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ADVANCED CHARACTERIZATION OF INTERFACES AND THIN FILMS

The Effect of Interface Cracks on the Electrical Performance of Solar Cells

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Among a variety of solar cell types, thin-film solar cells have been rigorously investigated as cost-effective and efficient solar cells. In many cases, flexible solar cells are also fabricated as thin films and undergo frequent stress due to the rolling and bending modes of applications. These frequent motions result in crack initiation and propagation (including delamination) in the thin-film solar cells, which cause degradation in efficiency. Reliability evaluation of solar cells is essential for developing a new type of solar cell. In this paper, we investigated the effect of layer delamination and grain boundary crack on 3D thin-film solar cells. We used finite element method simulation for modeling of both electrical performance and cracked structure of 3D solar cells. Through simulations, we quantitatively calculated the effect of delamination length on 3D copper indium gallium diselenide (CIGS) solar cell performance. Moreover, it was confirmed that the grain boundary of CIGS could improve the solar cell performance and that grain boundary cracks could decrease cell performance by altering the open circuit voltage. In this paper, the investigated material is a CIGS solar cell, but our method can be applied to general polycrystalline solar cells.

INTRODUCTION

Solar energy will be an important energy source for future generations, and the photovoltaic (PV) industry is growing rapidly. The PV market is expected to grow to 61.7 GW by the year 2018 compared to 35 GW in 2013.[1] A variety of new materials and fabrication processes have been examined for solar cell applications.[2] Modeling of PV performance is vital for the optimum design of solar cells. Especially, since flexible solar cells are undergoing such a variety of external loadings (i.e. rolling and bending), solar cells are subject to crack initiation and propagation. The objective of this research is to investigate the effect of interface cracks on the electrical performance of thin-film solar cells using a 3D simulation scheme. The interface cracks in this study include cracks between solar cell layers (delamination) and grain boundary cracks whose length scale ranges from nano-meters to micro-meters. There are a number of existing studies about crack effects on solar cell performance at the cell level (larger than centimeter scale) as well as the module level (larger than meter scale). Moreover, most of the published literature investigating crack effects on solar cell performance are based on either experimental results or simple 1D electric circuit modeling, whose length scale is at least centi-meter scale. There are few studies investigating how interface cracks, ranging from nano- to micro-meters, influence the electrical performance of solar cells using 3D simulation. In this paper, two types of interface cracks are created based on the microstructure of copper indium gallium diselenide (CIGS) solar cells: (1) cracks along the grain boundary interface, and (2) cracks along the layer interfaces (delamination), since solar cells are made of several layers including the main PV layer. Therefore, we will investigate (1) the effect of delamination (cracks along PV layers) and (2) the effect of grain boundary cracks (intergranular cracks) on the performance of CIGS solar cells. In order to achieve these goals, 3D finite element method (FEM) simulation is used due to its capability of solving both charge transport and continuum mechanics equations.

There are multiple studies on crack effects (including delamination) on solar cell performance at the cell scale and the module scale. Park et al.[3]

investigated the delamination effect on a 25-year-old PV module performance made of monocrystalline silicon. They found that delamination occurs at the interface between the encapsulant and solar cell, which caused 18% degradation of power output. Tracy et al.[4] experimentally quantified the delamination property (critical energy release rate, G_{Ic}) of every interface in silicon solar cell modules using fracture mechanics theory.

Pletzer et al.[5] experimentally compared the electrical performance of silicon solar cells before-crack and after-crack by comparing the parameters of two-diode model. They found that short circuit current and open circuit voltage decreased due to crack formation. Morlier et al.[6] studied the impact of cracks for polycrystalline silicon solar cells and found that crack direction is an important factor influencing solar cell performance. They also calculated the crack area in order to accurately predict the solar cell performance.

Generally, thin-film solar cells are made of several layers including the main PV layer. Figure 1 shows the structure of a CIGS solar cell. The CIGS solar cell consists of n-type ZnO (200 nm), n-type CdS (50 nm), and p-type CIGS (3 μm). The p-type CIGS is the main PV layer.

EXPERIMENTAL PROCEDURE

The CIGS solar cell used for our experiment was a FG-SM12-11 manufactured by Global Solar, which is a flexible thin-film solar cell for portable solar charger products. For the experiment, after placing the CIGS thin-film cell in a temperature-controlled chamber, a solar analyzer collects several different types of performance data such as open circuit voltage, short circuit current, efficiency, and current–voltage curve (I–V curve) while shining 1000 W/m^2 incident light.

