processes or

$$\alpha(h\nu) = \sum_{\mathrm{i}} \alpha_{\mathrm{i}}(h\nu). \tag{3.34}$$

In practice, measured absorption coefficients or empirical expressions for the absorption coefficient are used in analysis and modeling. The rate of creation of electron–hole pairs (# of electron–hole pairs per $\mathrm{cm}^3$ per second) as a function of position within a solar cell is

$$G(x) = (1 - s)\int_{\lambda} (1 - r(\lambda)) f(\lambda)\alpha(\lambda)\mathrm{e}^{-\alpha x}\,\mathrm{d}\lambda \tag{3.35}$$

where $s$ is the grid-shadowing factor, $r(\lambda)$ is the reflectance, $\alpha(\lambda)$ is the absorption coefficient, $f(\lambda)$ is the incident photon flux (number of photons incident per unit area per second per wavelength), and the sunlight is assumed to be incident at $x = 0$. Here, the absorption coefficient has been cast in terms of the light's wavelength through the relationship $h\nu = hc/\lambda$. The photon flux, $f(\lambda)$, is obtained by dividing the incident power density at each wavelength by the photon energy.

Free-carrier absorption, in which electrons in the conduction band absorb the energy of a photon and move to an empty state higher in the conduction band (correspondingly for holes in the valence band), is typically only significant for photons with $E < E_{\mathrm{G}}$ since the free-carrier absorption coefficient increases with increasing wavelength,

$$\alpha_{fc} \propto \lambda^{\gamma} \tag{3.36}$$

where $1.5 < \gamma < 3.5$ [9]. Thus, in single-junction solar cells, it does not affect the creation of electron–hole pairs and can be ignored (although free-carrier absorption can be exploited to probe the excess carrier concentrations in solar cells for the purpose of determining recombination parameters [10]). However, free-carrier absorption is a consideration in tandem solar cell systems in which a wide band gap ($E_{\mathrm{G1}}$) solar cell is stacked on top of a solar cell of smaller band gap ($E_{\mathrm{G2}} < E_{\mathrm{G1}}$). Photons with energy too low to be absorbed in the top cell ($h\nu < E_{\mathrm{G1}}$) will be transmitted to the bottom cell and be absorbed there (if $h\nu > E_{\mathrm{G2}}$). Of course, more solar cells can be stacked as long as $E_{\mathrm{G1}} > E_{\mathrm{G2}} > E_{\mathrm{G3}} \ldots$, and so on. The number of photons transmitted to the next cell in the stack will be reduced by whatever amount of free-carrier absorption occurs. Tandem cells are discussed more completely in Chapters 9 and 12.

### 3.2.6 Recombination

When a semiconductor is taken out of thermal equilibrium, for instance by illumination and/or injection of current, the concentrations of electrons ($n$) and holes ($p$) tend to relax back toward their equilibrium values through a process called *recombination* in which an electron falls from the conduction band to the valence band, thereby eliminating a valence-band hole. There are several recombination mechanisms important to the operation of solar cells – recombination through traps (defects) in the forbidden gap, radiative (band-to-band) recombination, and Auger recombination – that will be discussed here. These three processes are illustrated in Figure 3.9.