Excess carrier lifetime of 3C–SiC measured by the microwave photoconductivity decay method

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Excess carrier lifetime of 3C–SiC grown on a Si substrate by chemical vapor deposition is measured at room temperature by the noncontact microwave photoconductivity decay method. A N_2 laser is used to excite carriers in the SiC layer. The measured decay curves of the excess carrier concentration have fast ($\tau \approx 3\ \mu$s) and slow ($\tau > 200\ \mu$s) components. The origin of the slow decay is discussed on the basis of the numerical simulation of the recombination process, and the presence of traps with a very small electron capture cross section ($< 1\times10^{-21}$ cm^2) is predicted. © *1997 American Institute of Physics.* [S0003-6951(97)01613-6]

Cubic SiC (3C–SiC or β-SiC) is one of the candidate materials for high-temperature and high-power devices, but characterization techniques for it have not been established. For Si, characterization techniques are very well developed, and the material quality is constantly monitored during the device fabrication process. The lifetime measurement is one of the most popular characterization techniques for Si. The excess carrier lifetime is a very important physical parameter and influences performance of most of electronic devices.[1] The noncontact measurement based on observation of absorption or reflection of electromagnetic wave by free carriers is now adopted in many wafer and device factories. In this study, we use the noncontact microwave photoconductivity decay (μ-PCD) method to measure excess carrier lifetime of n-type 3C–SiC. The results show that the lifetime has fast and very slow components. To discuss the origin of the slow component, we perform a theoretical calculation taking into account a recombination center and a trap.

The samples used in this study are unintentionally doped, n-type 3C–SiC grown on a p-type (001) Si substrate (100 Ω cm) by a chemical vapor deposition (CVD). The thickness and the carrier concentration of the SiC layer is 4–9 μm and 1×10^{17} cm^{-3}, respectively. The carrier concentration was determined by the Hall measurement.

Figure 1 shows the schematic illustration of the apparatus for the μ-PCD measurement. The sample is irradiated by a pulsed light at room temperature. The microwave (10 GHz) is incident on the opposite side and penetrates the whole sample. An increase in the microwave reflectance after the pulsed light irradiation is thought to be proportional to the excess carrier concentration. The reflectance variation is monitored and recorded by a digital oscilloscope as a function of time after turn-off of the laser pulse. For the light source, we use both an N_2 laser (wavelength $\lambda = 337$ nm) and a laser diode (LD) ($\lambda = 904$ nm). The pulse width is 1 ns for the N_2 laser and 50 ns for the LD. The penetration depth for the N_2 laser light is about 2.5 μm for SiC,[2] and thus it is mainly absorbed by the SiC layer. On the other hand, SiC is transparent for the light of $\lambda = 904$ nm.

Figure 2 shows measured decay curves of the excess carrier concentrations for SiC/Si. When the LD is used, the decay curve has a single time constant of about 2 μs. The excess carriers are excited only in Si in this case, and thus this time constant corresponds to effective lifetime in Si. In contrast, the decay curve has fast and very slow components when the N_2 laser is used. Since such a slow decay is not observed for the excitation by the LD, it is attributed to the recombination process in SiC. The time constant of the initial (fast) decay is about 3.3 μs, which is defined as the time interval of the decay from the peak to $1/e$. Although we measured the decay curve for a time interval up to 4 ms, the time constant of the slow decay is difficult to obtain accurately because the decay is not rigorously exponential. The slope of the curve for $t > 30\ \mu$s corresponds to a time constant larger than 200 μs.

When the decay curve for the N_2 laser shown in Fig. 2 was recorded, the output of the laser was attenuated down to 4.5% by a filter. In this case, the excitation density is about 1×10^{16} cm^{-3} on average within the penetration depth, and thus the injection is low level. Figure 3 shows decay curves at various excitation levels. The excitation strength is represented as percentage with respect to the initial output of the

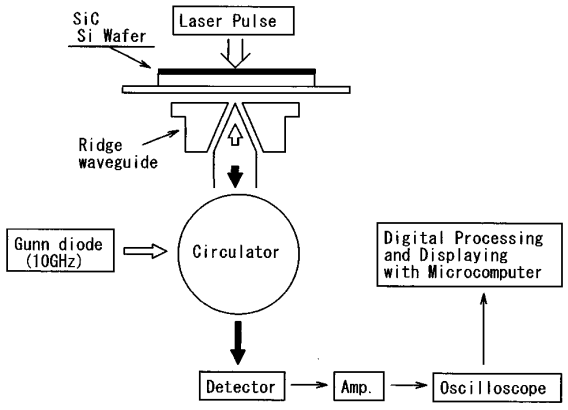

FIG. 1. Schematic illustration of apparatus for the μ-PCD measurement.

