MEET6-2
Invited

Rigorous Optoelectronic Modeling of $Cu(In,Ga)Se_2$ Solar Cells Considering the Optically-Incoherent Encapsulation Layers

Jungho Kim[1]

junghokim@khu.ac.kr
[1]Department of Information Display, Kyung Hee University, 26 Kyungheedae-ro, Dongdaemoon-gu, Seoul 02447, Republic of Korea
Keywords: photovoltaics, optoelectronic modeling, optical incoherence

ABSTRACT

We calculate optical and electrical characteristics of $Cu(In,Ga)Se_2$ solar cells including the effect of the incoherent encapsulation layers, whose thickness is greater than the coherence length of sunlight (~0.6 μm). The equispced thickness averaging method is used to efficiently model the incoherent property of the thick encapsulation layer.

1 INTRODUCTION

Thin-film solar cells based on a $Cu(In,Ga)Se_2$ (CIGS) active material have been investigated as one of the promising candidates of next-generation solar cells with low cost and high efficiency. Most of thin-film CIGS solar cells consist of multiple thin layers, having the total thickness of less than one micrometer. Thus, the optical interference effect plays an important role in optimizing the layer structure to obtain the best absorption efficiency [1].

In the module configuration, millimeter-thick front encapsulation layers are added on the top of the CIGS solar cell [1]. In this case, the thick encapsulation layer should be treated as optically incoherent because its thickness is greater than the coherence length of sunlight (~0.6 μm), within which the phase information of light is preserved [2]. Because the optical interference effect disappears in the incoherent thick encapsulation layer, the optical characteristics of the CIGS solar cell with the front encapsulation layer should be modeled as a mixed coherent-incoherent multilayer, which cannot be properly modeled based on coherent solutions of the wave equations. The reflectance of a mixed coherent-incoherent multilayer has been calculated by averaging hundreds of coherent calculation results over random phase shifts, which are assigned to the incoherent layer [3].

Recently, we have proposed a equispaced thickness averaging method (ETAM) to efficiently calculate the effect of the incoherent layer on the optical absorption characteristics of a mixed coherent-incoherent multilayer structure of the CIGS solar cell [4]. In the ETAM, a set of equispaced phase thicknesses (less than ten) are inserted into the initial thickness of the incoherent layer and their separate coherent simulation results are averaged. In this paper, we calculate the optical and electric characteristics of a grating-assisted CIGS solar cell considering the incoherent front encapsulation layer.

2 DEVICE STRUCTURE AND NUMERICAL MODEL

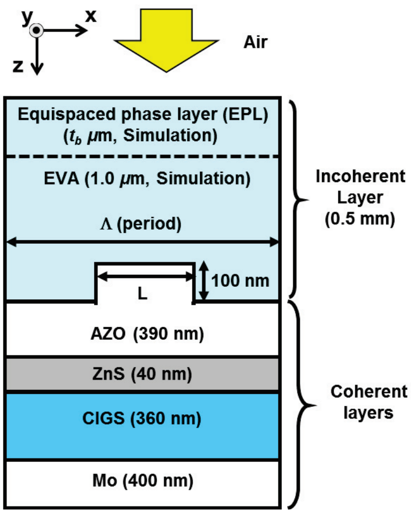

Fig. 1 Schematic diagram of the multilayer structure of the grating-assisted CIGS solar cell used in this study. The encapsulation layer of EVA is modeled as the incoherent layer. The period and length of the grating are Λ and L.

Fig. 1 show as schematic diagram of the multilayer structure of the grating-assisted CIGS solar cell, which is composed of molybdenum (Mo) (400 nm) as a bottom contact layer, CIGS (360 nm) as a p-doped layer, zinc sulfide (ZnS) (40 nm) as an n-doped layer, aluminum-doped zinc oxide (AZO) (390 nm) as a transparent conducting oxide, and ethylene vinyl acetate (EVA) (0.5 mm) as a front encapsulation layer. To enhance light absorption caused by light diffraction, a 100-nm-thick grating structure, having the period of Λ and the length of L, is located at the AZO/EVA interface. In the numerical calculation, we use Λ = 345 nm and L = 172.5 nm, which provides the best absorption efficiency

The 0.5-mm EVA encapsulation layer, the thickness of which is greater than the coherence length of sunlight (~0.6 μm), is optically modeled as incoherent while the remaining AZO, ZnS, CIGS, and Mo layers are considered as coherent layers. Because the ETAM does not require an actual thickness of 0.5 mm, we use 1 μm-thick initial EVA layer plus the equispaced phase layer (EPL). The incoherent characteristic of the EVA layer is calculated by averaging the coherent simulation results obtained with different thicknesses of the EPL. When 10 EPLs are used, the corresponding equispaced phase thicknesses are

$$t_1 = 0,\ t_2 = \frac{\lambda}{20n_{EVA}}, \cdots,\ t_{10} = \frac{9\lambda}{20n_{EVA}}, \tag{1}$$

where n_{EVA} is the refractive index of the EVA layer and λ is the wavelength of sunlight.

The numerical simulation of the CIGS solar cell is done using a finite-element-method-based commercial software of the COMSOL Multiphysics [5]. In the case of optical modeling, the wave equation is numerically solved with the assumption that the sunlight is normally incident to the CIGS solar cell in Fig. 1. The ETAM-applied spatial profile of the light absorption is obtained by [4]

$$Q^{ETAM}(\vec{r},\lambda) = \frac{1}{M}\sum_{b=1}^{M=10} Q(\vec{r},\lambda,t_b), \tag{2}$$

where $\vec{r}$ is the position vector, M is the number of the EPL layer, and t_b is the equispaced phase thickness defined in Eq. (1). Then, the spectral absorptivity of the CIGS solar cell is expressed as

$$A^{ETAM}(\lambda) = \frac{1}{S(\lambda)}\iint Q^{ETAM}(\vec{r},\lambda)d\vec{r}, \tag{3}$$

where $S(\lambda)$ is the solar irradiance of AM 1.5 sunlight.

