Parameters required to simulate electric characteristics of SiC devices

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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 a 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 these SiC devices, it is necessary to simulate their electric characteristics in a wide temperature range from startup temperatures ($< 30\,^{\circ}\mathrm{C}$) to steady-operation temperatures ($> 200\,^{\circ}\mathrm{C}$), that is, the carrier concentrations and mobilities in SiC.

The energy level of substitutional acceptors in p-type SiC becomes deep, indicating that the excited states of the acceptor influence the $p(T)$. Instead of the Fermi-Dirac distribution function that does not include the influence of excited states of acceptors, therefore, a distribution function suitable for acceptors in p-type wide bandgap semiconductors (i.e., GaN and diamond) has been proposed and experimentally tested[1].

In this article, we determine the parameters required to simulate the dependencies of the carrier concentrations and mobilities on the temperature and the doping density in SiC.

2. Free carrier concentration spectroscopy

Free carrier concentration spectroscopy (FCCS) can graphically determine the densities and energy levels of impurities from the temperature-dependent majority-carrier concentration $n(T)$ or $p(T)$, without the assumption of the number of impurity species [1]. In FCCS, the following function is defined using the experimental $n(T)$ [or $p(T)$];

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

which has a peak at the temperature correspond to each energy levels, where k is the Boltzmann constant, T is the absolute temperature, and E_{ref} is a 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 the opposite conductivity type substrate to eventually provide pn junctions.

They were cut into a 3×3 mm^2 size. Ohmic contacts (Al or Ni) were deposited on p- or n-type epilayers, and then the epilayers were annealed at $1000\,^{\circ}\mathrm{C}$. $p(T)$ or $n(T)$ and the temperature dependence of the majority-carrier mobility $\mu_{\mathrm{p}}(T)$ or $\mu_{\mathrm{n}}(T)$ were obtained from Hall-effect measurement in van der Pauw configuration.

4. Results and discussion

Using FCCS, the densities and energy levels of donors or acceptors are determined from $n(T)$ or $p(T)$, without any assumption regarding the number of impurity species. Two types of acceptor or donor species are detected in p- or n-type 4H-SiC epilayers, and the densities and energy levels of them are determined. In the case of the heaviest Al-doped epilayer, using the distribution function considering the influence of the excited states of acceptors, only one type of acceptor species is determined.

The shallow and deep donor levels (ΔE_{D1} and ΔE_{D2}) are assigned to isolated, substitutional N donors at hexagonal and cubic sites, while 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.

The dependence of each impurity level in 4H-SiC epilayer on total impurity density (N_{imp}) is summarized in Fig. 1. The solid lines are fitted by least-squares to

an empirical relation suggested by Peason and Bardeen for silicon [4];

$$\Delta E\left(N_{\text{imp}}\right) \equiv \Delta E(0) - \alpha N_{\text{imp}}^{1/3}, \qquad (2)$$

where $\Delta E(0)$ and α are the fitting parameters.

The mobility at > 250 K can be expressed as

$$\mu\left(T, N_{\text{imp}}\right) = \mu\left(300, N_{\text{imp}}\right)\left(\frac{T}{300}\right)^{-\beta\left(N_{\text{imp}}\right)}. \qquad (3)$$

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

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

$$\mu\left(300, N_{\text{imp}}\right) = \mu^{\min}(300) + \frac{\mu^{\max}(300) - \mu^{\min}(300)}{1 + \left(N_{\text{imp}} / N_{\text{ref}}^{\mu}\right)^{\gamma^{\mu}}}, \quad (4)$$

where $\mu^{\min}(300)$, $\mu^{\max}(300)$, N_{ref}^{μ}, and γ^{μ} are the fitting parameters. By a least-squares fit of Eq. (4) to $\mu\left(300, N_{\text{imp}}\right)$, these fitting parameters are determined. As the same way for illustrated for $\mu\left(T, N_{\text{imp}}\right)$, the following relationship is assumed:

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

where $\beta^{\min}$, $\beta^{\max}$, N_{ref}^{β}, and γ^{β} are the fitting parameters. By a least-squares fit of Eq. (5) to $\beta\left(N_{\text{imp}}\right)$, their fitting parameters are determined. Since all the parameters in Eqs. (4) and (5) are determined here, you can calculate the mobility for any impurity densities at T > 250 K.

5. Conclusion

The parameters, with which the dependencies of the majority-carrier concentration and the mobility in 4H-SiC epilayers on the temperature and the total impurity density can be simulated, are required to carry out device simulations. We have determined the parameters required to simulate the dependence of each impurity level on the total impurity density. Moreover, we have determined the parameters with which the mobility for any total impurity density at temperatures higher than 250 K can be simulated.

