Metal/Polymer Back Reflectors with Diffraction Gratings for Light Trapping in III-V Solar Cells

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***Abstract* — We report on the fabrication, characterization and simulation of diffraction gratings for back contact reflectors in III-V solar cells. The gratings are designed for thin-film solar cells incorporating absorbers with bandgap slightly lower than GaAs, such as InAs/GaAs quantum dot or GaInNAs solar cells. Metal/polymer back reflectors with a blazed grating or a pyramid grating were fabricated by nanoimprint lithography. The gratings are compared in terms of diffraction ability, which is the feature responsible for increasing the absorption. The pyramid grating showed higher diffraction of light compared to the blazed grating. The diffraction efficiency measurements were in agreement with the numerical simulations. The model validation enables tailoring the properties of the reflectors for other type of solar cells by adjusting the optimal dimensions of the gratings for different wavelengths.**

***Index Terms* — III-V solar cells, back reflector, diffraction gratings, dilute nitride, quantum dot solar cell.**

I. Introduction

For space solar power applications, III-V multi-junction solar cells have proven their ability to achieve high efficiencies exceeding 30% under AM0 [1]. Promising approaches to further enhance their efficiency include quantum dots (QDs) and lattice-matched $Ga_{1-x}In_xN_yAs_{1-y}$ sub-junction grown by molecular beam epitaxy (MBE) [2]. The extended absorption edge of the QD material allows to increase the photocurrent generation of the current-limiting junction. Moreover, QDs have potential benefit in terms of radiation hardness. However, the light absorption in the QD sheets is relatively low [3], and the growth of several closely placed layers poses difficult technological challenges owing to the lattice strain between the QDs and the host semiconductor. The main advantage offered by GaInNAs is the ability to tailor the bandgap in the range from approximately 0.8 eV to 1.42 eV, while remaining lattice-matched to GaAs and Ge. However, at least at relatively high N composition required to achieve bandgaps below 0.9 eV, the thickness of an absorbing layer is limited due to the short diffusion length and relatively high p-type background doping level [4], [5]. In both QDs and GaInNAs approaches, light trapping techniques may allow to overcome such limitations, by effectively increasing the optical absorption length.

As the simplest approach for applying light trapping, a highly reflective planar back reflector could effectively double the length of the optical path inside the absorbing layer of a solar cell. This approach has already been demonstrated with single-junction GaAs-based solar cells [6], [7] and InAs/GaAs QD solar cells [8]. The length of the optical path and the carrier photogeneration can be boosted even more with back reflector gratings that induce light diffraction. Various approaches of such gratings have been proposed [9]. Recently, [10] has reported nanostructured reflectors for GaAs solar cells. In general, research on light trapping structures implemented within a thin-film architecture – obtained by substrate removal - is gaining increasing attention owing to potential advantages such as high power-to-weight ratio, flexibility, and improved radiation durability which are beneficial for space and unmanned aerial vehicle applications [11], [12].

In this work, we study grating structures that provide increased diffraction at the wavelengths of interest for solar cells incorporating InAs QDs or GaInNAs materials. We focus on the gratings with periods larger than the wavelength. Larger periods are preferred in order to have a wider wavelength range in which the performance of the diffractive gratings is optimal. When the gratings are directly structured into the semiconductor material, parasitic losses may occur due to the surface plasmon effect [9]. To alleviate this, we make use of polymer gratings. We compare the diffraction properties of two back reflector gratings fabricated by nanoimprint lithography (NIL) into a polymer. The gratings were optimized for light trapping at the wavelengths corresponding to the energies slightly below the bandgap of GaAs. Simulated and experimental results are compared validating the design methodology. This enables the optimization of the proposed grating structures for light trapping in other types of solar cells by tuning the optimal grating geometric features at the wavelengths of interest.

