Donor Densities and Donor Levels in SiC Uniquely Determined by a New Method Based on Hall-Effect Measurements

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Silicon carbide (SiC) has been regarded as a promising semiconductor for power electronic applications owing to its excellent physical properties. In order to apply SiC wafers and epilayers to electronic devices, an accurate evaluation of densities and energy levels of dopants in SiC is essential. One of the authors has proposed and experimentally tested a graphical method for determining densities and energy levels of several dopants using the temperature dependence $n(T)$ of the majority carrier concentration obtained by Hall-effect measurements. We apply this method to determine donor densities (N_{D}) and donor levels (ΔE_{D}) in 4H-SiC and 3C-SiC.

In the proposed method, a function $H(T, E_{\mathrm{ref}})$ is defined as

$$H(T, E_{\mathrm{ref}}) \equiv \frac{n(T)^2}{(kT)^{2.5}} \exp\left(\frac{E_{\mathrm{ref}}}{kT}\right), \tag{1}$$

where k is the Boltzmann constant, T is the absolute temperature and E_{ref} is a parameter which can shift the peak temperature (T_{peak}) of $H(T, E_{\mathrm{ref}})$ within the measurement temperature range. Since T_{peak} corresponds to one ΔE_{D}, from each peak temperature and peak value, the values (ΔE_{D} and N_{D}) of the corresponding dopant can be accurately determined.

Let us consider n types of donors ($N_{\mathrm{D}i}$ and $\Delta E_{\mathrm{D}i}$ for $1 \le i \le n$) and one type of acceptor (density N_{A}). From the charge neutrality condition, $n(T)$ is given by

$$n(T) = \sum_{i=1}^{n} N_{\mathrm{D}i} \left[1 - f\left(\Delta E_{\mathrm{D}i}\right)\right] - N_{\mathrm{A}}, \tag{2}$$

where $f(\Delta E_{\mathrm{F}})$ is the Fermi-Dirac distribution function given by

$$f\left(\Delta E_{\mathrm{D}i}\right) = \frac{1}{1 + \frac{1}{2}\exp\left(\frac{\Delta E_{\mathrm{F}} - \Delta E_{\mathrm{D}i}}{kT}\right)} \tag{3}$$

and ΔE_{F} is the Fermi level measured from the bottom of the conduction band. On the other hand, $n(T)$ is also expressed as

$$n(T) = N_{\mathrm{C}}(T) \exp\left(-\frac{\Delta E_{\mathrm{F}}}{kT}\right) \tag{4}$$

where the effective density of states $N_{\mathrm{C}}(T)$ in the conduction band, which can be described as

$$N_{\mathrm{C}}(T) = (kT)^{1.5} N_{\mathrm{C0}}. \tag{5}$$

Substituting eq. (2) for one of the $n(T)$ in eq. (1) and substituting eq. (4) for the other $n(T)$ give

$$H(T, E_{\mathrm{ref}}) = \sum_{i=1}^{n} \frac{N_{\mathrm{D}i}}{kT} \exp\left(-\frac{\Delta E_{\mathrm{D}i} - E_{\mathrm{ref}}}{kT}\right) I_{\mathrm{D}}\left(\Delta E_{\mathrm{D}i}\right) - N_{\mathrm{A}} \frac{N_{\mathrm{C0}}}{kT} \exp\left(\frac{E_{\mathrm{ref}} - \Delta E_{\mathrm{F}}}{kT}\right), \tag{6}$$

where

$$I_{\mathrm{D}}\left(\Delta E_{\mathrm{D}i}\right) = \frac{N_{\mathrm{C0}}}{2 + \exp\left(\frac{\Delta E_{\mathrm{F}} - \Delta E_{\mathrm{D}i}}{kT}\right)}. \tag{7}$$

The function

$$\frac{N_{\mathrm{D}i}}{kT}\exp\left(-\frac{\Delta E_{\mathrm{D}i}-E_{\mathrm{ref}}}{kT}\right) \tag{8}$$

in eq. (6) has a peak value of $N_{\mathrm{D}i}\exp(-1)/kT_{\mathrm{peak}i}$ at a peak temperature ($T_{\mathrm{peak}i}=(\Delta E_{\mathrm{D}i}-E_{\mathrm{ref}})/k$), indicating that the peak value and peak temperature provide $N_{\mathrm{D}i}$ and $\Delta E_{\mathrm{D}i}$. Although $T_{\mathrm{peak}i}$ of $H(T,E_{\mathrm{ref}})$ is a little different from the above value due to the temperature dependence of $I_{\mathrm{D}}(\Delta E_{\mathrm{D}i})$, we can easily determine the accurate $N_{\mathrm{D}i}$ and $\Delta E_{\mathrm{D}i}$ from each $H(T_{\mathrm{peak}i},E_{\mathrm{ref}})$ and $T_{\mathrm{peak}i}$, using a personal computer.

32-μm-thick undoped 3C-SiC epilayers were grown on Si by chemical vapor deposition (CVD) using HMDS: $Si_2(CH_3)_6$. N-doped 4H-SiC epilayers were grown by CVD using SiH_4 and C_3H_8 on p-type 4H-SiC. $n(T)$ of the films were measured by the van der Pauw method.