The current-voltage (J-V) characteristic of the CIGS solar cell is calculated through the FEM-based solution of the coupled drift-diffusion and continuity equations. The detailed electrical modeling procedure is shown elsewhere [4]. Here, one of the input parameters in the continuity equation is the spatial profile of the electron-hole-pair generation rate, which is calculated through

$$G^{ETAM}(\vec{r}) = \int S(\lambda)\frac{Q^{ETAM}(\vec{r},\lambda)}{hc/\lambda}d\lambda, \tag{3}$$

where h is the Plank constant, and c is the speed of light, respectively. In addition, the periodic boundary condition is applied in the horizontal direction of the simulation domain for both optical and electrical modeling.

3 CALCULATION RESULTS

Fig. 2 shows the calculated spectral absorptivity of the grating-assisted CIGS solar cell without and with the inclusion of the incoherent EVA layer. For reference, the spectral absorptivity of the planar CIGS solar cell is also calculated. The absorption enhancement caused by light diffraction results in the absorptivity improvement of the grating-assisted CIGS solar cell over the planar CIGS solar cell. In addition, the absorptivity of the grating-assisted CIGS solar cell is over-predicted when the incoherent EVA is not considered in the calculation.

Fig. 3 shows the calculated J-V curves of the grating-assisted CIGS solar cell without and with the inclusion of the EVA layer. In accordance with the calculation results of the spectral absorptivity, the calculated J-V is over-estimated when the incoherent EVA layer is not included.

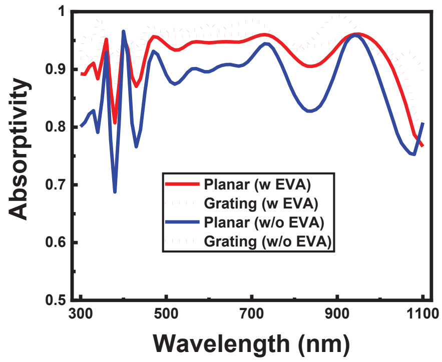

Fig. 2 Calculated spectral absorptivity of the grating-assisted CIGS solar cell without and with the inclusion of the incoherent EVA layer. For reference, the spectral absorptivity of the planar CIGS solar cell is also calculated.

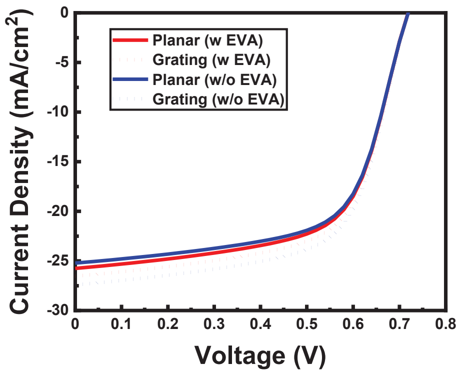

Fig. 3 Calculated J-V curves of the grating-assisted CIGS solar cell without and with the inclusion of the incoherent EVA layer. For reference, the J-V curve of the planar CIGS solar cell is also calculated.

4 CONCLUSIONS

We numerically investigated the effect of the incoherent EVA layer on the optical and electrical characteristics of a grating-assisted CIGS solar cell. We confirmed both the absorptivity and J-V curve of the grating-assisted CIGS solar cell were enhanced in reference to those of the planar CIGS solar cell. We found that the spectral absorptivity and J-V curve could be over-predicted when the incoherent EVA used in the module configuration was not included in the modeling. Thus, it is important to consider the incoherent encapsulation layer in the optoelectronic modeling of CIGS solar cells.

ACKNOWLEDGMENTS

This research was supported by the Korea Electric Power Corporation (grant number: R17XA05-14) and by the Basic Science Research Program through the National Research Foundation of Korea (NRF) funded by the Ministry of Education (grant number: NRF-2018R1D1A1B07047249).

REFERENCES

[1] K. Kang, S. Kim, and J. Kim, "Numerical modeling of the effect of multiple incoherent layers in $Cu(In,Ga)Se_2$ solar cells based on the equispaced thickness averaging method," Appl. Opt., Vol. 57, No.11, pp. 2758-2765 (2018).

[2] A. Donges, "The coherence length of black-body radiation," Eur. J. Phys., Vol. 19, No. 3, pp. 245–249 (1998).

[3] M. C. Troparevsky, A. S. Sabau, A. R. Lupini, and Z. Zhang, "Transfer-matrix formalism for the calculation of optical response in multilayer systems: from coherent to incoherent interference," Opt. Exp., Vol. 18, No. 24, pp. 24715-24721 (2010).

[4] J. Baik, J. Park, G. Lee, S. Kim, and J. Kim, "Effects of incoherent front cover glass on current-voltage characteristics of $Cu(In,Ga)Se_2$ solar cells: Investigation into calculation accuracy for cover glass modeled as optically coherent or incoherent," Appl. Sci. Vol. 10, No. 9, pp. 3312-1-3312-16 (2020).

[5] COMSOL Multiphysics, Version 4.4a Comsol Inc., http://www.comsol.com. (2013).