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PAPER

Light absorption enhancement and radiation hardening for triple junction solar cell through bioinspired nanostructures

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Abstract

Multi-junction solar cells constitute the main source of power for space applications. However, exposure of solar cells to the space radiation environment significantly degrades their performance across the mission lifetime. Here, we seek to improve the radiation hardness of the triple junction solar cell, GaInP/Ga(In)As/Ge, by decreasing the thickness of the more sensitive middle junction. Thin junctions facilitate the collection of minority carriers and show slower degradation due to defects. However, thinning the junction decreases the absorption, and consequently, the expected photocurrent. To compensate for this loss, we examined two bioinspired surface patterns that exhibit anti-reflective and light-trapping properties: (a) the moth-eye structure which enables vision in poorly illuminated environments and (b) the patterns of the hard cell of a unicellular photosynthetic micro-alga, the diatoms. We parametrize and optimize the biomimetic structures, aiming to maximize the absorbed light by the solar cell while achieving significant reduction in the middle junction thickness. The density of the radiation-induced defects is independent of the junction thickness, as we demonstrate using Monte Carlo simulations, allowing the direct comparison of different combinations of middle junction thicknesses and light trapping structures. We incorporate the radiation effects into the solar cell model as a decrease in minority carrier lifetime and an increase in surface recombination velocity, and we quantify the gain in efficiency for different combinations of junction thickness and the light-trapping structure at equal radiation damage. Solar cells with thin junctions compensated by the light-trapping structures offer a promising approach to improve solar cell radiation hardness and robustness, with up to 2% higher end-of-life efficiency than the commonly used configuration at high radiation exposure.

1. Introduction

Photovoltaic solar panels are the main power source for Earth-orbiting satellites and have proven their capabilities up to the orbit of Jupiter, with Juno [1] being the solar-powered mission that operated the furthest from the Sun to date. Solar cell efficiency and mass are of great interest for space applications, because improvements to either result in significant reduction in in-orbit solar array costs [2]. Multi-junction cells, achieving superior efficiency than their single-junction counterparts, are the norm for powering space vehicles and satellites [3]. However, the high efficiency of the multi-junction cells as produced (beginning-of-life, BOL) is half of the story;

the end-of-life (EOL) efficiency has also to be considered, which takes into account the performance degradation during the lifespan of the mission. The space radiation environment constitutes a significant contributor to the aforementioned degradation. Therefore, radiation hardness is an additional and decisive characteristic when selecting solar cells for space operations [4].

The common practice to diminish the radiation-induced effects on solar cells is to place a protective cover glass on their outer surface [5]. The cover glass 'slows down' the spectrum of incoming particles, lessening the damage. A complementary approach is to design the cell to be intrinsically more resilient to radiation. Thinning of the cell junctions facili-

tates the diffusion driven collection of minority carriers, making the cell less sensitive to the introduction of defects [6–11]. On the downside, thinner junctions absorb less light than their thicker counterparts, which is accompanied by losses on the generated photocurrent. Therefore, the light absorption on thin cells must be enhanced by engineering the optical structure beyond the single pass absorber. Enhanced absorption can be achieved by adding flat mirrors [9, 10] or nanostructures [12, 13] in the back of the cell, both of which increase the optical path. However, increasing the absorbed light is more challenging for multi-junction than for single junction cells; the optical structure has to be placed behind the junction which absorbs the least light, otherwise the subsequent junctions—having a lower bandgap—will absorb the incoming photons. This problem has restricted the strategies for compensating the thinning of the middle junction to using distributed Bragg reflectors (DBRs) between the middle and the bottom subcells [4, 8, 14]. These reflective elements are employed in conjunction with a front surface antireflective coating (ARC). Replacing the ARC with a light trapping structure (LTS) that bends the incident light and increase the coupling to the guided modes of the junctions offers the possibility to further compensate for this optical loss [15–22]. Although the current work focuses on space photovoltaics, the described light trapping schemes might also contribute to make III–V materials cost competitive in terrestrial applications by reducing the thickness, and consequently the cost, of III–V solar cells [12, 23, 24]. Similar efforts to reduce the cost of multi-junctions using photonics are currently under way [25].

The problem of maximizing light harvesting or minimizing surface reflectance has been tackled by several living organisms, which have developed elaborate photonic micro- or nanostructures [26, 27]. Specialized nanopore arrays on the transparent hard cell wall of diatoms, a family of single-cell micro-alga, has been shown to act as a photonic crystal that focuses and confines light [28–31], thus increasing the photosynthetic yield. Furthermore, moths and several butterfly species have evolved an array of protuberances on the cornea of their compound eyes (termed the corneal nipple array), which considerably reduces the reflectance at the surface of their eyes [32–34]. The diatom and the moth-eye structures are well described in the literature and are suitable as alternatives to the widely-used bilayer ARC; therefore, in the following we considered both structures.

The use of a bioinspired nanostructure as a means to improve the light absorption of solar cells has been previously considered, both for single [35, 36] and multi-junction solar cells [37–41]. The current paper examines an alternative application for the LTS; as a way to design thin junction solar cells with enhanced

radiation hardness, with minimal sacrifice in efficiency. We select a reference triple junction solar cell design that includes a DBR between the middle and bottom junctions [4] and determine the geometry of the bioinspired LTS that achieves the maximum BOL efficiency for a range of middle junction thicknesses. Then, we select the LTS geometry and junction thickness pairs that achieve comparable BOL efficiency in comparison to the reference solar cell and contrast their degradation at various radiation exposures. To this extend, we employed Monte Carlo simulations to quantify the radiation-induced defect density on the semiconductor materials and translate the changes in defect density into efficiency deprecation. Finally, we examine the trade-off between BOL and EOL efficiency.

The paper is organized as follows: in section 2 we present the description and modeling of the solar cell. Specifically, we introduce the solar cell and the LTS geometries, along with their parametrizations in section 2.1. We describe the solar cell model which allows us to estimate the cell efficiency in both the case of a pristine or an irradiated cell in sections 2.2 and 2.3, respectively. The modeling of the radiation damage on semiconductor material is detailed in section 2.4. The optimization procedure that allows us to determine the LTS parameters is outlined in section 2.5. The numerical results are presented in section 3 and further discussed in section 4. Section 5 presents the conclusions.

2. Methods

2.1. Solar cell and light trapping structures

We consider a prototypical triple junction space solar cell, based on the Azur 3G30C model [4]. The junctions from top to bottom are manufactured out of GaInP, InGaAs and Ge, as shown in figure 1(a), with band gaps at 1.9 eV, 1.4 eV and 0.66 eV. The material compositions were determined by matching the ternary lattice to the Ge substrate and is summarized in table 1. The ARC or the LTS is placed between the solar cell and the protective cover glass. The thickness of the top and middle junctions were determined from [4, figure 7] to be 0.60 μm and 1.87 μm respectively. In the actual 3G30C solar cell, a DBR is located in between the middle and bottom junctions. The DBR increases the photon recycling by reflecting the photoluminescence of the middle junction. For the sake of simplicity, we have abstracted the DBR layer by a selective perfect mirror (SPM) characterized by a perfect reflectance at wavelengths shorter than the wavelength that corresponds to the middle junction bandgap and perfect transmittance otherwise. Although the design of the DBR is not trivial, it can be isolated from the design of the LTS.

For the LTS, the underlying absorbing substrates have dissimilar optical properties from the ones found

Figure 1. Schematic of the solar cell and the antireflective structures. (a) Layers of the triple junction solar cell. (b) Bilayer ARC. (c) Unit cell of the moth-eye LTS. (d) Unit cell of the diatom LTS.

