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Investigation of carrier lifetime in 4*H*-SiC epilayers and lifetime control by electron irradiation

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Carrier lifetimes in 4*H*-SiC epilayers are investigated by differential microwave photoconductivity decay measurements. When the $Z_{1/2}$ concentration is higher than 10^{13} cm^{-3}, the $Z_{1/2}$ center works as a recombination center. In this case, carrier lifetimes show positive dependence on the injection level (number of irradiated photons). On the other hand, other recombination processes such as surface recombination limit the lifetime when the $Z_{1/2}$ concentration is lower than 10^{13} cm^{-3}. In this case, carrier lifetimes have decreased by increasing the injection level. By controlling the $Z_{1/2}$ concentration by low-energy electron irradiation, the lifetime control has been achieved. © *2007 American Institute of Physics*. [DOI: 10.1063/1.2740580]

Silicon carbide (SiC) is an attractive material for developing high-power, high-temperature, and high-frequency devices, owing to its superior properties. [1] To realize SiC power devices with a high blocking voltage more than several kilovolts, bipolar devices such as *p-i-n* diodes, thyristors, and insulated gate bipolar transistors possess great promise in terms of lower on resistance owing to the effect of conductivity modulation.[2,3] A long carrier lifetime is required for effective conductivity modulation. Although the lifetime of SiC epilayers has been investigated by several groups,[4–8] it does not exceed 1–2 μs, which is a few orders of magnitude shorter than that of high-purity silicon. Too long lifetimes, on the other hand, will cause considerably large reverse recovery, leading to limited switching frequency and excessive switching loss. Therefore, carrier lifetimes should be controlled to achieve an optimum lifetime value and its profile.

In this work, carrier lifetimes in 4*H*-SiC are investigated by differential microwave photoconductivity decay (μ-PCD) measurements. In particular, impacts of deep levels on carrier lifetimes are studied. From the results, control of carrier lifetimes is demonstrated by low-energy electron irradiation.

Epitaxial layers were grown on 8° off-axis 4*H*-SiC(0001) n^+ substrates by horizontal hot-wall chemical vapor deposition in a $SiH_4-C_3H_8-H_2$ system.[9] Substrates purchased from Cree or prepared at Toyota Central R&D Labs., Inc. were used in this study. Epitaxial growth was performed at 1650 °C with a typical reactor pressure of 80 Torr. The C/Si ratio was varied from 0.8 to 1.3 by changing C_3H_8 flow rate at a fixed SiH_4 flow rate All the epilayers were intentionally doped with nitrogen to the 10^{15} cm^{-3} range. Typical growth rate was 10–15 μm/h, and thickness of the epilayers was approximately 50 μm.

Carrier lifetimes of as-grown and electron-irradiated 4*H*-SiC epilayers were investigated by differential μ-PCD measurements. An yttrium aluminum garnet third harmonic generation laser (λ=355 nm) was used as an excitation source. The typical number of photons irradiated onto the sample surface per unit area was 2×10^{14} or 1×10^{15} cm^{-2}, which leads to a high injection level of low 10^{16}–low 10^{17} cm^{-3}. Electron irradiation was performed at an energy of 160 keV without intentional sample heating to introduce deep levels. Concentration of deep levels was evaluated by deep level transient spectroscopy (DLTS).

Figure 1 shows the photoconductivity decay curves measured for 4*H*-SiC epilayers grown with a C/Si ratio of 0.9 or

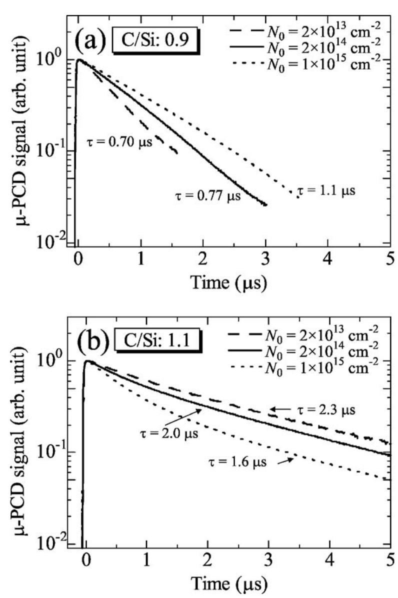

FIG. 1. Photoconductivity decay curves measured for 50-μm-thick 4*H*-SiC(0001) epilayers grown at a C/Si ratio of (a) 0.9 and (b) 1.1. The net donor concentration is $(1.2-1.5)\times10^{15}$ cm^{-3} for both samples. Trap ($Z_{1/2}$ center) concentration is 1.3×10^{13} cm^{-3} for the sample grown at a C/Si ratio of 0.9, and 4.4×10^{12} cm^{-3} for the sample grown at a C/Si ratio of 1.1, respectively. The illumination intensity for the measurement is from 2×10^{13} to 1×10^{15} cm^{-2}.

