and allows the diffusion coefficient to be directly computed from the mobility. Generalized forms of the Einstein relationship, valid for degenerate materials, are

$$\frac{D_n}{\mu_n} = \frac{1}{q} n \left[\frac{\mathrm{d}n}{\mathrm{d}E_\mathrm{F}} \right]^{-1} \tag{3.64}$$

and

$$\frac{D_p}{\mu_p} = \frac{-1}{q} p \left[\frac{\mathrm{d}p}{\mathrm{d}E_\mathrm{F}} \right]^{-1}. \tag{3.65}$$

The diffusion coefficient actually increases when degeneracy effects come into play.

The total hole and electron currents (vector quantities) are the sum of their drift and diffusion components

$$\vec{J}_p = \vec{J}_p^{\mathrm{drift}} + \vec{J}_p^{\mathrm{diff}} = q\mu_p p\vec{E} - qD_p\nabla p = -q\mu_p p\nabla\phi - qD_p\nabla p \tag{3.66}$$

$$\vec{J}_n = \vec{J}_n^{\mathrm{drift}} + \vec{J}_n^{\mathrm{diff}} = q\mu_n n\vec{E} + qD_n\nabla n = -q\mu_n n\nabla\phi + qD_n\nabla n \tag{3.67}$$

The total current is then

$$\vec{J} = \vec{J}_p + \vec{J}_n + \vec{J}_{\mathrm{disp}} \tag{3.68}$$

where $\vec{J}_{\mathrm{disp}}$ is the *displacement current* given by

$$\vec{J}_{\mathrm{disp}} = \frac{\partial \vec{D}}{\partial t}. \tag{3.69}$$

$\vec{D} = \varepsilon\vec{E}$ is the dielectric displacement field, where ε is the electric permittivity of the semiconductor. The displacement current is typically neglected in solar cells since they are static (dc) devices.

3.2.8 Semiconductor Equations

The operation of most semiconductor devices, including solar cells, can be described by the so-called semiconductor device equations, first derived by Van Roosbroeck in 1950 [13]. A generalized form of these equations is given here.

$$\nabla \cdot \varepsilon\vec{E} = q(p - n + N) \tag{3.70}$$

This is a form of Poisson's equation, where N is the net charge due to dopants and other trapped charges. The hole and electron continuity equations are

$$\nabla \cdot \vec{J}_p = q\left(G - R_p - \frac{\partial p}{\partial t}\right) \tag{3.71}$$

$$\nabla \cdot \vec{J}_n = q\left(R_n - G + \frac{\partial n}{\partial t}\right) \tag{3.72}$$