Notice that the recombination rate is solely dependent on the minority carrier (also called the limiting carrier). This is reasonable since there are far fewer minority carriers than majority carriers and one of each is necessary for there to be recombination.

If high-injection conditions prevail ($p \approx n \gg p_o, n_o$),

$$R_{\mathrm{SLT}} \approx \frac{n}{\tau_{\mathrm{SLT},p} + \tau_{\mathrm{SLT},n}} \approx \frac{p}{\tau_{\mathrm{SLT},p} + \tau_{\mathrm{SLT},n}}. \tag{3.40}$$

In this case, the effective recombination lifetime is the sum of the two carrier lifetimes. While the recombination rate is high due to the large number of excess holes and electrons, the carrier lifetime is actually longer than in the case of low injection. This can be of significance in the base region of solar cells, especially concentrator cells (solar cells illuminated with concentrated sunlight), since the base is the least doped layer.

Radiative (band-to-band) recombination is simply the inverse of the optical generation process and is much more efficient in direct band gap semiconductors than in indirect band gap semiconductors. When radiative recombination occurs, the energy of the electron is given to an emitted photon – this is how semiconductor lasers and light emitting diodes (LEDs) operate. In an indirect band gap material, some of that energy is shared with a phonon. The net recombination rate due to radiative processes is given as

$$R_\lambda = \mathrm{B}(pn - n_{\mathrm{i}}^2). \tag{3.41}$$

If we have an n-type ($n \approx n_o \gg p_o$) semiconductor in low injection ($p_o \leq p \ll n_o$), the net radiative recombination rate can be written in terms of an effective lifetime, $\tau_{\lambda,p}$,

$$R_\lambda \approx \frac{p - p_o}{\tau_{\lambda,p}} \tag{3.42}$$

where

$$\tau_{\lambda,p} = \frac{1}{n_o\mathrm{B}}. \tag{3.43}$$

A similar expression can be written for p-type semiconductors.

Auger recombination is somewhat similar to radiative recombination, except that the energy of transition is given to another carrier (in either the conduction band or the valence band), as shown in Figure 3.9. This electron (or hole) then relaxes thermally (releasing its excess energy and momentum to phonons). Just as radiative recombination is the inverse process to optical absorption, Auger recombination is the inverse process to *impact ionization*, where an energetic electron collides with a crystal atom, breaking the bond and creating an electron–hole pair. The net recombination rate due to Auger processes is

$$R_{\mathrm{Auger}} = (\Lambda_n n + \Lambda_p p)(pn - n_{\mathrm{i}}^2) \tag{3.44}$$

In an n-type material in low injection (and assuming Λ_n and Λ_p are of comparable magnitudes), the net Auger recombination rate becomes

$$R_{\mathrm{Auger}} \approx \frac{p - p_o}{\tau_{\mathrm{Auger},p}} \tag{3.45}$$