# Increased Performance of Thin-film GaAs Solar Cells with Improved Rear Interface Reflectivity

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***Abstract*—The highest efficiencies in single-junction solar cells are obtained with devices based on GaAs. As this material is reaching the limit in material quality, the optimization of the design of the cell becomes more important. In this study we implement a patterning technique to the bottom contact layer of thin-film GaAs solar cells that increases the reflectance of photons to the active layers. Both shallow junction and deep junction devices were evaluated, and for deep junction cells, both the short circuit current and the open circuit voltage increase with the reflectance. The radiative saturation current density also decreases, indicating increased photon recycling. Detailed model simulations are performed to further evaluate the mechanisms leading to the improved performance of the deep junction design. Based on the same model, the possibilities for further improvements utilizing the deep junction are also identified.**

***Index Terms*—GaAs solar cells, Thin-film technologies, Photon Recycling.**

## I. Introduction

The most suitable III-V material for a single junction solar cell is GaAs, since it has the optimal bandgap to achieve high energy conversion rates and it has already shown the highest conversion rate among all types of single junction solar cells [1]. In 2005 the first world record for single-junction thin-film GaAs solar cells was achieved by Radboud University, with an efficiency of 24.5%, and a few years later this geometry equaled the 26.1% efficiency of the substrate based cell [2]. The current world record of 28.8% was achieved by Alta Devices in 2012, and it is 2.3% higher than the current record for a substrate based GaAs cell [3]. Because this efficiency has not been surpassed to date, it is safe to assume that this material is very close to the limit in material quality and the design of the cells becomes a determinant parameter in order to further increase the performance of these cells.

The typical structure for a single junction solar cell has a shallow junction (SJ) design, with a thin highly doped n-type emitter and a thick lightly doped p-type base. However, Steiner et al. [4] have demonstrated an increase in thin-film cell efficiency, mainly as a result of a higher open-circuit voltage ($V_{oc}$), using a deep junction (DJ) design with a thick, lightly doped emitter and a thin highly doped base layer. The high $V_{oc}$ values that were obtained in the latest thin-film GaAs solar cells indicate an increase in the external radiative efficiency of the cell [5]. In the thin-film structure, radiatively emitted photons cannot escape to the substrate, but are reflected from a metallized back surface, resulting in the large increase in Voc. Because GaAs is a good absorber but also a very good emitter, the high internal emission in DJ devices makes the optical design of the final devices to be extremely important, and theoretical studies indicate that improvements in the back-side mirror reflectance to a level beyond 95% will further increase the cell efficiency super-linearly [6].

In the current state of developing thin-film GaAs solar cells, either by ELO, or by mechanically/chemically removing the substrate, the result is a structure with passivating phosphide containing layers on top and bottom of the pn-junction, and the first and last layers are highly doped GaAs contact layers, responsible for a good ohmic contact. The front and rear metal contacts are gold and the structure is mounted on a Cu metal carrier. In between the grid fingers of the front contact, the contact layer is etched away to avoid parasitic absorption of light. The bottom contact layer, however, typically remains whole so that it absorbs a large portion of the photons below the bandgap energy that otherwise would have been reflected back to the active layers of the cell [7]. To circumvent this loss mechanism in this study we implement a patterning process to the p-GaAs contact layer that increases the reflectance in the radiative emission wavelength region in both SJ and DJ solar cells and compare the differences in performance of both structures. The results are further evaluated utilizing model simulations to identify the critical parameters influencing the cell performance in both geometries. Based on these simulations the potential for further improvements is discussed.