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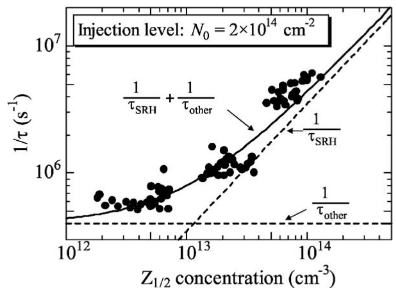

FIG. 2. Relation between the inverse of the carrier lifetime and the $Z_{1/2}$ concentration measured with an illumination intensity of 2×10^{14} cm^{-2}. All the samples used for this experiment are as-grown 4*H*-SiC epilayers with a thickness of 44–53 μm. Based on the model expressed by Eq. (1), the experimental data are fitted. The fitted result is shown by a solid line for $1/\tau_{SRH}+1/\tau_{other}$, and two broken lines for τ_{SRH} and τ_{other}, respectively.

1.1. The illumination intensity (number of irradiated photons per unit area: N_0) is from 2×10^{13} to 1×10^{15} cm^{-2}. The net donor concentration estimated from capacitance-voltage measurement $(1.2–1.5)\times10^{15}$ cm^{-3} for the samples. The $Z_{1/2}$ center ($E_C-0.65$ eV) (Ref. 10) and $EH_{6/7}$ center ($E_C-1.55$ eV) (Ref. 11) were dominant deep levels in the as-grown *n*-type 4*H*-SiC epilayers, and their concentrations were 1.3×10^{13} cm^{-3} ($Z_{1/2}$) and 1.2×10^{13} cm^{-3} ($EH_{6/7}$) for the sample grown at a C/Si ratio of 0.9, and 4.4×10^{12} cm^{-3} ($Z_{1/2}$) and 3.6×10^{12} cm^{-3} ($EH_{6/7}$) for the sample grown at a C/Si ratio of 1.1, respectively. A relatively long carrier lifetime of 2.3 μs could be obtained for the sample grown at a C/Si ratio of 1.1, probably because of low trap concentration of the sample. As shown in Fig. 1, the injection-level dependence of the lifetime is different between the samples: The carrier lifetime increased by increasing the injection level in the sample grown at a C/Si ratio of 0.9 and decreased in the sample grown at a C/Si ratio of 1.1. The result indicates that different types of lifetime killers affect carrier lifetimes for the different samples.

Figure 2 shows the relation between the inverse of carrier lifetime measured with an illumination intensity of 2×10^{14} cm^{-2} and the $Z_{1/2}$ concentration (the $EH_{6/7}$ concentration was always close to the $Z_{1/2}$ concentration). After the lifetime mapping and DLTS mapping measurements on four different samples, the $Z_{1/2}$ concentration and carrier lifetime at identical locations were plotted in the figure. When the $Z_{1/2}$ concentration is higher than $(1–2)\times10^{13}$ cm^{-3}, the inverse of carrier lifetime is proportional to the $Z_{1/2}$ concentration. However, the correlation between the lifetime and the $Z_{1/2}$ concentration is not clear when the $Z_{1/2}$ concentration is in the 10^{12} cm^{-3} range. In general, a carrier lifetime (τ) is given by

$$\frac{1}{\tau} = \frac{1}{\tau_{SRH}} + \frac{1}{\tau_{other}}, \quad (1)$$

where τ_{SRH} is the Shockley-Read-Hall (SRH) lifetime governed by a recombination center,[12,13] and τ_{other} is the carrier lifetime governed by other processes such as surface recombination. In Fig. 2, τ_{other} is constant irrespective of the $Z_{1/2}$ concentration. According to the SRH model, when the injection level is much higher than the steady-state carrier concentration (high injection level), the inverse of SRH lifetime (τ_{SRH}) is given by[14]

$$\frac{1}{\tau_{SRH}} = \frac{\sigma_p v_{th,p} \sigma_n v_{th,n}}{\sigma_p v_{th,p} + \sigma_n v_{th,n}} N_T = aN_T, \quad (2)$$

