# Improving the current output of GaInNAs solar cells using distributed Bragg reflectors

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***Abstract* — The influence of AlGaAs-based distributed Bragg reflector (DBR) on the performance of a GaInNAs n-i-p solar cells is reported. The DBR increased the short circuit current density by ~1 mA/cm$^2$, owing to increased external quantum efficiency in the wavelength range from 1120 nm to 1240 nm. As a result of the incorporation of the DBR structure, the series resistance of the cell was increased by 4 mOhm·cm$^2$.**

## I. Introduction

Dilute nitrides, i.e. GaInNAs, with 1 eV bandgap ($E_g$) have emerged as a promising approach for improving the efficiency of III-V multijunction solar cells [1]. Triple junction solar cells with dilute nitride sub-junction grown by molecular beam epitaxy (MBE) have already demonstrated conversion efficiencies exceeding 44% under concentrated sunlight [2]. However, in order to achieve device-grade GaInNAs materials, a thorough optimization procedure and a relatively tight growth parameter window is required. When not fully optimized, GaInNAs heterostructures could exhibit low charge carrier lifetimes, high background doping, and short minority carrier diffusion lengths leading to degradation of photovoltaic conversion. For example, the carrier lifetimes can vary from 10 ps for non-optimized growth condition, while can be as high as ~1 ns when proper fabrication parameters are used [3]. Moreover, the background doping levels in unintentionally doped GaInNAs are usually of the order of $10^{16}$ cm$^{-2}$ or larger which leads to depletion region widths of ~1 µm or shorter [4, 5, 6]. This leads to photocarrier collection from a reduced volume within the device, corresponding to roughly the sum of depletion width and the diffusion length of minority carriers. The reduced collection volume limits the short-circuit current density ($J_{sc}$) of a pn-junction, a p-i-n or an n-i-p type solar cell.

To alleviate the problems arising from increased background doping, one can use backside reflectors which artificially increase the optical path length of light within the solar cell. This can be done either by using metal mirrors [7] or using DBR structures [8–14], which consist of alternating layers of semiconductor materials with different refractive indices. The advantage of using such DBR structures is that they allow for monolithic fabrication of the mirror structure in one growth run during the MBE process, while the use of metal mirrors requires more complicated processing involving substrate removal. Despite this known advantage, DBRs have not been employed in connection with GaInNAs solar cells for increasing the tolerance of variations in the material quality and photocurrents of the dilute nitride junctions.

In this paper we report the influence of DBR mirrors on the current-voltage characteristics and external quantum efficiency (EQE) of a GaInNAs n-i-p solar cell.

## II. Experimental

### A. Fabrication of single junction GaInNAs solar cells

The structural layout of the single junction 1eV GaInNAs solar cells is shown in Fig. 1a. The structure was grown on p-GaAs(100) substrate using a Veeco GEN20 solid source MBE.

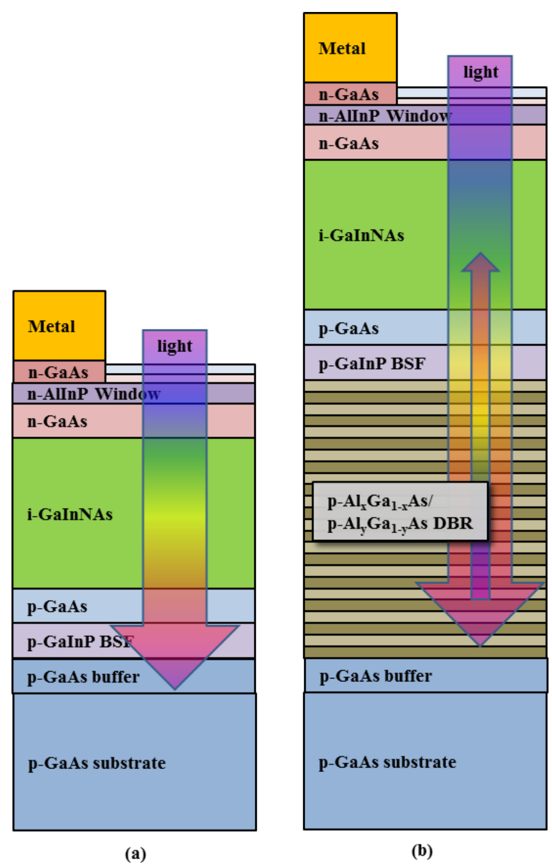


Fig 1. Generic test structures for the GaInNAs solar cells with AlInP window and GaInP back surface field (BSF) layers: (a) single junction GaInNAs solar cell and (b) GaInNAs solar cell with a DBR back reflector.

SUMO cells were used for group III elements and a valved cracker source was used for incorporation of As. Nitrogen was introduced by an RF plasma source. More details about the growth can be found in [4].

