Area: 2 Thin-Film Compound Semiconductor PV

OPTICAL AND RECOMBINATION LOSSES IN CIGSe, CZTSSe AND CdTe SOLAR CELLS DETERMINED BY GLOBAL EQE ANALYSIS METHOD

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In developing photovoltaic devices with high efficiencies, accurate determination of carrier loss mechanisms is crucial. In our previous study, we established a global analysis scheme for external quantum efficiency (EQE) spectra from which all the carrier losses induced by light reflection, parasitic absorption and carrier recombination can be determined systematically with a very low computational cost [1]. The developed method (e-ARC method) is appropriate for a wide variety of photovoltaic devices, including $Cu(In,Ga)Se_2$ (CIGSe), $Cu_2ZnSn(S,Se)_4$ (CZTSSe), CdTe and hybrid perovskite solar cells and, in this study, based on the results obtained from our EQE analyses, we discuss the carrier loss mechanisms in different types of solar cells.

Figure 1(a) shows the EQE analysis performed for a record-efficiency CZTSSe solar cell (12.6%) reported in Ref. [2]. The structure of this solar cell is indicated in Figure 1(b). In Figure 1(a), the open circles show the experimental EQE and reflectance spectra reported in Ref. [2], whereas the black lines indicate the calculated absorptance spectra of the component layers. In the e-ARC method, the carrier extraction is modeled by considering a carrier collection length (L_C) from the absorber interface and the calculation using L_C as a variable (red line) provides excellent fitting to the experimental EQE spectrum when L_C = 0.75 μm. The obtained L_C is much smaller than the CZTSSe absorber thickness (2.0 μm), indicating that the carrier collection occurs predominantly near the CdS/CZTSSe interface region with rather significant carrier loss in the CZTSe bottom region.

In Figure 1(b), the reflection, absorption and recombination losses deduced from the EQE analysis are summarized. It can be seen that, in this solar cell, the reflection loss (4.5 mA/cm^2), total absorption loss (7.0 mA/cm^2) and recombination loss (5.2 mA/cm^2) are quite large. In particular, large parasitic absorption occurs in the Mo layer due to the low reflectance at the rear interface. A similar EQE analysis implemented for a CIGSe solar cell [3] indicates that the carrier collection efficiency is almost 100%, while the intense light absorption in the Mo layer also occurs. In a CdTe solar cell [4], on the other hand, the parasitic light absorption is notably smaller, compared with CZTSSe and CIGSe solar cells. The above result demonstrates that the performance-limiting factors in solar cells can be determined quantitatively from the EQE analysis using the e-ARC method.

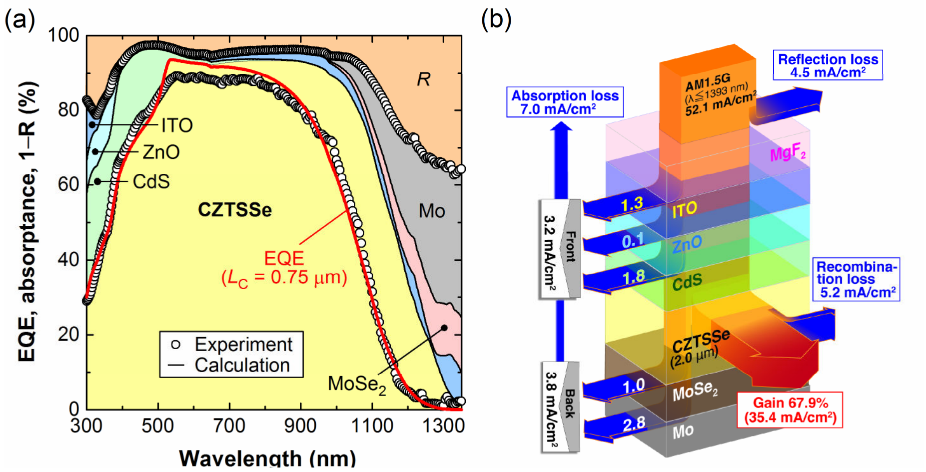

Figure 1: (a) Result of the EQE analysis performed for a record-efficiency CZTSSe solar cell reported in Ref. [3] and (b) optical and recombination losses of the solar cell determined from (a).

[1] Nakane et al., *J. Appl. Phys.* **120**, 064505 (2016). [2] Wang et al., *Adv. Energy Mater.* **4**, 1301465 (2014). [3] Hara et al., *Phys. Rev. Appl.* **2**, 034012 (2014). [4] Aramoto et al., *Jpn. J. Appl. Phys.*, **36**, 6304 (1997).