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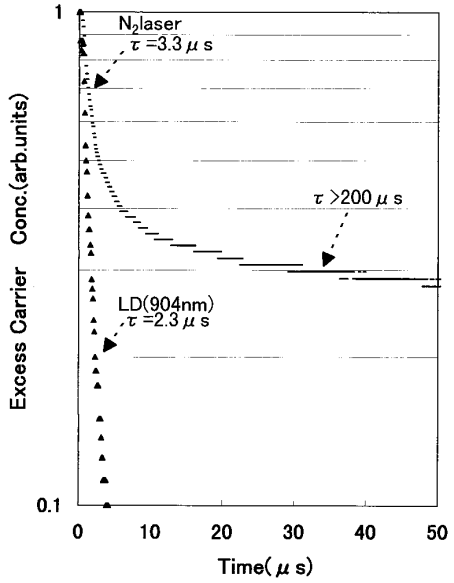

FIG. 2. Decay curves of excess carrier concentration in 3C–SiC/Si measured by the μ-PCD method. The decay curve has a single time constant when the laser diode was used for excitation, while it has a fast component ($\tau \approx 3$ μs) and a slow one ($\tau > 200$ μs) under the N_2 laser excitation.

laser. As shown in Fig. 3, the slow component becomes relatively smaller with increasing excitation level.

Okumura *et al.* observed a similar slow decay for 3C–SiC at room temperature.[3] Persistent photoconductivity has been observed for 6H–SiC but only at low temperatures, and its origin seems not clear.[4–6] In the following, we discuss the origin of the slow component in the decay curves.

It is known that certain minority carrier traps can increase apparent lifetime. The number of excess carriers which survive long is limited by the number of the traps. Thus the slow component due to trap should be relatively small under strong excitation. Therefore, the results in Fig. 3 indicate that the slow component is in fact due to some traps.

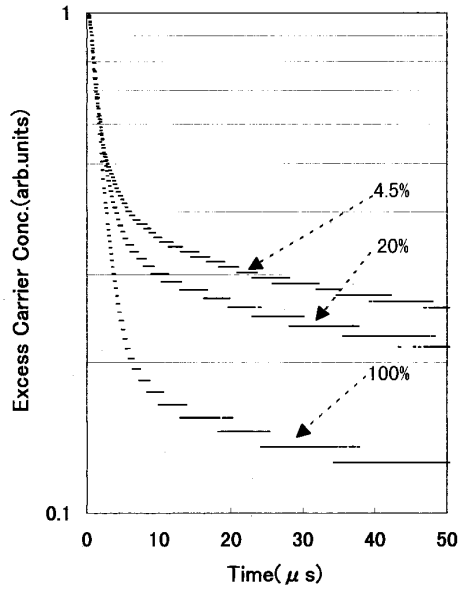

FIG. 3. Excess carrier decay curves of 3C–SiC/Si for various excitation strengths. The N_2 laser is used for excitation, and the intensity on the sample surface was varied from 100% to 4.5% of the initial output using filters.

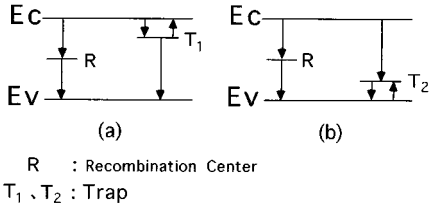

FIG. 4. Two defect models assumed in the simulation of the excess carrier decay curves.

Okumura *et al.* assigned the slow decay to the carrier emission process from the trap.[3] However, the following analyses show that this is in general not the case.

To cause the slow decay, the trap should effectively capture the minority carriers (holes) but not the majority carriers (electrons). If the trap captures both, it will act as a recombination center and shorten the lifetime. We carry out simulation of decay curves considering a single recombination center and a trap. Figure 4 shows the assumed models; the trap is either (a) in the upper half or (b) in the lower half of the band gap, and it can re-emit an electron (a hole) in the former (latter) case. The electron population in the trap level n_t is, in the case of Fig. 4(a), governed by

$$dn_t/dt = \sigma_n v_{\rm th} n(n_d - n_t) - e_n n_t - \sigma_p v_{\rm th} p n_t, \qquad (1)$$

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

There are several unknown parameters in the equations, and we set their values based on the following consideration. The initial excess carrier concentration is set 1×10^{16} cm^{-3} as expected from the excitation intensity in most cases, but higher excitation is also examined. All the capture cross sections of the recombination center and the trap are initially assumed to be 1×10^{-15} cm^2, which is a typical value (about the size of an atom) for levels without capture barriers, and the electron capture cross section of the trap σ_n is varied. The concentration of the recombination centers is fixed at 5×10^{13} cm^{-3} so that the rate of the recombination due to the center corresponds to the time constant of the fast component (about 3 μs). The level ($E_c - E_t$ or $E_t - E_v$) and the concentration (n_d) of the trap are varied.

