Influence of Excited States of Deep Acceptors on Hole Concentration in SiC

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Experimental acceptor levels ΔE_{A} in SiC, measured from the valence band E_{V}, are reported to be deeper than 150 meV. Moreover, the ground and first excited state levels of acceptors in SiC, calculated by hydrogenic acceptor [$\Delta E_r = 13.6(m^* / \varepsilon_s^2 r^2)$ eV], are 136 meV and 34 meV, respectively. The experimental ΔE_{A} is deeper than ΔE_1 because of central cell corrections, while ΔE_r $(r \geq 2)$ are considered to be reasonable, and should affect the hole concentration $p(T)$. Using three kinds of distribution functions, we theoretically and experimentally investigate the influence of the excited states on $p(T)$.

The proposed distribution function for electrons is expressed as

$$f\left(\Delta E_{\mathrm{A}}, n, \overline{E_{\mathrm{ex}}}\right) = \frac{1}{1 + 4\exp\left(-\dfrac{\overline{E_{\mathrm{ex}}}}{kT}\right)\cdot\left\{g_1 \exp\left(\dfrac{\Delta E_{\mathrm{A}} - \Delta E_{\mathrm{F}}}{kT}\right) + \sum_{r=2}^{n} g_r \exp\left(\dfrac{\Delta E_r - \Delta E_{\mathrm{F}}}{kT}\right)\right\}}, \quad (1)$$

where ΔE_{F} is the Fermi level measured from E_{V}, g_r is the $(r-1)$-th excited state degeneracy factor, and n is the highest excited state, which we consider in analysis. Here, the average acceptor level $\overline{\Delta E_{\mathrm{A}}}$ is expressed as $\overline{\Delta E_{\mathrm{A}}} = \Delta E_{\mathrm{A}} - \overline{E_{\mathrm{ex}}}$, and $\overline{E_{\mathrm{ex}}}$ is the ensemble average of the ground and excited state levels, which increases with T. The Fermi-Dirac distribution function corresponds to $f(\Delta E_{\mathrm{A}},1,0)$ and the conventional function is $f(\Delta E_{\mathrm{A}}, n, 0)$.

Using p-type 6H-SiC wafer, $p(T)$ was obtained by Hall-effect measurements. Using Free Carrier Concentration Spectroscopy (FCCS), ΔE_{A}, the acceptor density N_{A} and the compensating density N_{com} were determined, and are shown in Table 1. Figure 1 shows the $p(T) - 1/T$ curves, and Fig. 2 displays the FCCS curve given by $H(T, E_{\mathrm{ref}}) \equiv p(T)^2 \exp(E_{\mathrm{ref}}/kT)/(kT)^{5/2}$, where the simulation results mean the curves simulated using Table 1.

In $f(\Delta E_{\mathrm{A}},1,0)$, although the simulated $p(T)$ is in agreement with the experimental $p(T)$, the simulated $H(T, E_{\mathrm{ref}})$ is not, indicating that the excited states should affect $p(T)$. In $f(\Delta E_{\mathrm{A}}, n, 0)$, the density of holes bound to acceptors increases, which results in the unreasonable high N_{A}. In our case, there are good coincidences between the experimental data and simulation results in Fig. 1 as well as in Fig. 2, and N_{A} and ΔE_{A} are considered to be reasonable.

In summary, the influence of the excited states on $p(T)$ should be considered, and the distribution function used in deep acceptors should be $f(\Delta E_{\mathrm{A}}, n, \overline{E_{\mathrm{ex}}})$.

Table 1 Results determined by FCCS

	$f(\Delta E_{\mathrm{A}},1,0)$	$f(\Delta E_{\mathrm{A}},10,0)$	$f(\Delta E_{\mathrm{A}},10,\overline{E_{\mathrm{ex}}})$
N_{A} [cm^{-3}]	2.95x10^{19}	2.19x10^{20}	1.91x10^{18}
ΔE_{A} [meV]	182	205	189
N_{com} [cm^{-3}]	8.35x10^{17}	2.65x10^{18}	3.37x10^{16}

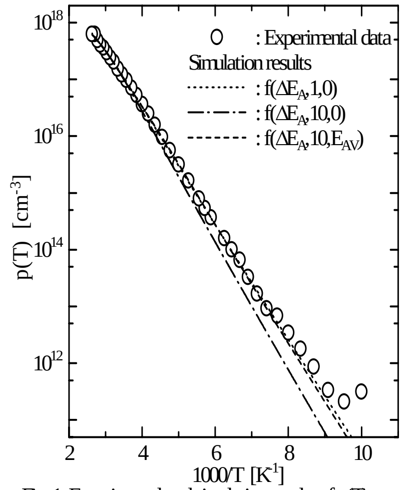

Fig. 1 Experimental and simulation results of p(T)

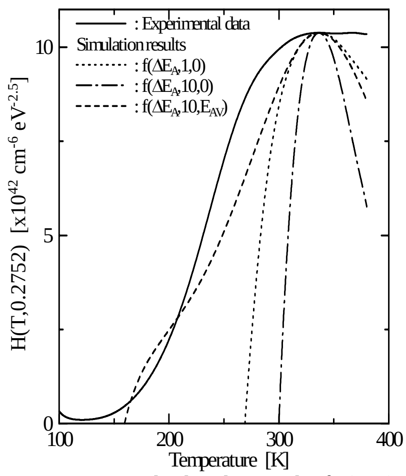

Fig. 2 Experimental and simulation results of H(T,E_{ref})