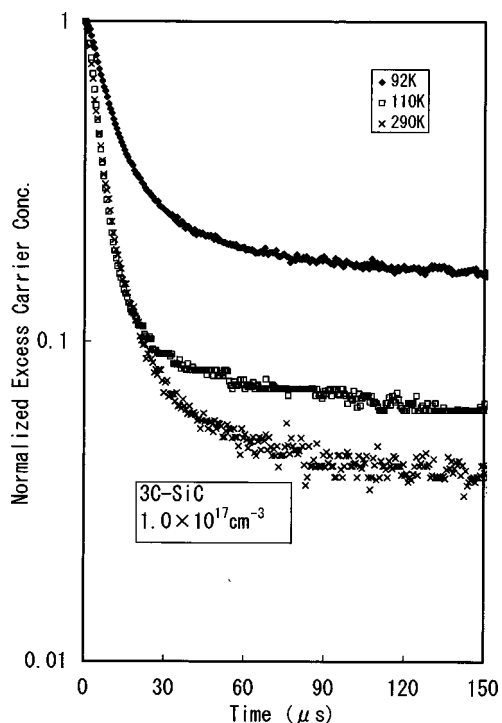


FIG. 4. Photoconductivity decay curves of 3C-SiC ( $n = 1 \times 10^{17} \text{ cm}^{-3}$ ) at three different temperatures.

initial fast decay is about  $10 \mu\text{s}$ ; smaller than in Fig. 1, while that of the slow component is nearly the same, i.e., about 4 ms. We characterized another sample with an intermediate carrier concentration ( $4 \times 10^{16} \text{ cm}^{-3}$ ) and, obtained decay curves are also intermediate of Figs. 1 and 4. Thus, the slow component tends to dominate as the carrier concentration decreases.

## DISCUSSION

The fast decay component may be attributed to the recombination process through various kinds of defects, i.e., defects in the SiC layer bulk, surface states, defects in the Si substrate, and interface states. We cannot separately estimate the contribution from the respective defect group, and thus the fast component is not discussed further in this article.

As noted earlier, the slow component is not observed when only the substrate is excited. Thus, the slow component should be due to the SiC layer. In the previous paper, we concluded that the slow decay is caused by a defect (trap) level with a very small electron capture cross section ( $< 10^{-21} \text{ cm}^2$ ). Defects which capture both electrons and holes act as a recombination center and shorten the carrier lifetime. On the other hand, if the capture cross section for majority carriers is much smaller than that for minority carriers, then the excess minority carriers trapped by the defects cannot readily recombine with majority carriers. Thus excess majority carriers remain for a long period in the band. The concentration of carriers which live long was determined by the trap concentration. Thus its relative amount is smaller when a larger amount of excess carriers are excited, as shown in Fig. 3. The time constant of the decay cannot be larger than inverse of the majority-carrier capture rate of the

traps. The time constant of the observed slow decay is of the order of 1 ms. Thus the rate of the majority-carrier capture should be smaller than  $10^3 \text{ s}^{-1}$ . The rate constant of the carrier capture is given by  $\sigma v_{\text{th}} n$ , where  $\sigma$  is the capture cross section,  $v_{\text{th}}$  the thermal velocity of carriers, and  $n$  the carrier concentration. For  $v_{\text{th}}$  of  $\sim 10^7 \text{ cm/s}$  and  $n$  of  $10^{17} \text{ cm}^{-3}$ , a slow decay with time constant of the order of 1 ms can appear only when  $\sigma < 10^{-21} \text{ cm}^2$ .

In the previous paper, we also obtained the following conclusions about the energy level of the trap.<sup>2</sup>

- (1) The level is at least 0.1 eV from the conduction band edge. Otherwise, the traps are occupied by holes (emit electrons) in equilibrium at RT and thus cannot capture photoexcited holes.
- (2) The level is more than 0.4 eV from the valence band edge. Otherwise, the trapped holes are re-emitted and recombine with excess electrons with a time constant much shorter than 1 ms.

However, we could not determine whether the level is in the lower half or the upper half of the band gap. In the following, we compare the present results with results of numerical simulation and determine more unambiguously the energy level of the trap.

