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## Preprint

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# Design of Semiconductor-based Back Reflectors for High $V_{oc}$ Monolithic Multijunction Solar Cells

Iván García, John Geisz, Myles Steiner, Jerry Olson, Daniel Friedman and Sarah Kurtz

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***Abstract* — State-of-the-art multijunction cell designs have the potential for significant improvement before going to higher number of junctions. For example, the $V_{oc}$ can be substantially increased if the photon recycling taking place in the junctions is enhanced. This has already been demonstrated (by Alta Devices) for a GaAs single-junction cell. For this, the loss of re-emitted photons by absorption in the underlying layers or substrate must be minimized. Selective back surface reflectors are needed for this purpose. In this work, different architectures of semiconductor distributed Bragg reflectors (DBR) are assessed as the appropriate choice for application in monolithic multijunction solar cells. Since the photon re-emission in the photon recycling process is spatially isotropic, the effect of the incident angle on the reflectance spectrum is of central importance. In addition, the DBR structure must be designed taking into account its integration into the monolithic multijunction solar cells, concerning series resistance, growth economics, and other issues. We analyze the tradeoffs in DBR design complexity with all these requirements to determine if such a reflector is suitable to improve multijunction solar cells.**

***Index Terms* — photon recycling, high $V_{oc}$, distributed Bragg reflector, multijunction solar cell.**

## I. Introduction

The possibility of approaching the Shockley-Queisser efficiency limit by enhancing the photon recycling in the solar cell, as predicted by theory [1], was recently demonstrated experimentally by Alta Devices for a GaAs single-junction cell [2]. In the radiative limit, i.e., when the radiative recombination dominates over non-radiative recombination processes, photon recycling can be enhanced by minimizing the transmission of re-emitted photons outwards from the photoactive layers of the subcells. For monolithic multijunction solar cells, where broadband metallic reflectors cannot be placed under each junction, the use of semiconductor selective reflectors is a possible path to attain the required photon confinement.

Distributed Bragg reflectors (DBRs) have been used in the past as semiconductor back reflectors in single-junction solar cells to mitigate the effect of low diffusion lengths in the material and obtain an improved carrier collection efficiency [3-5]. In these works the primary purpose was to achieve a high reflectance at the back of the solar cell for the light coming from the exterior. The design of the DBR concerning the center wavelength and bandwidth was carried out taking into account the spectral content of the light reaching the back surface of the solar cell base layer. A dual DBR is even proposed in [3] as a way to achieve a wider high reflectance band. In [5] the possible photon recycling enhancement obtained is pointed out as a side-effect and the implications of the DBR angular response are discussed.

In addition to the reflectivity requirements, the transmissivity and thickness of the DBRs to be used in a monolithic multijunction solar cell must be taken into account. The transmittance must be such that the short circuit current in the underlying subcells is not compromised. The thickness constraint for the DBR is related to its growth economics, since a given $V_{oc}$ increase attained may not be worth the additional structure thickness required. In this work different DBR designs for a GaAs subcell are assessed in order to determine the suitability of this kind of semiconductor reflectors to enhance the photon recycling in this subcell inside a GaInP/GaAs/(Ge or GaInAs) triple-junction solar cell.

## II. Modeling Approach

The model used to calculate the optical reflection, absorption and transmission of the semiconductor stack under study is based on the Transfer Matrix Method (see for example [7]). All layers have been assumed to be coherent given the thicknesses used in the structures. The reflectance and transmittance are calculated for p- and s-polarized light, and then their average is taken as the reflectance and transmittance of unpolarized light.

