A graphical peak analysis method for characterizing impurities in SiC, GaN and diamond from temperature-dependent majority-carrier concentration

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Abstract

Wide band gap semiconductors are regarded as a promising semiconductor for devices operating at high temperatures. In order to design the optimum device structures, it is necessary to simulate their electric characteristics in a wide temperature range from startup temperatures to steady-operation temperatures. Therefore, it is essential to determine the parameters (e.g., densities and energy levels of impurities) required to carry out the device simulations.

Using the temperature-dependent majority-carrier concentration (i.e., $n(T)$ for electrons or $p(T)$ for holes), these values are usually evaluated from the $\ln n(T) - 1/T$ or $\ln p(T) - 1/T$ curve. However, this analysis cannot be applied in semiconductors with more than two types of dopants or compensated semiconductors. Moreover, it is difficult to obtain reliable values by fitting a simulation to the experimental data, because it is necessary to assume the number of impurity species before the curve-fitting procedure.

Without any assumptions regarding impurity species, free carrier concentration spectroscopy (FCCS) can determine the densities and energy levels of impurities.[1] The FCCS signal is defined as[2,3]

$$H(T, E_{\mathrm{ref}}) \equiv \frac{n(T)^2}{(kT)^{5/2}} \exp\left(\frac{E_{\mathrm{ref}}}{kT}\right) \quad \text{or} \quad H(T, E_{\mathrm{ref}}) \equiv \frac{p(T)^2}{(kT)^{5/2}} \exp\left(\frac{E_{\mathrm{ref}}}{kT}\right),$$

and has a peak at the temperature corresponding to each impurity level, where E_{ref} is the parameter that can shift the peak temperature of $H(T, E_{\mathrm{ref}})$ within the measurement temperature range. From each peak, the density and energy level of the corresponding impurity can be accurately determined.

Since the energy levels of substitutional acceptors in p-type SiC, GaN, and diamond are deep, the distribution function including the influence of the excited states of the acceptor is required to analyze their experimental $n(T)$ or $p(T)$,[3-6] instead of the Fermi-Dirac distribution function that does not include this influence.

In this paper, we report on our investigation of accurate evaluation of impurities from $n(T)$ or $p(T)$ in SiC, GaN, and diamond using FCCS.

Figure 1 shows $n(T)$ and $H(T, E_{\mathrm{ref}})$ with $E_{\mathrm{ref}} = -2.54 \times 10^{-4}$ eV for undoped 3C-SiC, denoted by circles and solid curve, respectively. One peak and one shoulder appeared in the FCCS signal, indicating that at least two types of donor species are included in this 3C-SiC. The density and energy level of the donor corresponding to this peak were determined as 7.1×10^{16} cm^{-3} and 51 meV,

respectively. To evaluate the donor corresponding to the shoulder, the FCCS signal, in which the influence of the previously determined donor is removed, is calculated. From this peak, those of another donor were determined as 3.8×10^{16} cm^{-3} and 18 meV, respectively. Moreover, we determined densities and energy levels of donors or acceptors in 3C-SiC and 4H-SiC with several doping levels, and obtained the dependence of both energy levels of dopants and mobility on dopant density.

In p-type 4H-SiC, 6H-SiC, GaN and diamond, we attempted to obtain reliable dopant density from $p(T)$ using several distribution functions.

References

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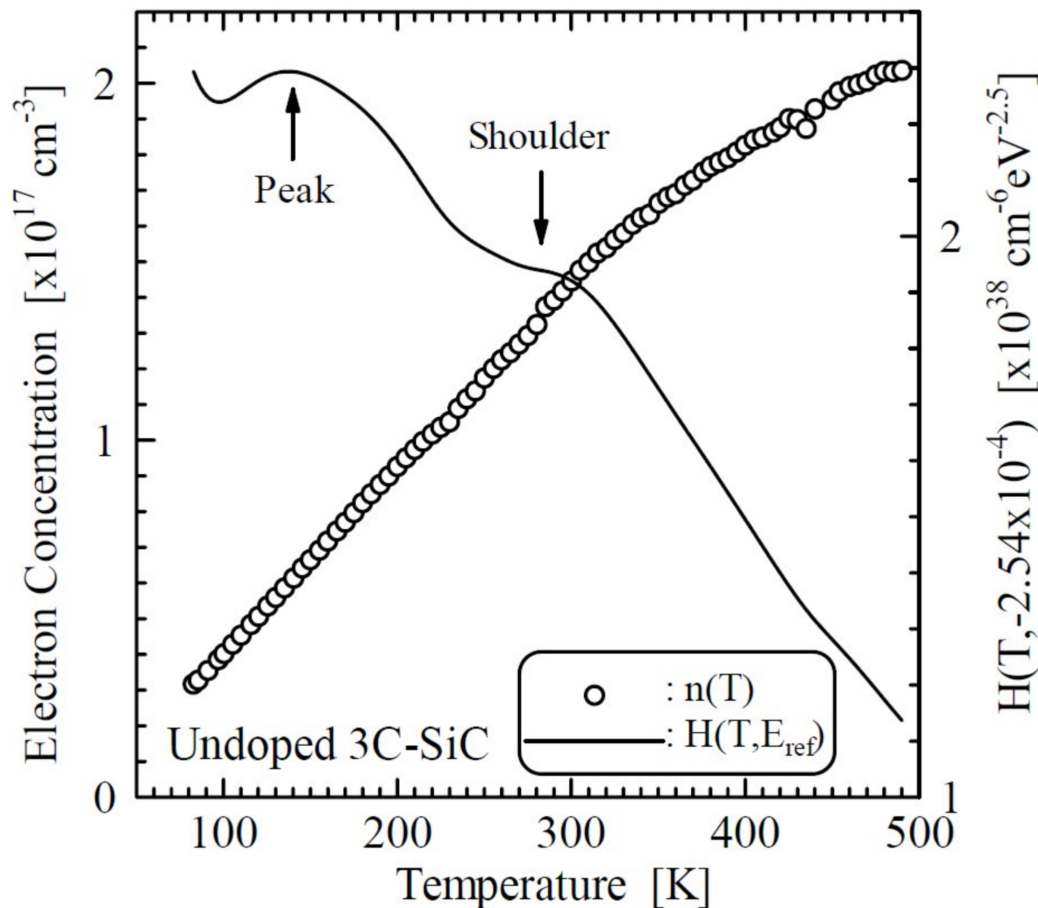

Fig. 1. Temperature-dependent electron concentration and FCCS signal for undoped 3C-SiC.