Ni/Au/Ge/Au finger patterns were formed using a shadow mask process and e-beam evaporation. The backside metallization was done using Ti/Pt/Au. The areas of the solar cells were 0.117 $cm^2$. The cells were antireflection (AR) coated with $TiO_2/SiO_2$ double layers, fabricated by e-beam evaporation.

### B. Integration of DBR back reflector

The p-AlGaAs DBR mirror structures were first grown on p-GaAs(100) substrates; the stopband of the DBR was designed for wavelengths just above the bandgap of the GaInNAs to reflect the wavelengths at which the quantum efficiency is typically low for GaInNAs solar cell. Then, the GaInNAs single junction solar cell structure was grown on the DBR and the solar cell devices were processed in identical fashion. The schematic layer structure of the dilute nitride solar cells with a DBR mirror is presented in Fig. 1b.

### C. Measurements

The light-biased current-voltage (LIV) measurements were performed on the cells in real sun conditions (AM1.5G) at $T$=20 °C. The light intensity was measured using a Kipp&Zonen CM11 pyranometer. The reflectance of the DBR mirror was measured using a spectrophotometer and the EQEs were measured using a 250 W quartz tungsten halogen lamp, a Digikrom DK240 monochromator, an SR830 lock-in amplifier and chopped light. NIST-calibrated Si and Ge reference detectors were used for the wavelength ranges of 400–800 nm and 800–1500 nm, respectively. The DBR reflectance was measured using a commercial RPM2000 tool and a silver reference mirror.

## III. Results and discussion

LIV characteristics of the cells are shown in Fig. 2a. The open circuit voltages ($V_{oc}$) of the devices are 0.41 V for both types of structures. The $J_{sc}$ values for the best GaInNAs single junction cells with and without DBR were ~34 $mA/cm^2$ and ~33 $mA/cm^2$, respectively.

The reflectance of the DBR mirror is shown in Fig. 2b together with EQEs. The stopband of the DBR is located from the band edge of GaInNAs down to about 1120 nm. The EQE of the sample with DBR is increased in the wavelength range corresponding to the DBR stopband. The EQE is not affected for other wavelengths than those corresponding to the stopband. This explains increase of the $J_{sc}$ when DBR is used. Another important point to compare between the cells with and without DBR is the series resistance. It is known that DBRs have multiple interfaces due to large amount of layers. Each interface may have a band discontinuity each of which incrementally increases the series resistance of the device. This eventually reduces the fill factor (FF) of the device. In our case the FF was 0.67 for the solar cell without DBR and 0.64 for the solar cell with DBR. Although there is a small

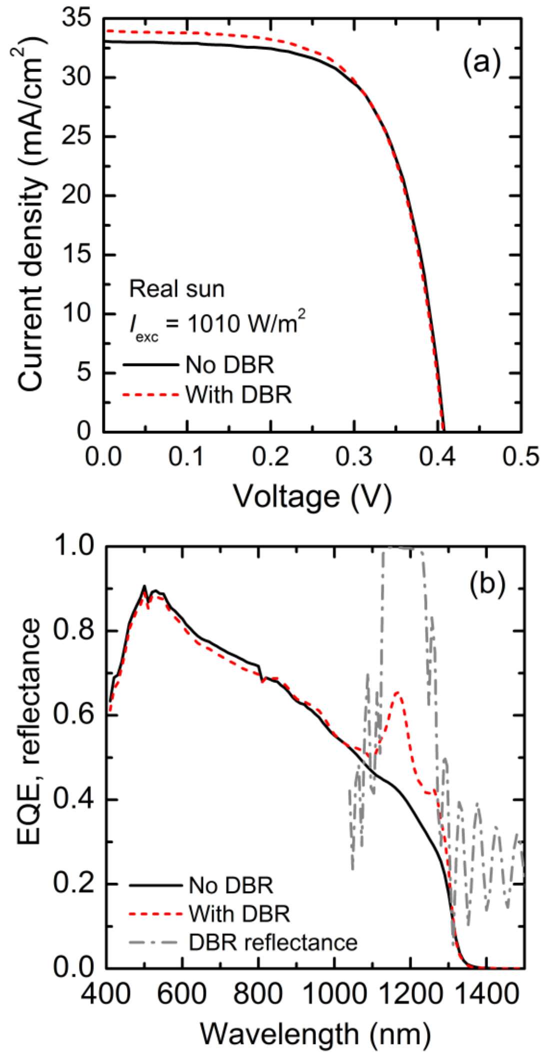


Fig. 2. (a) Measured LIVs from GaInNAs solar cells with and without DBR reflectors. (b) EQE and reflectance values for GaInNAs solar cells with and without DBR reflector showing the improvement of photocurrent in the GaInNAs junction.

degradation of the FF, the similar $V_{oc}$ values already indicate that the series resistance induced by the DBR structure is not substantially degrading the electrical characteristics of the GaInNAs junction. Therefore, such structures could potentially be used to improve the characteristics of multijunction solar cells containing dilute nitride sub-junctions.

