Photovoltaic Characteristics of Thin-Film GaAs Solar Cells with Spectrum Selective Filters

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ABSTRACT — **Light management holds promises to advance the power conversion efficiency of III-V solar cells with good material qualities. In this work, we investigate the characteristics of thin-film GaAs solar cells incorporated with spectrally selective optical filters. The introduced cavity design in the 2.6μm-thick photovoltaic devices is aimed to suppress the spontaneous emission into the substrate and to the front side of the device. We systematically compare the device characteristics for selective filters (SFs) with three different cutoff wavelengths of 795, 858, and 915 nm under the standard one-sun illumination condition. Preliminary results show that the net open-circuit voltage (V_{oc}) of the thin-film cells with the 858nm and 915nm cutoffs increased by 0.8 and 3.3mV, respectively, compared to that of devices before the deposition of SFs. Next, we develop an optical model based on the rigorous couple wave analysis (RCWA) and photon recycling model in order to quantify the V_{oc} enhancement of thin-film GaAs solar cells with various surface structures. The simulation results show that a thin-film device with nearly ideal material quality can exhibit a maximal net increase of 42.6mV in V_{oc} by introducing an 860nm-cutoff SFs. The benefits and tradeoffs between light extraction and light confinement in thin-film GaAs cells will be discussed via simulation of realistic filters and photonic structures.**

Index Terms **— single-junction GaAs solar cells, photonic crystals, open-circuit voltage, light extraction efficiency, photon recycling.**

I. INTRODUCTION

Since Shockley and Queisser proposed the limiting efficiency of solar cells in 1961 [1], crystalline semiconductor photovoltaic technologies based on silicon (Si) and gallium arsenide (GaAs) have reached their state-of-the-art power conversion efficiency of 25.6% and 28.9%, respectively, both approaching their limits of 29% and 33%. To bring close the gap to the theoretical limit, the two most important requisites have unarguably been the nearly-perfect material quality and control of photon-generated carrier losses, namely increased the minority carrier lifetime. For silicon, the later means suppression of the Auger recombination depicted by the nature of its indirect energy gap. For GaAs, the loss of photon-generated carriers to radiative recombination may be retrieved using light management techniques, also known as photon recycling. It has been demonstrated that optical enhancement of the open-circuit voltage via photon recycling play a significant role in approaching the Shockley and Queisser limit [2,3]. Over the past decade, various light management approaches have been proposed, including thin-film type Fabry-Perot resonators with a rear gold mirror, monolithically grown distributed Bragg reflectors, as well as spectrally and angularly SFs. The V_{oc} enhancement in these devices has been reported, according to the epitaxial material qualities and processing techniques. In this work, we investigate the characteristics of thin-film GaAs solar cells incorporated with spectrally selective optical filters. The introduced cavity design in the 2.6μm-thick photovoltaic devices is aimed to suppress the spontaneous emission into the substrate and the front side of the device. We systematically compare the device characteristics for selective filters (SFs) with three different cutoff wavelengths of 795, 858, and 915 nm under the standard one-sun illumination condition and establish a validated optical model for the proposed device structure.

II. EXPERIMENTAL

The fabrication of GaAs thin film solar cells involves first the evaporation of a gold seed layer on the rear surface, followed by electroplating of a 50μm-thick Nickle film as the carrier and wet chemical etch for substrate removal. Subsequently the definition and ohmic contact formation of frontal electrodes are carried out to realize flexible GaAs thin-film solar cells with average power conversion efficiency (PCE) of 16.1 % without the deposition of antireflective coatings. Instead, spectrally SFs based on the alternative TiO_2 and SiO_2 dielectric layers are designed and deposited to achieve minimal optical reflection from 400 nm to a specific cutoff wavelength and maximal reflection from the cutoff wavelength to beyond. As shown in Fig. 1, the contact bus bars of fabricated solar cells were first covered with the vacuum tape, and then a 75nm-thick SiN_x layer was deposited by plasma-enhanced chemical vapor deposition (PECVD), followed by the deposition of 12-pair alternative SiO_2/TiO_2 dielectric stacks using e-gun evaporation. Each periodic SiO_2/TiO_2 stack contains a λ/4-thick, high-reflective-index TiO_2 layer sandwiched by two λ/8-thick, low-reflective-index SiO_2 layers. Finally, the vacuum tape was removed for device characterizations.