## II. Materials and Methods

The cells were grown using low-pressure MOCVD on 2 inch GaAs wafers with (1 0 0) $2^o$ off to [1 1 0] orientation. In this work, two junction depths were tested: a SJ design with a 75 nm thick emitter and a 2000 nm base, and a DJ design with a 2000 nm emitter and a 75 nm base. Before growth of the actual solar cell structure, a 150nm thick AlInGaP etch-stop layer was grown in order to limit the etching of the wafer. The wafer was etched in a citric acid/hydrogen peroxide solution for approximately 2 hours and subsequently the etch-stop layer was removed with HCl 37%. The now exposed p-contact layer was patterned by photolithography, as illustrated in figure 1, and etched in an ammonia/hydrogen peroxide solution. Each 2 inch wafer was patterned into cells with 3 different rear surface area coverages ($C_r$) of 100%, 30% and 10%. On the etched areas, 60 nm of ZnS was applied by thermal evaporation and the rear metal contact was e-beam evaporated continuously, so at the etched areas it acts as a mirror. The final structure was mounted on a copper foil that serves as a conducting, flexible and stable carrier.

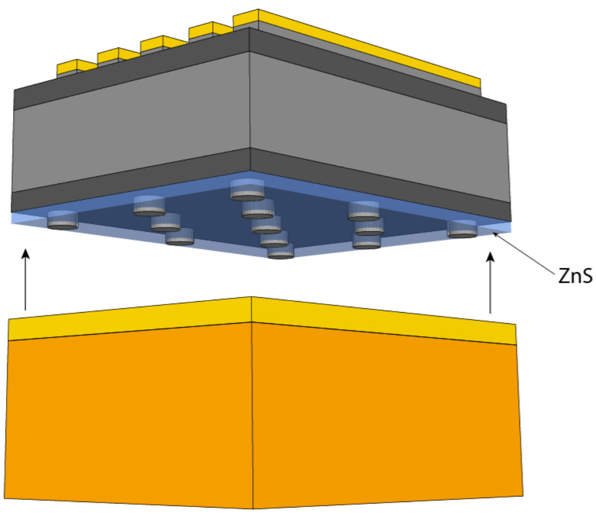


Fig. 1. Schematic (not to scale) depiction of the patterning process applied to the rear p-GaAs contact layer. Subsequently the removed contact area is filled with 60 nm ZnS and after that an Au/Cu metal foil reflector/carrier is applied to the entire rear side of the cell.

For probing convenience, a relatively large frontal grid coverage of 16.6% was applied, also by e-beam evaporation. 5 x 5 $mm^2$ solar cells were defined by a MESA etch, using an ammonia/hydrogen peroxide solution for the GaAs layer and a bromide solution for the phosphide layers. The n-GaAs contact layer was removed in between the grid fingers also with an ammonia/hydrogen peroxide solution, and an anti-reflection coating consisting of 44 nm of $MgF_2$ and 94 nm of ZnS was deposited by thermal evaporation.

After processing, J-V characterization (dark and illuminated) of the cells were performed using an ABET Technologies Sun 2000 Class AAA solar simulator, which provides a uniform illumination resembling the AM1.5G spectrum, over a 100 x 100 $mm^2$ area, with a maximum angular off set of $2^o$. The setup is equipped with a Keithley 2601B source meter and data acquisition is performed using ReRa Tracer3 software. The solar cells are kept at $25^o$C during measurement using a heating/cooling water thermostat and Pt100 temperature sensing. The reflectance measurements were performed using a FilMetrics spectrophotometer perpendicular to the analyzed surfaces.

## III. Results and Discussion

Radiatively emitted photons in GaAs have wavelengths ranging from 840 to 870 nm. Because radiative recombination is the major loss mechanism in high quality materials, the reflectance of the rear layers in the solar cell should be optimized for this region. The calculated reflectances at the bottom layers of the cells for both the region covered by the p-GaAs contact layer and for the region where the contact layer is etched away and replaced by ZnS are depicted in figure 2. There is a significant increase in reflectance in the wavelength regions between 700 nm and 870 nm for a wide range of angles of incidence in the etched structure.