SIMULATION PROCEDURE

COMSOL Multiphysics FEM software was used for our simulation since it can simulate material behaviors from micro-scale all the way to bulk-scale. COMSOL Multiphysics is also able to model charge transport of micro-scale solar cells by a conventional drift–diffusion approach using a partial differential equation (Poisson's equation) in conjunction with the continuity equations as shown in Eqs. 1–6.

$$\nabla \cdot (\varepsilon_s \nabla \emptyset) = -\rho \tag{1}$$

$$\frac{\partial n}{\partial t} = \frac{1}{q} \nabla \cdot J_n - U_n + G_n \tag{2}$$

$$\frac{\partial p}{\partial t} = \frac{1}{q} \nabla \cdot J_p - U_p + G_p \tag{3}$$

$$\rho = q(n - p + N_A - N_D) \tag{4}$$

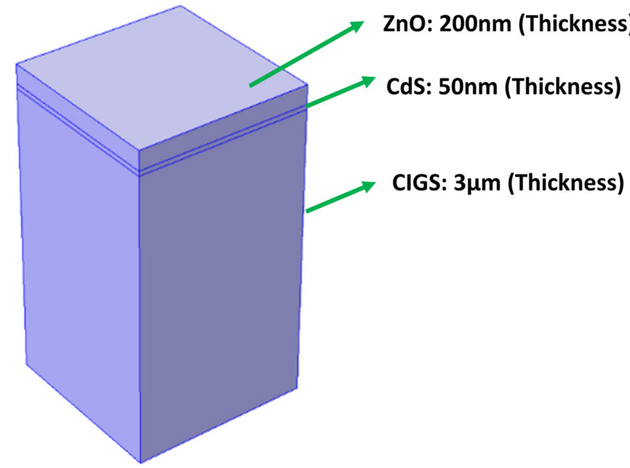

Fig. 1. CIGS solar cell (2 × 2 × 3.25 μm).

$$J_n = -q\mu_n n \nabla \emptyset + qD_n \nabla n \tag{5}$$

$$J_p = -q\mu_p n \nabla \emptyset + qD_p \nabla p \tag{6}$$

$\emptyset$ is the electrostatic potential, ρ the charge density, U_n the recombination rate for electrons, U_p the recombination rate for holes, G_n the generation rate for electrons, G_p the generation rate for holes, n the electron concentration, p the hole concentration, q the unit electronic charge, ε_s the semiconductor permittivity, N_A the acceptor concentration, N_D the donor concentration, μ_n the electron mobility, μ_p the hole mobility, D_n the diffusion coefficient of the electrons, D_p the diffusion coefficient of the holes ($D = \mu KT/q$), J_n electron current density, and J_p hole current density.

Micro-scale CIGS solar cell performance was simulated after generating a 3D CIGS structure as shown in Fig. 1. The model was composed of 3 layers: ZnO, CdS and CIGS, a typical type of CIGS solar cell. The material and layer properties used in this study are illustrated in Table I, many of which are obtained from the Gloeckler et al's baseline model.[7]

RESULTS AND DISCUSSION

After generating the 3D CIGS solar cell structure, we ran an electrical performance simulation of the CIGS solar cell using the basic semiconductor parameters from Table I. Figure 2 compares the J–V curve from both the simulation and the experiment.

In order to investigate the effect of delamination length on the solar cell performance, different sizes of delamination were generated between the CdS and the CIGS layer. The sizes of the delaminated cracks are 0.16 μm, 0.25 μm, 0.5 μm, 1 μm, and 1.5 μm. Figure 3a describes the current density of the CIGS solar cell in which arrows show the direction and magnitude of current density. The

Table I. CIGS solar cell parameters[7]

