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Parameters required to simulate electric characteristics of SiC devices

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Abstract. The temperature-dependent majority-carrier concentration $n(T)$ or $p(T)$ and mobility $\mu_{\mathrm{n}}(T)$ or $\mu_{\mathrm{p}}(T)$ in 4H-SiC epilayers with several doping densities are obtained from Hall-effect measurements. Using the graphical peak analysis method without any assumptions regarding the number of impurity species, two types of donor or acceptor species are detected from $n(T)$ or $p(T)$. Moreover, the densities and energy levels of them are determined. Using these results, we obtain the parameters with which the dependencies of $n(T)$ and $\mu_{\mathrm{n}}(T)$ (or $p(T)$ and $\mu_{\mathrm{p}}(T)$) on the total impurity density can be simulated.

1. Introduction

Silicon carbide (SiC) is a semiconductor with a wide bandgap, a high electron mobility, a high electron saturation drift velocity, and a high thermal conductivity. As these results, it is regarded as a promising semiconductor for devices operating at high powers, high frequencies, and high temperatures. In order to design optimum device structures for SiC devices, it is necessary to simulate their electric characteristics in a wide doping density and a wide temperature range from startup temperatures (<30°C) to steady-operation temperatures (>200°C).

Although the energy level of substitutional donors in n-type SiC is shallow, the energy level of substitutional acceptors in p-type SiC becomes deep, indicating that the excited states of the acceptor influence the hole concentration $p(T)$. In p-type wide bandgap semiconductors (i.e., GaN and SiC), a distribution function suitable for acceptor has been proposed and experimentally tested [1], instead of the Fermi-Dirac

distribution function that does not include the influence of excited states of acceptors.

In this article, we determine the parameters required to simulate the dependencies of the carrier concentration and mobility on the temperature and the doping density in 4H-SiC. These parameters are required to carry out device simulation for SiC devices.

2. Free carrier concentration spectroscopy

Free carrier concentration spectroscopy (FCCS) can graphically determine the densities and energy levels of impurities from the electron concentration $n(T)$ or $p(T)$ without any assumptions regarding the impurity species [1]. In FCCS, the following function is defined using the experimental $n(T)$ (or $p(T)$);

$$H(T, E_{\mathrm{ref}}) \equiv \frac{n(T)^2}{(kT)^{5/2}} \exp\left(\frac{E_{\mathrm{ref}}}{kT}\right), \tag{1}$$

which has a peak at the temperature corresponding to each energy level, where k is the Boltzmann constant, T is the absolute temperature, and E_{ref} is the parameter which can shift the peak temperature of $H(T, E_{\mathrm{ref}})$ within the measurement temperature range. From each peak value and peak temperature, we can determine the densities and energy levels of impurities accurately.

3. Experiment

Approximately 10-μm-thick n- or p-type 4H-SiC (0001) epilayers with different doping densities were grown on 4H-SiC substrate with the opposite conduction type in order to eventually fabricate pn junctions. They were cut into a 3×3 mm^2 size. Ohmic contacts (Ti/Al or Ni) were deposited on p- or n-type epilayers, and then the epilayers were annealed at 1000°C. $p(T)$ and hole mobility $\mu_{\mathrm{p}}(T)$ (or $n(T)$ and electron mobility $\mu_{\mathrm{n}}(T)$) were obtained from Hall-effect measurement in van der Pauw configuration.

4. Results and discussion

4.1. Determinations of impurity levels and impurity densities

Using FCCS, two types of donor or acceptor species are detected in n- or p-type 4H-SiC from $n(T)$ or $p(T)$. Moreover, the densities and energy levels of them are determined. On the other hand, only one type of acceptor species is detected in the most heavily Al-doped epilayer. In order to obtain reliable results, the distribution function considering the influence of the excited states of acceptors is used.

In n-type SiC, the shallow and deep donor levels (ΔE_{D1} and ΔE_{D2}) are assigned to isolated, substitutional N donors at hexagonal and cubic lattice sites. Furthermore, the ratio of shallow donor density to deep donor density is nearly equal to 1. Because, the ratio of the number of hexagonal lattice sites to the cubic lattice sites in 4H-SiC is unit, it is found that the probability for a N atom being put into each lattice site is an half.

In p-type SiC, the shallow acceptor level (ΔE_{A1}) is identified as a substitutional Al acceptor [2,3]. However, the origin of the deep acceptor level (ΔE_{A2}) is unfortunately unknown to date.

