and the absorption coefficient for direct transitions is [9]

$$\alpha(h\nu) \approx A^*(h\nu - E_G)^{1/2}, \tag{3.29}$$

where A^* is a constant. In some semiconductor materials, quantum selection rules do not allow transitions at $p = 0$ but allow them for $p \neq 0$. In such cases [9]

$$\alpha(h\nu) \approx \frac{B^*}{h\nu}(h\nu - E_G)^{3/2}, \tag{3.30}$$

where B^* is a constant.

In indirect band gap semiconductors like Si and Ge, where the valence-band maximum occurs at a different crystal momentum than the conduction-band minimum, conservation of electron momentum necessitates that the photon absorption process involve an additional particle. Phonons, the particle representation of lattice vibrations in the semiconductor, are suited to this process because they are low-energy particles with relatively high momentum. This is illustrated in Figure 3.7. Notice that light absorption is facilitated by either phonon absorption or phonon emission. The absorption coefficient, when there is phonon absorption, is given by

$$\alpha_a(h\nu) = \frac{A(h\nu - E_G + E_{ph})^2}{e^{E_{ph}/kT} - 1} \tag{3.31}$$

and by

$$\alpha_e(h\nu) = \frac{A(h\nu - E_G - E_{ph})^2}{1 - e^{-E_{ph}/kT}} \tag{3.32}$$

when a phonon is emitted [9]. Because both processes are possible,

$$\alpha(h\nu) = \alpha_a(h\nu) + \alpha_e(h\nu). \tag{3.33}$$

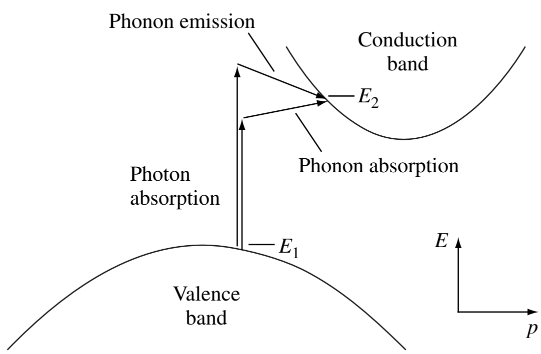

Figure 3.7 Photon absorption in an indirect band gap semiconductor for a photon with energy $h\nu < E_2 - E_1$ and a photon with energy $h\nu > E_2 - E_1$. Energy and momentum in each case are conserved by the absorption and emission of a phonon, respectively