We consider a deep recombination center, a trap, and a shallow donor. The carrier concentration is calculated from the rate equations describing carrier emission and capture processes at each defect level. For example, the rate equation for the electron population in the trap level,  $n_t$ , is expressed by

$$\begin{aligned} \frac{dn_t}{dt} = & \sigma_n v_{\text{th}} n (N_t - n_t) - e_n n_t - \sigma_p v_{\text{th}} p n_t \\ & + e_p (N_t - n_t), \end{aligned} \quad (1)$$

where  $\sigma_n$  ( $\sigma_p$ ) is the capture cross section for electrons (holes),  $e_n$  ( $e_p$ ) the emission coefficient for electrons (holes),  $N_t$  the trap concentration, and  $n$  and  $p$  are the carrier concentrations.  $e_n$  is related to  $\sigma_n$  and the energy level  $E_c - E_t$  by the equation  $e_n = \sigma_n v_{\text{th}} N_c \exp[-(E_c - E_t)/kT]$ , where  $k$  is the Boltzmann constant,  $N_c$  the effective density of states of the conduction band, and  $T$  the temperature.<sup>7</sup> Similar equations were written for the recombination center, the shallow donor, the conduction band, and the valence band, and these five differential equations were solved simultaneously by numerical integration.

Values of the parameters in the equations are set on the basis of the following considerations.

- (i) The recombination center: The capture cross sections for both the carriers are assumed to be  $1 \times 10^{-15} \text{ cm}^2$ , which is a typical value (about the size of an atom) for centers without capture barriers. The energy level is assumed to be at the midgap and thus the re-emission of carriers is completely negligible. The concentration is fixed at  $1 \times 10^{13} \text{ cm}^{-3}$  so that the rate of the recombination corresponds to the time constant of the fast decay ( $15 \mu\text{s}$ ). However, since the fast decay is in fact a complicated process involving many kinds of defects as discussed above, the parameters for the recombination center are just phenom-

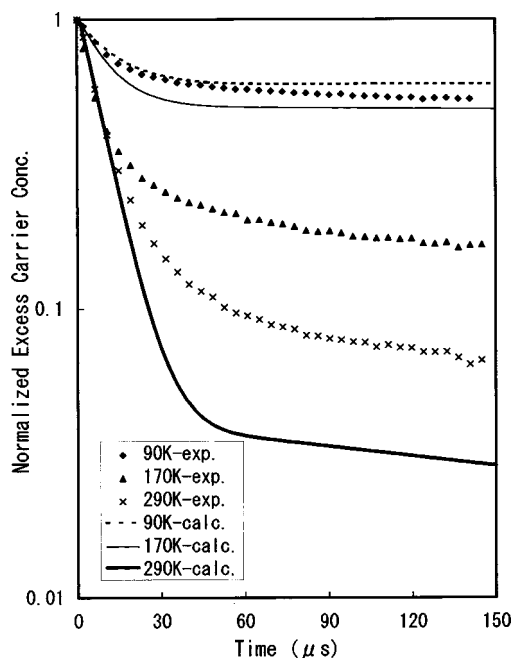


FIG. 5. Calculated and experimental decay curves of the excess carrier concentration at three different temperatures. The calculated data are represented by the lines and the experimental data by the symbols. The trap level  $E_t$  is set  $E_c - 0.12$  eV in the calculation. The experimental data are for the sample of  $n = 1.5 \times 10^{16} \text{ cm}^{-3}$ .

enological parameters which simply reproduce the apparent lifetime and do not correspond to actual physical property of the defect.

