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***Abstract*—We report on the development of light-trapping architectures applied to thin-film solar cells. In particular, we focus on enhancing the absorption at 1-eV spectral range for dilute nitride and quantum dot materials and report on the influence of planar back reflectors on the photovoltaic properties. Moreover, we discuss the properties of polymer diffraction gratings with enhanced light-trapping capability pointing to advantageous properties of pyramidal gratings. In order to understand the suitability of these polymer grating architectures for space applications, we have performed an electron irradiation study (1 MeV) revealing the absence of reflectance changes up to doses of 1×10^{15} e^{-}/cm^{2}.**

Keywords—solar cell, III-V semiconductor, quantum dot, back reflector, optical design, diffractive grating, electron irradiation

I. Introduction

Space photovoltaic generators require solar cells with high efficiency, high power-to-weight ratio, and additional functionality in terms of flexibility. To this end, III-V solar cells with substrate removal and employing light-trapping to enhance photogeneration are gaining increased attention. For example, by using a highly reflective planar reflector on the backside of the solar cell, the length of the optical path is effectively doubled while further enhancement of the absorption can be obtained by using diffraction gratings combined with back reflector [1]. Planar reflectors have been initially utilized for thin-film single-junction GaAs solar cells [2], and more recently also applied to more advanced GaInNAs solar cells [3], and quantum dot (QD) solar cells [4]. Furthermore, different approaches utilizing diffraction gratings as back reflectors have been published [1], [5] and introduced as nanostructured back reflectors in GaAs solar cells [6].

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In this work, we compare the performance of different planar reflectors and discuss the properties of diffraction gratings fabricated onto a polymer film deposited on the backside of the solar cells. The suitability of the polymer diffraction gratings for space application is assessed by performing electron irradiation study (1 MeV). In addition, we present the results of a thin-film QD solar cell with back reflector.

II. Back Reflectors

A. Planar Back Reflectors

In an initial study, different planar metal back reflectors were compared. The Ag/Cu reflector showed high reflectance and resulted in enhanced external quantum efficiency (EQE) when compared to conventional Ti/Au back metals for dilute nitride (GaInNAs) solar cells as shown in Fig. 1. The EQE results show correlation with the reflectance results of the back reflectors, revealing higher reflectance of the reflector

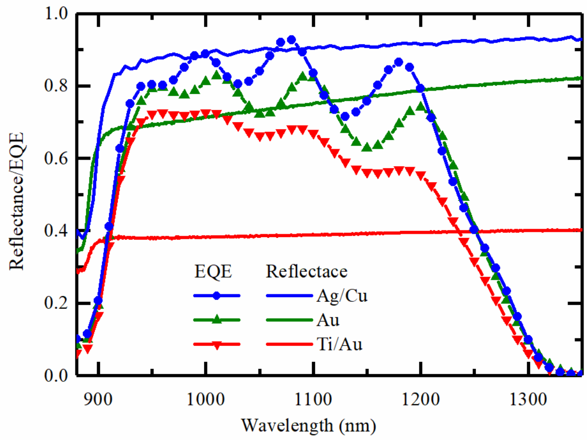

Fig. 1. Reflectance results of semi-insulating (SI) GaAs samples with the metal reflector are presented as solid lines and EQE results of GaInNAs solar cells with metal reflectors are presented as symbol and line.