Table 1. Composition of layers used in the optical simulations, layer name and references to their optical properties.

Material	Layer	Reference
Al_2O_3	Bilayer ARC	[43]
TiO_2	Bilayer ARC	[44] ^a
Si_3N_4	Diatom/moth-eye LTS	[45]
$\text{Al}_{0.5}\text{In}_{0.5}\text{P}$	Moth-eye LTS	[46]
$\text{Ga}_{0.51}\text{In}_{0.49}\text{P}$	Window	[47, 48]
$\text{In}_{0.01}\text{Ga}_{0.99}\text{As}$	Top junction	[45] ^b
Ge	Middle junction	[49]
	Bottom junction	[49]

^aProperties for polycrystalline anatase.

^bOptical properties of GaAs were used.

in nature and the spectrum of interest differs, therefore we have to redesign the structures to fit the requirements of the solar cell. The geometries of the LTS were parameterized and optimized, with the goal to achieve maximum solar cell efficiency. We compare the LTS performance to a reference ARC, which consists of two layers made of Al_2O_3 and TiO_2 with thicknesses h_1 and h_2 as shown in figure 1(b).

The moth-eye structure is abstracted as a square lattice of cones, similar to [39, 40], with lattice constant a_m . The unit cell is shown in figure 1(c). Each cone is described by the radius r_m and height h_m and it is placed on top of the base layer of thickness h_b , which accommodates the guided modes that participate in the light trapping. The cones and the base layer are made of TiO_2 . A spacer layer of thickness h_s , made out of Si_3N_4 and placed between the base and the solar cell, adds an additional degree of freedom for the optimization.

The diatom LTS is based on the hard cell wall (frustule) of the diatom species *Coscinodiscus wailesii* described in [38]. The frustule of the *C. wailesii* is composed of three layers decorated by a hexagonal lattice of pores: the cribellum (top), cribrum (middle) and areola (bottom). The cribellum pore size is much smaller (around 50 nm) than the typical wavelength of light; simulations of the individual layers have shown that the cribellum plays a minor role in the light enhancement and can be omitted [38]. In the present study, the diatom structure consists of two layers made of TiO_2 , resembling the areola and the cribrum, as shown in figure 1(d). The unit cell of the areola layer is a rectangle with sides a_a and $\sqrt{3}a_a$, perforated with holes of radii r_a . The cribrum consists of an identical unit cell, which is scaled down by an integer factor in comparison to areola $a_c = a_a/n_c$, $n_c \geq 2$, $n_c \in \mathbb{N}$. We denote the radius of the holes in the cribrum layer by r_c . The two layers are displaced relative to each other by the displacement vector

$r_0 \in \mathbb{R}^2$; for $r_0 = (0, 0)$ the centers of all the areola holes coincide with hole centers of the cribrum. We denote the thickness of the areola and the cribrum layers by h_a and h_c respectively.

2.2. BOL solar cell model

The propagation of light through the LTS structure and the solar cell was simulated using the Fourier modal method, also known as the scattering matrix method, a technique applicable to 3D layered structures with 2D periodicity. The absorption of wavelength λ at junction $i \in \{\text{GaInP}, \text{InGaAs}, \text{Ge}\}$, $a_i(\lambda)$, is computed by solving the scattering matrix for each layer, which connects the incoming light to the Poynting flux entering and exiting the layer bounds [42]. We sampled a_i at 500 wavelengths between 350 nm and 1900 nm. For all optical simulations, we assume that the cover glass layer has a constant refractive index of $n_{\text{cover}} = 1.4$. For the remaining materials we consider a complex dispersive refractive index (see table 1). We include in the optical simulations the window layer of the top junction, an AlInP layer 15 nm thick that prevents the recombination of carriers at the top interface; the window layer is in direct contact with the LTS and therefore critical to the optical performance of the LTS due to the high refractive index contrast that introduces. Subsequent window and back surface field layers have a small refractive index contrast and have been lumped in the respective junctions. We model the SPM by increasing the dielectric constant of the Ge substrate to a very large value ($\sim 10^9$) for photon energies > 1.4 eV, i.e. the gap of the middle junction. This creates a perfect dielectric mirror due to the high refractive index contrast. The number of basis functions for SSM was set to 51 per unit cell; for the diatom it translates to $51n_c$.

Given $a_i(\lambda)$, we estimate the BOL efficiency of the solar cell, η_0 , by considering an equivalent electrical circuit. Each junction is abstracted as a current source, which accounts for the junction photocurrent, with a radiative coupling component and an ideal diode connected in parallel. At BOL, we make the simplifying assumption of complete photocarrier collection, which is reasonable for high quality III–V solar cells. Moreover, this definition of BOL efficiency serves as an informative figure of merit for the optical performance of the cell. Thus, the photocurrent density at junction i becomes

$$J_{\text{ph},i} = \frac{q}{hc} \int_0^{\lambda_{g,i}} a_i(\lambda) \Phi_\lambda(\lambda) \lambda d\lambda, \quad (1)$$

where q is the charge of the electron, h is the Planck constant, c is the speed of light and $\lambda_{g,i}$ is the wavelength that corresponds to the bandgap of the junction. The spectral irradiance of the incident light, $\Phi_\lambda(\lambda)$, is computed using the AM0 spectrum. We include a radiative coupling model, which increases the photocurrent of the junction, if there is excess current in the junction above. The increase in current of

the i th junction is computed using the recursion [50]

$$J_i = \begin{cases} J_{\text{ph},i} + \beta \text{ERE}(J_{i-1} - J) & J_{i-1} > J \\ J_{\text{ph},i} & \text{otherwise} \end{cases}, \quad (2)$$

where J is the common current flowing through the cell, ERE is the external radiative efficiency and β is the radiative coupling parameter. No radiative coupling takes place in the first junction, namely $J_{\text{GaInP}} = J_{\text{ph,GaInP}}$, as the emission from the bottom cells is not absorbed by the higher bangap material of the top junction. Following [51], we assume constant values for $\beta = 11$ and $\text{ERE} = 0.01$ and we compute the reverse saturation current density as

$$J_{0,i} = \gamma_i J_{\text{db},i} / \text{ERE} \quad (3)$$

$$J_{\text{db},i} = \frac{2\pi q (kT)^3}{h^3 c^2} \left[\left(\frac{E_{g,i}}{kT} + 1 \right)^2 + 1 \right] e^{-E_{g,i}/kT}, \quad (4)$$

where k is the Boltzmann constant, T the absolute temperature of interest and $E_{g,i}$ is the band gap at the i th junction. The coefficient $\gamma_i = 1 + \beta$ for junctions with the ideal SPM (top and middle in the present study) and $\gamma_i = 1$ for the rest. The cell voltage is the sum of the voltage of each junction

$$V = -RJ + \sum_i \frac{kT}{q} \ln \left(\frac{J_i - J}{J_{0,i}} + 1 \right) \quad (5)$$

with the series resistor $R = 4 \times 10^{-5} \Omega \text{ m}^2$ lumping the contribution of all internal losses. We determine the maximum power per unit area numerically, $P_{\text{max}} = \max(VJ)$ and compute the BOL efficiency as:

$$\eta_0 = \frac{P_{\text{max}}}{\int \Phi_\lambda d\lambda}. \quad (6)$$

2.3. EOL solar cell model

To connect the radiation exposure to the cell efficiency, we expanded the solar cell model to account for defect-induced changes in the semiconductor properties. Specifically, we assume that the exposure to radiation decreases the minority carrier lifetime from the initial value of $\tau_{0,a}$ to the value τ_a and increases the recombination velocity at the junction interface from $S_{0,a}$ to S_a . The subscript a can refer either to electrons, n, or holes, p, depending on the type of doping. The relation of τ_a and S_a with the radiation exposure is described in detail in the subsequent section 2.4. For the analysis, we neglect the radiation damage on the top and bottom junctions because the deterioration in solar cell performance is dominated by the degradation of the middle junction [52–54]. For the top and middle junctions we assume complete photocarrier collection.