- (ii) The shallow donor: The most probable origin of the residual donor is nitrogen, and the energy level of the N donor is known to be about 60 meV from  $E_c$ . Thus, we assume the shallow donor level to be  $E_c - 60$  meV. The capture cross section for electrons  $\sigma_n$  is assumed to be  $1 \times 10^{-15} \text{ cm}^2$ . We assume that  $\sigma_p$  is  $1 \times 10^{-19} \text{ cm}^2$ , much smaller than  $\sigma_n$ . The capture of a hole by the shallow donor is a radiative process, whose probability is very small in an indirect-band-structure material, such as SiC. Therefore, the rate of the hole capture or recombination at the shallow donor is considered to be negligibly small.
- (iii) The trap: As discussed above, the capture cross section for electron  $\sigma_n$  is expected to be small,  $< 10^{-21} \text{ cm}^2$ . In the calculation,  $\sigma_n$  is assumed to be  $1 \times 10^{-21} \text{ cm}^2$  and  $\sigma_p$   $1 \times 10^{-15} \text{ cm}^2$ . For dependence of the decay curves on the capture cross section, see our previous paper.<sup>2</sup> The trap concentration  $N_t$  and the level  $E_t$  are varied.

First, we assume that the trap level is in the upper half of the band gap. Figure 5 shows the calculated decay curve for  $E_t = E_c - 0.12$  eV with the experimental data shown in Fig. 1. The initial excess carrier concentration is  $5 \times 10^{15} \text{ cm}^{-3}$  and the trap concentration  $4 \times 10^{15} \text{ cm}^{-3}$ . The donor concentration is  $1.5 \times 10^{16} \text{ cm}^{-3}$ . As shown in Fig. 5, the slow component tends to dominate as the temperature is reduced. This is because of change in the occupation probability of the trap level with temperature. At low temperatures, the traps are

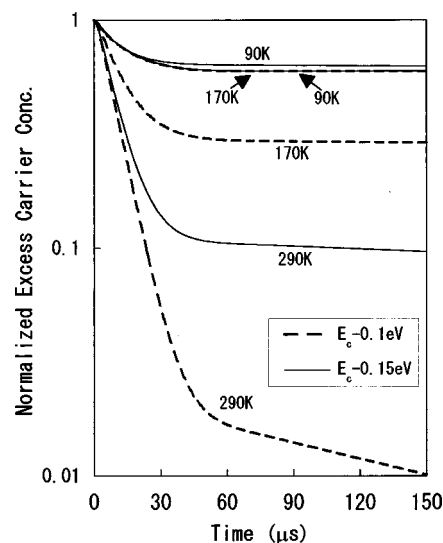


FIG. 6. Calculated decay curves for different trap levels. When the trap level is shallow ( $E_t = E_c - 0.1$  eV), the slow component is small at 290 K. When the trap is deeper ( $E_t = E_c - 0.15$  eV), the temperature dependence becomes weak below 200 K.

mostly occupied by an electron and thus are ready to capture a hole. At 290 K, majority of the traps emit an electron (or are occupied by a hole) at equilibrium and thus cannot capture an excess hole. The concentration of electrons which remain in the conduction band is equal to that of excess holes captured by the traps. Therefore, the slow component tends to diminish as the temperature is raised. It should be noted that this tendency is similar to the experimental results. However, for the calculated decay curves, the change with temperature in the lower temperature region (between 170 and 90 K) is considerably smaller than that in the higher temperature region (between 290 and 170 K). Such a tendency was not observed for the experimental results. The reason for this is not understood.

We examined dependence of the decay curve on each parameter, and the results are summarized as follows.

- (1) The trap level: The temperature dependence of the decay curves is most critically influenced by the trap level. The results for  $E_t = E_c - 0.1$  eV and  $E_c - 0.15$  eV are shown in Fig. 6. When  $E_t = E_c - 0.1$  eV, the slow component at 290 K is smaller than in Fig. 5 although the difference is negligible at 90 K. On the other hand, when  $E_t = E_c - 0.15$  eV, the temperature dependence is very weak below 200 K. When the level is more than 0.25 eV from  $E_c$  (and at least 0.4 eV from the valence band edge  $E_v$ , as discussed below), the decay curves are virtually independent of temperature below RT. Thus, the temperature dependence similar to that observed experimentally is reproduced by the calculation only when  $E_c - E_t = 0.1 - 0.15$  eV.
- (2) The trap concentration: The relative amount of the slow component is roughly proportional to the trap concentration and inversely proportional to the initial excess carrier concentration  $n_0$ . We set  $n_0 = 5 \times 10^{15} \text{ cm}^{-3}$  in the calculation, but it is rather arbitrary. Since  $n_0$  is ambiguous, the absolute value of the trap concentration is not

