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Light soaking induced doping increase and sodium redistribution in Cu(In,Ga)Se_2-based thin film solar cells

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ABSTRACT

Light-induced metastabilities of Cu(In,Ga)Se_2 (CIGS)-based thin film solar cells have been extensively researched for many years. It is commonly observed that junction capacitance and *p*-doping level in CIGS absorbers increase considerably after light soaking (LS). In this work, we focus on the LS behaviors of cells with different minority carrier lifetimes (τ_n). Experiments show that high efficiency cells with long τ_n lose open circuit voltage (V_{oc}) and fill factor (*FF*) upon LS, whereas low efficiency cells with short τ_n lose less or even gain V_{oc} and *FF*. The sodium content measured with glow discharge optical emission spectroscopy (GD-OES) increases in the region close to the CdS/CIGS interface with LS and may contribute to the observed LS behaviors. The change in electrical parameters is explained with simulations, which relate the V_{oc} and *FF* changes to a reduced recombination rate in the space charge region due to the light-induced doping increase. The simulations also suggest that cells with higher *n*-doping in the CdS are less sensitive to changes in interface recombination rate and doping of CIGS, which agrees with the hypothesis that the CdS buffer deposition is important for the LS behavior.
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1. Introduction

Demand in renewable energy has been increasing considerably in recent years due to climate change and global warming concerns resulting from extensive use of fossil fuels. Solar photovoltaics (PVs), which directly convert sunlight to electricity, has gained wide interest and is now one of the most important renewable energy sources in terms of globally installed capacity [1]. Thin-film technology, with the potential to enable low-cost production of highly efficient modules with a price meeting grid parity, is expected to surpass the dominating conventional PV technology in the long-term [2]. In particular, polycrystalline chalcopyrite Cu(In,Ga)Se_2 (CIGS) represents one of the most promising technologies, with conversion efficiencies exceeding 20% for lab-scale cells and reaching close to 16% on large-scale modules [3].

Long-term performance stability under working conditions is of crucial importance for commercial solar modules. It is well known that CIGS solar cells exhibit metastable performance changes under extended duration illumination, *i.e.*, light soaking (LS), which can be beneficial or detrimental, depending on the properties of the cell itself [4–6]. Extensive works have been done in the past years to understand the LS mechanism as well as to find approaches to avoid the detrimental LS effect [7–10]. It has been shown that junction capacitance and *p*-doping level in CIGS absorbers increase considerably after LS [11,12]. In this work, we focus on the effect of light-induced doping increase on cell performance. LS experiments on cells with different minority carrier lifetimes (τ_n) are carried out. Numerical simulations are performed to understand the experimental observed LS behaviors. In addition, elemental profiles for cells with different LS times are measured in order to gain insights into the mechanisms.

2. Experimental details

Three groups of samples, *i.e.*, samples A, B, and C with short, medium, and long τ_n, respectively, were prepared for the LS experiments. To avoid sodium incorporation from substrate, soda-lime glass with a 140-nm thick front side diffusion barrier was used. Mo back electrode with a thickness of 300 nm was deposited using sputtering. The CIGS absorber layer was grown in a high-vacuum evaporation chamber at a maximum substrate temperature of 530 °C and the thickness is about 2.1 μm as measured by a stylus profiler (DektakXT, Bruker Corp.). A NaF precursor layer was evaporated before the CIGS deposition for precise control of Na supply. The τ_n of the samples is controlled by using raw materials with different impurities. After the absorber growth, the samples were taken out from the evaporation chamber and a 50-nm thick CdS buffer layer was grown by chemical bath deposition. The front contact was formed by sputtering a bilayer of 50 nm intrinsic ZnO (IZO) and 300 nm Al-doped ZnO (AZO) and evaporating a Ni/Al contact grid. The completed cells were characterized using current *versus* voltage (*I*–*V*) measurements with illumination from an ELH

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lamp under standard test conditions (1000 W/m^2, 25 °C). Quantum efficiency (QE) spectra were measured using an IQE-200 EQE/IQE measurement system (Newport) to investigate the photo-generation of minority carriers. To characterize the doping profile in CIGS absorber, capacitance–voltage (C–V) measurements were performed using a HM8118 LCR-bridge (HAMEG Instruments) at a frequency of 100 kHz and with a DC bias ranging from −2 to 0.25 V. For analysis of elemental profiles, glow discharge optical emission spectroscopy (GD-OES) was performed in a Spectruma GDA 750 (Spectruma Analytik GmbH, Germany). τ_n of completed cells was measured by time-resolved photoluminescence (TRPL) and then extracted by fitting two exponential decay curves to the measured data [13].

3. Results and discussion

τ_n of samples A, B, and C measured by TRPL are 26, 43, and 65 ns, respectively. Variability charts for cell parameters before and after LS are depicted in Fig. 1. Sample A with short τ_n shows significantly lower open circuit voltage (V_{oc}), fill factor (FF), and efficiency (η) comparing to samples B and C due the higher recombination rate in CIGS absorber. LS behaviors of the three samples differ greatly among them, *i.e.*, sample A with short τ_n gains V_{oc} and FF after LS, while samples B and C with medium and long τ_n loss V_{oc} and FF. QE plots for the samples are shown in Fig. 2(a). The effective collection length (L_{eff}) for photo-generated minority carriers can be estimated by $L_{eff} = W_{SCR} + L_n$, where W_{SCR} is the thickness of the space charge region (SCR) and L_n is the electron diffusion length in the CIGS absorber [14]. Low collection in the long wavelength region is observed for sample A, indicating short τ_n and L_n in the CIGS absorber, which is in good agreement with the TRPL results. Meanwhile, all samples show collection loss in the long wavelength region after LS. As shown by the Mott–Schottky plots in Fig. 2(b), the apparent p-doping (N_A) level in CIGS absorber increases significantly after LS for all samples, possibly due to the metastable capture of photo-generated electrons by deep-level traps in the SCR [15], leading to reduction in W_{SCR} and L_{eff}, and thus collection loss in the long wavelength region.

