The back contact could also be treated as an ideal ohmic contact, so that

$$\Delta n(W_P) = 0. \tag{3.97}$$

However, solar cells are often fabricated with a *back-surface field* (BSF), a thin more heavily doped region at the back of the base region. The BSF keeps minority carriers away from the back ohmic contact and increases their chances of being collected and it can be modeled by an effective, and relatively low, surface recombination velocity. This boundary condition is then

$$\left.\frac{\mathrm{d}\Delta n}{\mathrm{d}x}\right|_{x=W_P} = -\frac{S_{\mathrm{BSF}}}{D_n}\Delta n(W_P), \tag{3.98}$$

where S_{BSF} is the effective surface recombination velocity at the BSF.

All that remains now is to determine suitable boundary conditions at $x = -x_N$ and $x = x_P$. These boundary conditions are commonly referred to as the *law of the junction*.

Under equilibrium conditions, zero applied voltage and no illumination, the Fermi energy, E_{F}, is constant with position. When a bias voltage is applied, it is convenient to introduce the concept of quasi-Fermi energies. It was shown earlier that the equilibrium carrier concentrations could be related to the Fermi energy (equations 3.15 and 3.16). Under nonequilibrium conditions, similar relationships hold. Assuming the semiconductor is nondegenerate,

$$p = n_{\mathrm{i}}\mathrm{e}^{(E_{\mathrm{i}}-F_P)/kT} \tag{3.99}$$

and

$$n = n_{\mathrm{i}}\mathrm{e}^{(F_N-E_{\mathrm{i}})/kT} \tag{3.100}$$

It is evident that under equilibrium conditions $F_P = F_N = E_{\mathrm{F}}$. Under nonequilibrium conditions, assuming that the majority carrier concentrations at the contacts retain their equilibrium values, the applied voltage can be written as

$$qV = F_N(-W_N) - F_P(W_P) \tag{3.101}$$

Since, in low-level injection, the majority carrier concentrations are constant throughout the quasi-neutral regions, that is, $p_P(x_P \le x \le W_P) = N_{\mathrm{A}}$ and $n_N(-W_N \le x \le -x_N) = N_{\mathrm{D}}$, $F_N(-W_N) = F_N(-x_N)$ and $F_P(W_P) = F_P(x_P)$. Then, assuming that both the quasi-Fermi energies remain constant inside the depletion region,

$$qV = F_N(x) - F_P(x) \tag{3.102}$$

for $-x_N \le x \le x_P$, that is, everywhere inside the depletion region. Using equations (3.99) and (3.100), this leads directly to the *law of the junction*, the boundary conditions used at the edges of the depletion region,

$$p_N(-x_N) = \frac{n_{\mathrm{i}}^2}{N_{\mathrm{D}}}\mathrm{e}^{qV/kT} \tag{3.103}$$