First, we discuss the case Fig. 4(a). Figure 5 shows calculated decay curves of excess carriers for various values of σ_n. The trap level and concentration are assumed to be 1.0 eV and 5×10^{15} cm^{-3}, respectively. As shown there, a slow component appears when σ_n is very small ($< 1 \times 10^{-21}$ cm^2). It is due to excess electrons which are not captured by the traps. Figure 6 shows the calculated decay curves with the trap level as a parameter. σ_n is set 10^{-22} cm^2. The bold lines correspond to the model Fig. 4(a)

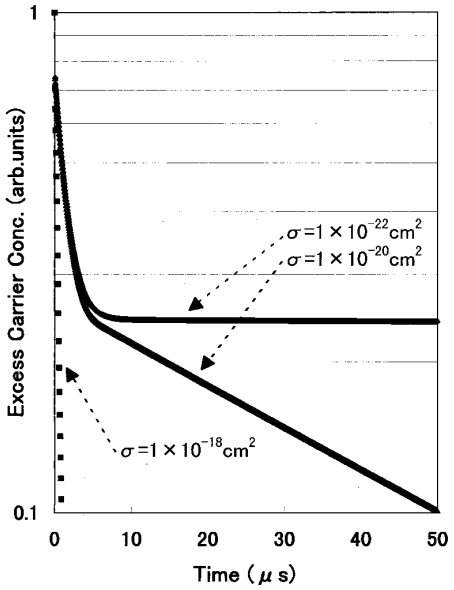

FIG. 5. Decay curves calculated with the electron capture cross section of the trap σ_n as a parameter. The trap level and concentration are 1.0 eV and 5×10^{15} cm^{-3}, respectively.

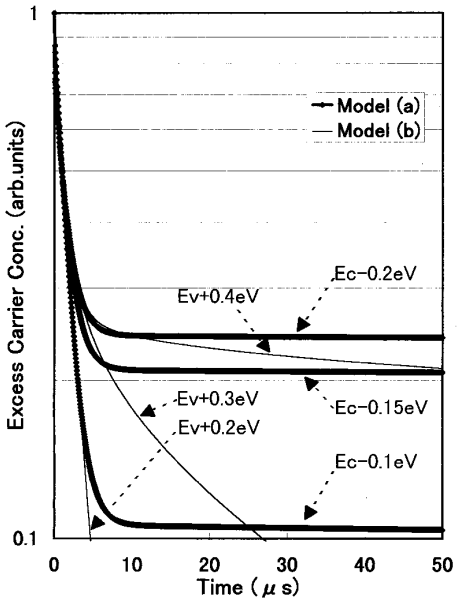

FIG. 6. Calculated decay curves for various values of the trap level. The model Fig. 4(a) is assumed for the bold lines and the model Fig. 4(b) for the thin lines. σ_n is 1×10^{-22} cm^2 and n_d 5×10^{15} cm^{-3}.

and the thin lines the model Fig. 4(b). In the case of Fig. 4(a), the shape of the decay curve does not depend on the trap level significantly unless the level is less than about 0.1 eV. When $E_c-E_t\leqslant0.1$ eV, some of the traps are occupied by a hole under the equilibrium and thus cannot capture an excess hole. Then, the slow component diminishes.

From simulations with various sets of parameters, we obtain the following additional results for the case of Fig. 4(a):

(1) When n_d is decreased, the slow component begins to appear at a smaller (normalized) excess carrier concentration; the relative amount of the slow component is almost proportional to n_d.
(2) In the simulation for various excitation strengths, the normalized decay curves exhibit the same tendency as Fig. 3, i.e., the slow component becomes relatively small under strong excitation.

Similar results are obtained assuming the model Fig. 4(b). The only difference is that the trap level should be deeper than 0.4 eV ($E_t-E_v\geqslant0.4$ eV) for the decay curve to have a very slow component, as shown by the thin lines in Fig. 6. If the level is shallow, the trapped holes are reemitted and recombine with electrons at the recombination centers. In the model Fig. 4(a), the slow component always corresponds to the rate of the electron capture by the trap. In the model Fig. 4(b), the slow component is also attributed to the electron capture by the trap when $E_t-E_v>0.4$ eV, and to the hole emission from the trap only when $E_t-E_v\approx0.4$ eV. Thus, although Okumura *et al.* assumed in their analysis that the slow component is necessarily related to the hole emission from the trap, their assumption is valid only in a special case, i.e., the model Fig. 4(b), $E_t-E_v\approx0.4$ eV.

Comparing the experimental and theoretical results, we can draw the following conclusions about the traps in our 3C–SiC films:

(1) The traps have a very small capture cross section for electrons ($<1\times10^{-21}$ cm^2).
(2) The trap concentration will be of the order of 1×10^{15} cm^{-3}.
(3) The trap level is either in the upper-half or in the lower-half of the band gap. The trap level will be deeper than 0.1 eV in the former case and deeper than 0.4 eV in the latter case.

However, it should be noted that the experimental decay curves are seen to consist of more than two exponential decays. This may indicate that although we consider a single trap and a recombination center in the analysis, there are more defect levels which influence the recombination process. For more rigorous discussion, the deep-level transient spectroscopy (DLTS) study is now in progress, and the results will be reported in future publications.

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