The effect of the reduced lifetime of the solar cell efficiency is accounted for by expanding the BOL model to include 1D diffusion dynamics. Appendix A describes the 1D diffusion model and proposes an

analytical solution. Two main adjustments are introduced in comparison to the complete photocarrier collection assumption. First, the photocurrent is limited by the collection probability, P_c , which modifies (1) as

$$J_{\text{ph,InGaAs}} = \frac{q}{hc} \int_0^{h_{\text{InGaAs}}} \int_0^{\lambda_g} P_c(x) \alpha(\lambda, x) \times \Phi_\lambda(\lambda) \lambda d\lambda dx, \quad (7)$$

where x is the depth in the junction measured from the top, h_{InGaAs} is the thickness of the middle junction and $\alpha(\lambda, x)$ denotes the derivative of the Poynting flux with respect to x , normalized by the flux entering the cell. Second, the junction saturation current increases due to the diffusion dynamics by the term J_{d0} as

$$J_{0,\text{InGaAs}} = \gamma J_{\text{db,InGaAs}}/\text{ERE} + J_{d0}. \quad (8)$$

The calculation of the radiative coupling is performed as before, with the difference that $J_{\text{ph,InGaAs}}$ is calculated using (7). The EOL efficiency, η , is computed analogously to (6).

For the undamaged cell, we assume that $\tau_{0,a}$ is dominated by the radiation recombination lifetime and depends on the dopant concentrations as $\tau_{0,n} = (BN_a)^{-1}$ and $\tau_{0,p} = (BN_d)^{-1}$, with N_a and N_d being the acceptor and donors concentrations respectively. The previous relations have been derived under the assumption that the majority carrier concentrations are approximately equal to the respective dopant concentrations.

2.4. Radiation damage modeling

The impact of radiation on τ_a and S_a was assessed using Monte Carlo simulations. As high energy particles traverse through a material, they lose energy that falls into one of two categories [55, 56]: (a) electronic energy loss, which includes interactions of the projectile with the bound electrons of the medium and (b) nuclear energy loss, which accounts for the collisions between the projectile and the atoms of the medium. Semiconductor degradation is connected to a portion of the nuclear energy loss referred to as the nonionizing energy loss (NIEL). The deposited NIEL disturbs the nuclei off the semiconductor lattice, leading to the appearance of atomic displacements. Specifically, the energy deposited on atomic displacement per unit mass of the semiconductor, termed the damage dose D_d , has been directly connected to the Frenkel pairs (FP, vacancy–interstitial pairs) density [55, 57].

The damage dose induced by a radiation source with spectral fluence ϕ (number of particles per area per energy) is equal to

$$D_d = \int \phi(E_p) \frac{dE_{\text{de}}(E_p)}{d\chi} dE_p, \quad (9)$$

where E_p is the energy of the incoming particle and $dE_{\text{de}}/d\chi$ is the displacement mass stopping power,

namely the energy deposited on atomic displacements per unit path length normalized by the material density. Semiconductor atoms recoil with energy E_r after interaction with the particles and permanent defects occur if E_r is greater than a material dependent displacement threshold energy E_d . Even if $E_r \geq E_d$, only part of E_r contributes to stable defect formation, captured by the Lindhard partition $L(E_r)$, whereas the rest is dissipated as lattice vibrations [58, 59]. Hence, the mass stopping power for all interaction is given as a function of E_p as

$$\frac{dE_{\text{de}}(E_p)}{d\chi} = \frac{N_A}{A} \sum_k \int_{E_d}^{E_M} E_r L(E_r) \frac{d\sigma_k(E_p, E_r)}{dE_r} dE_r, \quad (10)$$

where N_A is the Avogadro number, A is the atomic weight of the medium, $d\sigma_k/dE_r$ is the differential cross section of the k th reaction and E_M is the maximum recoil energy achievable by E_p . The summation is taken over all possible reactions between the projectile and the semiconductor atoms. For protons and electrons interactions with the lattice atoms occur through Coulomb scattering. Additionally, for protons with energies above ~ 10 MeV, nuclear elastic and inelastic reactions has to be taken into account [60]. Equation (10) is valid for simple substances, whereas for compound materials Bragg's rule applies; the mass stopping power is calculated as the sum of the mass stopping power of each material weighted by its mass fraction [52].

We employed the Geant4 software [61] to assess the impact of thinning the middle junction on D_d (see appendix B for simulation details). During the simulations, we track the particle path and record E_r of primary knock-on atoms (PKA, atoms that were displaced due to interaction with the energetic particles) in the middle junction. We set $E_d = 21$ eV, value that has been proposed for GaAs [52, 54], and use the formulation in [58] for $L(E_r)$. We approximate (9) as

$$D_d = \frac{\phi_0}{\phi m_s} \sum_{n=1}^N E_{r,n} L(E_{r,n}), \quad (11)$$

where n is the event index, N is the total number of recorded PKA events, m_s is the mass of the middle junction and ϕ_0 is a reference fluence. The Frenkel pair concentration is computed by means of the modified Kinchin–Pease formula [55]

$$\text{FP} \sim \frac{D_d \rho_s}{E_d}, \quad (12)$$

where ρ_s is the density of the middle junction material. We treat quantities that are computed from the Monte Carlo simulations as random variables and report the mean values with the 99% confidence interval (CI). For D_d , the mean value is computed from (11) and the variance from

$$\sigma_D^2 = \left(\frac{\phi_0}{\phi m_s} \right)^2 \sum_{m=1}^M [E_{r,m} L(E_{r,m})]^2. \quad (13)$$

The distribution of D_d is assumed normal due to the large number of recorded events, similar to [62].

The FP density is connected to τ_a as follows: the increase in the inverse of the lifetime has been shown to be proportional to FP [55], and as a consequence of (12) is also proportional to D_d . Therefore, after irradiation

$$\frac{1}{\tau_a} = \frac{1}{\tau_{0,a}} + K_a D_d, \quad (14)$$

where K_a is the damage coefficient. We note that (14) is equivalent to the commonly used formula that connects the increase in the inverse of the lifetime to ϕ [53, 63]. For the surface recombination velocity, we use the linear relation proposed in [63]

$$S_a = S_{0,a} + K_{Sa} D_d, \quad (15)$$

where K_{Sa} is the interface damage rate.

2.5. Geometry optimization

For optimizing the LTS geometries, we are interested in attaining the maximum efficiency, η , while keeping the thickness of the middle junction, h_{InGaAs} , to a minimum. These requirements form a multi-objective optimization problem:

$$\begin{aligned} \min_{z_p} & (-\eta_0, h_{\text{InGaAs}}) \\ \text{s.t. } & z_p \in Z, \end{aligned} \quad (16)$$

where z_p is a vector holding the parameters of the LTS geometry. The set of allowable solutions, Z , incorporates the constraints on the parameters that encode meaningful solutions. We note that Z can be extended to include additional constraints, like maximum or minimum allowable dimensions dictated by a given fabrication method. The solution to (16) is intended to find the set of points, referred to as the Pareto front, that cannot be further improved without sacrificing at least one of the objectives.