References

[1] H. Matsuura, *et al*, "Dependencies of acceptor levels and hole mobility on acceptor density and temperature in Al-doped p-type 4H-SiC epilayers", *J. Appl. Phys.*, to be published in the September 1 issue.

[2] M. Ikeda, *et al*, "Site effect on the impurity levels in 4*H*, 6*H*, and 15*R* SiC", *Phys. Rev. B*, 1980, Vol. **22,** pp.2842-2854.

[3] W. Götz, *et al*, "Nitrogen donors in 4*H*-silicon carbide", *J. Appl. Phys.*, 1993, Vol. **73**, pp.3332-3338.

[4] G.L. Peason and J. Bardeen, "Electrical Properties of Pure Silicon and Silicon Alloys Containing Boron and Phosphorus", *Phys. Rev.*, 1949, Vol. **75**, pp.865-883.

[5] D.M. Caughey and R.E. Thomas, "Carrier Mobilities in Silicon Empirically Related to Doping and Field", *Proc. IEEE*, 1967, Vol. **55**, pp.2192-2193.

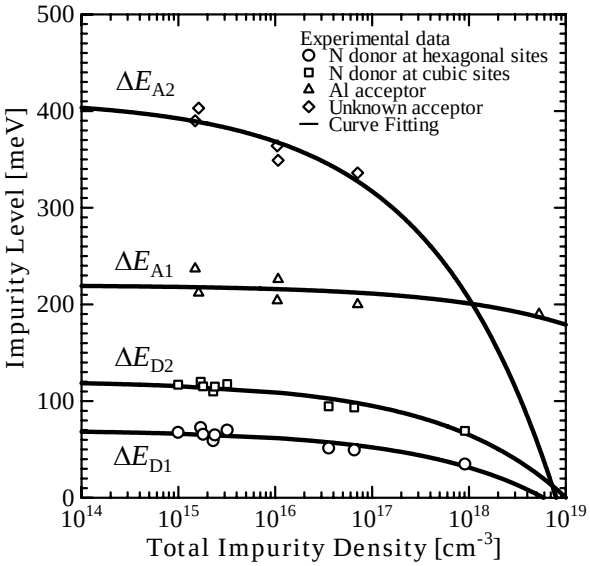

Fig. 1 $\Delta E\left(N_{\text{imp}}\right)$ simulations

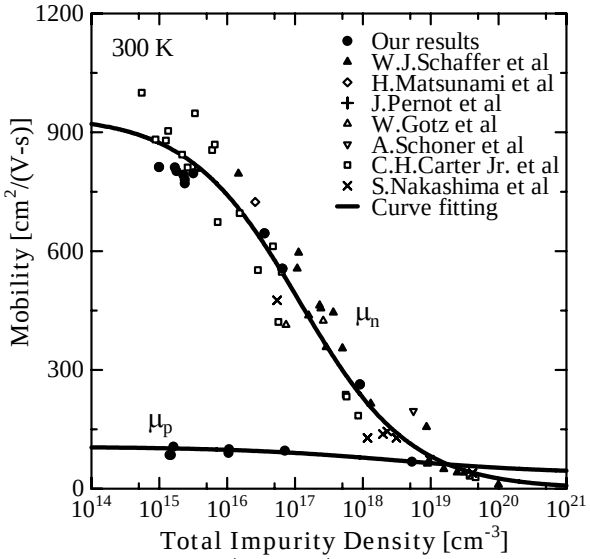

Fig. 2 $\mu\left(300, N_{\text{imp}}\right)$ simulations

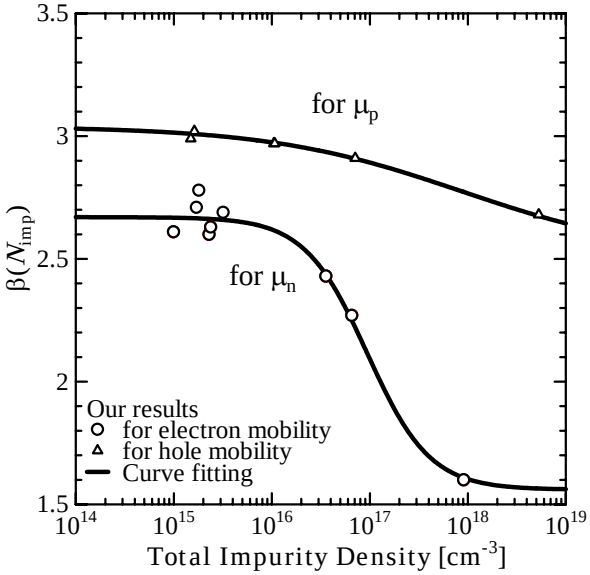

Fig. 3 $\beta\left(N_{\text{imp}}\right)$ simulations