Carrier transport of Cu$_2$ZnSn(S,Se)$_4$ solar cell materials with various secondary phases

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Cu$_2$ZnSn(S,Se)$_4$ (CZTSSe) and its related compounds are promising for thin-film solar cells because of their abundance, low toxicity, and good optical absorption. The precursors of Cu/SnS/ZnS were grown on Mo/Soda lime glass by a stacking sputtering method. The thickness of ZnS layer was controlled in precursors of CZTSSe composition which have significant different with conversion efficiency and device performances. The highest conversion efficiency of CZTSSe thin-film solar cell achieved ~9% with 334 nm of ZnS thickness. We investigated the secondary phases with various depths of absorber layer by Raman scattering spectroscopy. In the middle of the depth of absorber, there exist ZnSe secondary phase and the MoSe$_2$ secondary phase appear in the bottom. Kelvin probe force microscopy and conductive atomic force microscopy were used to explore the electrical properties of grain boundaries (GBs) in the CZTSSe thin-films. The GBs in kesterite thin-film solar cell are acting as an efficient carrier collection regions. Therefore, exploring the GBs properties is very important. In our result, the high efficiency CZTSSe thin-film has the uniform surface phase and negative band bending that of the beneficial for carrier separation near GBs. We can understand the ZnS thickness in precursor can affect to the electronic properties of the GBs, formation of the secondary phases and device performances.