II. EXPERIMENTS AND MODELLING

The gratings under study are designed for InAs/GaAs quantum dot solar cells (QDSCs) in the wavelength range of 900 nm – 1200 nm [13]. In particular, we have considered a QD solar cell structure with a 2.6 µm thick GaAs solar cell embedding 20 InAs/GaAS QD layers with a total thickness of 400 nm. Further details of the structure can be found in reference [14]. The optical model of the QD layers was defined from external quantum efficiency measurements [8].

The gratings were simulated using the rigorous coupled-wave analysis method (RCWA) with the RSoft DiffractMOD software (Synopsys) and the planar structures were analyzed with transfer-matrix method. In the 2D simulations, the results are an average of the TE and TM polarizations for each of the diffraction orders. In the 3D case, the gratings are symmetric and therefore both polarizations are equal for direct angle of incidence. The RCWA simulation provide the distribution of the absorbed photon density across the cell. Then, the absorbance spectrum was calculated by integrating the absorbed photon density in the cell active region only. The corresponding QD photocurrent density was calculated by integrating the absorbance over the AM1.5G spectrum in the range of 895 nm – 1200 nm and assuming unitary quantum yield. In order to maximize the photocurrent, an optimum height/period aspect ratio of 0.32-0.38 [15], [14] was identified.

The experimental structures, including a planar reference and two types of gratings are presented in Fig. 1. Additional experimental work can be found in reference [16]. As a substrate, we used a double-side polished semi-insulating GaAs (SI-GaAs) wafer of thickness 350 µm. Single-layer SiN_x antireflection coatings (ARCs) optimized for a wavelength of 900 nm were deposited by plasma enhanced chemical vapor deposition on the both sides of the substrate. The properties of the SiN_x layers were tuned by changing the deposition parameters. The ARC thicknesses and refractive indices are presented in Fig. 1.

Two gratings were structured into a commercial OrmoComp NIL photoresist (Micro Resist Technology GmbH). A commercial master (Thorlabs) and an in-house fabricated Si master were used for the blazed grating and the pyramid grating, respectively. The grating structures from the masters were transferred into polydimethylsiloxane stamps, which were used for imprinting the gratings into OrmoComp photoresist. To finalize the reflector, 200 nm Ag was deposited on top of the polymer by electron beam evaporation.

The specular reflectance at an incident angle of 8° was measured with a spectrophotometer (PerkinElmer Lambda 1050, unpolarized illumination). In addition, the total reflectance was measured with the integrating sphere module of the spectrophotometer. The spectral diffraction efficiency was measured at the diffraction orders of m=0, ±1, and ±2 by variable angle measurement technique, where the sample is illuminated by white light beam at an incident angle of 8°. The diffracted light is collected with an optical fiber connected to a spectrophotometer at variable angles from 8° to 48°.

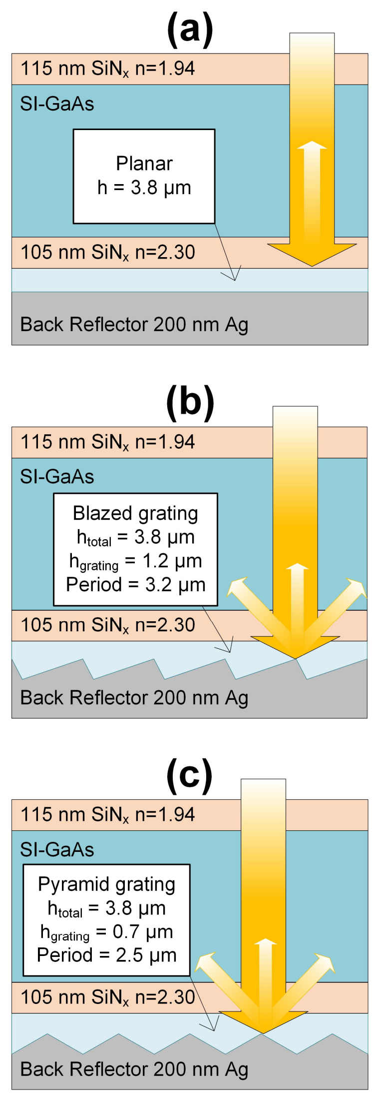

Fig. 1. Schematic drawing of the planar (a), blazed grating (b) and pyramid grating (c) studied experimentally.