To study the electrical parameters in more detail, we used a 2-diode modeling of the LIVs. The model is based on the Eq. 1 [15].

$J = J_{ph} - J_{01}[\exp(V+JR_s)/(n_1 v_T)-1] - J_{02}[\exp(V+JR_s)/(n_2 v_T)-1] - [(V+JR_s)/R_p]$, (Eq. 1)

Where $J_{ph}$, $J_{01}$, and $J_{02}$ are the photocurrent density and reverse saturation current densities for diodes 1 and 2, respectively. $V$ is the applied voltage, $J$ is the current density, $v_T$ is thermal velocity of carriers, $n_1$ and $n_2$ are the ideality factors for diodes 1 and 2, and $R_s$ and $R_p$ are the series and parallel resistances, respectively. The best fit 2-diode parameters, obtained using a Matlab-based code [16, 17], are summarized in Tables I and II. In the fitting procedure, the $n_1$ was fixed to 1 for both samples.

Table I. Electrical parameters of the measured solar cells deduced from the 2-diode fitting. $V_{mpp}$ is the voltage at maximum power point, $J_{mpp}$ is the current density at the maximum power point, $P_{mpp}$ is the output power at maximum power point, and $\eta$ is the solar cell efficiency.

| Sample | DBR | $V_{oc}$ (V) | $V_{mpp}$ (V) | $J_{mpp}$ (A/cm²) | $P_{mpp}$ (W/cm²) | FF (%) | Eta (%) |
|---|---|---|---|---|---|---|---|
| G0869 | no | 0.408 | 0.317 | 0.028 | 0.009 | 0.67 | 8.96 |
| G0871 | yes | 0.409 | 0.303 | 0.029 | 0.009 | 0.64 | 8.91 |

The $V_{oc}$ values are almost the same for both samples. The $V_{mpp}$ is degraded by 14 mV while the $J_{mpp}$ is increased by one mA/cm$^2$ for the sample with DBR, when compared to the sample with no DBR. The overall efficiencies of the devices are almost identical.

Table II. 2-diode model parameters obtained for the measured solar cells.

| Sample | DBR | $J_{01}$ (A/cm²) | $J_{02}$ (A/cm²) | $J_{photo}$ (mA/cm²) | $R_{ser}$ (Ohm·cm²) | $R_{par}$ (Ohm·cm²) | $n_1$ | $n_2$ |
|---|---|---|---|---|---|---|---|---|
| G0869 | no | 1.79E-17 | 4.08E-06 | 32.72 | 0.045 | 5.88E+13 | 1.0 | 1.800 |
| G0871 | yes | 1.61E-12 | 1.20E-05 | 34.01 | 0.049 | 5.71E+12 | 1.0 | 2.024 |

The 2-diode model fit reveals that the series resistances of the two samples are almost the same. There is only 4 mOhm·cm$^2$ increase in the $R_s$ for the sample with DBR. Such an increase in $R_s$ does not considerably affect the functioning of solar cells operated at one sun illumination. Also, the parallel resistance remains at a high level indicating that fabrication of the DBR below the GaInNAs junction did not considerably increase the shunt behavior of the dilute nitride sub-junction. The largest difference between the samples is seen in the $J_{01}$. The $J_{01}$ of the sample with DBR is five orders of magnitude larger than that of the sample without DBR. This points to increased recombination in the GaInNAs junction, likely as a consequence of higher number of defect species generated in the dilute nitride junction by the cumulated compressive strain during the growth of the DBR.

The results from the LIV measurements and the 2-diode model fitting indicate that DBRs can be used for increasing the current densities at the maximum power point of dilute nitride sub-junctions and thus they can be used for current matching of multijunction solar cells employing dilute nitrides.

## IV. Conclusion

The results show that AlGaAs based DBR mirrors can be successfully used for tuning the electrical characteristics of the dilute nitride solar cells. The DBR improved the photocurrent production of the GaInNAs junction by 1 mA/cm$^2$. The DBR structure only marginally increased the series resistance of the solar cell. Such DBR structures have a great potential to be used for refining the current matching of multijunction solar cells with dilute nitride sub-junctions.

## Acknowledgment

The authors acknowledge the Finnish Funding Agency for Technology and Innovation, Tekes, via project ‘Nextsolar’ #40239/12. The authors want to thank also Mr. Pekka Malinen, Mr. Joel Salmi, and Ms. Wenxin Zhang for their valuable experimental support.

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