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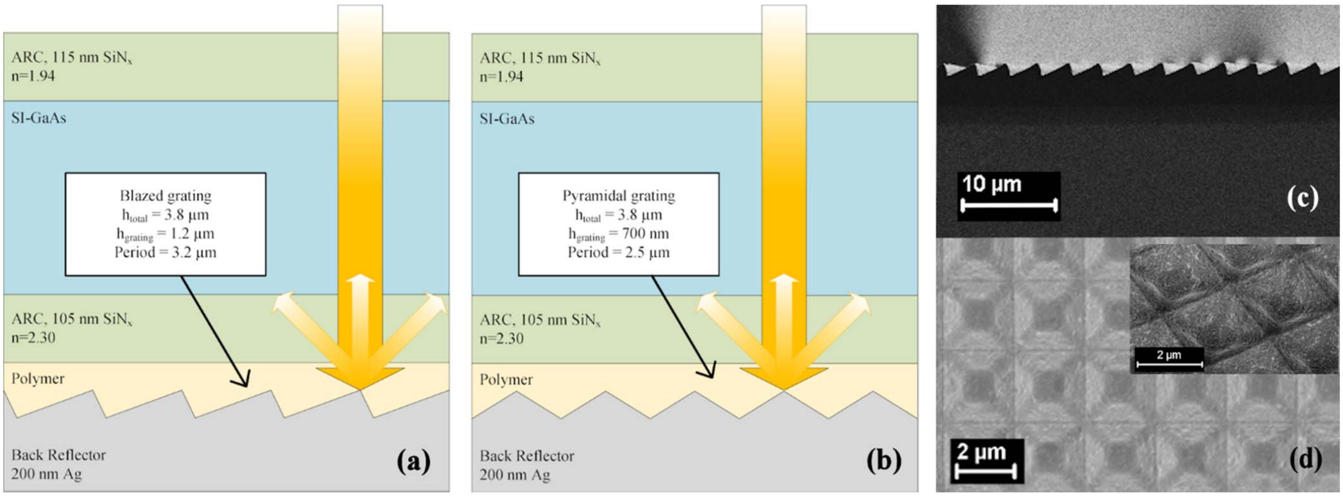

Fig. 2. Schematic drawing of (a) blazed gratings and (b) pyramidal gratings. SEM images of (c) blazed gratings and (d) pyramidal gratings.

resulted in higher EQE. Detailed study of the metal reflectors showed Ag/Cu and Au reflectors to be suitable for use in thin-film solar cell design [3]. In particular, the metal adhesion to semiconductor showed no peeling in the adhesion tests and the contact resistivity values were of the order of magnitude of 10^{-6} Ω/cm^2, which indicates to the formation of ohmic contact. Moreover, no discernible diffusion of metals into semiconductor was observed after thermal annealing (at 200 °C).

B. Back Reflector with Diffractive Gratings

To further enhance the EQE, two different diffractive gratings, blazed and pyramidal, were fabricated using a commercial nanoimprint lithography (NIL) polymer (Ormocomp) with a Ag reflector [7]. If the diffractive gratings would be directly structured into the semiconductor, parasitic losses may occur due to surface plasmon effect resulting from the large microstructured interface area between the semiconductor and the metal [1]. For this reason, the diffractive gratings were fabricated onto a polymer, which acts as an interlayer, alleviating the parasitic losses. Schematic drawings and scanning electron microscopy (SEM) images of the fabricated grating structures are presented in Fig. 2, where the dimensions of the gratings are also shown. Prior to the fabrication of the diffractive gratings, optimum dimensions of the gratings for wavelength range of 900–1300 nm were simulated [8]. The simulation result pointed to the use of a height/period aspect ratio of 0.32–0.38, which was then used in the fabrication.

