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

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Using a temperature-dependent majority-carrier concentration (i.e., $n(T)$ for electrons or $p(T)$ for holes), the density and energy level of impurities are usually evaluated from $\ln n(T)-1/T$ or $\ln p(T)-1/T$ curve. However, this analysis cannot be applied in semiconductors with more than two types of impurity species 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 accurately determine the densities and energy levels of impurities. [1,2] The FCCS signal is defined as[1,2]

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

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 of $H(T,E_{\mathrm{ref}})$, the density and energy level of the corresponding impurity can be accurately determined.

Since the energy levels of substitutional acceptors in p-type SiC and GaN are deep, the distribution function $f_{\mathrm{MC}}(E_{\mathrm{A}})$ including the influence of the excited states of the acceptor is required to analyze their experimental $p(T)$,[2,3] instead of the Fermi-Dirac distribution function $f_{\mathrm{FD}}(E_{\mathrm{A}})$ that does not include this influence.

In this paper, we report on our investigation of accurate evaluation of impurities in diamond by FCCS using several distribution functions for acceptors. A 1.73-μm-thick p-type single crystalline diamond epilayer was grown on a synthesized single crystal 1b diamond, and the B-doping level (C_{B}) was 2×10^{17} cm^{-3}.[4] The $p(T)$ was obtained by Hall-effect measurements in the van der Pauw configuration. Figure 1 shows $p(T)$ and $H(T,E_{\mathrm{ref}})$ with E_{ref} of 0.31 eV, denoted by circles and triangles, respectively. Using $f_{\mathrm{FD}}(E_{\mathrm{A}})$, the acceptor density ($N_{\mathrm{A}}$) and energy level ($E_{\mathrm{A}}$), and the compensating density (N_{comp}) were determined from the peak of $H(T,E_{\mathrm{ref}})$ as 9.7×10^{17} cm^{-3}, $E_{\mathrm{V}}+0.34$ eV, and 4.0×10^{16} cm^{-3}, respectively. However, the determined N_{A} is approximately 5 higher than the C_{B}. Using $f_{\mathrm{MC}}(E_{\mathrm{A}})$, on the other hand, those were determined as 2.8×10^{17} cm^{-3}, $E_{\mathrm{V}}+0.32$ eV, and 2.0×10^{16} cm^{-3}, respectively. In this case, the determined N_{A} was close to the C_{B}, indicating that the effect of the excited states of the B acceptor in diamond on $p(T)$ should not be ignored.

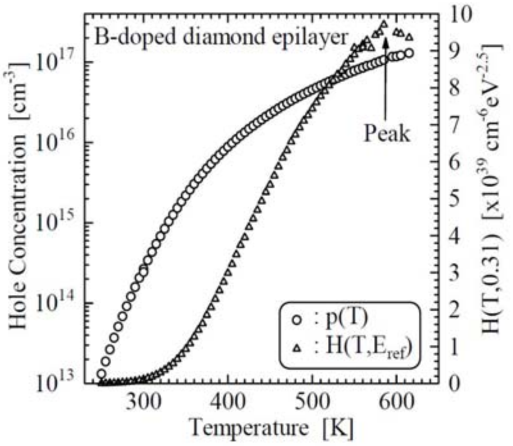

Fig. 1. Temperature-dependent hole concentration and FCCS signal.

References

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