Characterization of a 12.3% efficient $Cu_2Zn(Sn_{1-x}Ge_x)Se_4$ thin-film solar cell

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Kesterite devices, $Cu_2ZnSn(S_xSe_{1-x})_4$ (CZTSSe) have been attracting attention because earth abundant and non-toxic absorber is a potential replacement for the $Cu(In_{1-x}Ga_x)Se_2$ (CIGS) in thin-film solar cells. CZTSSe thin-film solar cell achieved the highest conversion efficiency of 12.6 % with a modulated band gap (E_g) of 1.13 eV; E_g of CZTSSe is controlled by the S/(S+Se) ratio. However, CZTSSe devices have exhibited large open circuit voltage (V_{OC}) deficit (E_g/q-V_{OC}, q: electron charge), which widens with increasing the S/(S+Se) ratio. In the previous results, we revealed $Cu_2Zn(Sn_{1-x}Ge_x)Se_4$ (CZTGSe) thin-films solar cells; their E_g was in the range of ~1.0 ~ 1.5 eV, where the gap was controlled by the Ge/(Sn+Ge) cation ratio. Also, we archived conversion efficiency of 10.03% and exhibited improved V_{OC} deficit (= 0.647) compared to CZTSSe device (V_{OC} deficit = 0.711) with similar E_g ~ 1.2 eV.

In this study, we demonstrate new efficiency of CZTGSe thin-film solar cell. We archived new conversion efficiency of 12.3% with a very high fill factor (*FF* = 0.727), which is the main parameter for high conversion efficiency (Fig. 1). In addition, greatly improved V_{OC} deficit (= 0.583 V) was observed. We fitted I-V curve using single diode model to compare with our previous results, and found high *FF* device showed reduced diode ideality factor (*A*) and reverse saturation current (J_0). Improved diode parameters, V_{OC} deficit, *A* and J_0, are indicating improved junction quality and reduced recombination at the absorber/buffer interface and/or space chare region, which can be possible reason for highly improved *FF*.

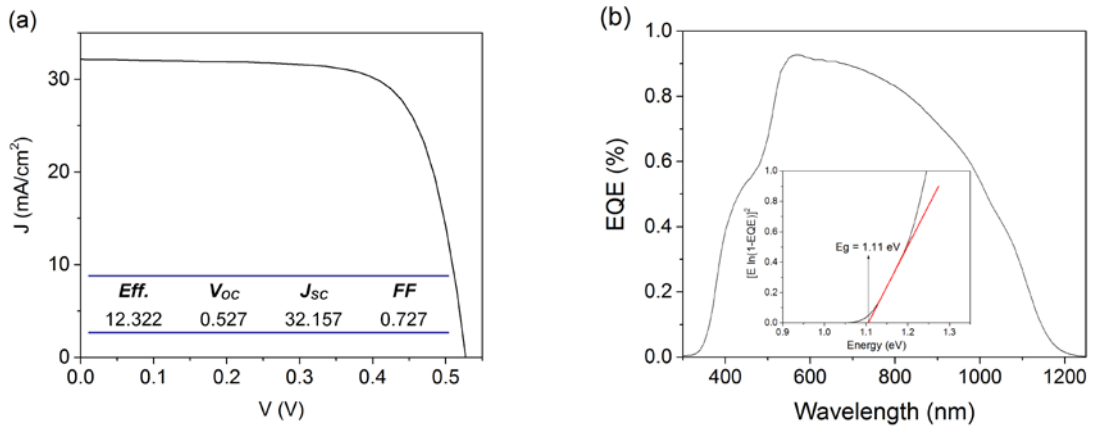

Figure 1. (a) I–V measurement results for the 12.3% efficient CZTGSe thin-film solar cell and (b) its EQE results. Plot of $[E \ln(1 - EQE)]^2$ vs. E used to determine the band-gap is inset into the EQE figure.