# Design considerations on GaInNAs solar cells with back surface reflectors

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***Abstract* — We report on design considerations for developing dilute nitride solar cells with back surface reflectors. Two different scenarios including specular and diffuse reflectors were modeled and their effects on solar cell characteristics were compared with cells without reflectors. We show that for optimal performance of the solar cell with back surface reflectors, the layer structure of the cell has to be optimized taking into account the reflector properties. Using high quality reflectors the usable background doping range for GaInNAs sub-junctions can be extended to above $1\times10^{16}$ cm$^{-3}$.**

## I. Introduction

Dilute nitrides (GaInNAs) based materials are offering unique properties for developing high-efficiency III-V multijunction solar cell [1]. Efficiency levels exceeding 44% have already been demonstrated using dilute nitrides fabricated by molecular beam epitaxy (MBE) as bottom junction in triple junction solar cells [2].

While they offer widely tuneable bandgaps and lattice matching to GaAs, dilute nitrides often exhibit short carrier lifetimes and short minority carrier diffusion lengths, as well as high background doping concentrations, prompting for extensive optimization of the fabrication conditions. It has been shown that the carrier lifetime in low quality GaInNAs is only a few tens of picoseconds and while it can approach ns level when the fabrication conditions are optimized [3]. Short carrier lifetimes with rather low electron and hole mobilities lead to the fact that the carrier collection probability in GaInNAs n-i-p solar cells is largely dependent on the width of the depletion region and thus on the background doping of the unintentionally doped intrinsic GaInNAs layer. To reach depletion widths larger than 1 μm, thus allowing high photocurrent generation and at the same time high carrier collection probability, the GaInNAs layer usually should have background doping level below $10^{16}$ cm$^{-3}$ [5]. Such low background doping levels can be controllably achieved by using MBE but not so easily by using MOCVD [6]. Therefore, to alleviate at least partially the requirement for low background doping level, structural modifications are needed. For example, the optical path of photons inside the GaInNAs layer can be extended using more complex optical designs [7-9]. Metallic back surface reflectors and distributed Bragg reflectors (DBR) inserted below the GaInNAs junctions have already been used for increasing the photogeneration in GaInNAs solar cells. [10-12]. To this end, it is however, important to understand how the choice of the reflector affects the optimal layer design. Here, we present results of a study aiming to understand how the use of back reflector affects the design constrains of GaInNAs solar cell.

## II. Experimental

The solar cells comprised an unintentionally doped GaInNAs layer sandwiched between n-GaAs and p-GaAs layers. The cell contained a p-GaInP back surface field (BSF) layer and a thin AlInP window layer. .

We studied two reflector concepts, shown in Fig. 1. The first reflector is a highly reflecting metal mirror producing a specular reflection at the rear side of the GaInNAs junction. The second reflector scheme provides a highly efficient diffuse reflection at the rear of the junction.

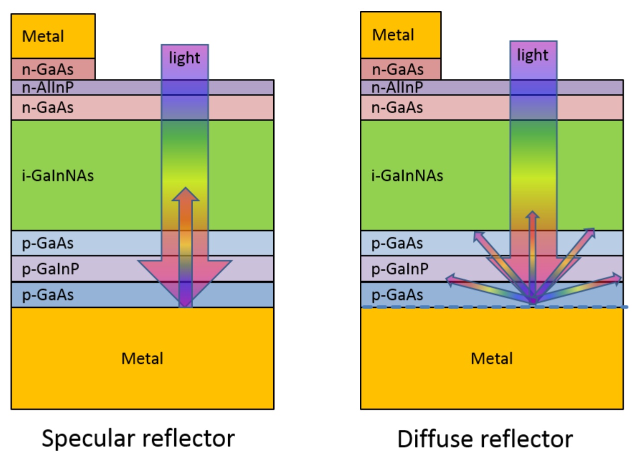


Fig 1. Generic test structures for the GaInNAs back surface reflector solar cell with different reflector types.

The operation of the cells was first simulated using PC1D for which we have developed a model adapted to GaInNAs [13, 14].

First, the electrical parameters of a standard GaInNAs junction were modeled and the results were checked against experimental results from similar structures to validate the model. The front side of the cell was assumed to be antireflection (AR) coated. For the specular and diffuse reflectors, we assumed a lump reflectance for all the wavelengths to allow for simpler comparison between the two approaches.

The short circuit current density ($J_{sc}$), open circuit voltage ($V_{oc}$), and efficiency ($\eta$) were modeled for junctions with specular and diffuse reflectors. GaInNAs layer thickness, doping level and backside reflectance were set as variables in the simulations.