4.2. Dependence of each impurity level on total impurity density

The dependence $\Delta E_i(N_{\mathrm{imp}})$ of each impurity level on total impurity density (N_{imp}) is summarized in Fig. 1. An ideal donor level $\Delta E_i(0)$ is the energy required to emit one electron from the donor site into infinity on the conduction band. Since an n-type semiconductor is electrically neutral, each positively charged donor is shielded by one electron on the conduction band. This shielding electron is assumed to be located within

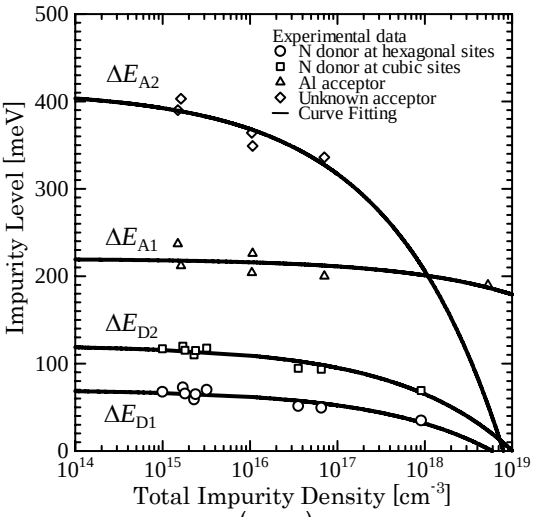

Figure 1. $\Delta E_i\left(N_{\text{imp}}\right)$ simulations.

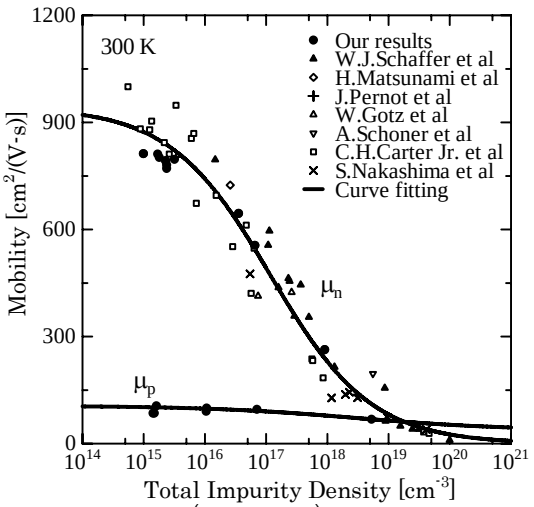

Figure 2. $\mu\left(300, N_{\text{imp}}\right)$ simulations.

Table 1. The parameters for impurity levels in 4H-SiC epilayers.

Dopant	$\Delta E_1(0)$[meV]	α_1[meV·cm]	$\Delta E_2(0)$[meV]	α_2[meV·cm]
N	70.9	3.38×10^{-5}	123.7	4.65×10^{-5}
Al	220	1.90×10^{-5}	413	2.07×10^{-4}

an half $(\bar{r})$ of an average distance $\left(N^{-1/3}\right)$ of donors, indicating that the donor level is lowered by the energy higher than $q/\left(4\pi\varepsilon_s\varepsilon_0\bar{r}\right)$ due to Coulomb's attraction. The situation in p-type semiconductors is the same. Therefore [4],

$$\Delta E_i\left(N_{\text{imp}}\right) \equiv \Delta E_i(0) - \alpha_i N_{\text{imp}}^{1/3} \tag{2}$$

and

$$\alpha_i \geq \frac{q}{8\pi\varepsilon_s\varepsilon_0} = 2.44\times10^{-5}\,\text{meV}\cdot\text{cm}, \tag{3}$$

where q is the electron charge, ε_0 is the free space permittivity, and ε_s is the dielectric constant for 4H-SiC. By a least squares fit of Eq.(2) to data in Fig. 1, the fitting parameters are obtained and listed in Table 1. Moreover, the $\Delta E_i\left(N_{\text{imp}}\right)$ simulations are denoted by solid lines in Fig. 1. Since both α_i are close to the value in Eq. (3), they are considered to be reasonable.

4.3. Dependencies of mobility on temperature and total impurity density

Since the majority-carrier mobility at >250 K can be expressed as

$$\mu\left(T, N_{\text{imp}}\right) = \mu\left(300, N_{\text{imp}}\right)\left(\frac{T}{300}\right)^{-\beta\left(N_{\text{imp}}\right)}, \tag{4}$$

$\mu\left(300, N_{\text{imp}}\right)$ and $\beta\left(N_{\text{imp}}\right)$ can be evaluated individually.