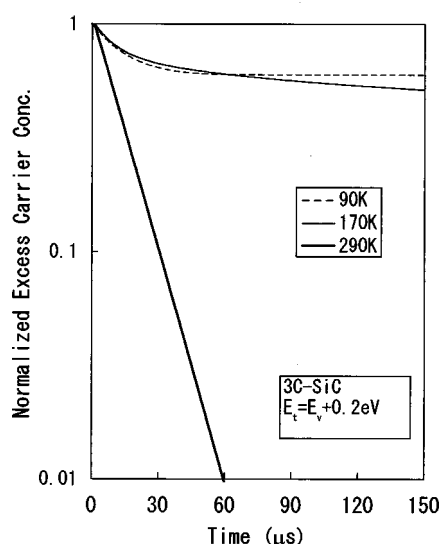


FIG. 7. Calculated decay curves at three different temperatures. The trap level is assumed to be close to the valence band ( $E_t = E_v + 0.2$  eV).

determined from the normalized decay curves. However, we may make rough estimate from the absolute intensity of the slow decay. Since the absolute signal intensity of the slow component is 1%–5% of the total voltage drop at the sample, the trap concentration will be of the order of  $10^{14}$ – $10^{15}$  cm $^{-3}$  (1%–5% of the carrier concentration).

- (3) The donor concentration: As the electron concentration increases, the Fermi level goes up and more traps are occupied by an electron. Therefore, if the trap concentration is constant, the slow component becomes more dominant as the donor concentration increases. This is contradictory to the experimental results, where the slow component is less dominant in the more heavily doped sample. To reproduce the experimental results, the trap concentration should be decreased as the donor concentration is increased.

Next, we assume that the trap level is in the lower half of the band gap. As stated earlier, if the trap level is close to  $E_v$ , the trapped holes can be re-emitted. Then the time constant of the slow decay is primarily influenced by the rate of hole emission from the trap, which has temperature dependence given by  $\exp\{-(E_t - E_v)/kT\}$ . Figure 7 shows calculated decay curves for  $E_t = E_v + 0.2$  eV. The slow decay does not appear because of immediate hole re-emission at 290 K, and a change in temperature leads to a change in the slope. This tendency is inconsistent with the experimental results, in which the slope is almost temperature independent. For the decay curve to have a time constant larger than 1 ms at RT,  $E_t - E_v$  should be larger than 0.4 eV. Then the calcu-

lated decay curves do not depend on temperature significantly below RT. Thus, the experimental results cannot be explained assuming the trap level is close to the valence band.

The origin of the trap is unknown. We have carried out a deep-level transient spectroscopy (DLTS) measurement with variable injection pulse width, but have not found a trap with such a small capture cross section.<sup>8</sup> The activation energy of the trap may be out of the energy range which can be scanned by our system (0.15–0.6 eV). One might expect that the trap is related to the residual donor or the donor itself, like the DX center in  $\text{Al}_x\text{Ga}_{1-x}\text{As}$ ,<sup>9</sup> but this is not probable because the slow component is less dominant in a more heavily doped sample. It is known from a thermodynamic analysis that the equilibrium concentration of a donorlike defect decreases with increasing electron concentration.<sup>10</sup> Thus, the trap is expected to be another donorlike defect, different from the dominant residual donor. To identify the origin, the relationship between the trap concentration and the growth condition needs to be investigated.

## CONCLUSION

3C-SiC on Si has been characterized by the photoconductivity decay method. A very slow component was observed in photoconductivity decay curve. A numerical simulation considering a trap with a very small capture cross section for electrons ( $< 1 \times 10^{-21}$  cm $^2$ ) was able to reproduce the main qualitative features of the experimental results. From comparison of the experimental decay curves with the theoretical ones, we have drawn the following conclusions about the trap in 3C-SiC.

- (1) The trap level is close to the conduction band,  $E_c - E_t = 0.1$ – $0.15$  eV.
- (2) The trap concentration cannot be quantitatively determined but expected to be  $10^{14}$ – $10^{15}$  cm $^{-3}$  from the absolute signal intensity. The concentration is considered to decrease with increasing donor concentration.

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