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

A function to be evaluated is defined as

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

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

$$p(T) = \sum_{i=1}^{n} N_{\mathrm{A}i} f(\Delta E_{\mathrm{A}i}) - N_{\mathrm{com}}, \tag{2}$$

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

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

ΔE_{F} is the Fermi Level measured from the top (E_{V}) of the valence band, $g_{\mathrm{A}i}$ is the degeneracy factor of i-th acceptor, N_{com} is the compensating density expressed as

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

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

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

where

$$N_{\mathrm{V}}(T) = N_{\mathrm{V0}} k^{3/2} T^{3/2}, \tag{6}$$

$$N_{\mathrm{V0}} = 2\left(\frac{2\pi m^*}{h^2}\right)^{3/2}, \tag{7}$$

m^* is the electron effective mass and h is the Planck constant.

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

$$H1(T, E_{\mathrm{ref}}) = \sum_{i=1}^{n} \frac{N_{\mathrm{A}i}}{kT} \exp\left(-\frac{\Delta E_{\mathrm{A}i} - E_{\mathrm{ref}}}{kT}\right) I_i(\Delta E_{\mathrm{A}i}) - \frac{N_{\mathrm{com}} N_{\mathrm{V0}}}{kT} \exp\left(\frac{E_{\mathrm{ref}} - \Delta E_{\mathrm{F}}}{kT}\right) \tag{8}$$

where

$$I_i(\Delta E_{\mathrm{A}i}) = \frac{N_{\mathrm{V0}}}{g_{\mathrm{A}i} + \exp\left(\dfrac{\Delta E_{\mathrm{F}} - \Delta E_{\mathrm{A}i}}{kT}\right)}. \tag{9}$$