III. RESULTS AND DISCUSSION

SEM images of the blazed grating and the pyramid grating are presented in Fig. 2. The SEM image of the pyramid grating is from the back surface of the sample with Ag, whereas the blazed grating image is the cross-section of the polymer without Ag. The pyramid grating shows a flattened peak, which was observed in the Si master, indicating that the transfer of the pattern was successful.

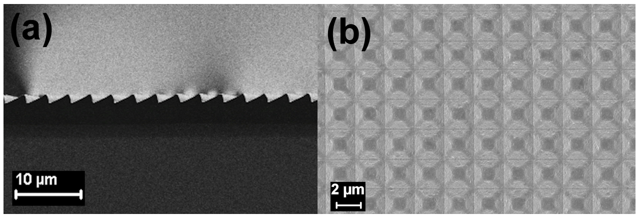

Fig. 2. SEM images of the blazed grating (a) and the pyramid grating (b).

A. Reflectance Results

The reflectance measurements and simulations of the blazed grating and the pyramid grating are presented in Fig. 3. The difference between the total and the specular reflectance represents the diffused reflectance, which is presented as a green double-headed arrow. Both gratings have a rather low specular reflectance, which is a signature of high diffraction efficiency. However, the blazed grating showed a reduced total reflectance both in the measurements and in the simulations compared to the pyramid grating. This refers to some additional losses in the blazed grating structure, which potentially arise from the surface plasmon resonance (SPR) in the Ag reflector.

For both the blazed grating and the pyramid grating, the simulated total reflectance is approximately 10 percentage points lower than the measured due to the simulations are probably overestimating the losses in the structured Ag reflector. In fact, the calculated distribution of absorbed photon density (not shown here) indicated large optical loss at the polymer/metal interface of patterned structures, whereas marginal optical loss were observed in the reflector of the planar structure. The lower loss observed in experiments could be attributed to a reduction of the SPR effect owing to the flattening of the fabricated structures with respect to the nominal ones. Despite this, a good agreement between the measured and the simulated results is achieved, supporting the conclusions of the diffractive properties of the structures.

In addition, the single-layer ARC has the local minimum reflectance at the wavelength of 900 nm. Consequently, part of the light is reflected from the surface of the sample without reaching the diffraction grating, increasing the measured specular reflectance. The simulated reflectance of the front surface is presented in Fig. 3(b).

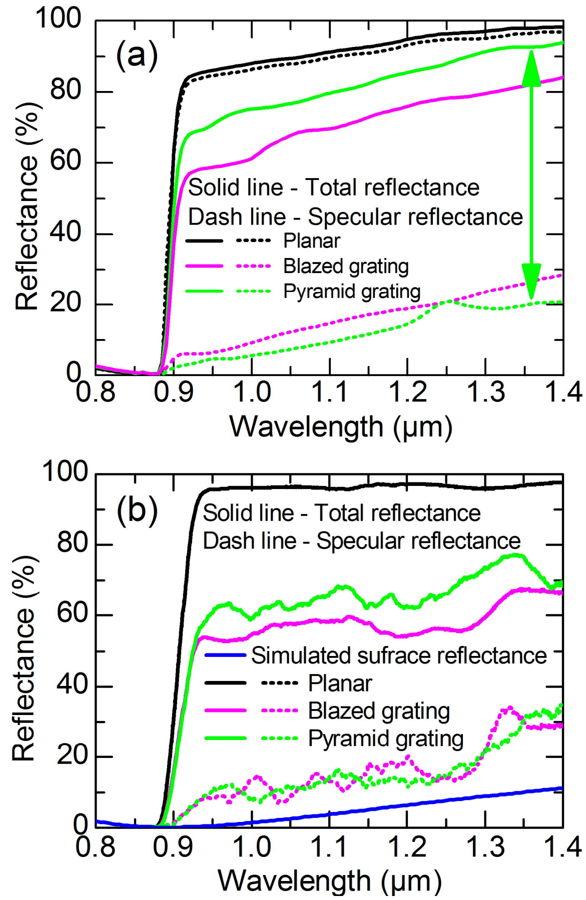

Fig. 3. Measured (a) and simulated (b) reflectance results.