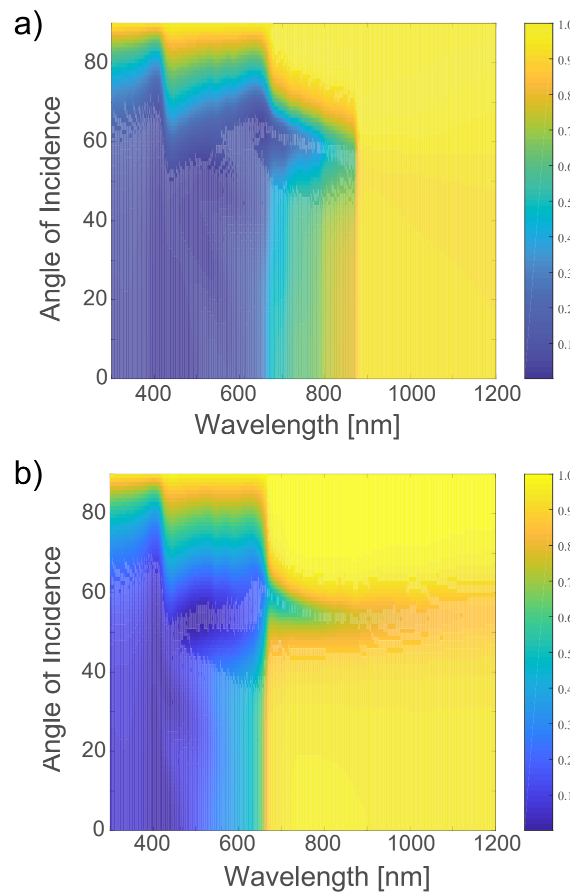


Fig. 2. Reflectance maps of light emitted at the active GaAs layers in the rear surfaces of a) a regular structure, with 100 nm of p-GaAs contact layer, and b) the etched structure with 60 nm of ZnS. Both structures have gold as the rear mirror.

The reflectance of photons in the rear layers directly affects the probability of spontaneously emitted photons to be reabsorbed in the solar cell. This probability is modeled in detail in the literature [4], and will be here referred to as the photon recycling factor ($f_{PR}$). In a solar cell, both the thickness of the active layers and the reflectance of the rear mirror directly affect the $f_{PR}$ value. For these calculations, the rear reflectance of the whole device was estimated to be a linear interpolation of both the etched and non-etched fractions of the rear contact. Figure 3 relates the thickness of the active layers with the resulting $f_{PR}$ for structures with different $C_r$ values. It is important to notice that a solar cell with $C_r$ = 0 % would not be operational, but it indicates the maximum increase in reflectance that this method would provide.

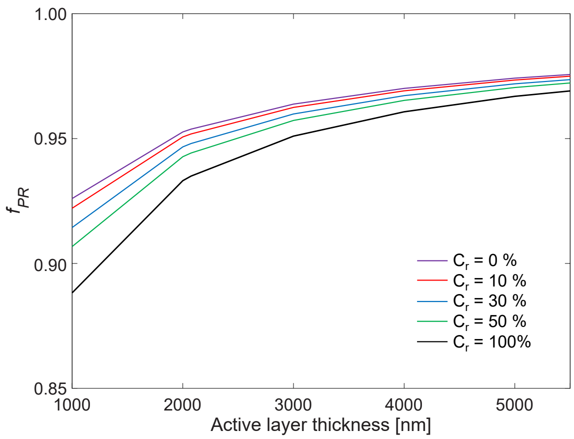


Fig. 3. Photon recycling factor ($f_{PR}$) as a function of the active layer thickness of solar cells with different $C_r$ values.

For thicker devices (around 3000 nm), the $f_{PR}$ is close to 0.95 without the need for changes in the rear contact design. As the devices become thinner, the rear contact reflectance should influence the $f_{PR}$ more strongly, since the probability of emitted photons to reach the rear mirror is higher in thinner devices. The solar cells used in this study have 2075 nm of active GaAs, and with this thickness, the expected increase in $f_{PR}$ obtained by the pattern with $C_r$ = 10 % is close to the maximum theoretical one ($C_r$ = 0 %), suggesting that further reducing the coverage should not bring significant benefits.