Layer	ZnO	CdS	CIGS
Layer properties			
Thickness (nm)	200	50	3000
Relative permittivity, ε	9	10	13.6
Electron mobility, μ_n (cm^2/Vs)	100	100	100
Hole mobility, μ_p (cm^2/Vs)	25	25	25
Band-gap, E_g (eV)	3.3	2.4	1.15
Effective density of states, N_c conduction band (cm^{-3})	2.2×10^{18}	2.2×10^{18}	2.2×10^{18}
Effective density of states, N_V valance band (cm^{-3})	1.8×10^{19}	1.8×10^{19}	1.8×10^{19}
Electron affinity, χ_e (eV)	4.4	4.2	4.5
Carrier density, $N_{A/D}$ (cm^{-3})	N_D:10^{18}	N_D:10^{18}	N_D:10^{18}
Gaussian (midgap) defect states			
Defect density, $E_{A/D}$(cm^{-3})	D:10^{17}	A:10^{18}	D:10^{14}
Capture cross-section, σ_n	10^{-12}	10^{-17}	5×10^{-13}
Capture cross-section, σ_p	10^{-15}	10^{-12}	5×10^{-13}
Schottky contact properties			
		Front contact	Back contact
Surface recombination velocity, electrons: S_e (cm/s)		10^7	10^7
Surface recombination velocity, holes: S_p (cm/s)		10^7	10^7
Metal work function, ψ		5.45	4.45

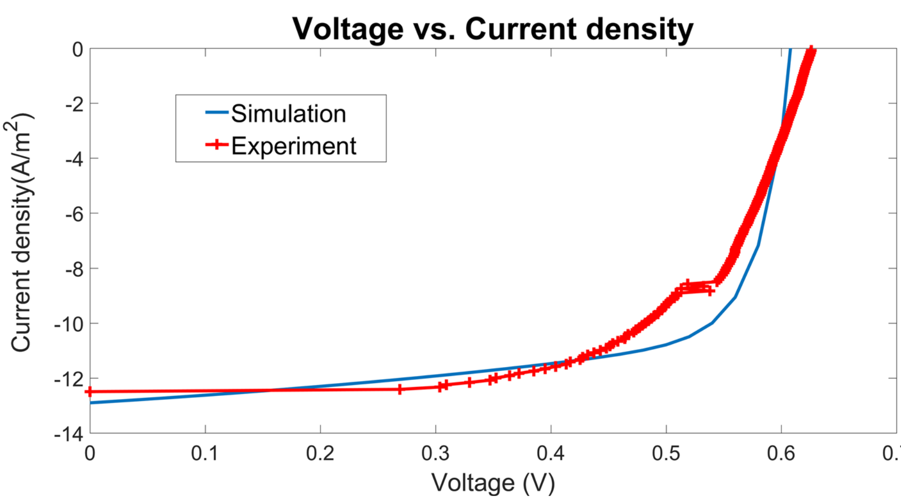

Fig. 2. J–V curve comparison between experiment and simulation of CIGS solar cells.

sliced area in the figure illustrates the norm of the log of current density. Simulation results clearly show that current hardly flows in the delaminated region and the direction of current is horizontal in the ZnO layer. Previously, it was found that the current direction in the ZnO layer was vertical when there was no delamination. Figure 3b compares the open circuit voltage with different sizes of delamination and shows that open circuit voltage decreases as delamination size increases.

In general, the efficiency of polycrystalline solar cells is less than that of single crystalline because grain boundaries (GBs) usually contain defects that enhance recombination and decrease device performance. However, there are some exceptional materials such as copper indium gallium diselenide (CIGS) and cadmium telluride (CdTe), which are the main materials for flexible thin-film solar cells. It has experimentally been found that the GB of CIGS has electric potential, which can enhance device performance.[8–11] Fisher et al.[12] claim that "the unique doping profile that forms near GB is beneficial for cell performance".

In order to simulate the effect of GB and GB cracks on CIGS performance, we generated a 3D CIGS solar cell structure with GBs in the CIGS layer as well as a 0.25-μm crack along the GB, as shown in Fig. 4a. For the grain boundary region