Figure 1 shows $n(T)$ denoted by open circles and $H(T,-0.002)$ denoted by the solid line of undoped 3C-SiC. In $H(T,-0.002)$, two peaks appear, indicating that at least two types of donors exist in the 3C-SiC. From the detailed analysis, three types of donors are found to exist. Their ΔE_{D} and N_{D} are determined to be 14 meV and 4.7×10^{16} cm^{-3}, 54 meV and 8.1×10^{16} cm^{-3}, and 120 meV and 1.0×10^{17} cm^{-3}, respectively. The acceptor density (N_{A}) is estimated to be 5.7×10^{15} cm^{-3}. Figure 2 shows the experimental $n(T)$ and the $n(T)$ simulated with the obtained values. Since the simulated $n(T)$ is quantitatively in good agreement with the experimental $n(T)$, the obtained values are considered to be reliable.

Figure 3 shows $n(T)$ denoted by open circles and $H(T,0)$ denoted by the solid line of N-doped 4H-SiC. In $H(T,0)$, one peak and one shoulder appear, indicating that at least two types of donors exist in the 4H-SiC. From the detailed analysis, their ΔE_{D} and N_{D} are determined to be 65 meV and 6.5×10^{15} cm^{-3}, and 124 meV and 3.0×10^{16} cm^{-3}, respectively. N_{A} is estimated to be 6.1×10^{13} cm^{-3}. Figure 4 shows the experimental $n(T)$ and the $n(T)$ simulated with the obtained values. Since the simulated $n(T)$ is quantitatively in good agreement with the experimental $n(T)$, the obtained values are considered to be reliable.

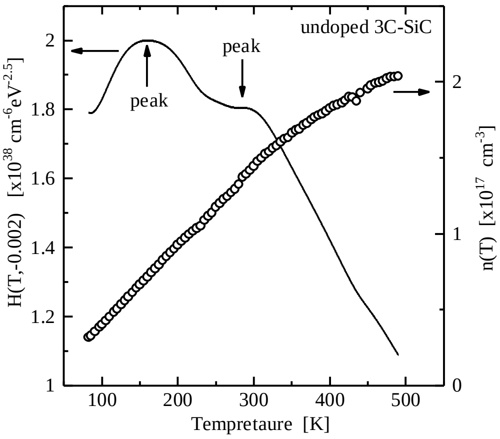

Fig.1 n(T) and H(T,-0.002)

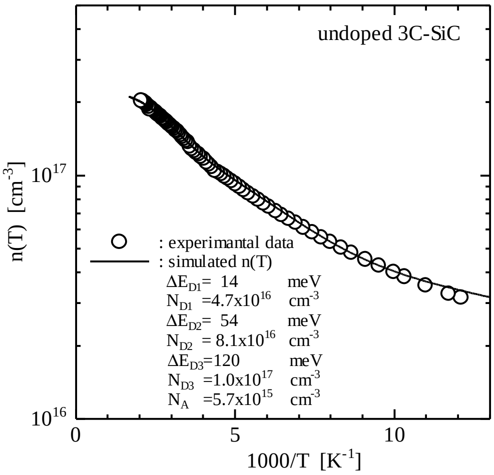

Fig. 2 Experiemtal and simulated n(T)

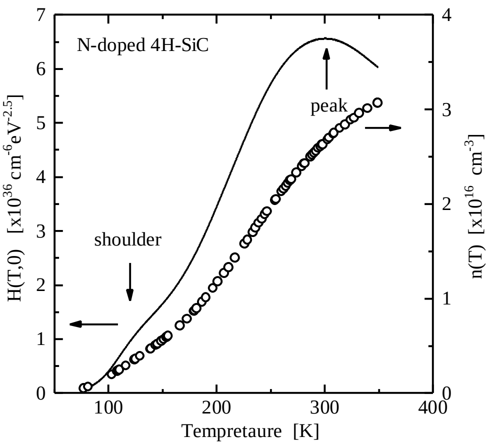

Fig. 3 n(T) and H(T,0)

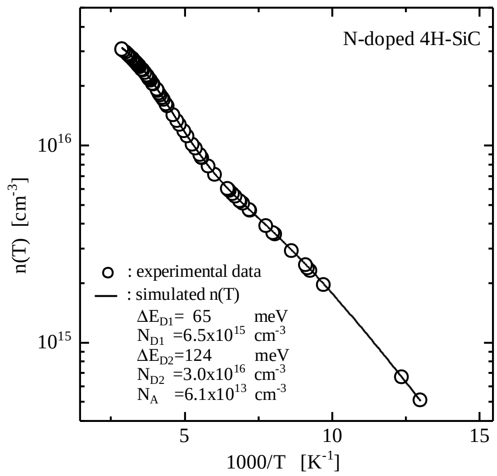

Fig. 4 Experimental and simulated n(T)

References 1) H. Matsuura: Jpn. J. Appl. Phys. **36**(1997)3541.

2) H. Matsuura, Y. Uchida, T. Hisamatsu and S. Matsuda: Jpn. J. Appl. Phys. **37**(1998)6034.

3) H. Matsuura, T. Kimoto and H. Matsunami: Jpn. J. Appl. Phys. **38**(1999)4013.

4) H. Matsuura: Jpn. J. Appl. Phys. **38**(1999)5176.