In figure 1, the scheme of the modeling approach used is shown. We will deal, on the one hand, with light coming from the external illumination of the cell, which is almost unidirectional and perpendicular to the semiconductor layers. On the other hand, the re-emission of the absorbed photons is

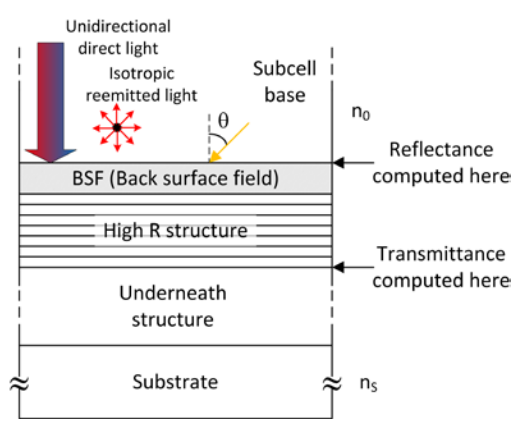


Fig. 1. Schematic representation of the structures that were modeled and the interfaces where the reflectance and transmittance were computed (layers not to scale).

directionally isotropic, so these photons will impinge the interface under study at all $\theta$ angles from 0 to 90°. This is also indicated in figure 1. The Transfer Matrix Method also accounts for the light angle, as required for our study.

Once the reflectance vs. incidence angle is calculated, the total integrated reflectance ($R_{int}$) for all the incidence angles must be obtained. The amount of re-radiated power lost or retained through the back interface can be quantified by the integral [6]:

$$R_{\text{int}} = \frac{\int_0^{2\pi}\int_0^{\pi/2} R(\theta)\cos(\theta)\sin(\theta)d\theta d\phi}{\int_0^{2\pi}\int_0^{\pi/2} \cos(\theta)\sin(\theta)d\theta d\phi} = \\ = 2\int_0^{\pi/2} R(\theta)\cos(\theta)\sin(\theta)d\theta \quad (1)$$

where $\theta$ is the angle of the light with respect to the normal to the surface and $\phi$ is the angle of rotation around this normal (the reflectivity is independent of this angle). This integral assumes isotropic emission over each differential solid angle $d\Omega=\sin(\theta)d\theta d\phi$ throughout the whole volume of the emitter+base of the solar cell and considers the power per unit area reflected at the interface with the $R(\theta)\cos(\theta)$ term.

The effect of the back reflectance on actual photon recycling enhancement depends on the relative radiative to non-radiative recombination near $V_{oc}$. Assuming only Auger non-radiative recombination reference [6] predicts a considerable boost in $V_{oc}$ for $R_{int} > 0.9$. Using a gold reflector on the back of an inverted GaAs actual solar cell (see inset figure 2) with realistic SRH non-radiative recombination, we show in figure 2 an experimental boost in the $V_{oc}$ as a function of the calculated $R_{int}$ as the thickness of the absorbing contact layer is varied. This shows a strong motivation to achieve $R_{int}$

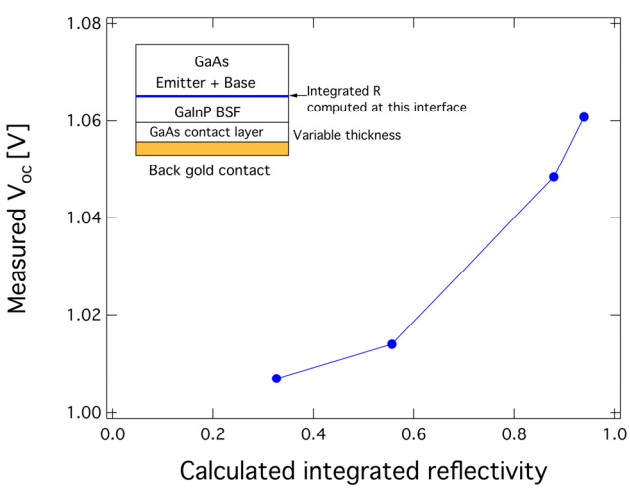


Fig. 2. Measured $V_{oc}$ of inverted GaAs cells plotted against the calculated reflectivity (@880 nm) at the base/BSF interface. This reflectivity is varied in the experimental cells by changing the thickness of the back contact layer (see inset – layers not to scale).

