be negligible so long as the minority-carrier diffusion length is small compared to the total Cu(InGa)Se_2 thickness. If $L + W \approx d$, a back surface field may be implemented, for example, by increasing the Ga content near the Mo to give a band gap gradient.

In real Cu(InGa)Se_2 materials with imperfect structures, trap defects will not exist at discrete energies but form defect bands or tails at the valence and conduction bands. Then the total recombination current can be determined by integrating over the defect spectrum. Recombination through an exponential bandtail was used to explain the temperature dependence in A observed in some devices [175]. Analysis of the temperature dependence of A was further explained by a tunneling enhancement of the recombination current, particularly at reduced temperatures [176]. The same defects in the Cu(InGa)Se_2 space charge region that control recombination were also used to explain observed metastabilities including persistent photoconductivity and open-circuit voltage decay [177]. Admittance spectroscopy has proved to be a useful tool to characterize the distribution of electronic defects in Cu(InGa)Se_2/CdS solar cells [178] and the density of an acceptor state ~0.3 eV from the valence band has been correlated to V_{OC} [179]. The minority-carrier lifetime is another valuable parameter to characterize Cu(InGa)Se_2/CdS devices. Transient photocurrent [180] and time-resolved photoluminescence [167] measurements each were used to calculate lifetimes in the range of 10 to 100 ns for high-efficiency devices. Still, a critical problem that remains is to identify which of the calculated or measured defects discussed in Section 13.2 provides for the recombination traps that limit voltage in the devices. A good review of the characterization of electronic defects and their effect on Cu(InGa)Se_2 devices is provided by Rau and Schock [27].

In practice, analysis of $J-V$ data is commonly used to determine the diode parameters J_O, A, and Φ_b. This requires that R_S and G are negligible, or suitable corrections are made to the data, and that J_L is independent of V. Failure to account for $J_L(V)$ can lead to errors in analysis of current–voltage data [166] and in many cases the fundamental diode parameters cannot be reliably determined except from $J-V$ data measured in the dark. In addition, it must be verified that there are no nonohmic effects at any contacts or junctions, which cause the appearance of a second diode for which equation (13.7) does not account. Such nonohmic behavior is often observed at reduced temperatures [170, 172]. Once it has been demonstrated that all these parasitic effects are negligible, or corrections have been made, then J_O can be determined by a linear fit to a semilogarithmic plot of $J + J_L$ versus $V - R_S J$ and A can be determined from the slope of the derivative $\mathrm{d}V/\mathrm{d}J$ versus $1/J$ in forward bias [181], or both J_O and A can be obtained by a least squares fit to equation (13.7). Finally, Φ_b can be determined from the temperature dependence of V_{OC} as in Figure 13.18.

It must be noted that most descriptions of transport and recombination ignore the effect of grain boundaries, implicitly assuming that grains are columnar and all transport can proceed without crossing grain boundaries. However, this is rarely, if ever, strictly true, so a comprehensive description of Cu(InGa)Se_2 solar cells must account for the possibility of recombination at grain boundaries reducing current collection or voltage. The effect of grain boundaries can be expressed as an effective diffusion length, leading to the conclusion that grain-boundary recombination is small [27]. This can occur if the grain boundaries are doped more p-type than the bulk grains so that electrons are prevented from reaching and recombining at defects in the grain boundaries [169].