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Light trapping structures for radiation hardness enhancement of space solar cells

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A B S T R A C T

In an effort to reduce the radiation degradation of triple-junction solar cells, imbedded photon management is investigated as a means for reducing the middle subcell thickness while maintaining output. The (In)GaAs subcells of the conventional lattice-matched InGaP/(In)GaAs/Ge triple-junction solar cells with back-side light-reflecting structures were simulated. Subcells with two-dimensional dielectric moth-eye reflection grating show promising results: more than 70% of incident in-band light is reflected into the non-zero diffraction orders which allows the thickness of the subcell to be decreased from 3.5 to 1.25 μm. This reduction of the subcell thickness substantially enhances the radiation hardness of the multi-junction solar cell.

1. Introduction

Solar cells (SCs) used for space applications suffer from power losses due to the radiation environment they are exposed to on-orbit. Energetic protons and electrons continuously bombard the cell, resulting in increased point defect formation and commensurate reduction of minority carrier diffusion length (MCDL) (a review of such defects introduced in GaAs SCs by radiation and changes in MCDL is given in [1]). Cell designers must take this fact into consideration and optimize their cell design to maximize its performance at end of life (EOL) (in other words, after a given radiation dose). This consideration limits the ultimate performance that can be achieved, as there are trade-offs that must be made in the design, such as thinning the top subcell to allow for excess current generation in the radiation-soft middle subcell of a triple-junction solar cell (TJSC).

Given that the reduced MCDL is the primary cause of power loss at EOL, an obvious choice is to reduce the thickness of the radiation-soft subcell sufficiently to minimize the impact of a reduced MCDL. In the case of a typical (In)GaAs middle subcell in a TJSC, this would mean reducing the thickness below 1 μm to minimize the impact for the reduced MCDL under a typical 10^{15} cm^{-2} fluence of 1 MeV electrons [2].

However, given the optical absorption coefficient of (In)GaAs this would result in insufficient current generation. The only means to recover losses in photocurrent caused by thinning of the SC is to enhance absorption of the incident light. One of the ways to enhance light absorption is to increase the propagation length of photons by trapping them within SC [3]. There are two approaches to light trapping in SCs: a traditional one is based on geometric (or ray) optics and the second one - on wave optics. Within first traditional approach effective optical path length enhancement can be realized by texturing surface of Si by chemical wet etching [4]. Unfortunately, the well-developed texturing features of such light trapping is tens of microns and thus cannot be applied to SCs with sub-micron thicknesses. This is why for thin-film SCs the second approach is applied. Distributed Bragg reflectors (DBR) on back surface of SC [5,6] and diffraction gratings with sub-micron features on front, back, or both surfaces of SC [7–18] are used to trap light in sub-micron thin SCs. We are mainly interested in using reflection gratings as back-side reflectors. Ping Sheng was first who suggested in 1983 to use diffraction grating as a back-side reflector in thin film SCs [7]. In 1995 Heine and Morf [8] and in 2000 Zaidi and co-authors [9] experimentally investigated crystalline Si SCs with reflection diffraction gratings. Since then "myriad photonic structures" with sub-micron features were suggested [10]. Excellent reviews on light trapping exploiting sub-micron structures are given in [11,12].

The DBRs reflect light only specularly and therefore the maximum optical path length enhancement is equal 2. In order to have higher optical path length enhancement the reflection diffraction gratings are used to reflect incident light into angles greater than the angle of total internal reflection. The amount of photons reflected into specific angles of diffraction (or into the orders of diffraction) is defined by the diffraction efficiency. The diffraction efficiency of gratings itself depends on several parameters such as: 1) period, 2) duty cycle, 3) aspect ratio, 4) dimensionality, and 5) symmetry. For simplest one-dimensional (1D) lamel1ar and blaze gratings their optimal periods, duty cycles, and aspect ratios are well established [13–15]. The diffraction efficiency of gratings critically depends on their dimensionality and symmetry [12].