TABLE I
COMBINATION OF LAYERS FOR SEMICONDUCTOR DBRS LATTICE MATCHED TO GAAS

| DBRs for maximum R at λ= 880 nm (GaAs emission), at normal light incidence | | | | |
|---|---|---|---|---|
| **Materials** | **refractive index, n** | **Layer thick. [nm]** | **Bandwidth Δλ [nm]** | **N for R > 0.9** |
| AlAs/GaAs | 2.99/3.63 | 73/60 | 106.6 | 10 |
| $Ga_{0.5}In_{0.5}P$/GaAs | 3.19/3.63 | 68/60 | 71.6 | 15 |
| $Al_{0.5}In_{0.5}P$/GaAs | 2.78/3.63 | 78/60 | 147.1 | 7 |
| $Al_{0.5}In_{0.5}P/Ga_{0.5}In_{0.5}P$ | 2.78/3.19 | 78/68 | 75.8 | 13 |

> 0.8 - 0.9 for improvements as a result of photon recycling in our multijunction solar cells, but this must be attained using DBR as selective reflectors instead of an opaque metal layer.

## III. GENERAL ANALYSIS OF THE REFLECTORS

For the monolithic integration of a DBR into a multijunction solar cell, a limited combination of materials can be used. A set of material combinations appropriate for a structure that is lattice-matched to GaAs, is shown in Table 1. The characteristics of the DBRs designed to have their maximum reflectivity at the GaAs emission wavelength are indicated. The higher the refractive index contrast, the higher the maximum reflectivity and bandwidth for the same number of pairs (N) used. The transmission of light through the structure is also important: the requirements depend on the subcells that are underneath the DBR. A reduced number of pairs (i.e., a reduced total thickness) in the DBR contributes to a more cost effective and less technologically challenging multijunction solar cell structure.

### *A. Center wavelength, bandwidth and maximum reflectivity.*

Concerning photon recycling, the DBR reflection band must be placed around the bandgap wavelength of the emitting material and with a bandwidth as broad as or broader than this emission, which for III-V semiconductor materials is normally narrow, with a full width at half maximum (FWHM) of typically a few tens of meV for high quality materials.

However, when designing the reflector, the transmission of light to underlying subcells in the multijunction solar cell must also be taken into account. The DBR properties define how the light is transmitted to the underlying cells, affecting their $J_{sc}$. The high reflectance/low transmittance band of the DBR centered at the wavelength of emission in a subcell can cover wavelength ranges of photons that should be transmitted to underlying cells. As will be shown in next sections, this gets more complicated for DBRs designed for off-normal incidence angles, required for our photon recycling application, where the DBR high reflectance band is shifted to higher wavelengths than that of the emission of the subcell, or the DBR has more than one band.

*B. Dependence on incidence angle.*

The primary objective of a back reflector designed to enhance photon recycling is to reflect the light coming from re-emission of photons in the subcell. This re-emission is isotropic so the photons generated reach the reflector structure in all the possible directions. Therefore, its reflectance must be kept high in the range of wavelengths of the re-emitted photons and for impinging light angles from 0 to 90°. In a DBR, the high reflectance band shifts toward the low wavelength photon range as the incident angle moves away from 0. Moreover, its bandwidth shrinks, its shape changes and the maximum reflectivity obtained decreases. This is due to an increased optical path length for the light in the DBR, to the variation of the reflectivity with angle at each interface crossed and to the different configuration of the interference processes that take place inside the structure.