We approximate the Pareto front using the software package *pygmo* [64]. We employed the widely used evolutionary algorithm NSGA-II, which imitates the process of natural selection. Every distinct LTS geometry is seen as an ‘individual’, which is entirely described by its ‘chromosome’ z_p . An initial population in Z is selected randomly. At each step (generation), new individuals are created by crossover (mating) and mutation operations. Each new individual is assigned a fitness score, in our case the tuple $(-\eta_0, h_{\text{InGaAs}})$, and the next population is selected by taking the fitness score into account (survival of the fittest) as well as favoring solutions in under-represented areas of the Pareto front (crowding distance). Different populations are allowed to evolve simultaneously and to exchange individuals during their evolution (island model with migration). The results for the diatom LTS were obtained using a single population of 52 individuals evolved for at least 270 generations. The moth-eye geometry instead was

optimized by evolving four fully connected islands of 24 individuals each for 50 generations.

3. Results

3.1. Optimized LTS

Figure 2(a) compares the Pareto fronts for the diatom with $n_c = 2$ and moth-eye LTS to the bilayer ARC, as resulted from the optimization procedure. Both LTSs achieve higher η_0 values for thin middle junctions in comparison to the bilayer ARC. As h_{InGaAs} increases, the efficiency gap between the moth-eye structure and the bilayer ARC diminishes, whereas η_0 for the diatom structure reaches a plateau at around 1 μm of middle junction thickness. For the degradation analysis, it is informative to compare the different cell designs at fixed values of h_{InGaAs} . As a worst case scenario, we select for the moth-eye cell $h_{\text{InGaAs}} = 1.13 \mu\text{m}$, a thickness that achieves comparable BOL efficiency to the reference design. We set h_{InGaAs} for the diatom LTS equipped cell at the same value as the moth-eye design to access any role of the optics in radiation degradation. The selected designs are marked in figure 2(a) by the points and the associated absorption profiles are contrasted in figure 2(b) for the wavelengths of interest of the middle junction.

We present the geometrical parameters of the optimized diatom and moth-eye structures in appendix C. For the bilayer ARC, the optimal layer thickness was determined to be relatively constant at $h_1 = 81 \text{ nm}$ and $h_2 = 46 \text{ nm}$. We further turn our attention to the diatom LTS, because the set of parameters introduced in section 2.1 does not encode all the possibilities and do not shed light on the importance of the cribrum layer. Thus, we repeated the optimizations for two additional configurations: a reversed ordering diatom, with the areola placed on top of the cribrum and a single dielectric layer with pores in a hexagonal lattice. We describe the latter configuration using the geometrical parameters of the areola, e.g. we use a_a for the lattice constant. Additionally, we performed the optimization with the normal ordering for the diatom including $n_c \in [2, 5]$ as an optimization parameter. The achieved maximum efficiency for the aforementioned configurations is shown in figure 3. The normal ordering is the most successful for wide range of h_{InGaAs} . Only for very thin junctions, below 0.4 μm , is the reversed configuration able to achieve the highest efficiencies. Optimizations with n_c as a free parameter did not achieve substantially improved results in comparison to fixing $n_c = 2$. The single layer with pores attained the lowest η_0 for the vast range of h_{InGaAs} or comparable for thick junctions.

3.2. Radiation-induced damage

The LTSs open the possibility of a substantial decrease in the thickness of the middle junction. To quantify the potential improvement in radiation hardness, we first assess the impact of junction thinning on

Figure 2. Optimization results for the LTS. (a) Comparison of the BOL efficiency between the LTS and the BL ARC. (b) Detail of the absorption of the middle junction per wavelength for the solar cells marked with points in panel (a). The wavelength ranges indicate the approximate absorption window of each subcell.

Figure 3. Optimal solar cell efficiency for different configurations of the diatom LTS. Four configurations are shown: normal layer ordering (DA), reversed ordering with the areola on top of the cribrum layer (DA rev), single layers with hexagonal pores (1L) and normal layer ordering with n_c as an optimization parameter (DA LS).

D_d and consequently on the defect density. The relation between D_d and h_{InGaAs} allows us to determine the decrease in the minority carrier lifetime for different cell designs at the same radiation exposure. To isolate the effects coming from the junction thinning alone, we simulated the damage dose deposition on middle junctions with thicknesses ranging from 0.2 μm to 2.0 μm for the bilayer ARC design. The material and thickness of the remaining cell layers were the same as the one used in the optical simulations, without the protective cover glass. The thickness of the bottom junction was fixed at 148 μm . Figures 4(a) and (b) plots D_d inflicted on the middle junction for monoenergetic electrons of 1 MeV and 5 MeV, and protons of 3 MeV and 10 MeV at normal incidence; D_d depends on the energy and the type of the incident particle but not on the thickness of the middle junction. The independence of D_d from the junction thickness implies that for a given particle and energy, $dE_{de}/d\chi$ remains almost constant as the particle traverses the middle junction. This is confirmed by the recorded values of $dE_{de}/d\chi$ for the aforementioned cases, which are shown in figures 4(c)

and (d) for the two extreme cases of middle junction thickness.

Still, the dissimilar materials and thicknesses of the layers between the ARC and the LTS may affect the induced defect density. We repeat the simulation for the three cell designs, with the optimized LTS and reference ARC, which we discuss in section 3.1. We selected a representative space radiation environment, composed of electrons and protons meeting the solar cell at angles ranging from 0° to 90°. Three different orbits were considered: a low-earth orbit (LEO), a highly elliptical orbit (HEO) and a geostationary orbit (GEO). Appendix B details the energy spectra the cells encounter in these orbits. All cells were simulated with a protective cover glass of 100 μm . Table 2 compares the D_d for the three solar cell designs, verifying that the solar cell degradation is connected to the radiation environment and not to the junction thickness or the LTS.

3.3. EOL efficiency analysis

The radiation-induced defect density on the middle junction is independent from the junction thickness and the ARC or the LTS, as discussed in section 3.2. Therefore, the deterioration in cell efficiency for different combinations of junction thickness and LTS can be compared at a given radiation exposure by computing η at equal values of τ_a and S_a .

We assume a reference middle junction with geometry and doping similar to [63, device SB-SJ], with electrical characteristics that are summarized in table 3 (see also schematic in figure A1). We remark that the structure of the single junction devices in [63] include window layer and back surface field layer materials typically used in multi-junction devices (AlInP and GaInP, respectively). Therefore the obtained bulk, surface and interface recombination parameters are applicable to the present case. Figure 5(a) compares the cell degradation at different radiation exposures for the three solar cell designs from section 3.1. We included the experimental η values for the 3G30C cell [4] for comparison. The η values for 3G30C cell are reported for

Figure 4. Radiation damage for different thicknesses of the middle junction. (a) Damage dose in arbitrary units deposited on the middle junction of a solar cell for incident electrons of 1 MeV and 5 MeV. The middle junction thickness varies from 0.2 μm to 2.0 μm , while all the other layers are kept constant. (b) Same as panel (a) for proton of 3 MeV and 10 MeV. (c) Mass stopping power as measured along the normalized junction depth. The values correspond to the two extreme thickness of panel (a). Solid lines for 1 MeV, dashed lines for 5 MeV electrons. CI has been omitted for the sake of clarity. (d) Similar to panel (c) for proton irradiation.

Table 2. Comparison of D_d (10^9 MeV g^{-1}) between solar cells with the LTS (DA: diatom, ME: moth-eye) and the bilayer ARC (BL). Results for one year in orbit (LEO: low-earth, HEO: highly elliptical, GEO: geostationary) with ϕ_0 equal to the total particle fluence.