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It is widely recognized that asymmetrical [8,9] and two-dimensional (2D) bi-periodic gratings [12,16–18] are superior in light absorption enhancement than 1D ones.

In this work, we examine 2D dielectric moth-eye diffraction grating and distributed Bragg reflector (DBR) that may be integrated into the architecture of lattice-matched TJSC to allow for increased optical absorption in the subcell needing to be thinned to accommodate the reduction in MCDL. In the generic case, we consider the (In)GaAs middle subcell of a standard TJSC, given that this subcell is the weakest in terms of its radiation hardness and here we focus on moth-eye diffraction grating used as back-side reflector to increase path length of photons within solar cell, especially of photons near the band edge of (In)GaAs.

2. Optical simulation

The design of a TJSC includes a number of important components, one of which is the anti-reflection coating (ARC). The design of an ARC for a TJSC is more challenging than for a single-junction solar cell since the spectral range of light absorption is wider. The lattice-matched $In_{0.49}Ga_{0.51}P/In_{0.01}Ga_{0.99}As$/Ge solar cell absorbs light in the range from 0.3 μm to 1.8 μm. The problem of choosing an appropriate ARC is simplified because the short-circuit current in the bottom Ge subcell is significantly higher than in InGaP and (In)GaAs subcells. Thus, the critical spectral region for an ARC design becomes much smaller: from 0.3 μm to 0.9 μm. An appropriate ARC for this spectral region is a double-layer anti-reflection coating (DLAR) such as MgF_2/ZnS or SiO_2/Ta_2O_5 [19]. Simulations done using commercial Lumerical software show that the light reflectance from MgF_2/ZnS DLAR is very low [20].

One of the characteristics that defines reflectance from an ARC is its solar-weighted reflection (SWR) [21] which is defined as

$$SWR = \frac{\int_{\lambda_1}^{\lambda_2} \lambda\ R\ (\lambda)\ P_{\mathrm{AM0}}(\lambda)}{\int_{\lambda_1}^{\lambda_2} \lambda\ P_{\mathrm{AM0}}(\lambda)} d\lambda. \tag{1}$$

Here $R(\lambda)$ is the wavelength-dependent surface reflectance and $P_{\mathrm{AM0}}(\lambda)$ is the AM0 solar power spectral density. In the spectral range from $\lambda_1 = 0.3$ μm to $\lambda_2 = 0.65$ μm the SWR from the surface covered by MgF_2/ZnS DLAR is about 1.5%, which is close to the values from [19]. In the spectral range from 0.3 to 0.9 μm it is about 3% which corresponds to the results from [21].

The second important component of TJSC design is the thickness of the InGaP subcell. Depending on its thickness, the top subcell can be made current-rich or current-poor in comparison with the middle (In)GaAs subcell. As it was mentioned earlier, the middle subcell is made current-rich because of its weak radiation hardness. Thus, the current of a typical TJSC is limited by the current of the top subcell at the beginning of life (BOL). In such a configuration, its thickness is reduced to 600 nm. The thickness of the middle subcell is large enough to provide higher current than in the top subcell at BOL. The numerical integration of the external quantum efficiencies (EQE) of the $In_{0.49}Ga_{0.51}P/In_{0.01}Ga_{0.99}As$ tandem SC (the schematic parameters of the tandem SC are described in [20]) gives us the values of the short-circuit current density, J_{SC}, of two subcells equal approximately to 17 mA/cm^2 and 18 mA/cm^2, respectively. Here, we assumed that the internal quantum efficiencies (IQE) of both subcells are of 100%. As is seen from Fig. 1, the photocurrent in the top cell is mostly generated by the absorption of light in the spectral region from 0.3 to 0.65 μm, and in the middle cell - from 0.65 to 0.9 μm. This fact makes simulation of multi-junction SCs much easier. Instead of simulating the whole structure, the optical and electrical models of the constituent single-junction SCs can be analyzed.