B. Diffraction Efficiency Results

The diffraction efficiency results for the blazed grating and the pyramid grating are presented in Fig. 4. For the pyramid grating, the measured second diffraction order was not observed, because the measurements were performed at up to 48° angle where m=2 is not present. However, according to the simulations, the power coupling also occurs to the second diffraction order. The diffraction orders for the pyramid structure are equivalent for all directions due to the symmetric 3D structure. For the blazed grating, the asymmetric structure leads to the differentiation of the m=±1 and m=±2 diffraction orders. Significant coupling to the first two diffraction orders is observed. In addition, the diffraction efficiency simulations are supporting the measurements for both gratings, even though they are not perfectly matching.

Furthermore, the measured diffraction efficiency of the zero order for both gratings is in agreement with the specular reflectance measurements presented in Fig. 3.

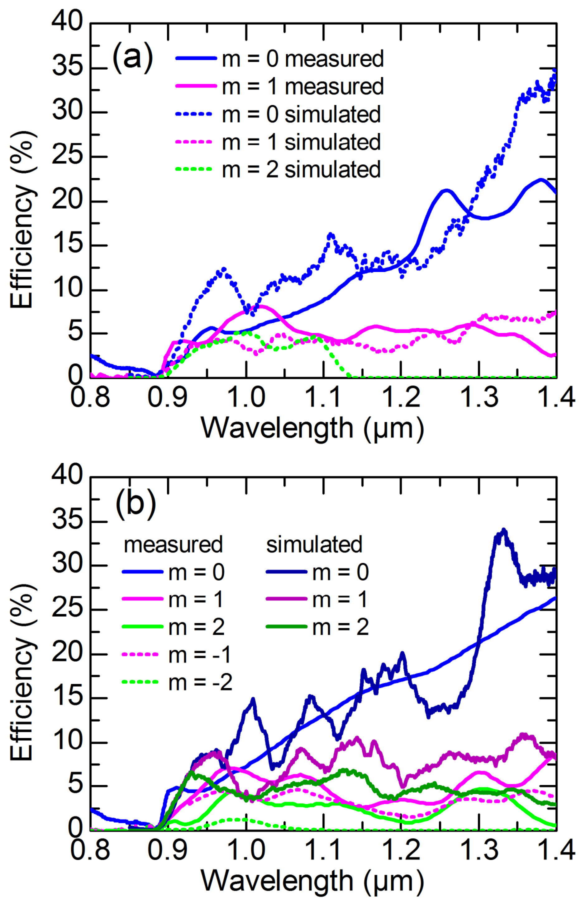

Fig. 4. Measured and simulated diffraction efficiency results for the pyramid grating (a) and the blazed grating (b).

IV. Summary of the Work

Structured back reflectors with the blazed grating and the pyramid grating for the light trapping in the III-V solar cells were fabricated and analyzed. For both structures, efficient diffuse reflectance was observed enabling increased absorption and current generation in thin-film solar cells. The pyramid grating showed the highest diffraction of light in the wavelengths corresponding to the absorption in InAs/GaAs QDs and the GaInNAs solar cells. Simulations predict a photocurrent density of 0.024 mA/cm^2 per layer in the substrate based solar cell, which increases to 0.095 mA/cm^2 per-layer in the thin-film solar cell integrating the pyramid grating. Thus, the light trapping design enables four times higher current density from the quantum dots, a worth-to enhancement when considering the effort needed to achieve the corresponding photocurrent by means of epitaxial growth of numerous QD layers.

The proposed microstructures are applicable to other type of solar cells by modifying the dimensions of the gratings to match the required wavelength range.

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