Orbit	BL	DA	ME
LEO	6.8 ± 1.6	7.0 ± 2.0	6.2 ± 1.2
HEO	1357.4 ± 104.8	1284.0 ± 75.2	1263.8 ± 77.9
GEO	40.2 ± 30.4	53.3 ± 58.0	35.7 ± 16.1

1 MeV electron irradiation and the same applies for K_a and $K_{s,a}$ values: the conversion from particle fluence to D_d is performed with the coefficient $2.246 \times 10^{-5} \text{ MeV cm}^2 \text{ g}^{-1}$ computed in section 3.2. Moreover, in figure 5(b) we plot the mean collection probability over the total width of the junction, h_{InGaAs} ,

$$P_t = \frac{1}{h_{\text{InGaAs}}} \int_0^{h_{\text{InGaAs}}} P_c(x) dx \quad (17)$$

which captures adequately the trends in η . The alteration of the electrical response of the solar cell due to the radiation exposure is exemplified in figure 6, which compares the current density versus the applied voltage between the pristine and the irradiated cells. The reduction in both the short-circuit current and the open-circuit voltage is evident for all designs.

The LTS equipped cells demonstrate higher radiation hardness, with η being distinctly higher for exposure $D_d \geq 10^{10} \text{ MeV g}^{-1}$ in comparison to the

ARC design. The moth-eye cell retains a 1.8% to 2.6% higher efficiency than the reference design at high radiation doses, with the gain in η being from 1.3% to 2.1% for the diatom LTS equipped cell at the same D_d range. Both LTS designs exhibit an identical degradation pattern, hinting that the absorption profile inside the junction influences the total photocurrent, but has little effect on the degradation dynamics. The simulated η degradation shows a similar trend to the experimental results for the 3G30C cell, without any fitting of the parameters. We further verified that the efficiency as a function of D_d follows the well known behavior described by the remaining factor, $\text{RF}_\eta = \eta \eta_0^{-1}$,

$$\text{RF}_\eta = 1 - C \log_{10} \left(1 + \frac{D_d}{D_x} \right) \quad (18)$$

which has been used extensively in the literature [5, 52, 54, 65], with C and D_x being fitting parameters. In all three cases we have found the coefficient of

Table 3. Electrical properties of the middle junction used in the simulations.

Quantity	Symbol	Value	Units	Reference
Donor concentration (emitter)	N_d	3×10^{18}	cm^{-3}	[63]
Acceptor concentration (base)	N_a	3×10^{16}	cm^{-3}	[63]
Emitter width	$\bar{w}_n$	0.1	μm	[63]
Recombination velocity (p-doped)	$S_{0,p}$	100	cm s^{-1}	[63]
Recombination velocity (n-doped)	$S_{0,n}$	360	cm s^{-1}	[63]
Radiative recombination rate	B	2×10^{-10}	$\text{cm}^3 \text{s}^{-1}$	[53]
Intrinsic carrier concentration	n_i	2×10^6	cm^{-3}	[53]
Dielectric constant	ϵ_s	1.16×10^{-10}	F m^{-1}	
Damage coefficient (p-doped)	K_p	0.04	$\text{g MeV}^{-1} \text{s}^{-1}$	[63]
Damage coefficient (n-doped)	K_n	0.23	$\text{g MeV}^{-1} \text{s}^{-1}$	[63]
Interface damage rate (p-doped)	K_{Sp}	7.6×10^{-7}	$\text{g cm MeV}^{-1} \text{s}^{-1}$	[63]
Interface damage rate (n-doped)	K_{Sn}	0	$\text{g cm MeV}^{-1} \text{s}^{-1}$	[63]

Figure 5. Comparison of EOL efficiency at different D_d . (a) Efficiency deterioration for various levels of D_d for different cells designs (BL for bilayer ARC, DA for diatom LTS, ME for moth-eye LTS). Values for the 3G30C cell from [4] are included for comparison. (b) Mean collection probability over the junction width for the same cases as panel (a). **Figure 6.** J - V curves at BOL and EOL conditions. Current density versus cell voltage for the three solar cells designs (BL for bilayer ARC, DA for diatom LTS, ME for moth-eye LTS) at BOL (dashed lines, no radiation exposure) and EOL (solid lines, $D_d = 10^{12} \text{ MeV g}^{-1}$).

determination $R^2 > 0.999$, illustrating the validity of our model.

So far we have looked into the LTS and junction thickness pairs that achieve comparable BOL to the reference design. For applications where the EOL alone is of interest, enhanced radiation harness can be attained at the cost of BOL efficiency. To quantify the BOL efficiency to radiation hardness trade-off, we simulated the EOF efficiency of the solar cell

designs depicted in figure 2 at a medium ($D_d = 2 \times 10^{10} \text{ MeV g}^{-1}$) and high ($D_d = 10^{11} \text{ MeV g}^{-1}$) radiation exposure. For all cells junctions we used the same electrical characteristics as before, given in table 3. Figure 7 plots the efficiency of the optimized bilayer ARC and LTS for a wide range of h_{InGaAs} . At any given D_d , there is an optimal middle junction thickness for the bilayer ARC and the LTS cells, which balances the gains of increased photocarrier generation due to absorption to the losses due to the diffusion-driven collection. At this particular thickness, the efficiency after irradiation is the highest, even when compared to cells with significantly higher BOL efficiency. At the tested D_d , the diatom and the moth-eye LTS were able to achieve from 0.4% to 1.2% and from 0.8% to 1.9% higher efficiency than the bilayer ARC respectively. The bilayer ARC design displayed the highest sensitivity with respect to the middle junction thickness where the maximum η appears, moving from $1.28 \mu\text{m}$ at $D_d = 2 \times 10^{10} \text{ MeV g}^{-1}$ to $0.87 \mu\text{m}$ at $D_d = 10^{11} \text{ MeV g}^{-1}$. For the same D_d values, the diatom LTS design is less sensitive with the maxima appearing at $1.06 \mu\text{m}$ and $0.76 \mu\text{m}$, whereas the moth-eye LTS with $h_{\text{InGaAs}} = 0.72 \mu\text{m}$ achieved consistently the highest η . Therefore, both LTSs enable the solar cell to operate closer to the optimum η for a wider range of radiation exposures than the bilayer ARC by properly selecting h_{InGaAs} .

4. Discussion

The LTS, inspired by the moth-eye and the diatom patterns, increases the efficiency of the solar cell in comparison to the bilayer ARC commonly used in industry for cells with a thin middle junction. The bilayer ARC improves light absorption by decreasing the reflectance of the front surface, minimizing the optical losses. The LTS further boosts the efficiency by diffracting light which, in combination with the SPM, couples at the guided modes of the middle junction. The diatom LTS incorporates two photonic crystals of different lattice constant, opening more diffraction orders due to the combined effect of the stack. The higher enhancement in η_0 observed for the normal and the reversed diatom configurations, in comparison to the single perforated layer, can be attributed to this fact. These results reflect that the two-fold diffraction introduced by two stacked photonic crystals is indeed very beneficial to enhance the efficiency of the solar cell above the single layer case. Chen *et al* [38] showed for an ultra-thin (50 nm) organic absorber that the total enhancement is the combination of each individual photonic crystal contribution, which agrees with our results. In the reverse order, the large lattice constant a_a is facing the front medium which might introduce reflection losses. This can explain the reduction in efficiency for the thick layers (see figure 3), where diffraction is not as important as the anti-reflection mechanism. For thin InGaAs, the efficiency of both orderings are similar, being even higher for the thinnest cases studied. This again is in line with the results of [38], as the authors show a similar enhancement for the reversed order for the ultra-thin absorber. Still, the enhancement due to the diatom LTS is comparable to the moth-eye structure only for h_{InGaAs} smaller than approximately $0.4 \mu\text{m}$.

