the voltage. Finally, there are parasitic losses, such as series resistance, shunt conductance, and voltage-dependent current collection, which are most evident by their effect on the fill factor but can also reduce J_{SC} and V_{OC}.

13.5.1 Light-generated Current

The highest efficiency $Cu(InGa)Se_2$ device has $J_{SC} = 35.2$ mA/cm^2 [1] out of a possible 42.8 mA/cm^2 available for a band gap of 1.12 eV under AM1.5 global illumination. Quantum efficiency is a valuable tool to characterize the losses responsible for this difference in current. The light-generated current is the integral of the product of the external quantum efficiency (QE_{ext}) and the illumination spectrum. QE_{ext} is controlled by the band gap of the $Cu(InGa)Se_2$ absorber layer, the CdS and ZnO window layers, and a series of loss mechanisms. These losses are illustrated in Figure 13.14 where typical QE curves at two different voltage biases, 0 V and -1 V, are shown. The QE curve at -1 V is slightly higher at longer wavelengths. The current loss under 100 mW/cm^2 illumination is listed in Table 13.4 for each of these mechanisms. Losses 1 to 5 are optical and 6 is electronic. In practice, the magnitude of each of these losses will depend on the details of the device design and optical properties of the specific layers. The losses include the following:

1. Shading from a collection grid used for most devices. In an interconnected module this will be replaced by the area used for the interconnect, as discussed in Section 13.6.2.
2. Front surface reflection. On the highest-efficiency devices this is minimized with an antireflection layer for which an evaporated MgF_2 layer with thickness ~100 nm is commonly used. However, this is not practical in a module in which a cover glass is typically required.

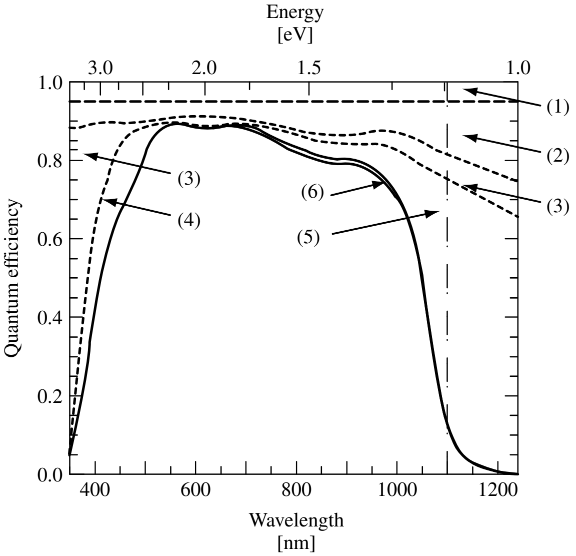

Figure 13.14 Quantum efficiency (solid lines) at 0 V and -1 V and optical losses for a $Cu(InGa)Se_2$/CdS solar cell in which the $Cu(InGa)Se_2$ has $E_g = 1.12$ eV