The increase in reflectance with the rear contact patterning in the produced solar cells was verified with a spectrophotometer. With this technique the reflectance is measured at the front surfaces of the cell. Because below the bandgap wavelength basically all the light is absorbed in the cell structure, only the behavior of the longer wavelength range of the incident light can be analyzed. The reflectance in this region is, however, a good indication of the reflectance just below the bandgap wavelength. In figure 4, the obtained reflectance curves show that for both SJ and DJ devices there is a large increase in the total reflectance with decreasing rear contact coverage.

The illuminated J-V curves of the produced solar cells are presented in figure 5. For the SJ solar cells, the shape of the J-V curves indicates that the patterning of the rear side has an overall detrimental effect, where the $J_{sc}$ values remain almost constant, but both the $V_{oc}$ and the FF decrease as $C_r$ decreases. For the DJ solar cells, however, there is a mild increase in $J_{sc}$ of 0.15 mA/cm$^2$ and a more than linear increase in $V_{oc}$ up to 8 mV. The fill factor, on the other hand, has a reduction of 3.4% as $C_r$ is further decreased from 30%

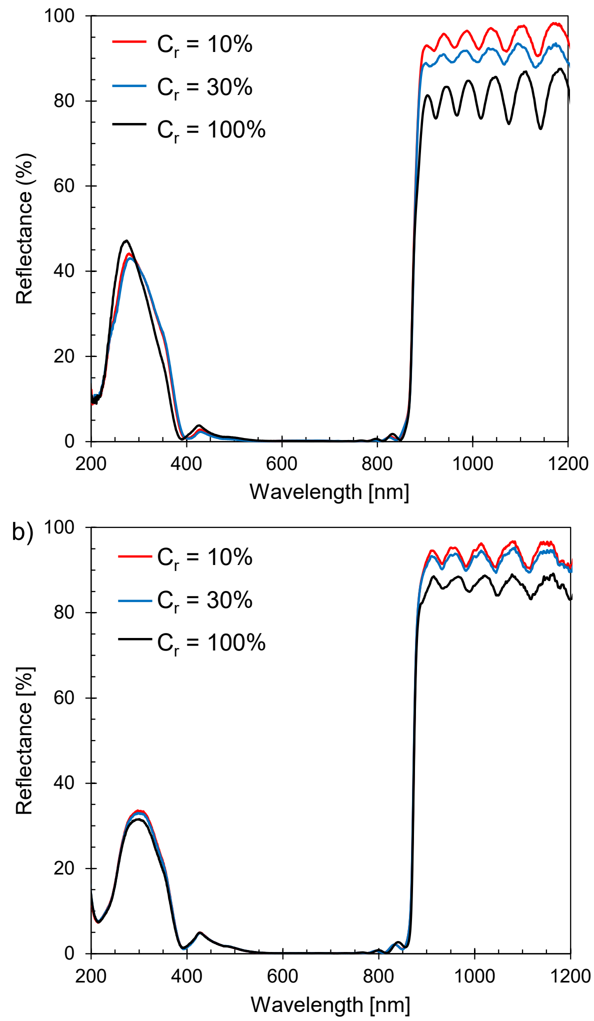


Fig. 4. Measured wavelength dependent reflectance of a) SJ and b) DJ solar cells with different Cr values.

to 10%. Because the rear contact consist of a thin Au layer and a thick Cu foil, contact resistances effects from this side can be disregarded, and the fill factor drop is associated to a large lateral resistance that carriers face from the point they are generated to the contact points.

The analysis of the dark curve of the cells shown in figure 6 allows a further understanding of differences in performance between the SJ and the DJ cells. Applying forward bias to a solar cell in the dark will generate a recombination current density $J_{rec}$ that can be approximated by two diodes in parallel, and is described by:

$$J_{rec} = J_{01}\left(e^{\frac{q[V-J_{rec}R_s]}{kT}}-1\right)+J_{02}\left(e^{\frac{q[V-J_{rec}R_s]}{2kT}}-1\right) \quad (1)$$

where $J_{01}$ is the saturation current density of the n=1 component and $J_{02}$ is the saturation current density of the n = 2 component. The ratio between the two components of the recombination current is voltage dependent, with non-radiative recombination dominating $J_{rec}$ at low voltages (the n