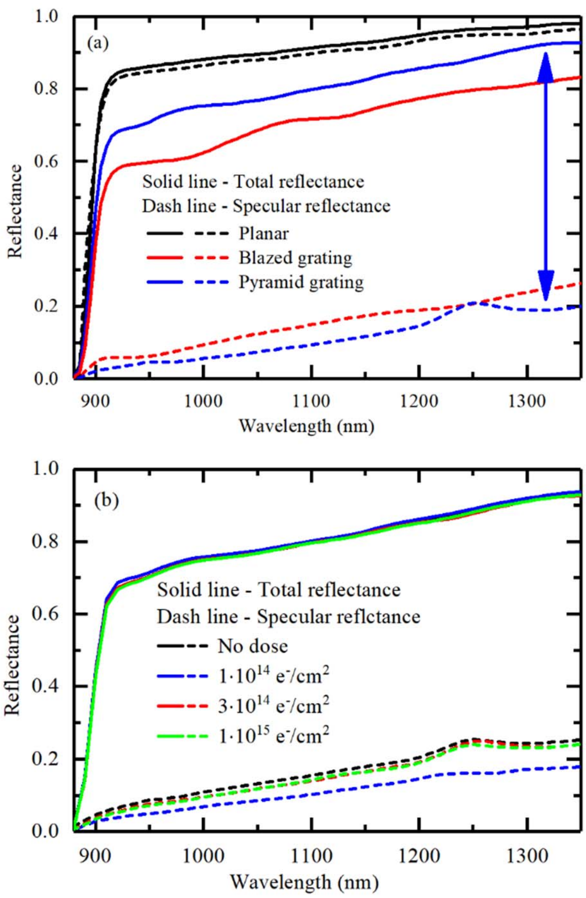

Fig. 3. (a) Reflectance of the diffractive grating structures. (b) The reflectance of the pyramidal grating structure after electron irradiation.

The diffractive gratings were characterized by measuring the total and specular (at 8° angle) reflectance spectra, which are presented in Fig. 3(a). The diffuse light is defined as the difference between the total and specular reflectance. The pyramidal grating showed higher diffuse reflectance when compared to blazed gratings in the wavelength range corresponding to dilute nitride junction and QD solar cells (900 nm to 1300 nm). Blazed grating showed also low specular reflectance, which is beneficial for high diffraction of light. However, the total reflectance of the blazed grating was reduced compared to the pyramidal grating, indicating some extra losses in the structure, potentially originating from parasitic absorption in the metal reflector. In addition to diffractive grating samples, a reference sample with planar polymer layer and Ag reflector was fabricated, showing almost identical specular and total reflectance spectra, verifying that only specular refection occurs in the planar reflector.

C. Electron Irradiation of the Diffractive Gratings

The samples with pyramidal gratings were exposed to 1 MeV electron irradiation with three different doses, to study the suitability of the polymer gratings in the space environment. The total and specular reflectance results after the irradiation are presented in Fig. 3(b). These results reveal that the performance is mainly equivalent to the sample without the irradiation. Only for the sample exposed to the lowest dose (1×10^{14} e$^-$/cm^2), the specular reflectance was decreased, which might possibly originate from the fabrication of the sample or from the handling of the sample during irradiation, transport, and measurement. However, the higher dose samples showed no changes in the specular reflectance relative to the sample without any irradiation dose. These irradiation results indicate that the polymer are suitable for diffractive gratings in space solar cells in terms of radiation hardness.

III. Thin-Film QD Solar Cell with Back Reflector

A. EQE of the QD Layers

The effect of a planar back reflector on photocurrent generation in QD layers was experimentally investigated for InAs/GaAs solar cells containing 10 QD layers fabricated by molecular beam epitaxy [9]. QD solar cells were processed both as thin-film with Au reflector and wafer-based (i.e. with the substrate and without the back reflector) configurations. The measured EQE of the cells are presented in Fig. 4(a), which shows an increased photogeneration in the QD solar cell with back reflector when compared to QD solar cell without the reflector.

The photocurrent generation in QD layers (900–1100 nm) was calculated by integrating the EQE over the AM1.5D spectrum (1 000 W/m^2). The QD solar cell with reflector increased the current density (J_{sc}) component obtained from the QD layers by a factor of two when compared to the QD layers without the back reflector. The additional current density components to J_{sc} were 0.35 mA/cm^2 and 0.17 mA/cm^2 for QD solar cell with the reflector and QD solar cell without the reflector, respectively.

