Characterization of a 12.3% efficient Cu$_2$Zn(Sn$_{1-x}$Ge$_x$)Se$_4$ thin-film solar cell

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Kesterite devices, Cu$_2$ZnSn(S,Se$_{1-x}$)$_4$ (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$_2$Zn(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 charge region, which can be possible reason for highly improved $FF$.

![Figure 1](image_url)

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.