This high sensitivity of the DBR reflectance to the light angle has obvious implications to our purpose. In figure 3, the reflectivity (at 880 nm) at the base-BSF of a GaAs solar cell with an AlInP/$Al_{0.1}Ga_{0.9}As$ DBR structure is plotted against the incidence angle. At high angles above the total internal reflection angle, the reflectivity is 1. For low angles, the reflectivity is also 1, due to the effect of the DBR structure. In between the reflectivity is low because the DBR high reflectance band is away from 880 nm for these angles. The total integrated reflectivity for all angles is 0.61 for the AlInP BSF case. The "weighting" of $\cos(\theta)\sin(\theta)$ in equation (1) results in the reflectivity at low angles and high angles contributing much less to the total integrated reflectivity than the reflectivity at angles around 45°. This suggests that a high reflectivity must be attained for the angles right below the total internal reflection angle (see figure 3).

## IV. DBR Design Approaches

Given the characteristics of the DBR explained in the previous section, different approaches have been analyzed in order to maximize the integrated reflectivity at the base/BSF interface of a solar cell. A GaAs cell has been used for the study. Although different DBR options of Table I have been analyzed, we are presenting here the results corresponding to an AlInP/$Al_{0.1}Ga_{0.9}As$ DBR, where a 10% Al has been added to the GaAs layers to reduce absorption around 880 nm in the DBR. This reflector gave the best results concerning DBR performance and total thickness.

*A. Lowering total internal reflection angle.*

As shown in Figure 3, at high incidence angles, total internal reflection occurs. To increase the total integrated reflectivity, a total internal reflection angle as low as possible would be desirable. The lowest total internal reflection angle in our monolithic GaAs solar cell can be achieved using a BSF with the lowest refractive index possible. Normally, GaInP or $Al_{0.3}Ga_{0.7}As$ are used as the BSF material in GaAs solar cells.

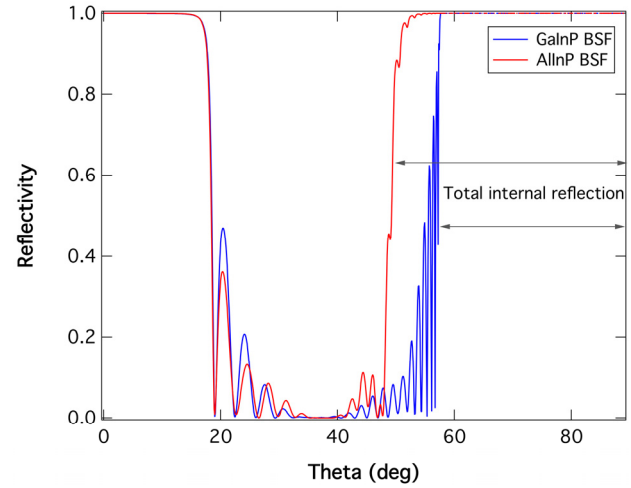


Fig. 3. Reflectivity (@ 880 nm) at the base-BSF of a GaAs solar cell with an AlInP/$Al_{0.1}Ga_{0.9}As$ (12 pairs) DBR structure inserted below the BSF, against the angle of incident light (Theta, $\theta$), for two different BSF materials.

With these materials, total internal reflection angles around 61° and 68°, respectively, are obtained, as compared to 50° if we use AlInP instead. This is illustrated in figure 3. The total integrated reflectivities are 0.48 and 0.61 for the GaInP and AlInP BSFs, respectively. Therefore, changing the BSF material provides us with a significant increase in absolute integrated reflectivity.

*B. Optimizing design angle.*

A DBR can be designed to operate optimally at a certain angle of the incident light. For this, the thickness of its quarter-wave layers must be calculated using equation (2):

$$d = \frac{\lambda}{4n\cos(\theta)} \tag{2}$$

where the cos(θ) accounts for the different optical path length of the light in each DBR layer as incident angle changes. However, not only the optical path length changes as the incident angle moves away from 0. As commented in section III, the Fresnel reflectivity at each DBR layer interface and the interference processes also change. Moreover, the sensitivity of the DBR to the incident angle becomes higher as the angle increases, since the derivative of cos(θ) increases. All these effects result in a DBR optimized for a given angle exhibiting different properties than the same DBR designed for 0°, including different maximum reflectance, wavelength bandwidth and width of the high reflectivity band when plotted against the incident angle.