## III. RESULTS AND DISCUSSION

The modeled $J_{sc}$ values of solar cells without reflector and with specular or diffuse reflectors as a function of GaInNAs thickness are shown in Fig. 2. The cell structure was considered similar to what was studied in [14]. Both reflectors were assumed to provide a very high reflectance, which is feasible for high quality metal reflectors. We considered an AM1.5G spectrum and a 900 nm long-pass filter that was inserted between the light source and the solar cell to mimic the conditions below the GaAs sub-junction of a GaInP/GaAs/GaInNAs triple junction or GaInP/GaAs/GaInNAs/Ge four junction solar cell.

The cell without a reflector produces a $J_{sc}$ of only 12.4 mA/cm$^2$, which is well in line with real measurements of similar cells. Therefore, the GaInNAs sub-junction would limit the current in triple junction cells. However, when a specular reflector is used, the maximum $J_{sc}$ increases to 13.9 mA/cm$^2$. The corresponding value for a diffuse reflector is 14.4 mA/cm$^2$. Such parameters would already be closely current matched in triple junction cells [15, 16]. For the four junction cells, $J_{sc}$ without reflector would be enough for current matching.

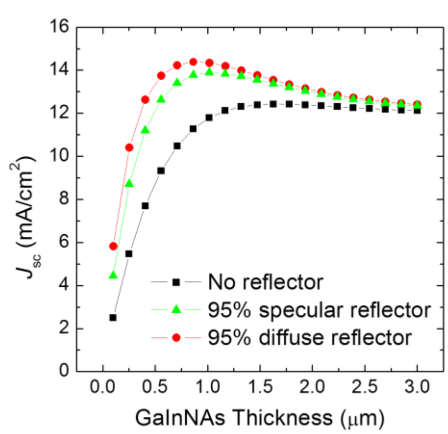


Fig. 2. Comparison of calculated $J_{sc}$ vs. GaInNAs thickness for solar cells with and without reflectors. The simulation parameters for the cell are taken from [14]. The background doping level of the GaInNAs layer is $2.2\times10^{16}$ cm$^{-3}$.

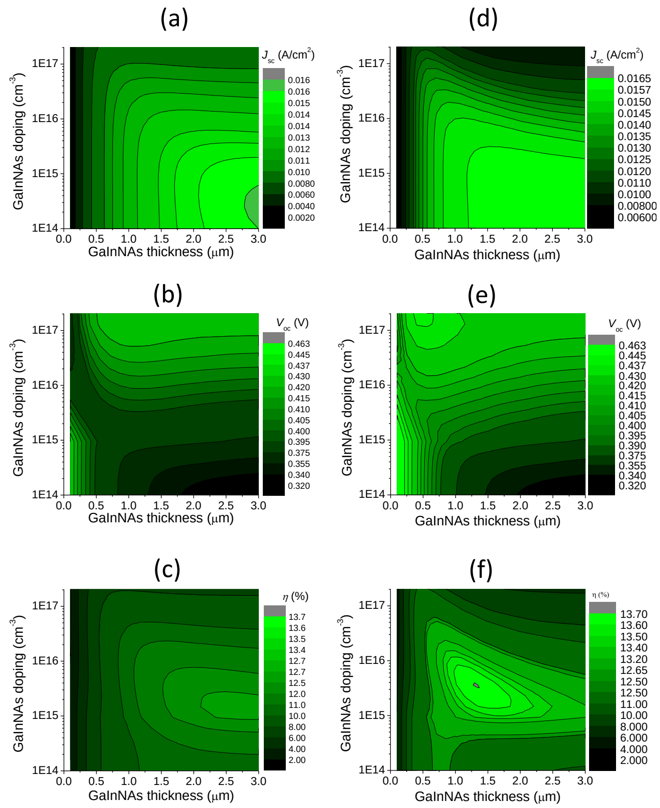


Fig. 3. (a)-(c) Modeled GaInNAs n-i-p solar cell characteristics without backside reflector. (d)-(e) Modeled GaInNAs n-i-p solar cell characteristics with a 95% diffuse backside reflector.

The $J_{sc}$ results show that there is clearly an optimal thickness for the GaInNAs layer for each type of reflector. Another important detail is that the optimal GaInNAs thickness is considerably reduced for the cells having a backside reflector. For this particular cell type, the optimum GaInNAs thickness with a 95% specular reflector is at about 1 μm, and for a 95% diffuse reflector the optimal thickness is reduced even further down to 850 nm. The ability to reduce the GaInNAs layer thickness without losing its functionality has favorable effects on the fabrication costs of the multijunction solar cells due to increased throughput and reduced material costs.