where σ_p and σ_n are the capture cross section of the recombination center for holes and electrons, $v_{th,p}$ and $v_{th,n}$ are the thermal velocities of holes and electrons, N_T is the concentration of the recombination center, and a is the constant. Based on this model expressed by Eq. (1), the experimental data were fitted, where the τ_{other} and a are the fitting parameters. The fitted result is shown by a solid line for $1/\tau_{SRH}+1/\tau_{other}$, and two broken lines for τ_{SRH} and τ_{other}, respectively. As shown in the figure, the inverse of carrier lifetimes (τ) is proportional to the $Z_{1/2}$ concentration when the concentration is higher than $(1–2)\times10^{13}$ cm^{-3}. Therefore, the $Z_{1/2}$ center (or $EH_{6/7}$ center) works as an effective recombination center. On the other hand, the inverse of carrier lifetime is almost constant irrespective of the $Z_{1/2}$ concentration when the $Z_{1/2}$ concentration is lower than $(1–2)\times10^{13}$ cm^{-3}. In this case, the inverse of SRH lifetime is very small because the trap concentration is low, and the carrier lifetime may be governed by other recombination processes.

The inverse of the carrier lifetime is proportional to the $Z_{1/2}$ concentration when the trap concentration is high enough. Since the $Z_{1/2}$ concentration can be selectively increased by low-energy electron irradiation,[15,16] the lifetime control has been attempted. The starting material was a 50-μm-thick 4*H*-SiC epilayer doped to 1.5×10^{15} cm^{-3}, the $Z_{1/2}$ concentration in which is about 2×10^{13} cm^{-3}. Electron irradiation was performed with the fluence range from 2×10^{16} to 1×10^{18} cm^{-2}, and subsequent annealing was performed at 950 or 1550 °C for 30 min. In 160 keV electron-irradiated samples annealed at 950 °C, the $Z_{1/2}$ and $EH_{6/7}$ concentrations are predominantly increased in the upper half of band gap of 4*H*-SiC.[16] In the lower half of band gap several kinds of hole traps are also observed after electron irradiation at 160 keV and subsequent annealing at 950 °C, while all the traps except for the *D* center[17] are annealed out at 1550 °C.[18] Note that the annealing at 1550 °C does not influence the $Z_{1/2}$ and $EH_{6/7}$ concentrations very much.

The map for fluence of the electron irradiation and the distribution of the $Z_{1/2}$ concentration in the irradiated epilayer is schematically illustrated in Fig. 3(a). Since selective electron irradiation was performed by using a copper mask, different $Z_{1/2}$ concentrations ranging from 1.6×10^{13} to 1.5×10^{15} cm^{-3} for six areas were realized in the sample. In Fig. 3(b), the map of carrier lifetimes of the electron-irradiated sample (annealed at 950 °C for 30 min) for an illumination intensity of 1×10^{15} cm^{-2} is shown. The carrier lifetime is shorter in the area where the $Z_{1/2}$ concentration is higher. Moreover, very uniform carrier lifetimes can be realized in each area. These results indicate that the carrier lifetime can be reasonably controlled by electron irradiation.

Figure 4 shows the relation between the inverse of carrier lifetime and the $Z_{1/2}$ concentration in as-grown and electron-irradiated epilayers, where the lifetimes measured with an illumination intensity of 2×10^{14} and 1×10^{15} cm^{-2} are presented by open and closed symbols, respectively. In the figure, carrier lifetimes in as-grown (circles) and electron-irradiated samples annealed at 950 °C (triangles) and 1550 °C (squares) are plotted against the $Z_{1/2}$ concentration. The broken lines denote $1/\tau_{SRH}$ and $1/\tau_{other}$ in Eq. (1), and the solid lines represent the sum of them for both illu-

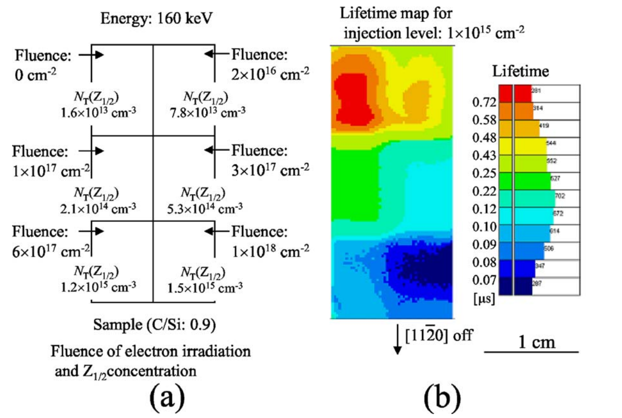

FIG. 3. (Color online) (a) Fluence of electron irradiation and distribution of $Z_{1/2}$ concentration in a 50-μm-thick 4*H*-SiC epilayer selectively irradiated with a Cu mask. Electron irradiation was performed onto the sample grown at a C/Si ratio of 0.9 (donor concentration: 1.5×10^{15} cm^{-3}). (b) Maps of carrier lifetimes in the electron-irradiated sample annealed at 950 °C for an illumination intensity of $N_0=1\times10^{15}$ cm^{-2}.