In order to design the optimum DBR for each angle, the thicknesses of the low and high index layers of an AlInP/$Al_{0.1}Ga_{0.9}As$ DBR were swept for different incident

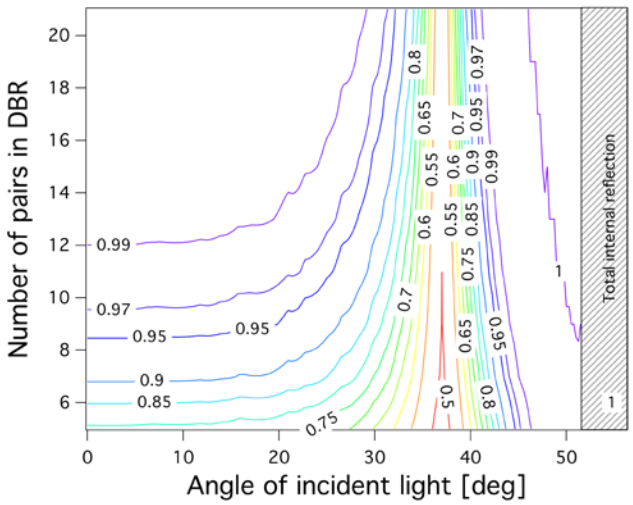


Fig. 4. 880 nm reflectivity at the base-BSF of a GaAs solar cell with an AlInP/$Al_{0.1}Ga_{0.9}As$ DBR structure inserted below the BSF, plotted against the angle of incident light and number of DBR pairs. For each incidence angle and number of pairs, the DBR thicknesses are optimized to give the maximum reflectivity at 880 nm.

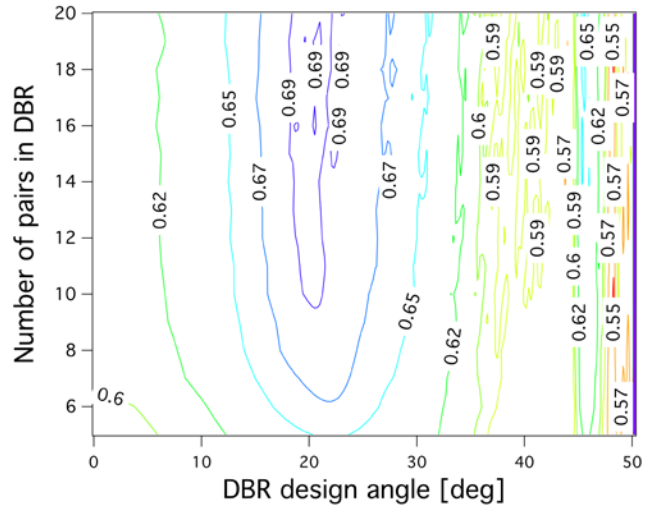


Fig. 5. Integrated reflectivity of the DBR under study, plotted against the design angle and the number of pairs in the DBR. Design angles above the total internal reflection angle are omitted because designing the DBR for these angles is useless.

angles and number of layer pairs in the DBR. The highest reflectivities at 880 nm in each case, were picked up and plotted against the incident angle and number of DBR pairs. The result is shown in figure 4.

As can be observed, as the incident light angle increases, the maximum reflectivity of the DBR optimized for that angle decreases, for a constant number of pairs in the DBR. For low angles, this can be compensated for by increasing the number of pairs in the DBR. However, as the angle further increases, the number of pairs required becomes clearly impractical. Around the Brewster angle of the $Al_{0.1}Ga_{0.9}As$/AlInP interfaces (38.4° at 880 nm), the reflectivity reaches its lowest value, due to the minimum reflectivity that the p-polarized light exhibits at this angle. For this reason, the reflectivity achievable at 880 nm is limited for incidence angles around 38.4°.