Aside from the solar cell performance, the adoption of light trapping technologies is also governed by cost considerations. The bilayer ARC, composed of two simple layers, is definitely the simplest to manufacture. Progress in manufacturing processes has

made large-scale production of 3D structures possible. The moth-eye cone pattern has been transferred to Si_3N_4 by laser interference lithography [40], a low cost technique capable of uniformly patterning large areas [66]. Moreover, nanocone arrays have been manufactured out of Si [67], TiO_2 [68, 69] and glass [37] using plasma and dry etching. The double photonic crystal arrangement of the diatom structure makes its assembly a challenging task. Precise porous hexagonal arrays, resembling the single diatom layer, have been fabricated using the photochemical etching technique [70], but bonding of the two layers is necessary to complete the diatom structure. A fabrication process is explained in [71] for a square lattice, although the authors recognize the challenge it represents. The implementation of the SPM poses similar issues. A selective reflective mirror can be realized as a DBR. For the DBR to achieve the necessary wavelength bandwidth (the absorption window of the middle junction), the optical design requires the use of either thick structures with hundreds of layers or materials with a high refractive index contrast. Additionally, the extinction coefficient of the DBR material should be as low as possible to avoid any parasitic losses. These requirements can be met with either thick graded buffer Bragg reflectors [14], or by using, for example, a dielectric $\text{SiO}_2/\text{TiO}_2$ DBR [72]. The former increases the final price in its actual form, and the latter is incompatible with III–V epitaxy reactors. Therefore, there is a separate and necessary task in identifying a DBR structure that could combine lower price and monolithic growth. Combining the structures presented in this work with an optimized DBR will impact positively on radiation-hard solar cells for space applications, and lower the material usage and cost of III–V multijunctions, fundamental also for future terrestrial applications.

According to our simulations, the radiation damage sustained by thin cell junctions in space is mainly governed by the radiation environment. Taking into account the energy deposition mechanism, this is a reasonable observation. The energy of the incident particle dictates the rate of energy loss along the

trajectory through a given material. For highly energetic particles the total energy deposit is small compared to the initial energy, since the solar cell structure is relatively thin. Therefore, the energy of the particle remains almost constant along its path and so does the deposited energy per unit path length, resulting in an almost constant D_d . There are cases where localized energy deposit may take place in the semiconductor material, like for low energy protons that can be stopped inside the junction with a Bragg peak produced at the end of the track. The continuous energy spectrum of the typical space environment and the wide range of incident angles would diminish any localized effect. This conclusion of approximately uniform damage distribution throughout the cell active region is in agreement with [73], where omnidirectional proton irradiation was analyzed.

Thinning of the middle junction, when combined with the absorption enhancement of the LTS, provides a compelling way to increase the robustness and the radiation hardness of multi-junction solar cells. Sacrificing BOL efficiency allows for optimal operation of the cell for a wider range of D_d . Although not examined in the present study, reduction in junction thickness should be accompanied by systematic tuning of the junction electrical characteristics, such as emitter width and doping concentration, to extort the maximum possible improvement with respect to cell radiation hardness. Previous studies have addressed these issues; the emitter width has been connected to the radiation hardness of solar cells, with shallow emitters exhibiting slower degradation [63]. Lowering the base doping concentrations has a positive effect on radiation hardness, as suggested by [9, 53].

From the mission design point of view, the thickness of the protective cover glass has been the single design parameter to control the radiation degradation for space solar cells, an approach that has been extensively discussed previously [5, 74]. The cover glass thickness affects the sustained damage by altering the energy spectrum perceived by the solar cell material through shielding. Reducing the sensitivity of the cells to radiation is a complementary approach to shielding and both methods can be applied simultaneously. This can result in reduction of the array weight, either from reducing the protective glass thickness or the number of panels needed to achieve the EOL power requirements.

5. Conclusion

In the present study, we reported an indirect biomimetic approach to increase the radiation hardness of space solar cells; the model organisms are not directly related to the radiation problem but provide solutions to the issues arising from adopting designs that are insensitive to radiation cells. To this end, we employed comprehensive models to analyze the

behavior of multi-junction (GaInP/InGaAs/Ge) solar cells starting from their optical performance and their interaction with radiation-induced defects. Then, we incorporated the optical- and radiation-related results in an electrical model which predicts the cell efficiency and allows us to directly compare different junction and LTS designs. We showed that thinning of the middle junction, when accompanied by optical compensation, provides an attractive approach to developing radiation hardened and robust solar cells. Specifically, our proposal enables an increase of up to 2% in EOL efficiency in comparison to the currently used cell design, which in turn can lead to a significant reduction in the weight of spaceborne solar panel arrays.

Future work includes addressing fabrication issues in more detail and assessing potential costs associated with the large scale manufacture of such structures.

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Data availability statement

The data that support the findings of this study are available upon reasonable request from the authors.

Appendix A. 1D diffusion model

The modeling approach of the present section is based on the analytical model of p–n homojunctions and the underlying assumptions found in [75, section 4.4]. The main difference is that in the present analysis we consider an arbitrary absorption profile inside the junction, which is described by $\alpha(\lambda, x)$, in contrast to the commonly assumed exponential profile based on the Beer–Lambert law. This is crucial in order to capture the effect of the LTS on the junction photocurrent.

We discuss a junction composed of an n-type emitter with donor density N_d connected and a p-type base with acceptor density N_a . The junction is divided into three regions, as shown in figure A1; the n-type quasi-neutral area (QNA, emitter), the p-type QNA (base) and the depletion region. The width of the emitter and base is $\bar{w}_p$ and $\bar{w}_n$ respectively. The depletion area has its center at x_W from the

light entering face and extends by w_p and w_n toward the two QNAs. In the following, we use the coordinate system $\bar{x}$, which has its origin at the interface between the depletion region and the n-type QNA (see figure A1).

At steady state, the constant current density, J , is the result of the sum of the electron, J_n , and hole, J_p current densities. Since J is constant throughout the structure, it can be evaluated at any given plane. For convenience, we perform the computation at the plane $\bar{x} = 0$, i.e. at the interface between the depletion region and the n-type QNA.

$$J = J_p(0) + J_n(0). \quad (\text{A.1})$$

The hole current density at this plane is related to the excess minority carrier density, δp , as [75]

$$J_p(0) = -qD_p \frac{d\delta p(0)}{d\bar{x}}, \quad (\text{A.2})$$

where q is the elementary charge (e) and D_p is the hole diffusion constant.

