and

$$\vec{J}_{n,P}(x) = qD_n \frac{\mathrm{d}\Delta n_P}{\mathrm{d}x} \tag{3.111}$$

The total current is given by

$$I = A[J_p(x) + J_n(x)] \tag{3.112}$$

and is true everywhere within the solar cell (A is the area of the solar cell). Equations (3.110) and (3.111) give only the hole current in the n-type region and the electron current in the p-type region, not both at the same point. However, integrating equation (3.72), the electron continuity equation, over the depletion region, gives

$$\int_{-x_N}^{x_P} \frac{\mathrm{d}\vec{J}_n \mathrm{d}x}{\mathrm{d}x} \mathrm{d}x = \vec{J}_n(x_P) - \vec{J}_n(-x_N) = q \int_{-x_N}^{x_P} [R(x) - G(x)]\,\mathrm{d}x \tag{3.113}$$

$G(x)$ is easily integrated and the integral of the recombination rate can be approximated by assuming that the recombination rate is constant within the depletion region and is $R(x_m)$ where x_m is the point at which $p_\mathrm{D}(x_m) = n_\mathrm{D}(x_m)$ and corresponds to the maximum recombination rate in the depletion region. If recombination via a midgap single level trap is assumed, then, from equations (3.37), (3.99), (3.100), and (3.102), the recombination rate in the depletion region is

$$R_\mathrm{D} = \frac{p_\mathrm{D} n_\mathrm{D} - n_\mathrm{i}^2}{\tau_n(p_\mathrm{D} + n_\mathrm{i}) + \tau_p(n_\mathrm{D} + n_\mathrm{i})} = \frac{n_\mathrm{D}^2 - n_\mathrm{i}^2}{(\tau_n + \tau_p)(n_\mathrm{D} + n_\mathrm{i})} = \frac{n_\mathrm{D} - n_\mathrm{i}}{(\tau_n + \tau_p)} = \frac{n_\mathrm{i}(\mathrm{e}^{qV/2kT} - 1)}{\tau_\mathrm{D}} \tag{3.114}$$

where τ_D is the effective lifetime in the depletion region. From equation (3.113), $\vec{J}_n(-x_N)$, the majority carrier current at $x = -x_N$, can now be written as

$$\begin{aligned}\vec{J}_n(-x_N) &= \vec{J}_n(x_P) + q \int_{-x_N}^{x_P} G(x)\,\mathrm{d}x - q \int_{-x_N}^{x_P} R_\mathrm{D}\mathrm{d}x \\ &= \vec{J}_n(x_P) + q(1-s) \int_\lambda [1 - r(\lambda)] f(\lambda) [\mathrm{e}^{-\alpha(W_N - x_N)} - \mathrm{e}^{-\alpha(W_N + x_P)}]\,\mathrm{d}\lambda \\ &\quad - q \frac{W_\mathrm{D} n_\mathrm{i}}{\tau_\mathrm{D}} (\mathrm{e}^{qV/2kT} - 1)\end{aligned} \tag{3.115}$$

where $W_\mathrm{D} = x_P + x_N$. Substituting into equation (3.112), the total current is now

$$I = A\left[J_p(-x_N) + J_n(x_P) + J_\mathrm{D} - q\frac{W_\mathrm{D} n_\mathrm{i}}{\tau_\mathrm{D}}(\mathrm{e}^{qV/2kT} - 1)\right] \tag{3.116}$$

where

$$J_\mathrm{D} = q(1-s) \int_\lambda [1 - r(\lambda)] f(\lambda) (\mathrm{e}^{-\alpha(W_N - x_N)} - \mathrm{e}^{-\alpha(W_N + x_P)})\,\mathrm{d}\lambda \tag{3.117}$$

is the generation current from the depletion region and A is the area of the solar cell. The last term of equation (3.116) represents recombination in the space-charge region.