In figure 5, the integrated reflectivity is plotted against the design angle (DBR thicknesses obtained using equation (2)) and the number of pairs in the same DBR. As can be observed, the optimum design angle is ~21°. There is a narrow local maximum also at ~45°. When designing the DBR for an angle higher than 0°, two issues must be taken into account:

1) Designing the DBR for angles above 0° implies thickening its layers, as can be deduced from equation 2. For 21° the increase in thickness is ~7%.

2) Changing the DBR thickness to optimize it for a given incidence angle and to maximize its integrated reflectivity gives rise to a shift of the DBR center wavelength and, consequently, of its reflectance and transmittance. This is important when designing the DBR for a subcell other than the bottom cell in a multijunction. In this case, the transmittance in the range of wavelengths of interest for the underlying subcells must be considered. This is illustrated in Figure 6, where the transmittance of 12-pair DBRs designed for 0°, 21° and 45° are shown. The short circuit current density of a Ge and 1–eV GaInAs ideal bottom cell (Quantum Efficiency (QE)=1), with a GaAs middle cell + DBR, are calculated using the G173D solar spectrum and the transmittances shown in Figure 6. The results are shown in table II, together with the DBR total thickness required for each case.

TABLE II

THICKNESS OF AlInP/$Al_{0.1}Ga_{0.9}As$ 12 PAIR DBR FOR A GAAS MIDDLE CELL AND CURRENT DENSITY IN THE IDEAL QE=1 BOTTOM CELL INDICATED (G173D SOLAR SPECTRUM)

| Design angle | DBR thickness [nm] | $J_{sc}$ (Ge bottom cell) [mA/cm$^2$] | $J_{sc}$ (1-eV bottom cell) [mA/cm$^2$] |
|---|---|---|---|
| No DBR | - | 30.34 | 16.97 |
| 0° | 1782 | 25.48 | 12.10 |
| 21° | 1974 | 21.91 | 8.57 |
| 45° | 3749 | 21.70 | 14.09 |

The minimum $J_{sc}$ required in the bottom cell of a GaInP/GaAs/(Ge or GaInAs) triple-junction cell, so as not to limit the current of the whole device, is around 15 mA/cm$^2$. Therefore, the 21°-optimized DBR can be used for a GaAs middle cell in a GaInP/GaAs/Ge triple junction cell with a Germanium bottom cell. The transmittance obtained is high enough as to assure the required current in this bottom cell. However, this is not the case for a 1-eV GaInAs bottom cell, which is the optimum bandgap to combine with a GaAs middle cell and GaInP top cell in a triple-junction solar cell. Incidentally, another interesting result is the different effect of the design angle on the $J_{sc}$ of the Ge and 1-eV bottom cells:

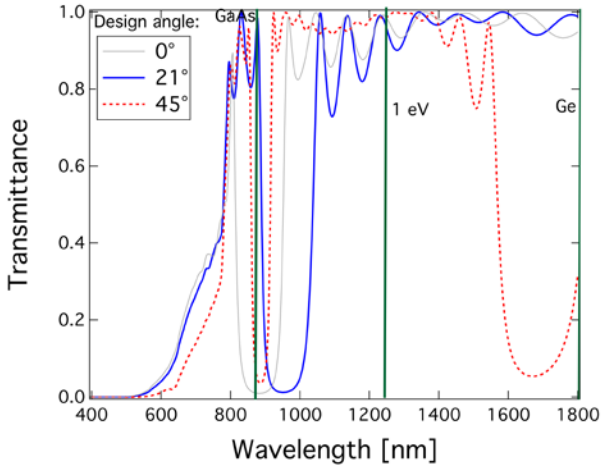


Fig. 6. Transmittance at 0° of the DBR optimized for maximum integrated reflectivity at 0°, 21° and 45° of incident light. The bandgap wavelengths of a GaAs, Ge and 1-eV subcell are indicated.

