Real Relationship between Acceptor Density and Hole Concentration in Al-implanted 4H-SiC

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Experimental acceptor energy levels (ΔE_{A}) in SiC, measured from the top of the valence band (E_{V}), are reported to be deeper than 150 meV [1]. Acceptor densities (N_{A}) determined by a least-squares fit of the charge neutrality equation to the temperature dependence of the hole concentration [$p(T)$] are much higher than the Al concentration (N_{Al}) determined by secondary ion mass spectroscopy (SIMS) [2]. On the other hand, the first excited state of an acceptor in SiC, calculated by the hydrogenic acceptor model [$\Delta E_r = 13.6\left(m^* / \varepsilon_{\mathrm{s}}^2 r^2\right)$ eV], is 34 meV, which is very close to ΔE_{A} of B in Si. This indicates that the excited states of the acceptor should affect $p(T)$ in SiC very much.

In order to consider the influence of the excited states of the acceptor on $p(T)$, we have proposed a distribution function for electrons corresponding to deep acceptors [3];

$$f\left(\Delta E_{\mathrm{A}}\right) = \frac{1}{1 + 4\exp\left(-\dfrac{\overline{E_{\mathrm{ex}}}}{kT}\right) \cdot \left\{\exp\left(\dfrac{\Delta E_{\mathrm{A}} - \Delta E_{\mathrm{F}}}{kT}\right) + \displaystyle\sum_{r=2} g_r \exp\left(\dfrac{\Delta E_r - \Delta E_{\mathrm{F}}}{kT}\right)\right\}}, \tag{1}$$

where ΔE_{F} is the Fermi level measured from E_{V}, g_r is the ($r-1$)th excited state degeneracy factor, and $\overline{E_{\mathrm{ex}}}$ is the ensemble average of the ground and excited state levels of the acceptor, which is expressed as

$$\overline{E_{\mathrm{ex}}} = \frac{\displaystyle\sum_{r=2} \left(\Delta E_{\mathrm{A}} - \Delta E_r\right) g_r \exp\left(-\dfrac{\Delta E_{\mathrm{A}} - \Delta E_r}{kT}\right)}{g_1 + \displaystyle\sum_{r=2} g_r \exp\left(-\dfrac{\Delta E_{\mathrm{A}} - \Delta E_r}{kT}\right)}. \tag{2}$$

Here, an effective acceptor energy level ($\overline{\Delta E_{\mathrm{A}}}$) is expressed as $\overline{\Delta E_{\mathrm{A}}} = \Delta E_{\mathrm{A}} - \overline{E_{\mathrm{ex}}}$. Equation (1) coincides with the Fermi-Dirac distribution function [$f_{\mathrm{FD}}\left(E_{\mathrm{A}}\right)$] when $r = 1$ and $\overline{E_{\mathrm{ex}}} = 0$, while Eq. (1) coincides with the conventional distribution function [$f_{\mathrm{conv}}\left(\Delta E_{\mathrm{A}}\right)$] when $\overline{E_{\mathrm{ex}}} = 0$.

After Al ions were implanted into an n-type 4H-SiC epilayer at room temperature and the Al-implanted SiC layer was annealed at 1575 °C, $p(T)$ in the Al-implanted p-type 4H-SiC layer was obtained by Hall-effect measurements. The value of N_{Al} determined by SIMS was approximately 5×10^{18} cm^{-3}. Using Free Carrier Concentration Spectroscopy (FCCS) [3], the values of ΔE_{A}, N_{A} and the compensating density (N_{comp}) were determined for each distribution function, and are shown in Table I. Open circles in Fig. 1 show the experimental $p(T)$, and open circles in Fig. 2 display the experimental FCCS signal given by $H\left(T, E_{\mathrm{ref}}\right) \equiv p(T)^2 \exp\left(E_{\mathrm{ref}} / kT\right) / (kT)^{5/2}$. The $p(T)$ and $H\left(T, E_{\mathrm{ref}}\right)$ curves simulated using the values in Table I are also shown as solid, broken and dotted curves for $f\left(\Delta E_{\mathrm{A}}\right)$, $f_{\mathrm{FD}}\left(E_{\mathrm{A}}\right)$ and $f_{\mathrm{conv}}\left(\Delta E_{\mathrm{A}}\right)$, respectively.