The bulk recombination rate depends on the N_A in CIGS absorber. Highest recombination rate in the CIGS absorber occurs at the position where the electron and hole concentrations are equal, *i.e.*, $n = p$. With higher N_A, the difference between n and p next to the position of highest recombination rate rises more quickly, leading to a thinner high recombination zone and lower total recombination rate in CIGS

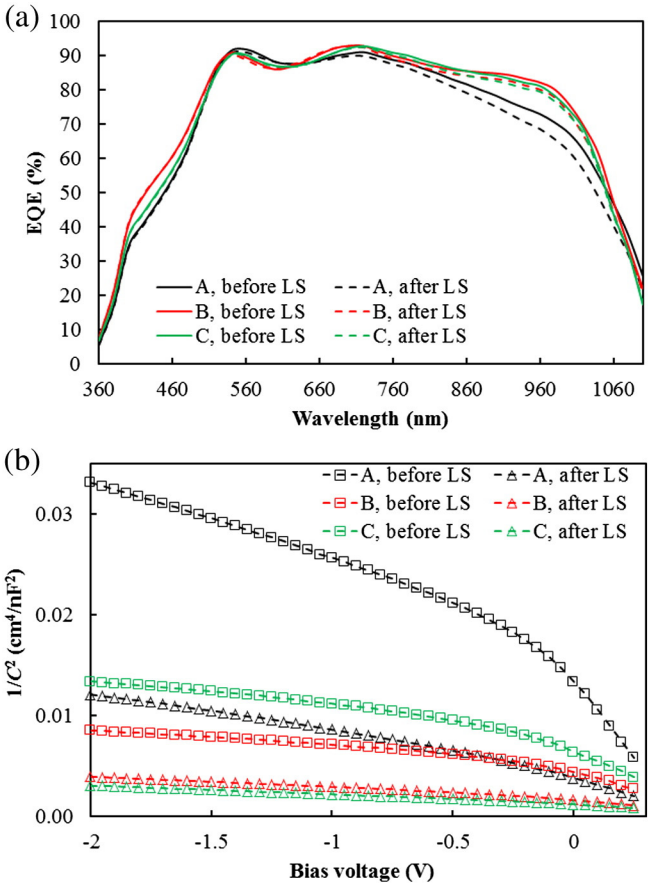

Fig. 2. (a) External quantum efficiency (EQE) spectra and (b) Mott–Schottky plots of C–V measurements of samples A, B and C before and after LS.

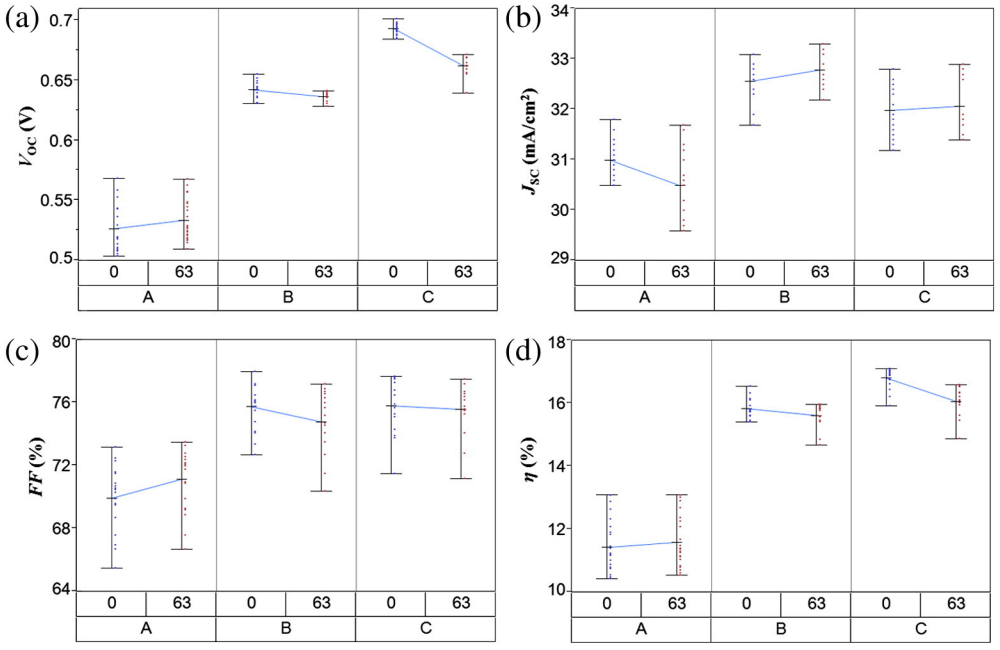

Fig. 1. Variability charts for I–V parameters of samples A, B, and C before and after 63 h of LS.

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