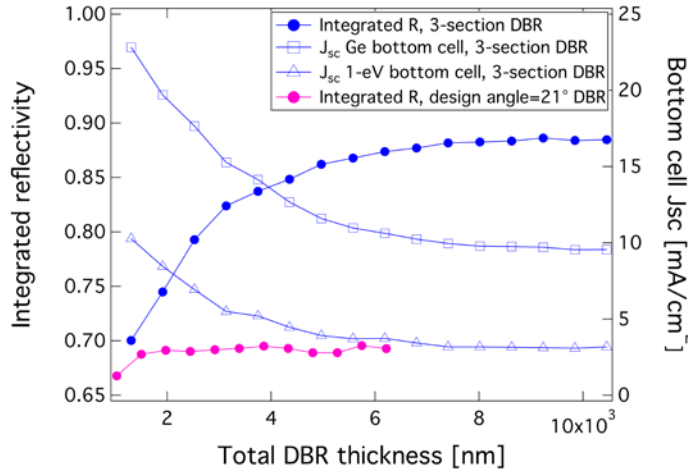


Fig. 7. Integrated (880 nm) reflectivity plotted against the total DBR thickness, for the DBRs indicated. The design angles in the 3-section DBR are 44°, 31° and 18°, respectively. The $J_{sc}$ of ideal (QE = 1) bottom cells made of Ge and 1-eV GaInAs material, in a triple-junction with a GaAs middle cell with the DBR, are also plotted on the right axis.

for a Ge bottom cell, the best design angle is 21°, while for a 1-eV bottom cell it is 45°. The reason for this is clearly made apparent by Figure 6.

*C. Designing a multi-section DBR.*

As shown in the previous section, a low total internal reflection angle and an optimum DBR design angle can be used to attain a total integrated reflectivity of ~0.69 at 880 nm (figure 5). According to Figure 2, this would lead to a $V_{oc}$ increase around 15 mV in our GaAs solar cells.

The next approach investigated to further increase the integrated reflectivity is to design a multi-section DBR, in which each of its sections is optimized for a different incident angle. The interaction of the light coming out of each DBR section produces that this composition of sections does not give rise to just the sum of the reflectances that each section would have separately. Therefore, a multi-variable search of the optimum combination has to be carried out. In the literature of DBRs used for semiconductor laser devices (see for example [8] and references) this is a common approach in which the thickness of every layer in the DBR is varied, giving rise to a high number of variables to be swept. Different algorithms can be used for this, the so-called simplex method being the most common. For the initial global search, genetic algorithms and others are used in these works.

For this work, a method consisting of dividing the DBR in three sections, each with constant thickness pairs, was chosen as a first approximation suitable for our assessment. A brute force algorithm has been used to look for the optimum combination of DBR sections, using the design angle in each section as the variables. The optimum combination found is 44°, 31° and 18° for each section, respectively. In Figure 7 the integrated reflectivity obtained is plotted against the total DBR thickness (higher thickness means higher number of pairs in each section), together with the $J_{sc}$ of ideal (QE = 1) Ge and 1–eV GaInAs bottom cells placed below the GaAs middle cell with the DBR. The reflectivity result for the 1-section DBR analyzed in the previous section is also shown for comparison.

Firstly, it can be observed that the 3-section DBR can reach an integrated reflectivity value approaching 0.88 as its total thickness increases. However, the transmittance of the DBR, at the range of wavelengths of interest for a Ge or 1-eV GaInAs bottom junction, decreases as the DBR total thickness increases. For the 1-eV GaInAs bottom cell, the DBR transmittance is not enough to obtain the required $J_{sc}$ in a current matched GaInP/GaAs/GaInAs triple-junction cell (around 15 mA/cm$^2$), for any DBR thickness. For the Ge bottom cell, DBRs of ~3.7 µm and below provide enough transmittance to get an appropriate $J_{sc}$. With this thickness restriction, the maximum integrated reflectivity obtained is ~0.83, as compared to ~0.69 obtained with the single-section DBR with performance optimized for 21° of incident light.