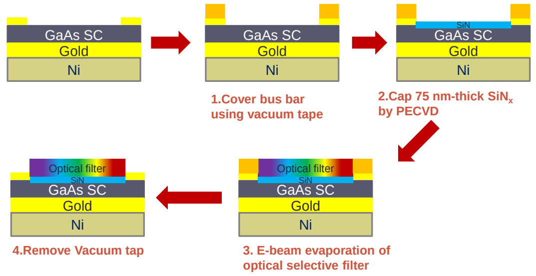

Fig. 1. Fabrication of thin-film GaAs solar cells with selective filters.

III. RESULTS AND DISCUSSION

We first examine the optical properties of the deposited SFs. As shown in Figure 2, the measured cutoff wavelengths, defined at where the 50% reflectivity is, correspond to 795nm, 858nm, and 915nm from the silicon wafer reference. Here, <R> indicates the weighted reflectance of the SFs using AM1.5G solar radiation in the 350-870nm wavelength range. On the thin-film devices, the weighted reflectance <R> is improved from 21.7% from the bare cells to 14.5%, 12.3%, and 12.1% from the cells with the 795, 858, 915nm SFs, respectively. Consequently, the corresponding short-circuit current (J_{sc}) is increased by 0.7, 2.7, and 3.7 mA/cm^2, as indicated in Fig. 3(a). Preliminary experimental results show that V_{oc} and PCE increase with the increase of cutoff wavelengths (Fig. 3(b) and 3(c)) while the fill factor (FF) decreases (Fig. 3(d)).

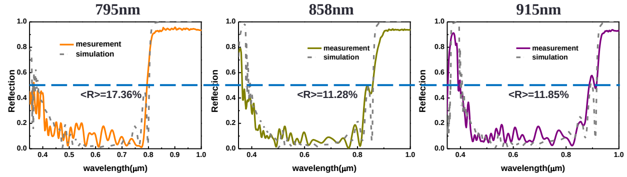

Fig. 2. Spectral responses of the simulated and deposited selective filters on silicon with cutoff wavelengths of 795, 858, and 915 nm.

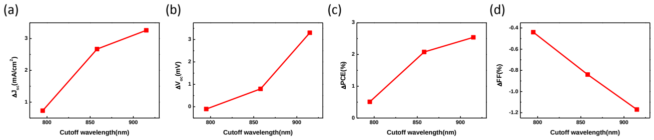

Fig. 3. Differences of current-voltage characteristics: (a) ΔJ_{sc} (b) ΔV_{oc} (c) ΔPCE (d) ΔFF for thin-film cells before and after the deposition of SFs .

The dependence of V_{oc} on the cutoff wavelength is similar to that of J_{sc}, which presumably is originated from the improved optical absorption. It also indicates that the saturation current is dominated by non-radiative recombination. To investigate further, we import realistic optical models of SFs into the approximated V_{oc} equation (Eq. (1)) to evaluate the dependence of V_{oc} on light extraction and confinement. Here η_{ext} is defined as the external radiation efficiency (Eq. (2)) and depicted by the internal radiative efficiency, η_{int} and photon recycling effect[4,5].

$$qV_{OC} = kT\ln(\frac{J_{sc}}{J_{0,rad}}) + kT\ln(\eta_{ext}) \tag{1}$$

$$\eta_{ext} = \frac{J_{rad,ext}}{J_{tot-recomb}} \tag{2}$$

The photonic structure incorporated in a solar cell modifies the angular absorption spectrum, α(λ,θ,ϕ), as well as the reflectance and transmittance at the interface, which together can be used to calculate J_{sc}, $J_{0,rad}$, and η_{ext} to yield the modified V_{oc}. Figure 4 shows the variations of V_{oc} as a function of the cutoff wavelengths for cells with a (a) poor material quality, η_{int}=0.06 and (b)good material quality η_{int}=0.98. The former case corresponds to the experimental fitting result of the presented devices. As shown in Fig. 4, the net V_{oc} increase with a realistic SF could as high as 32.9mV and 42.6 mV at the 860nm cutoff wavelength for material quality η_{int}=0.06 and η_{int}=0.98, respectively. Other surface structures such as photonic crystals could be explored in a similar manner and will be discussed.

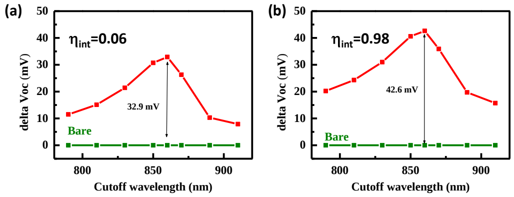

Fig. 4. Variations of V_{oc} as function of the cutoff wavelengths of SFs for (a) poor material quality, η_{int}=0.06 and (b) η_{int}=0.98.

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