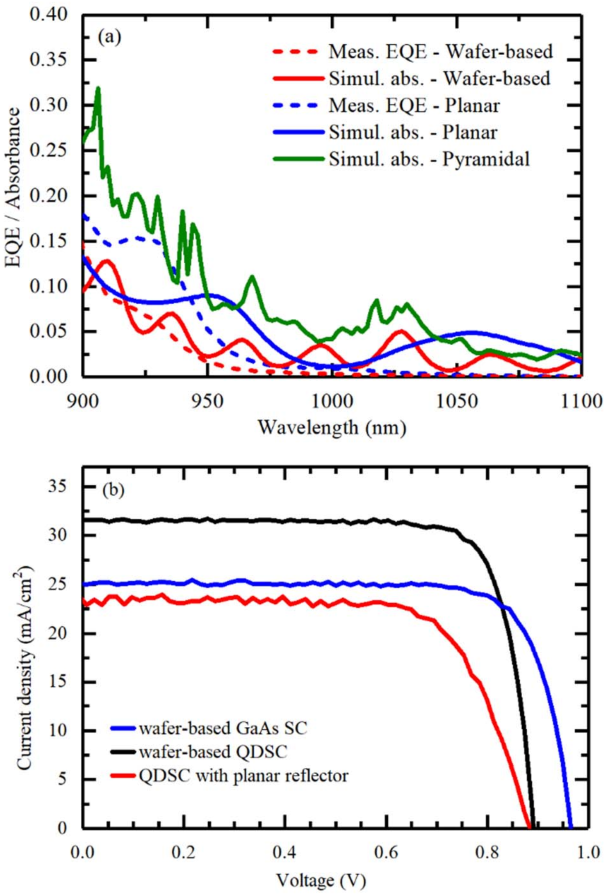

Fig. 4. *IV* results of the QD solar cell with and without planar back reflector and GaAs solar cell without reflector.

The absorbance spectrum of the QDs were simulated by using the rigorous coupled wave analysis method and the results are presented in Fig. 4(a). In addition to planar reflector, the absorbance of the QD solar cell utilizing a reflector with pyramidal grating was simulated, revealing a theoretical four-fold increase in the additional J_{sc} component originating from the QD layers.

B. Current-Voltage Characteristics

The measured current-voltage (*IV*) characteristics of the QD solar cells with and without the planar reflector are presented in Fig. 4(b). In addition, Fig. 4(b) shows the *IV* results of a GaAs solar cell, which was fabricated as a reference. The comparison of the measured J_{sc} values is not simplistic due to the structural differences in the epitaxial layers of the QD solar cells and GaAs solar cell. For example, QD solar cell with back reflector has a 600 nm thick window layer, which absorbs photons lowering the J_{sc} when compared to wafer-based QD solar cell, which has 20 nm thick window layer. In addition, the thicknesses of the p-GaAs base are 750 nm, 2 100 nm, and 900 nm for QD solar cell with reflector, wafer-based QD solar cell and wafer-based GaAs solar cell, respectively. However, despite these differences, the comparison of the open circuit voltage (V_{oc}) values is meaningful. The QD solar cell with back reflector has a very similar V_{oc} to the QD solar cell with substrate, indicating that the high V_{oc} is preserved during the thin-film process. The measured V_{oc} of 0.884 V for thin-film QD solar cell with back reflector is high when compared to the reported values for thin-film QD solar cells [4], [10].

IV. Conclusions

Diffraction grating structures implemented as back reflector were developed for light-trapping in thin-film III-V solar cells. Pyramidal gratings in Ormocomp polymer showed high diffuse reflectance and ability to enhance photocurrent generation in 1-eV cells, e.g. in multijunction solar cells with dilute nitride bottom junction and in QD solar cells. In addition, the polymer was resistant against the electron irradiation indicating possible suitability for space applications.

The effect of the planar back reflector on the performance of InAs/GaAs QD solar cell was studied by fabricating thin-film QD solar cell with back reflector. The photocurrent generation in the QD layers increased by a factor of two when QD solar cell with planar back reflector was compared to wafer-based configuration and at the same time the Voc remained high as in the wafer-based sample. The photocurrent generation could be further enhanced with a back reflector based on pyramidal gratings.

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