Table 13.4 Current loss, ΔJ, for $E > 1.12$ eV due to the optical and collection losses illustrated in Figure 13.14 for a typical Cu(InGa)Se_2/CdS solar cell

Region in Figure 13.14	Optical loss mechanism	ΔJ [mA/cm^2]
(1)	Shading from grid with 4% area coverage	1.7
(2)	Reflection from Cu(InGa)Se_2/CdS/ZnO	3.8
(3)	Absorption in ZnO	1.8
(4)	Absorption in CdS	0.8
(5)	Incomplete generation in Cu(InGa)Se_2	1.9
(6)	Incomplete collection in Cu(InGa)Se_2	0.4

3. Absorption in the TCO layer. Typically, there is 1 to 3% absorption through the visible wavelengths, which increases in the near IR region, $\lambda > 900$ nm, where free-carrier absorption becomes significant, and for $\lambda < 400$ nm near the ZnO band gap.
4. Absorption in the CdS layer. This becomes appreciable at wavelengths below ~520 nm corresponding to the CdS band gap 2.42 eV. The loss in QE for $\lambda < 500$ nm is proportional to the CdS thickness since it is commonly assumed that electron–hole pairs generated in the CdS are not collected. Figure 13.14 shows a device with a ~30 nm-thick CdS layer. In practice, the CdS layer is often thicker and the absorption loss greater.
5. Incomplete absorption in the Cu(InGa)Se_2 layer near the Cu(InGa)Se_2 band gap. Band gap gradients, resulting from composition gradients in many Cu(InGa)Se_2 films, also affect the steepness of the long-wavelength part of the QE curve. If the Cu(InGa)Se_2 is made thinner than ~1.0 μm, this loss becomes significant [163] because of insufficient absorption at long wavelengths.
6. Incomplete collection of photogenerated carriers in the Cu(InGa)Se_2, discussed below.

QE_{ext} is then given by

$$QE_{\text{ext}}(\lambda, V) = [1 - R(\lambda)][1 - A_{\text{ZnO}}(\lambda)][1 - A_{\text{CdS}}(\lambda)]\, QE_{\text{int}}(\lambda, V) \tag{13.5}$$

where R is the total reflection, including the grid shading, A_{ZnO} is the absorption in the ZnO layer and A_{CdS} is the absorption in the CdS layer. QE_{int}, the internal quantum efficiency, is the ratio of photogenerated carriers collected to the photon flux that arrives at the absorber layer and can be approximated by [164]

$$QE_{\text{int}}(\lambda, V) \cong 1 - \frac{\exp[-\alpha(\lambda)W(V)]}{\alpha L + 1} \tag{13.6}$$

where α is the Cu(InGa)Se_2 absorption coefficient, W is the space charge width in the Cu(InGa)Se_2, and L is the minority carrier diffusion length. This approximation assumes that all carriers generated in the space charge region are collected without recombination loss. Since W is a function of the applied voltage bias, QE_{int} and total light-generated current are, in general, voltage-dependent, so the latter can be written as $J_{\text{L}}(V)$. Values of W in the range 0.1–0.5 μm have been reported for typical cells at 0 V.