## 7.2 CRYSTALLINE SILICON AS A PHOTOVOLTAIC MATERIAL

### 7.2.1 Bulk Properties

Crystalline silicon has a fundamental indirect band gap $E_G = 1.17$ eV and a direct gap above 3 eV [3] at ambient temperature. These characteristics determine the variation of optical properties of Si with wavelength, including the low absorption coefficient for carrier generation for near band gap photons [4]. At short ultraviolet (UV) wavelengths in the solar spectrum, the generation of two electron–hole pairs by one photon seems possible, though quantitatively this is a small effect [5]; at the other extreme of the spectrum parasitic free-carrier absorption competes with band-to-band generation [6]. The intrinsic concentration is another important parameter related to the band structure; it links carrier disequilibrium with voltage [7].

At high carrier densities, doping- or excitation-induced, the band structure is altered leading to an increase in the effective intrinsic concentration: this is one of the so-called heavy doping effects that degrade the PV quality of highly doped regions [8].

Recombination in Si is usually dominated by recombination at defects, described with Shockley–Read–Hall (SRH) lifetimes. The associated lifetime $\tau$ (which can also be described in terms of diffusion length $L$) increases for good quality materials. Auger recombination, on the contrary, is a fundamental process that becomes important at high-carrier concentration [9]. The Auger coefficients are reported to be higher at moderate carrier densities due to excitonic effects [10]. Band-to-band direct recombination is also a fundamental process but quantitatively negligible (it is instructive, however, to notice that record-efficiency solar cells have such extraordinarily low SRH recombination levels that they perform as 1%-efficient light-emitting diodes, that is, radiative recombination is significant [11]).

At low and moderate doping, electrons present mobilities about three times higher than holes, both limited by phonon scattering. Impurity scattering dominates for higher doping densities [12, 13]. Carrier–carrier scattering affects transport properties in highly injected material [14].

### 7.2.2 Surfaces

#### *7.2.2.1 Contacts*

Contacts are structures built on a semiconductor surface that allow charge carriers to flow between the semiconductor and the external circuit. In solar cells, contacts are required to extract the photogenerated carriers from the absorbing semiconductor substrate. They should be selective, that is, should allow one type of carrier to flow from Si to metal without energy loss while blocking the transport of carriers of the opposite type.

Direct Si-metal contacts, in general, do not behave this way. As an exception, good hole contacts to highly doped $p$-Si substrates with aluminum are possible. But the