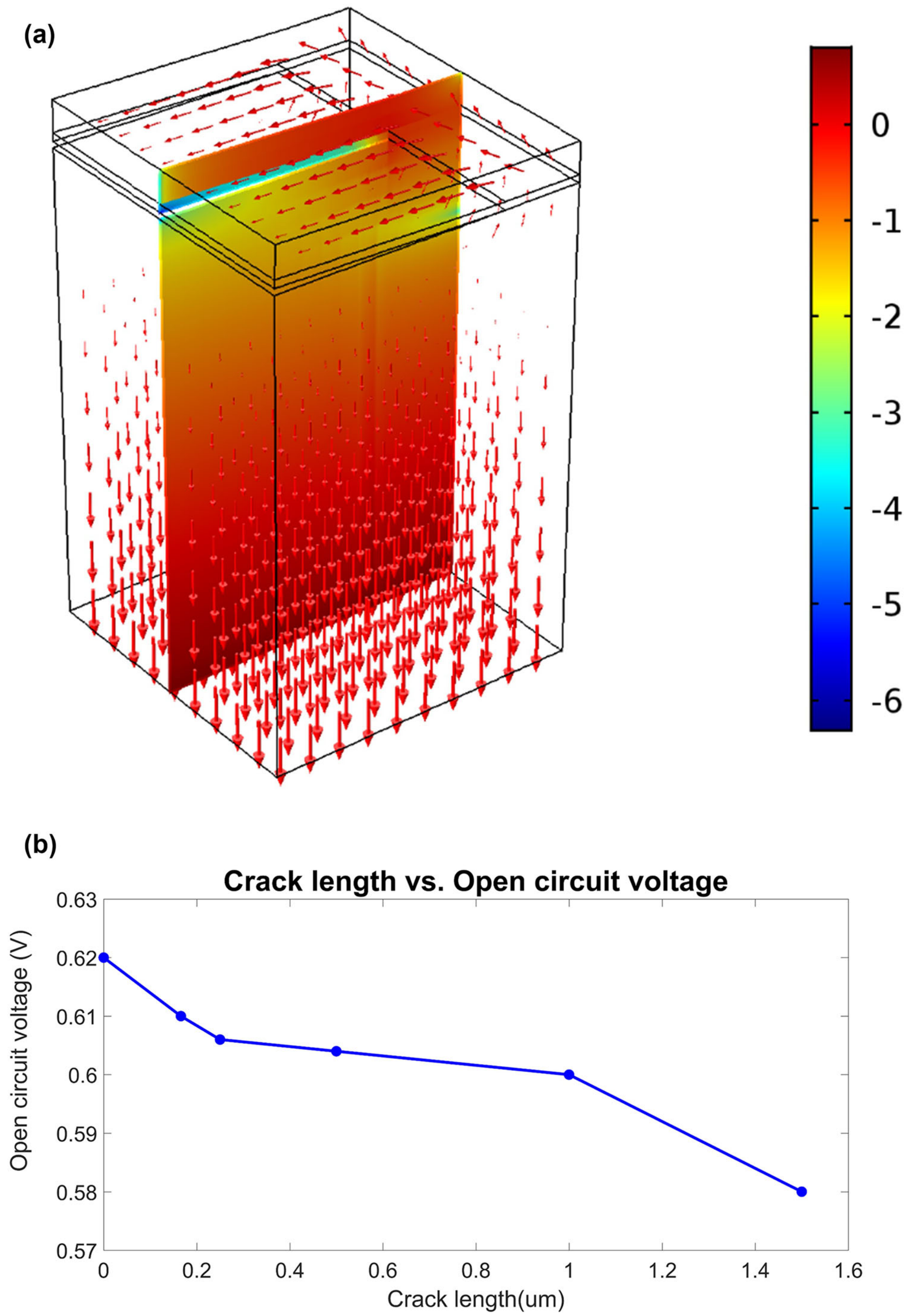

Fig. 3. (a) Electron current density at 0.6 V with 1.5-μm delamination (arrow represents magnitude and direction of current density while color represents electron concentration). (b) Relationship between open circuit voltage and the delamination size (Color figure online).

(20 nm), acceptor doping of 2.02e19 (1/cm^3) and donor doping of 2.71e18 (1/cm^3) were applied similar to the paper of Metzger et al.[8] Figure 4b compares the J–V curve of CIGS solar cells for 3 different CIGS structures: (1) CIGS without an explicit GB region (2) CIGS with an explicit GB region, and (3) CIGS with an explicit GB region and a 0.25-μm crack along the GB. Based on the simulation results, we can infer that the GB can improve solar cell performance by increasing the open circuit voltage and a crack along the GB can degrade cell performance by decreasing the open circuit voltage.