In order to find *J-V* characteristics of single-junction cells optical simulations were carried out using Lumerical FDTD SOLUTIONS tool which solves three-dimensional (3D) Maxwell's equations. The photogeneration data obtained by these optical simulations were used as an input for electrical simulations by Lumerical DEVICE CT tool, which solves 3D Poisson and 3D drift-diffusion equations and allows to find directly current-voltage characteristics of the SC [22].

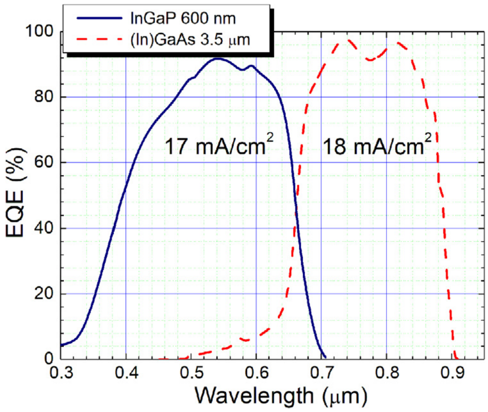

Fig. 1. The EQE of the simulated InGaP/(In)GaAs tandem solar cell with MgF_2/ZnS DLAR.

The optical model of the simulated single-junction SC includes a plane wave source which is situated over the DLAR coating. Periodic boundary conditions in the *x*, *y*-directions and perfectly matched layer (PML) condition in the *z*-direction substantially simplifies the simulation of the device. These assumptions allow full 3D simulations (even using desktop computer) of the structures that cannot be reduced to 2D models.

In the undertaken simulations the following single-junction SCs were analyzed: 1) 600 nm thick InGaP cell, 2) (In)GaAs cells with different thicknesses ranging from 3.5 to 1.25 μm (further, we will consider 3.5 μm thick (In)GaAs cell as a reference cell 1), 3) (In)GaAs cell with moth-eye grating (Figs. 2(a), (b)), and 4) (In)GaAs cell with DBR (which we will consider as reference cell 2) (Fig. 2(c)). The optimal parameters of moth-eye grating as back-side reflector were chosen using the following assumptions. In the case of 1D symmetrical gratings light is trapped in SC if the chosen period of grating satisfies the following inequality:

$$\Lambda < \frac{\lambda}{m} \tag{2}$$

where λ is the wavelength of light in vacuum and m is the number of diffracted order [23]. In the published literature the average aspect ratio, h/Λ (height/period), for both 1D and 2D gratings is around 0.25 [5,7,18,24–26] and for 2D gratings the highest reflection can be achieved for the ratio Λ_y/Λ_x around 1.4 [5]. Having these guidelines in mind the search for optimal moth-eye grating periods Λ_x and Λ_y was done for interval 400–1200 nm, for the height of grating h_1 in the interval 150–600 nm, and for the height of dielectric layer h_2 in the interval from 100 to 500 nm. The undertaken simulations defined the most effective grating: it is an asymmetric grating which resembles an array of closely-packed half-ellipsoids with height $h_1 = 360$ nm and length of semi-axes $a = 500$ nm and $b = 800$ nm (the periods Λ_x and Λ_y coincide with length of semi-axes a and b.) The height of dielectric layer, where these half-ellipsoids are placed, is $h_2 = 250$ nm. Such moth-eye gratings can be fabricated using several wafer-scale technologies such as nanoimprinting [27], photolithography [28] or using spin-coated silica colloidal monolayers as etching masks [29].

All SCs were illuminated by normally incident light from FDTD plane wave source with a Gaussian-like pulse. The reflection of incident light by moth-eye grating was very high: more than 70% of incident light was reflected into non-zero diffraction orders and the total reflection is close to 100% as it is seen in Fig. 3(a) and (b). The angles of reflection of non-zero orders were greater than the angle of total internal reflection (~ 16°) (see Fig. 3(a)). Thus, the optical path length enhancement should be much greater than 2 since even reflection only