mination intensities. When the $Z_{1/2}$ concentration was higher than mid-10^{13}–low 10^{14} cm^{-3}, the inverse of the carrier lifetime increased by increasing the $Z_{1/2}$ concentration with a slope close to unity for each injection level. Therefore, the $Z_{1/2}$ center works as a recombination center, as described for as-grown epilayers. As shown in Fig. 4, carrier lifetimes were almost unchanged irrespective of annealing temperature. As mentioned above, several kinds of hole traps could be observed after electron irradiation and subsequent annealing at 950 °C, while many of them disappeared after annealing at 1550 °C.[18] Therefore, most hole traps do not seem to work as an effective recombination center.

In previous reports by Tawara *et al.*[6] and Klein *et al.*,[8] the carrier lifetime showed correlation with the trap ($Z_{1/2}$) concentration even when the $Z_{1/2}$ concentration is lower than 1×10^{13} cm^{-3}. This difference may be due to difference in the τ_{other} value. For example, a lower injection level ($\leqslant 2\times10^{13}$ cm^{-3} in Ref. 8) may lead to longer τ_{other}, as expected from Fig. 4. In such a case, SRH recombination may be always dominant.

As shown in Fig. 4, the carrier lifetime increases by increasing the illumination intensity when the lifetime is governed by the $Z_{1/2}$ concentration. This result can explain positive dependence of carrier lifetimes on injection level for

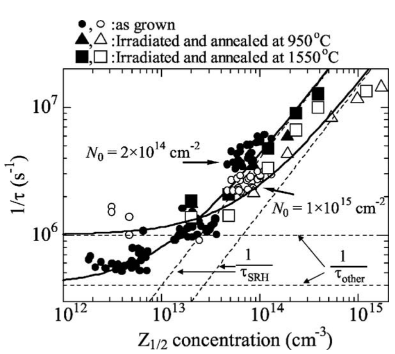

FIG. 4. Relation between the inverse of the carrier lifetime and the $Z_{1/2}$ concentration in as-grown 4*H*-SiC (○,●) and electron-irradiated 4*H*-SiC epilayers annealed at 950 °C (△,▲) and at 1550 °C (□,■) for illumination intensities of $N_0=2\times10^{14}$ cm^{-2} (●,▲,■) and $N_0=1\times10^{15}$ cm^{-2} (○,△,□).

the epilayer grown at a C/Si ratio of 0.9 [Fig. 1(a)]. Since the $Z_{1/2}$ concentration for the sample is relatively high, 1.3×10^{13} cm^{-3}, the $Z_{1/2}$ center worked as effective lifetime killer, and the carrier lifetime shows positive dependence on the injection level. When the recombination via other paths is dominant (the $Z_{1/2}$ concentration is lower than 10^{13} cm^{-3}), the lifetime decreases by increasing the illumination intensity, in good agreement with the result shown in Fig. 1(b). A long lifetime under high injection condition is desirable for effective conductivity modulation. On the other hand, a short lifetime under low-injection condition is desirable for reduction of switching loss. Therefore, due to the positive dependence of lifetime on the injection level, introduction of the $Z_{1/2}$ center as a lifetime killer is suitable for control of the carrier lifetime in SiC bipolar power devices.

In summary, carrier lifetimes in 4*H*-SiC epilayers were investigated by μ-PCD measurements. The $Z_{1/2}$ center works as an effective recombination center when the concentration is higher than low 10^{13} cm^{-3}. By controlling the $Z_{1/2}$ concentration by low-energy electron irradiation, control of carrier lifetimes could be realized. When the carrier lifetime is limited by the $Z_{1/2}$ center, the carrier lifetime shows positive dependence on the injection level. On the other hand, other recombination paths than deep levels such as surface recombination might limit carrier lifetimes when the $Z_{1/2}$ concentration is lower than 10^{13} cm^{-3}. In this case, the carrier lifetime decreases by increasing the injection level.

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