First we turn our attention to the n-type QNA, where δp follows the diffusion equation

$$\frac{d^2 \delta p}{d\bar{x}^2} - \frac{1}{L_p^2} \delta p + G(\bar{x}) = 0, \quad (\text{A.3})$$

where $L_p = \sqrt{D_p \tau_p}$ is the minority carrier diffusion length. The generation rate is given, similarly to (1), as

$$G(\bar{x}) = \frac{D_p}{hc} \int_0^{\lambda_g} \alpha(\lambda, \bar{x}) \Phi_\lambda(\lambda) \lambda d\lambda. \quad (\text{A.4})$$

Two boundary conditions accompany (A.3):

$$\frac{d\delta p(\bar{w}_n)}{d\bar{x}} = -\frac{S_p}{D_p} \delta p(\bar{w}_n) \quad \bar{x} = \bar{w}_n \quad (\text{A.5})$$

$$\delta p(0) = p_0 \left(e^{\frac{E_{Fp}}{kT}} - 1 \right) \quad \bar{x} = 0, \quad (\text{A.6})$$

where p_0 is the equilibrium hole density, E_{Fp} is the quasi-Fermi level and S_p is the rear surface recombination velocity. We obtain the solution to (A.3) using

the Green's function approach. The Green's function satisfies

$$\frac{d^2 \mathcal{G}(\bar{x}, s)}{d\bar{x}^2} - \frac{1}{L_p^2} \mathcal{G}(\bar{x}, s) = \delta(\bar{x} - s) \quad (\text{A.7})$$

with $\delta(\bar{x} - s)$ Dirac's δ function. The general solution to (A.7) is of the form

$$\mathcal{G}(\bar{x}, s) = \begin{cases} c_1(s) \cosh\left(\frac{\bar{x}}{L_p}\right) + c_2(s) \sinh\left(\frac{\bar{x}}{L_p}\right) & \bar{x} < s \\ c_3(s) \cosh\left(\frac{\bar{x}}{L_p}\right) + c_4(s) \sinh\left(\frac{\bar{x}}{L_p}\right) & \bar{x} \geq s \end{cases}, \quad (\text{A.8})$$

where the coefficients c_1 to c_4 depend solely on s . At the point $\bar{x} = s$, $\mathcal{G}(\bar{x}, s)$ is continuous and satisfies (A.7), resulting in

$$c_1 - c_3 = L_p \sinh\left(\frac{s}{L_p}\right) \quad (\text{A.9})$$

$$c_4 - c_2 = L_p \cosh\left(\frac{s}{L_p}\right). \quad (\text{A.10})$$

Given $\mathcal{G}(\bar{x}, s)$, the excess minority carrier density becomes

$$\begin{aligned} \delta p(\bar{x}) &= - \int_0^{\bar{w}_n} \mathcal{G}(\bar{x}, s) G(s) ds \\ &= \bar{c}_1 \cosh\left(\frac{\bar{x}}{L_p}\right) + \bar{c}_2 \sinh\left(\frac{\bar{x}}{L_p}\right) - (\mathcal{K} * G)(\bar{x}), \end{aligned} \quad (\text{A.11})$$

where $\bar{c}_1 = - \int_0^{\bar{w}_n} c_1 G ds$ and $\bar{c}_2 = - \int_0^{\bar{w}_n} c_2 G ds$. The last term in (A.11) stands for the convolution of the kernel $\mathcal{K} = L_p \sinh(\bar{x} L_p^{-1})$ with the generation rate

$$(\mathcal{K} * G)(\bar{x}) = \int_0^{\bar{x}} L_p \sinh\left(\frac{\bar{x} - s}{L_p}\right) G(s) ds. \quad (\text{A.12})$$

Likewise, the derivative of δp with respect to $\bar{x}$ becomes

$$\frac{d\delta p}{d\bar{x}} = \frac{\bar{c}_1}{L_p} \sinh\left(\frac{\bar{x}}{L_p}\right) + \frac{\bar{c}_2}{L_p} \cosh\left(\frac{\bar{x}}{L_p}\right) - \left(\frac{d\mathcal{K}}{d\bar{x}} * G\right)(\bar{x}). \quad (\text{A.13})$$

The remaining constants can be determined by applying the boundary conditions:

$$\bar{c}_1 = p_0 \left(e^{\frac{V}{kT}} - 1 \right) \quad (\text{A.14})$$

$$\begin{aligned} \bar{c}_2 &= \frac{L_p}{c_p} \left[(\mathcal{P} * G)(\bar{w}_n) - \frac{\bar{c}_1}{L_p} \sinh\left(\frac{\bar{w}_n}{L_p}\right) \right. \\ &\quad \left. - \frac{\bar{c}_1 S_p}{D_p} \cosh\left(\frac{\bar{w}_n}{L_p}\right) \right] \end{aligned} \quad (\text{A.15})$$

$$c_p = \cosh\left(\frac{\bar{w}_n}{L_p}\right) + \frac{S_p L_p}{D_p} \sinh\left(\frac{\bar{w}_n}{L_p}\right) \quad (\text{A.16})$$

$$\mathcal{P}(\bar{x}) = \frac{d\mathcal{K}(\bar{x})}{d\bar{x}} + \frac{S_p}{D_p} \mathcal{K}(\bar{x}), \quad (\text{A.17})$$

where we have substituted $E_{Fp} = V$ under the assumption that the quasi-Fermi level is constant

throughout the depletion region [75]. The hole current density is computed from (A.2) and (A.13), as

$$J_p = -\frac{q\mathcal{D}_p}{L_p}\bar{c}_2. \quad (\text{A.18})$$

Two contributions can be identified in $\bar{c}_2$. The first comes from the photocurrent, which is computed as the integral of the generation rate in the QNA multiplied by the collection probability

$$P_c(\bar{x}) = c_p^{-1}\mathcal{P}(\bar{w}_n - \bar{x}). \quad (\text{A.19})$$

The last two terms depend on the applied voltage and contribute to the diode saturation current.

A similar analysis can be performed in the p-region to compute $J_n(0)$. However, it is more

convenient to compute this current contribution at the interface between the p-type QNA and the depletion region, $\bar{x} = -w_p - w_n$. The current density at $\bar{x} = 0$ is obtained from the continuity condition:

$$J_n(0) = J_n(-w_p - w_n) + J_R, \quad (\text{A.20})$$

where J_R is the current density accounting for the recombination losses in the depletion region. We assume that J_R is independent of τ_p and τ_n and it is given from (3). See [75] for further details.

Adding the current density of the QNAs to the one of depletion area, where we assume complete photocarrier collection, the total photocurrent is computed as in (7) with

$$P_c(x) = \begin{cases} c_p^{-1} \left[\cosh\left(\frac{x}{L_p}\right) + \frac{S_p L_p}{\mathcal{D}_p} \sinh\left(\frac{x}{L_p}\right) \right] & 0 \leq x \leq \bar{w}_n \\ 1 & \bar{w}_n < x < h_i - \bar{w}_p \\ c_n^{-1} \left[\cosh\left(\frac{h_i - x}{L_n}\right) + \frac{S_n L_n}{\mathcal{D}_n} \sinh\left(\frac{h_i - x}{L_n}\right) \right] & h_i - \bar{w}_p \leq x \leq h_i, \end{cases} \quad (\text{A.21})$$

where h_i is the total width of the junction, $\mathcal{D}_n$ is the electron diffusion constant, S_n is the front surface recombination velocity and

$$c_n = \cosh\left(\frac{\bar{w}_p}{L_n}\right) + \frac{S_n L_n}{\mathcal{D}_n} \sinh\left(\frac{\bar{w}_p}{L_n}\right). \quad (\text{A.22})$$

The origin of the coordinate system in (A.21) has been moved to the light-entering face of the junction, to be in accordance with (7). The increase in the saturation current is obtained by the sum of the contribution of each QNA, $J_{d0} = J_{d0,n} + J_{d0,p}$, with

$$J_{d0,n} = \frac{q\mathcal{D}_n n_0}{c_n L_n} \left[\sinh\left(\frac{\bar{w}_p}{L_n}\right) + \frac{S_n L_n}{\mathcal{D}_n} \cosh\left(\frac{\bar{w}_p}{L_n}\right) \right] \quad (\text{A.23})$$

$$J_{d0,p} = \frac{q\mathcal{D}_p p_0}{c_p L_p} \left[\sinh\left(\frac{\bar{w}_n}{L_p}\right) + \frac{S_p L_p}{\mathcal{D}_p} \cosh\left(\frac{\bar{w}_n}{L_p}\right) \right], \quad (\text{A.24})$$

where n_0 is the equilibrium minority carrier concentration. We point out that for negligible recombination velocity at the edges of the junction, $L_p \gg \bar{w}_p$ and $L_n \gg \bar{w}_n$, we retrieve the original model with $P_c = 1$ throughout the junction and no contribution to the saturation current from the QNAs.