## V. Discussion

The theoretical calculations carried out show that the design of DBRs as effective back reflectors to enhance photon recycling in multijunction solar cells is strongly dictated by the sensitivity of the DBR reflectance to the light angle. The DBR designs analyzed, for application as back reflectors in a GaAs solar cell, allow increasing the integrated back reflectivity from ~0.47 (no DBR) to ~0.69 with an angle-optimized DBR, and to ~0.88 with a thick (> 10 µm) 3-section DBR. Reaching this 0.88 integrated reflectivity would only be

applicable, if the DBR thickness would not be a concern, for a GaAs single-junction cell, or in a multijunction where the GaAs cell is the bottom cell. The low transmittance in this DBR, and, consequently, the low $J_{sc}$ that would be attained in any bottom subcell placed below, is the cause. Decreasing the 3-section DBR thickness (by decreasing its number of pairs) to values below ~3.7 μm can be used to increase the transmittance of this DBR and make it applicable for a GaAs middle cell in a GaInP/GaAs/Ge triple-junction cell, at the cost of a lower total integrated reflectance, down to 0.83 or lower.

According to figure 2, at this reflectivity the $V_{oc}$ increase, from the case without DBR, would be around 35 mV. The applicability of the DBR structures to practical solar cells, technologically and economically speaking, has also to be analyzed. In a GaAs single-junction cell, with around 3.5 μm total thickness, growing an additional ~3.7 μm thick structure underneath implies a total thickness increase of around 100%. In a triple-junction, where the total thickness (without DBR) is around 10 μm, the increase would be of 37%. Although exact cost effectiveness calculations remain to be done, the economical viability of these approaches appears doubtful.

The experimental corroboration of the effectiveness of the DBRs designed will have to deal with technical difficulties in obtaining such thick structures with the required optical properties: sharp interfaces between layers, good morphology, etc; and electrical properties, mainly a low series resistance. These factors will be decisive in determining if the use of these DBRs to enhance photon recycling and $V_{oc}$ are technologically worthwhile or not.

Similar calculations have been carried out for other DBR material combinations of Table I, looking for a better transmittance behavior. No better result was obtained in this sense, and the thickness required to obtain similar reflectivities was significantly higher than in the AlInP/$Al_{0.1}Ga_{0.9}As$ case, as was predictable from the data shown in Table I. A more challenging option would be to use materials such as Ge or GaInAs(Sb), that would produce a higher index contrast to AlInP, but exhibit a high absorption, require the growth of lattice mismatched structures, growth of polar material/non-polar material structures, etc, which are more difficult to make compatible with the needed optical properties for a DBR.

Thought not in the scope of this work, mechanical stacked multijunction cells appear to be much better candidates to effectively exploit the possibility of enhancing the photon recycling in the solar cell by using back reflectors, thanks to the possibility of accessing the backside of each subcell and depositing a wide range of materials suitable to make almost ideal reflectors.

## VI. Conclusion

The designing of a semiconductor back reflector, based on a DBR, for monolithic single and multi-junction solar cells has been assessed. The application of a DBR as an effective back reflector to enhance photon recycling and the $V_{oc}$ in a solar cell has been shown to have a questionable potential to be technologically and economically feasible. Limited total integrated reflectivity attainable, low transmission in the range of wavelengths of interest for underlying subcells, and DBR integration in the structure are the most important technological problems found, while the large thickness required for the DBR is the main economical problem. The use of more complex multivariable designing procedures and the investigation of lattice-mismatched materials, with higher index contrast, remain to be studied as possible approaches to make semiconductor DBRs appropriate for photon recycling applications in monolithic multijunction solar cells.

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