According to the literature [5], $\mu\left(300, N_{\text{imp}}\right)$ can be described as

$$\mu\left(300, N_{\text{imp}}\right) = \mu^{\min}(300) + \frac{\mu^{\max}(300) - \mu^{\min}(300)}{1 + \left(N_{\text{imp}}/N_{\text{ref}}^{\mu}\right)^{\gamma^{\mu}}}, \tag{5}$$

where $\mu^{\min}(300)$, $\mu^{\max}(300)$, N_{ref}^{μ}, and γ^{μ} are the fitting parameters. By a least-squares fit of Eq.(5) to data in Fig. 2, these fitting parameters are obtained and listed in Table 2. In Fig. 2, the solid lines represent the $\mu\left(300, N_{\text{imp}}\right)$ simulations.

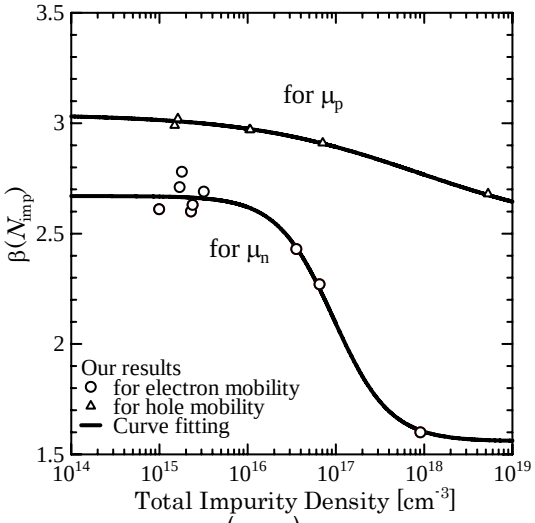

Figure 3. $\beta(N_{\mathrm{imp}})$ simulations.

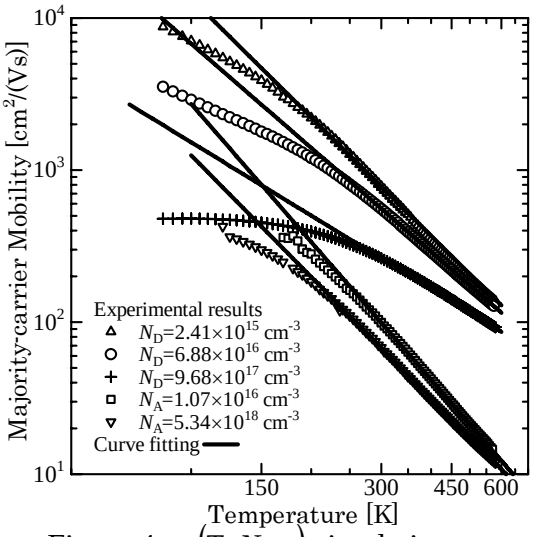

Figure.4 $\mu(T, N_{\mathrm{imp}})$ simulations.

Table 2. The parameters for $\mu(300, N_{\mathrm{imp}})$ and $\beta(N_{\mathrm{imp}})$.

Dopant	$\mu^{\min}$ [cm^2/(V·s)]	$\mu^{\max}$ [cm^2/(V·s)]	N_{ref}^{μ} [cm^{-3}]	γ^{μ}	$\beta^{\min}$	$\beta^{\max}$	N_{ref}^{β} [cm^{-3}]	γ^{β}
N	0	977	1.17×10^{17}	0.49	1.54	2.62	1.14×10^{17}	1.35
Al	37.6	106.0	2.97×10^{18}	0.356	2.51	3.04	8.67×10^{17}	0.456

Since acoustic phonon scattering and inter-valley scattering are considered to affect the electron mobility in SiC [6,7], the following relationship is assumed:

$$\beta(N_{\mathrm{imp}}) = \beta^{\min} + \frac{\beta^{\max} - \beta^{\min}}{1 + \left(N_{\mathrm{imp}} / N_{\mathrm{ref}}^{\beta}\right)^{\gamma^{\beta}}}, \tag{6}$$

where $\beta^{\min}$, $\beta^{\max}$, N_{imp}, and γ^{β} are the fitting parameters. By a least-squares fit of Eq.(6) to data in Fig. 3, their fitting parameters are obtained and listed in Table 2. In Fig. 3, the solid lines represent the $\beta(N_{\mathrm{imp}})$ simulations. Since the values of $\beta(N_{\mathrm{imp}})$ for the acoustic phonon scattering and the inter-valley scattering are 1.5 and 2.6, the obtained parameters are considered to be reasonable in n-type 4H-SiC.

Figure 4 shows the $\mu(T, N_{\mathrm{imp}})$ simulations. It is clear from Fig. 4 that you can calculate the mobility for any impurity densities at T>250 K.

5. Conclusion

In order to obtain some of the parameters required in device simulation for 4H-SiC devices, Hall-effect measurements were conducted. We determined the parameters required to simulate the dependence of each impurity level on total impurity density and the parameters with which the mobility could be simulated at > 250 K

References

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