The values for $\mathcal{D}_p$ and $\mathcal{D}_n$ for GaAs were computed using the relations from [76] under the assumption that the minority carrier mobility is equal the majority carrier mobility at any given region. The parameters of the depletion region were determined

using the abrupt junction approximation under the assumption that the majority carrier concentration is equal to the dopant concentration. Specifically, the equilibrium densities were computed as $p_0 = n_i^2 N_d^{-1}$ and $n_0 = n_i^2 N_a^{-1}$, where n_i is the intrinsic carrier concentration. The depletion region width is calculated from

$$w_p = \sqrt{\frac{2\epsilon_s kT}{q^2} \frac{N_d}{N_a} \frac{1}{N_d + N_a} \ln\left(\frac{N_d N_a}{n_i^2}\right)} \quad (\text{A.25})$$

and $w_n = N_d^{-1} N_a w_p$, where ϵ_s is the dielectric constant. The previous relation neglects any shrinkage of the depletion region due to the applied voltage.

Appendix B. Geant4 validation and simulation details

All Geant4 simulations were performed using the dedicated physics list for the space radiation environment (QBBC) [77], with the multiple scattering models being substituted by a single scattering one at the middle junction. It is possible to track the PKAs in the semiconductor material, only if the dedicated single Coulomb scattering physics [56, 78] are selected in the physics list. The single scattering model though is computationally more expensive than the commonly used multiple scattering model [79] and its use is restricted when the highest possible accuracy is needed.

We are interested in the PKAs occurring in the middle junctions, which constitutes less than 1.5%

Table B1. Comparison of D_d [arb.u.] for single (SSC) and combined single/multiple scattering (MSC) models.

Source	SSC	MSC
1 MeV electron	0.021 ± 0.002	0.020 ± 0.002
5 MeV electron	0.054 ± 0.009	0.052 ± 0.008
3 MeV proton	14.875 ± 0.671	14.918 ± 0.683
10 MeV proton	6.084 ± 1.200	6.154 ± 1.058

Figure B1. Integral particle fluence over the course of one year for three different orbits. (a) LEO at 800 km with 98.0° inclination. (b) HEO at 700 km $\times$ 12 050 km with 63.4° inclination. (c) GEO.

of the total thickness of the solar cell stack. To keep the simulations' time within reasonable limits, we combine the multiple and single scattering models in our code. The layers of the solar cell are grouped in two regions: (a) layers where the D_d needs to be calculated and (b) the remaining layers. For the first region, the single scattering model was selected and the secondary production range cut was set to 40 nm, whereas for the second region the multiple scattering is used and the secondary production range cut was set to 400 nm. We validated the code by comparing the simulations results to the ones with uniform single scattering model and 40 nm secondary production range cut over the whole cell geometry. Table B1 contrasts the D_d values from the two implementations for monoenergetic 1 MeV and 5 MeV electron, and 3 MeV and 10 MeV proton sources with incident normal to the solar cell for 10^6 primary events. The difference between the computed values lie inside the CI bounds. The relative speedup for the single/multiple scattering combined physics list was measured between 41 and 77 times.

A realistic space radiation environment can be constructed for given Earth trajectories. The spectrum contains three contributions: trapped electron and protons, and solar protons. In our simulations we considered three orbits: a LEO at 800 km with 98.0° inclination, a HEO at 700 km $\times$ 12 050 km with 63.4° inclination and a GEO. The trapped particle spectrum was determined using the AP-8 and AE-8 models and the solar proton spectrum was calculated from ESP total fluence model, using the software SPENVIS [80]. The integral particle fluence over the time span of one year is shown in figure B1.

Appendix C. Geometrical parameters for optimized LTS

The optimal geometrical parameters of the three structures studied in figure 3 are gathered in figures C1(a)–(d). For the single layer, the optimal a_a assumes roughly two values: around 0.60 μm for $h_{\text{InGaAs}} < 0.80 \mu\text{m}$ and 0.35 μm for $h_{\text{InGaAs}} > 0.80 \mu\text{m}$. This implies that the scattering of light is playing an important role in the former case. Wavelengths

Figure C1. Geometrical parameters for the optimized diatom structures. Parameters for three configurations are shown: normal layer ordering (DA), reversed ordering (DA rev) and single layers with hexagonal pores (1L).

Figure C2. Geometrical parameters for the optimized moth-eye structures.

smaller than a_a/n_{cover} can be back-diffracted hence introducing reflection losses. In contrast, diffraction inside of the cell is beneficial for light-trapping. A trade-off is established between both processes. Light-trapping is critical for thin absorbers to expand the optical path length and, therefore, a_a is larger than in the case of thick ones. A similar split into two distinct regions is observed for the single layer h_a and r_a parameters. This means that the average refractive index is higher as holes reduce, i.e. that the single layer acts more as a single layer ARC than as a light-trapping element for thick InGaAs. This is also supported by the reduction of the h_a approaching toward the typical thickness of an interferential filter.

For the diatom configuration, a_a follows a similar pattern at almost double the value of the single layer,

with the transition taking place at $h_{\text{InGaAs}} = 0.50 \mu\text{m}$. That means that the cribrum lattice constant takes a value very close to that of the single layer. Likewise, the thickness and the pore radius shows the same trend as a_a . As the thickness of the middle junction increases, r_a and r_c converge to the value of $0.12 \mu\text{m}$, which coincides with the pore radius for the single layer. The relative displacement between the two layers plays a secondary role, with the optimized values exhibiting a spread; there is a slight preference for a constant value toward the diagonal of the unit cell, with x_0/a_c and $y_0/(\sqrt{3}a_c)$ both adopting values close to 0.5. For the reversed diatom configuration, two regions are present with the transition happening at $h_{\text{InGaAs}} = 1.20 \mu\text{m}$. The relative displacement in this case seems to play a secondary role in the η_0 enhancement. The geometry of cribrum layer for diatom configuration

and the single layer are similar for thick junctions, implying that the areola layer plays a supporting role on the first.

The parameters for the optimized moth-eye (ME) LTS are shown in figure C2. The lattice constant a_m shows a softer evolution than a_a with h_{InGaAs} . The cones help in balancing the trade-off between reflection losses and diffracted light if compared with the hole arrangement constituting the diatom structure. Indeed, the ME can be seen as an averaged graded index layer, which helps in reducing the impedance mismatch between the solar cell layers and the cover glass. The radius is always larger than $0.2 \mu\text{m}$ which means that the cone base tends to completely fill the unit cell area, i.e. $r_m/a_m \approx 0.5$. The cone height h_m takes very large values, close to 800 nm in the region of interest, i.e. for thin middle junctions. The base and spacer thicknesses h_b and h_s are almost constant along the whole optimization range, the latter being almost negligible. If h_c is added to h_m we get the total amount of TiO_2 needed to fabricate the structure. A layer of $1 \mu\text{m}$ is indeed needed. This is an experimental challenge, as high index and high quality TiO_2 is difficult to obtain beyond 100 nm . More research and alternative proposals will be addressed in the future to cope with this issue.

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