value of current, the tandem cell is at zero bias; hence J_{SC}. This behavior illustrates the general principle that for subcells without significant leakage or reverse-bias breakdown, *the tandem* J_{SC} *is constrained to be, to a very good approximation, the lesser of the* J_{SC}*s of the subcells.* (Note that this current-limiting characteristic makes series-connected multijunction cells of the type considered here much *worse* than single-junction cells for conversion of narrowband spectra such as the light from a laser! The reader should try to make sure to understand why this is the case.)

To model multijunction devices quantitatively, we need expressions for the subcell J–V curves, $V_i(J)$. To proceed, we use the classical ideal–photodiode J–V equations (neglecting the depletion region), [19]

$$J = J_0[\exp(\mathrm{eV}/kT) - 1] - J_{SC} \tag{9.12}$$

where e is the electric charge, and we have assumed that the diode ideality factor is 1. An important special case of this is

$$V_{OC} \approx (kT/e)\ln(J_{SC}/J_0) \tag{9.13}$$

because, in practice, $J_{SC}/J_0 \gg 1$. The dark current density J_0 is given by

$$J_0 = J_{0,\mathrm{base}} + J_{0,\mathrm{emitter}} \tag{9.14}$$

where

$$J_{0,\mathrm{base}} = \mathrm{e}\left(\frac{D_\mathrm{b}}{L_\mathrm{b}}\right)\left(\frac{n_i^2}{N_\mathrm{b}}\right)\left(\frac{(S_\mathrm{b}L_\mathrm{b}/D_\mathrm{b}) + \tanh(x_\mathrm{b}/L_\mathrm{b})}{(S_\mathrm{b}L_\mathrm{b}/D_\mathrm{b})\tanh(x_\mathrm{b}/L_\mathrm{b}) + 1}\right) \tag{9.15}$$

and a similar equation describes $J_{0,\mathrm{emitter}}$. The intrinsic carrier concentration n_i is given by

$$n_i^2 = 4M_\mathrm{c}M_\mathrm{v}(2\pi kT/h^2)^3(m_\mathrm{e}^* m_\mathrm{h}^*)^{3/2}\exp(-E_\mathrm{g}/kT) \tag{9.16}$$

where m_e^* and m_h^* are the electron and hole effective masses, and M_c and M_v are the number of equivalent minima in the conduction and valence bands, respectively. $N_{\mathrm{b(e)}}$ is the base (emitter) ionized-impurity density.

Each junction in a multijunction structure is described by eqs. (9.12)–(9.16); the ith junction will have dark current $J_{0,\mathrm{i}}$ short-circuit $J_{SC,\mathrm{i}}$ etc, with a corresponding J–V characteristic $V_\mathrm{i}(J)$. Adding these $V_\mathrm{i}(J)$ curves for the individual junctions gives the full multijunction $V(J)$ curve of eq. (9.11). The maximum-power point $\{J\mathrm{mp}, V\mathrm{mp}\}$ can be calculated numerically as the point on the $V(J)$ curve that maximizes $J \times V(J)$. The various solar cell performance parameters of interest can be extracted from the J–V curve in the usual way; for example, $V_{OC} = V(0)$, $FF = J\mathrm{mp}V\mathrm{mp}/(V_{OC}J_{SC})$.

9.5.4 Efficiency versus Band Gap

To obtain concrete, numerical values for the cell performance, we need to choose numbers for the material properties of the junctions. Reference [7] provides a reasonable model of a two-junction n/p cell, in which the bottom junction has the properties of GaAs, except