Next, different combinations of thickness and the doping level of GaInNAs were modeled for cells with and without diffuse reflector and the results are shown in Fig. 3. It is evident, that the highest $J_{sc}$ for both samples is obtained when low doping level and rather thick GaInNAs layers are used. However, the $V_{oc}$ behaves the differently, i.e., it has a minimum when the doping level is low and the GaInNAs thickness is large. As consequence, the efficiency of the GaInNAs solar cell is maximized at a unique combination of GaInNAs thickness and doping level, which for the cell without reflector is at 2.75 μm and $1.5\times10^{15}$ cm$^{-3}$, respectively. For the 95% diffuse reflector the maximum efficiency is obtained when GaInNAs thickness is 1.3 μm and the doping level is $4\times10^{15}$ cm$^{-3}$. Using the latter values, the cell made of GaInNAs would have potential for $J_{sc}$ of 15.5 mA/cm$^2$ and $V_{oc}$ of 0.402 V when a highly reflective diffuse reflector is inserted at the back of the junction. This indicates, that for optimal behavior, the background doping level of GaInNAs should be reduced from $2.2\times10^{16}$ cm$^{-3}$ down to $4\times10^{15}$ cm$^{-3}$.

With the GaInNAs solar cell material discussed in [14] as an initial point, the thickness of the GaInNAs layer can also be optimized for various reflectance values of the back surface reflector. This is depicted in Fig. 4, in which the efficiency of a GaInNAs solar cell is shown as functions of backside reflectance and GaInNAs layer thickness. The results indicate that for each backside reflectance value, a unique GaInNAs layer thickness is required to maintain the highest possible performance of the solar cell. For this particular cell, the highest efficiency without reflector is obtained with GaInNAs thickness of about 1.7 μm.

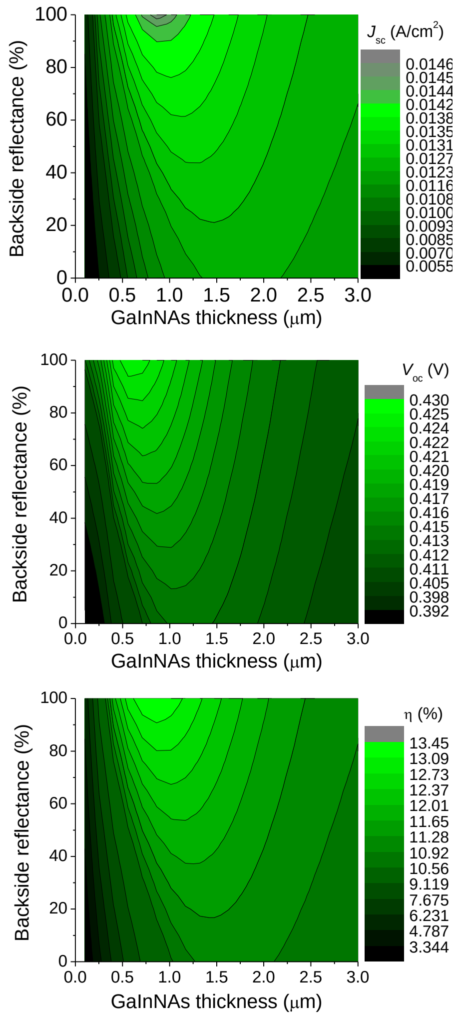


Fig. 4 $J_{sc}$, $V_{oc}$ and $\eta$ of a n-i-p solar cell as functions of reflectance of the diffuse reflector and GaInNAs thickness.

In addition, as the backside reflectance is varied, the $J_{sc}$ and $V_{oc}$ are not maximized at the same GaInNAs thickness. When designing the use of GaInNAs sub-junctions with backside reflectors, it is important to pay attention to the fact that regardless of the backside reflectance, the maximum $J_{sc}$ is always obtained with thicker GaInNAs layer than what is needed to obtain the maximum $V_{oc}$. For example, in Fig. 4 the maximum $J_{sc}$ of a junction with a 100% reflector is obtained for GaInNAs thickness of 0.87 μm and the maximum $V_{oc}$ is obtained at 0.6 μm.

The model used here does not take into account multiple reflections at the back and front surfaces. This would most likely have some effect on the modeled optimal layer thicknesses. However, because the AR-coating has already reflectance of only a few percentage points the amount of light for the second roundtrip within the cell is very small and thus we have neglected this possibility.

## IV. Conclusion

We have used a PC1D based model for simulation of the effect of back surface reflectors on GaInNAs single junction n-i-p solar cells. The results show that using diffuse reflectors it is possible to extend the usable background doping range for GaInNAs to levels above $1\times10^{16}$ cm$^{-3}$ and yet maintain high current production needed for the bottom sub-junction of high-efficiency triple junction solar cell.


## Acknowledgment

The authors want to thank European Research Council for financial support under the ERC Advanced Grant AMETIST #695116.


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