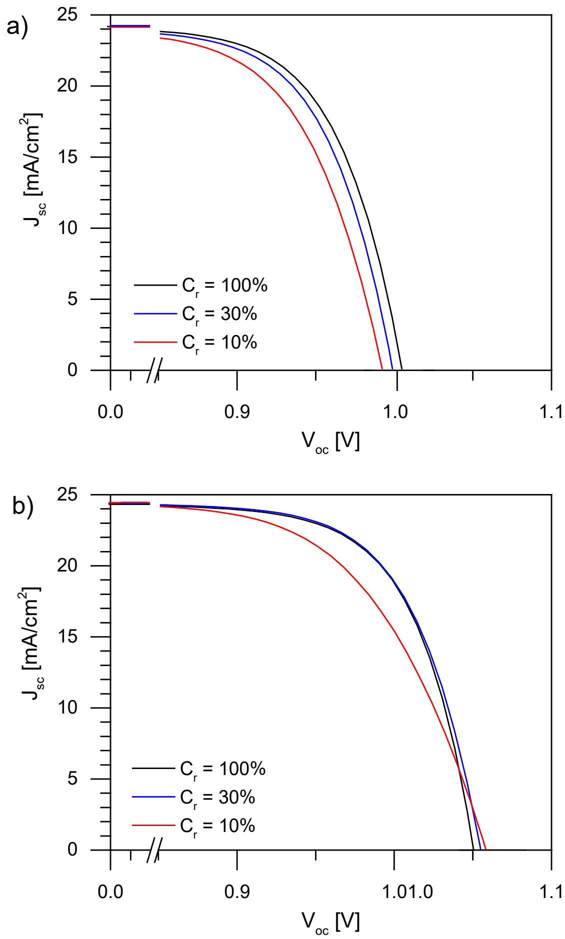


Fig. 5. Illuminated J-V curves of a) SJ and b) DJ solar cells with different Cr values.

= 2 region) and radiative recombination dominating at higher voltages (the n = 1 region).

For $C_r$ = 100% the generated dark curves presented values for $J_{02}$ of 1.5x$10^{-11}$ A/cm$^2$ for the SJ cell and 4.7x$10^{-12}$ A/cm$^2$ for the DJ cell. For the increase in reflectance to have sufficient impact on the performance of the cells by an increase in the $V_{oc}$, $J_{02}$ has to be sufficiently low so that $J_{01}$ configures a larger fraction of $J_{rec}$ [8]. The fact that the SJ device exhibits a $J_{02}$ value that is one order of magnitude higher than that of the DJ cells shows that at operating voltage $J_{rec}$ of the SJ cell is mostly non-radiative.

In the DJ cells, a decrease in the $J_{01}$ value from 8.8x$10^{-20}$ A/cm$^2$ for $C_r$ = 100% to 6.0x$10^{-20}$ A/cm$^2$ for $C_r$ = 10% confirms that the increase in voltage is indeed a result of a more efficient re-absorption of emitted photons. It has been previously stated that thin-film solar cells can only achieve efficiencies closer to 30 % in a deep junction geometry [8], and the results showed in this work support this suggestion. The production of good quality single crystalline epitaxial cells with a deep junction and high internal emission combined with a well-designed rear mirror have the potential to achieve efficiencies close to the theoretical limit of 33.5 %

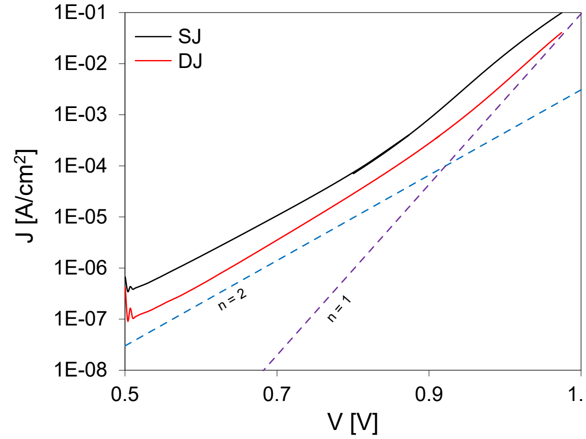


Fig. 6. Dark I-V curves of the SJ and DJ solar cells with Cr = 100%.

