with

$$\tau_{\text{Auger},p} = \frac{1}{\Lambda_n n_o^2}. \tag{3.46}$$

A similar expression can be derived for minority electron lifetime in p-type material.

Each of these recombination processes occurs in parallel and there can be multiple and/or distributed traps[2] in the forbidden gap; thus the total recombination rate is the sum of rates due to each process

$$R = \left[\sum_{\text{traps } i} R_{\text{SLT},i}\right] + R_\lambda + R_{\text{Auger}}. \tag{3.47}$$

An effective minority-carrier lifetime for a doped material in low-level injection is given as

$$\frac{1}{\tau} = \left[\sum_{\text{traps } i} \frac{1}{\tau_{\text{SLT},i}}\right] + \frac{1}{\tau_\lambda} + \frac{1}{\tau_{\text{Auger}}}. \tag{3.48}$$

The distribution of traps in the energy gap for specific materials is given in other chapters.

Interfaces between two dissimilar materials, such as, those that occur at the front surface of a solar cell, have a high concentration defect due to the abrupt termination of the crystal lattice. These manifest themselves as a continuum of traps within the forbidden gap at the surface; electrons and holes can recombine through them just as with bulk traps. This is illustrated in Figure 3.10. Rather than giving a recombination rate per unit volume per second, surface traps give a recombination rate per unit area per second. A general expression for surface recombination is [11]

$$R_{\text{S}} = \int_{E_{\text{V}}}^{E_{\text{C}}} \frac{pn - n_{\text{i}}^2}{(p + n_{\text{i}}\text{e}^{(E_{\text{i}}-E_{\text{t}})/kT})/s_n + (n + n_{\text{i}}\text{e}^{(E_{\text{t}}-E_{\text{i}})/kT})/s_p} D_{\Pi}(E_{\text{t}})\,\text{d}E_{\text{t}} \tag{3.49}$$

where E_{t} is the trap energy, $D_{\Pi}(E_{\text{t}})$ is the surface state concentration (the concentration of traps is probably dependent on the trap energy), and s_n and s_p are surface recombination velocities, analogous to the carrier lifetimes for bulk traps. The surface recombination rate is generally written, for simplicity, as [11]

$$R_{\text{S}} = S_p(p - p_o) \tag{3.50}$$

in n-type material and as

$$R_{\text{S}} = S_n(n - n_o) \tag{3.51}$$

in p-type material. S_p and S_n are effective surface recombination velocities. It should be mentioned that these effective recombination velocities are not necessarily constants, though they are usually treated as such.

[2] It is unlikely that more than one trap will be involved in a single recombination event since the traps are spatially separated.