Application of Zn$_{1-x}$Mg$_x$O:Al to transparent conductive oxide of Cu(In,Ga)(S,Se)$_2$ solar cell

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19.47%-efficient Cu(In,Ga)(Se,S)$_2$ (CIGSSe)-based solar cell is obtained by replacing traditional CdS/ZnO buffer layers with Cd$_{0.75}$Zn$_{0.25}$S/Zn$_{0.79}$Mg$_{0.21}$O layers to increase short-circuit current density since its external quantum efficiency is increased in a short wavelength range of 320-520 nm. In addition, it was theoretically reported that difference of conduction band minimum ($E_C$) between transparent conductive oxide (TCO) layer and absorber plays a role in reducing carrier recombination at interface for enhancing the conversion efficiency (η), especially open-circuit voltage ($V_{OC}$) and fill factor (FF) [1]. In this work, Zn$_{1-x}$Mg$_x$O:Al was utilized as alternative TCO layer in CIGSSe solar cell to experimentally investigate influence of the $E_C$ difference between TCO layer and CIGSSe absorber to boost cell performances, especially $V_{OC}$ and FF. The difference of $E_C$ between Zn$_{1-x}$Mg$_x$O:Al layer and CIGSSe absorber is optimized by varying $[\text{Mg}] / ([\text{Mg}]+[\text{Zn}])$, x. It is demonstrated that Zn$_{1-x}$Mg$_x$O:Al films with $[\text{Mg}]/([\text{Mg}]+[\text{Zn}])$ of 0.1-0.12, enhancing band-gap energy ($E_g$) to 3.72-3.76 eV, are appropriate as TCO because of their enhanced mobility and decreased carrier density. The addition of 12% Mg into ZnO:Al for TCO layer effectively decreases surface carrier recombination and improves $V_{OC}$ and FF. This is first experimental proof of the concept for optimizing $E_C$ difference between TCO and absorber to minimize surface carrier recombination. Ultimately, conversion efficiency of CIGSSe solar cell with alternative Cd$_{0.75}$Zn$_{0.25}$S/Zn$_{0.79}$Mg$_{0.21}$O/Zn$_{0.88}$Mg$_{0.12}$O:Al layers is improved over 20% as illustrated in the figure.

![Photo-J-V characteristic of CIGSSe solar cell with alternative Cd$_{0.75}$Zn$_{0.25}$S buffer/Zn$_{0.79}$Mg$_{0.21}$O window/Zn$_{0.88}$Mg$_{0.12}$O:Al (TCO) layers.](image)


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