[6].

## IV. Conclusion

In this study, the effect of the junction depth and the reflectance of the bottom layers in thin-film GaAs solar cells is evaluated. A patterning approach that removes part of the absorbing contact layer and increases the rear side reflectance was applied to both shallow junction and deep junction solar cells. The processing of solar cells with different $C_r$ on the same growth wafer allowed for direct comparison between the applied geometries. The resulting solar cells exhibited an increase of more than 20% in reflectance of the incident light for wavelengths just above the band-gap at the lowest $C_r$ value.

The effect of the patterning was found to be detrimental for the performance of the SJ devices, even though the reflectance was increased. For the DJ devices, however, both Jsc and $V_{oc}$ increased with decreasing $C_r$ values. The dark current analysis suggests that the differences in performance is due to a much larger non-radiative saturation current density in the SJ devices. The results in this study experimentally confirm the previously reported relationship between the reflectance of the rear contact and the parameters of thin-film GaAs solar cells. Furthermore, it was shown that the deep junction geometry is required in order to produce devices with high internal emission, which allows the dark current to be further reduced without changes to the active cell structures. The presented concept together with further reduction of the non-radiative losses at the perimeter of the cells represent a viable approach to produce single junction GaAs solar cells with efficiencies closer to 30%.

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## REFERENCES


[1] W. Yang, J. Becker, S. Liu, Y. Kuo, J. Li, B. Landini, K. Campman, Y. Zhang, Ultra-thin GaAs single-junction solar cells integrated with a reflective back scattering layer, J. Appl. Phys. 115, 203105 (2014).

[2] G. J. Bauhuis, P. Mulder, E. J. Haverkamp, J. C. C. M. Huijben, J. J. Schermer, 26.1% thin-film GaAs solar cell using epitaxial lift-off, Solar Energy Materials and Solar Cells 93 (2009) 1488-1491.

[3] M. A. Green, Y. Hishikawa, W. Warta, E. D. Dunlop, D. H. Levi, J. Hohl-Ebinger, A. W. H. Ho-Baillie, Solar cell efficiency tables (version 50), Prog Photovolt Res Appl. 2017; 25:668676.

[4] M. A. Steiner, F. J. Geisz, I. Garca, D. J. Friedman, A. Duda, S. R. Kurtz, Optical enhancement of the open-circuit voltage in high quality GaAs solar cells, J. Appl. Phys. 113, 123109 (2013).

[5] E. D. Kosten, B. M. Kayes, H. A. Atwater, Experimental demonstration of enhanced photon recycling in angle-restricted GaAs solar cells, Energy Environ. Sci., 1907-1912 (2014).

[6] O. D. Miller, E. Yablonovitch, S. R. Kurtz, Strong internal luminescence as solar cells approach the Schokley-Queisser limit, IEEE Journal of Photovoltaics. Vol 2. No 3 (2012)

[7] N. Gruginskie, S. C. W. van Laar, G. Bauhuis, P. Mulder, M. van Eerden, E. Vlieg, J. J. Schermer, Increased performance of thin-film GaAs solar cells by rear contact/mirror patterning. Submitted to Thin Solid films in 2018.

[8] G. Bauhuis, P. Mulder, Y. Hu, J. Schermer, Deep junction III-V solar cells with enhanced performance, Phys. Status Solidi A 2016, No. 8, 2216-2222

[9] B. M. Kayes, H. Nie, R. Twist, S. G. Spruytte, F. Reinhardt, I. C. Kizilyalli, G. S. Higashi, 27.6% Conversion efficiency, a new record for single-junction solar cells under 1 sun illumination, Conference Record of the IEEE Photovoltaic Specialists Conference (2011)