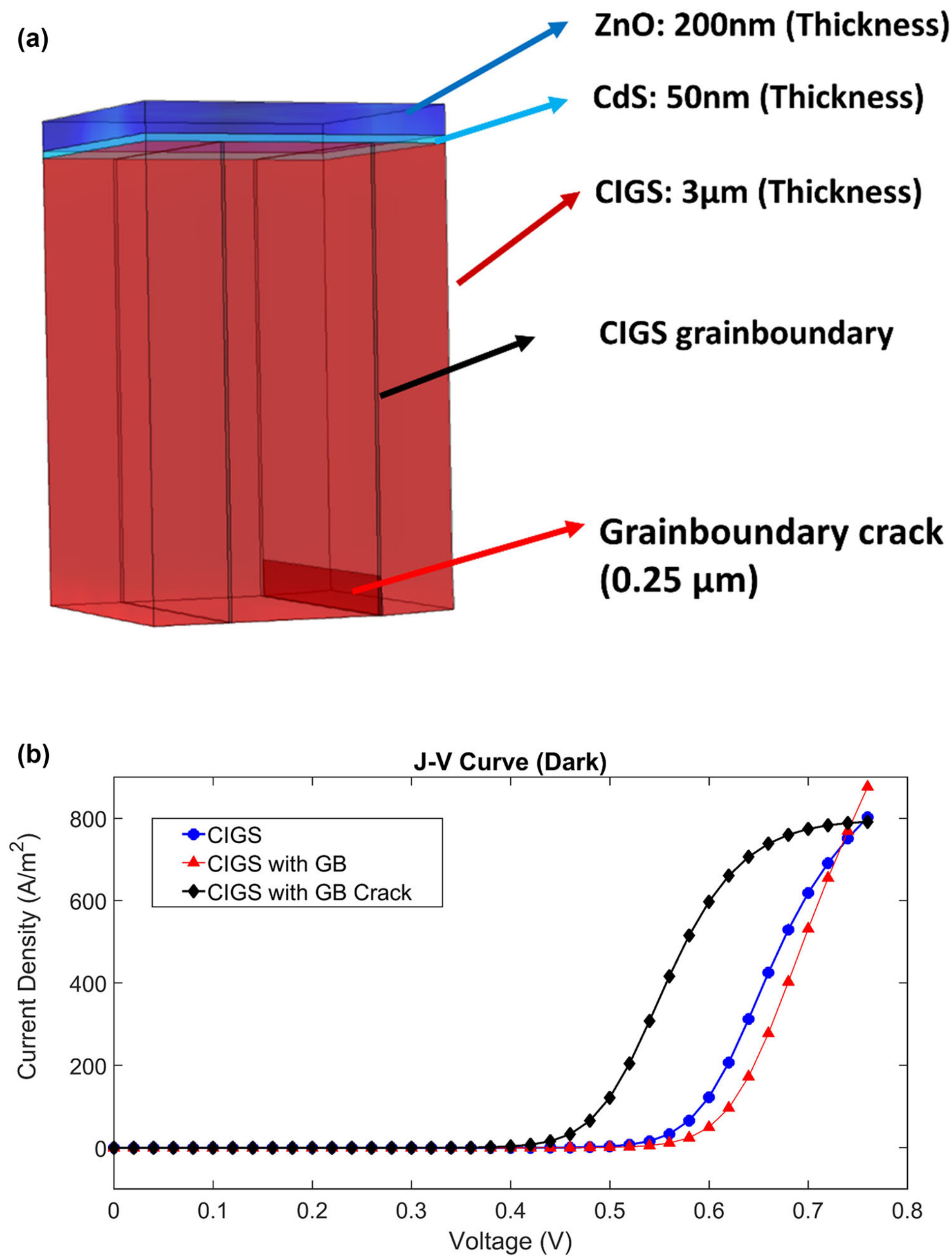

Fig. 4. (a) CIGS structure with 0.25 μm crack along the GB boundary. (b) J–V curves of 3 different CIGS structures: (1) CIGS without an explicit GB region, (2) CIGS with an explicit GB region, and (3) CIGS with an explicit GB region and a 0.25-μm crack along the GB.

CONCLUSION

The effects of layer delamination and GB cracks on 3D thin-film solar cells at micro-meter scale were investigated. We used FEM simulation for modeling both the electrical performance and the cracked structure of 3D solar cells. We were able to generate J–V curves for delaminated CIGS solar cell (delamination between the CdS and the CIGS layer) ranging from 0.16 m to 1.5 μm. The simulation results show the inversely proportional relationship between delamination length and open circuit voltage. Moreover, it was confirmed that the GB could improve the solar cell performance, while a GB crack could significantly degrade the performance by altering the open circuit voltage.

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