N_{A} obtained from $f\left(\Delta E_{\mathrm{A}}\right)$ is considered to be the most appropriate since this value was the closest to N_{Al}, while all the ΔE_{A} were close to ΔE_{A} obtained by photoluminescence. The $H\left(T, E_{\mathrm{ref}}\right)$ curve (solid curve) simulated with the values obtained using $f\left(\Delta E_{\mathrm{A}}\right)$ was in better agreement with the experimental data than the other distribution functions, while all the simulated $p(T)$ were in good agreement with the experimental data.

When $p(T)$ in p-type SiC is analyzed, therefore, the influence of the excited states of an acceptor should be considered, and the proposed distribution function expressed by Eq. (1) should be used. Moreover, FCCS is found to be suitable for investigating the effect of the excited states of acceptors.

In order to precisely simulate the electric characteristics of pn diodes, Schottky barrier diodes and MOSFETs (metal-oxide-semiconductor field-effect transistors), both the space-charge density in the depletion layer and the free carrier concentration in the bulk should be actual values. Since the space-charge density is equal to N_A and the free carrier concentration is equal to $p(T)$, the distribution function is important to obtain correct N_A and $p(T)$, indicating that $f(\Delta E_A)$ should be used in the device simulation.

Using $f(\Delta E_A)$, furthermore, the dependence of N_A on the annealing temperature of Al-implanted SiC layers has been investigated.

References
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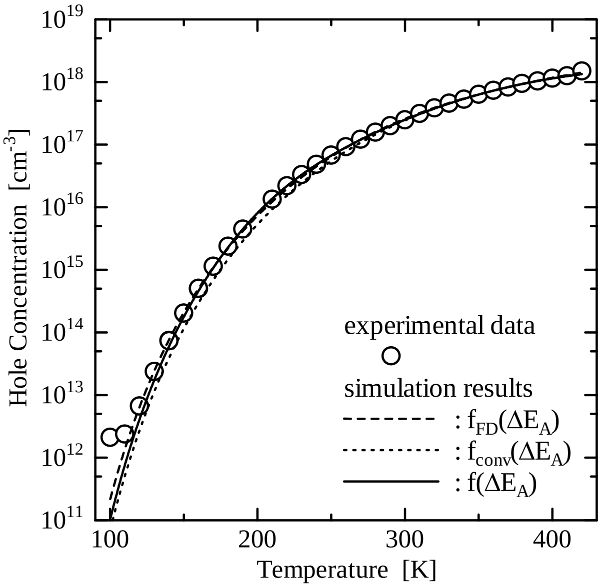

Fig. 1 Experimental and simulated $p(T)$.

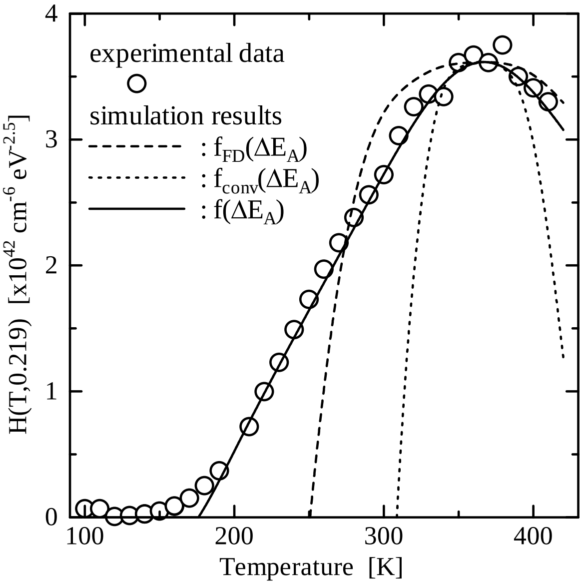

Fig. 2 Experimental and simulate $H(T, E_{ref})$.

Table I Results determined by FCCS.

	$f_{FD}(\Delta E_A)$	$f_{conv}(\Delta E_A)$	$f(\Delta E_A)$
N_A [cm^{-3}]	3.51×10^{19}	6.03×10^{20}	5.46×10^{18}
ΔE_A [meV]	162	176	177
N_{comp} [cm^{-3}]	1.28×10^{18}	1.36×10^{19}	7.42×10^{16}