Free Carrier Concentration Spectroscopy (FCCS) for n-type semiconductor

A function to be evaluated is defined as

$$H1(T, E_{\mathrm{ref}}) \equiv \frac{n(T)^2}{(kT)^{5/2}} \exp\left(\frac{E_{\mathrm{ref}}}{kT}\right), \tag{1}$$

where k is the Boltzmann constant, T is the measurement temperature, and E_{ref} is a parameter which can shift peak temperatures of $H1(T, E_{\mathrm{ref}})$.

We consider n different donor species (density $N_{\mathrm{D}i}$ and energy level $\Delta E_{\mathrm{D}i}$ of the i-th donor for $1 \le i \le n$), one completely ionized donor above the measurement temperatures (density N_{D}), and one acceptor (density N_{A}). From the charge neutrality condition, the free electron concentration $n(T)$ can be derived as

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

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

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

ΔE_{F} is the Fermi Level measured from the bottom (E_{C}) of the conduction band, $g_{\mathrm{D}i}$ is the degeneracy factor of i-th donor, N_{com} is the compensating density expressed as

$$N_{\mathrm{com}} = N_{\mathrm{A}} - N_{\mathrm{D}}. \tag{4}$$

On the other hand, using the effective density of states $N_{\mathrm{C}}(T)$ in the conduction band, we can describe $n(T)$ as

$$n(T) = N_{\mathrm{C}}(T) \exp\left(-\frac{\Delta E_{\mathrm{F}}}{kT}\right), \tag{5}$$

where

$$N_{\mathrm{C}}(T) = N_{\mathrm{C0}} k^{3/2} T^{3/2}, \tag{6}$$

$$N_{\mathrm{C0}} = 2\left(\frac{2\pi m^*}{h^2}\right)^{3/2} M_{\mathrm{C}}, \tag{7}$$

m^* is the electron effective mass, h is the Planck constant, and M_{C} is the number of equivalent minima in the conduction band.

Substituting Eq. (2) for one of the $n(T)$ in Eq. (1) and substituting Eq. (5) for the other $n(T)$ in Eq. (1) give

$$H1(T, E_{\mathrm{ref}}) = \sum_{i=1}^{n} \frac{N_{\mathrm{D}i}}{kT} \exp\left(-\frac{\Delta E_{\mathrm{D}i} - E_{\mathrm{ref}}}{kT}\right) I_i(\Delta E_{\mathrm{D}i}) - \frac{N_{\mathrm{com}} N_{\mathrm{C0}}}{kT} \exp\left(\frac{E_{\mathrm{ref}} - \Delta E_{\mathrm{F}}}{kT}\right) \tag{8}$$

where

$$I_i(\Delta E_{\mathrm{D}i}) = \frac{N_{\mathrm{C0}}}{g_{\mathrm{D}i} + \exp\left(\dfrac{\Delta E_{\mathrm{F}} - \Delta E_{\mathrm{D}i}}{kT}\right)}. \tag{9}$$