HIGH EFFICIENCY THIN FILM GaAs SOLAR CELLS WITH IMPROVED RADIATION HARDNESS

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ABSTRACT: In the present work, the performance of thin film GaAs solar cells with a mirror back contact is compared to regular GaAs cells on a substrate. A world record efficiency of 24.5% AM1.5G is obtained for a thin film cell with a gold mirror. The thin film cell thickness is only half of the regular GaAs cell thickness, which improves the radiation resistance for use in space applications and enhances the open-circuit voltage by more than 10 mV. The efficiency of the thin film cell, which is 0.5% lower at this stage, has the potential to surpass that of regular GaAs cells in the near future.
Keywords: III-V Semiconductors, thin film, radiation damage

1 INTRODUCTION

Using the Epitaxial Lift-Off (ELO) technique a III-V device structure can be separated from its GaAs substrate by selective wet etching of a thin release layer. The thin film structures obtained by the ELO process can be cemented or Van der Waals bonded on arbitrary smooth carriers for further processing. The ELO method, initially able to separate millimetre sized GaAs layers with a lateral etch rate of about 1 mm/h, has been developed to a process capable to free entire 2" epitaxial structures from their substrates with etch rates up to 30 mm/h [1]. After cleaning, the substrate can be reused for epitaxial growth. With these characteristics the method has a large potential for the production of high efficiency thin-film solar cells. By choosing the right deposition and ELO strategy, the thin-film III-V cells can be adequately processed on both sides allowing for an entire range of new cell structures.

Initially, a process was developed in which the sample with the carrier is mounted upside down above the etch solution in a closed container [2]. A variable weight attached to the foil provides the required external force (see fig. 1a). A disadvantage of this separation method is that the flexible carrier can bend too much, resulting in cracking of the epitaxial layer structure. For this reason a set-up was developed in which the slit is forced open with a constant radius of curvature by guiding the foil and the part of the film that is separated over a curved surface (see fig. 1b).

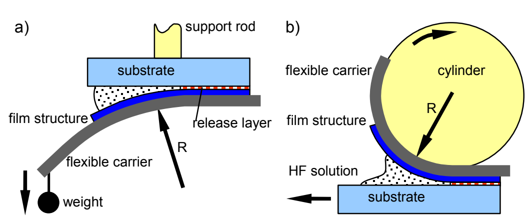

Figure 1: Schematic representation of the ELO process. (a) using a weight, (b) using a cylinder

The ability to transfer the cell structure to an arbitrary carrier allows for the creation of new device structures which can be optimized for different purposes. At the Radboud University processing schemes have been developed to produce thin film III-V cells with a grid contact pattern on both sides (bifacial) or with a front grid pattern and a full back contact. If applied correctly this back contact acts as a mirror which reflects the photons that reach the back side of the cell.

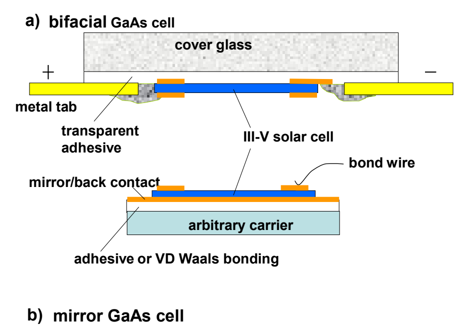

Figure 2: Two types of thin film GaAs cells: (a) bifacial, (b) with mirror on backside

Both cell types require only half the thickness of a regular GaAs cell to absorb the incoming photons. The reflected photons are absorbed relatively close to the *p-n* junction of the cell. Thus created electron-hole pairs have a higher collection probability than those created by photons that are absorbed deep in cells with larger base thicknesses. For optimal radiation hardness of GaAs cells the base layer must be as thin as possible, because degradation of the base layer diffusion length is the main cause for efficiency loss in space. Therefore, thin film cells are expected to perform better in this respect.

In a previous study the performance of bifacial GaAs cells as a function of their base thickness was examined [3]. The thin film cells were subjected to front side illumination (FSI) as well as back side illumination (BSI), showing efficiencies of 20.3 and 15.4%, respectively. For these cells the maximum performance was obtained for a base thickness of 1.5 µm for FSI as well as BSI.

In the present work the optimization of GaAs cells with a mirror back contact will be discussed. The performance of these thin film cells is compared to that of regular GaAs cells on a substrate (i.e. without being subjected to the ELO process).

2 EXPERIMENTAL

The solar cells were grown by low pressure metal organic vapour phase epitaxy (MOVPE) on GaAs 2 inch wafers with a (100) 2^o off to [110] orientation. Arsine and phosphine were used as group-V source gasses, trimethyl-gallium, trimethyl-indium and trimethyl-aluminium as group-III precursors. For *n*- and *p*-type doping disilane and diethyl-zinc were used, respectively. The growth temperature and pressure were 650 ^oC and 20 mbar. An AlAs release layer with a thickness of 5-10 nm was grown first, followed by the layers for the solar cell in normal order. The solar cell structure of the *n*-on-*p* cell contains an AlInP window layer (0.03 µm, $n=1.5*10^{17}$ cm^{-3}), *n*-type GaAs emitter (0.1 µm, $n=3*10^{18}$ cm^{-3}), *p*-type GaAs base (thickness varied, $p=1*10^{17}$ cm^{-3}) and $(Al_{0.4}Ga_{0.6})_{0.5}InP$ back surface field (BSF) layer (0.07 µm, $p=1*10^{18}$ cm^{-3}). The *p*-type GaAs base layer thickness was varied between 1.25 and 2.0 µm. For comparison a regular GaAs cell on a substrate was grown. The overall structure of this cell is identical to that of the thin film cell, apart from the base layer thickness which was enhanced to 3.5 µm.

A separate set of ELO samples was grown to investigate the reflectance of different mirror materials. Since most of the high-energy photons are absorbed near the surface, the reflectance of the mirror is most critical for low-energy photons. Therefore, thin film InGaP layers, which are transparent in the part of the GaAs cell wavelength range between 650 and 900 nm, were lifted-off and a metal mirror was evaporated on the back side. Four metals were selected to be tested as mirror: silver, aluminum, gold and copper.

For reflectance measurements, light coming from a xenon source and subsequently a monochromator was fed to a fiber and directed to the samples at an angle of 0^0 (normal incidence). A silicon detector was used to determine the reflectance. Since these reflection curves only show relative reflectance, a calibration of the Cu mirror sample was done with a Woollam Variable Angle Spectroscopic Ellipsometer.

To optimize the base thickness, a number of 7x8 mm^2 thin film GaAs cells with a 20% grid coverage were measured with the IV- and SR-setup at the Radboud University. AM1.5G measurements of the 5x20 mm^2 GaAs thin films (see fig. 3) and substrate cell took place at the Fraunhofer ISE CalLab in Freiburg, Germany. These cells have a 2% grid coverage and an optimized ZnS/MgF_2 anti-reflection coating (ARC) as determined by our in house developed software tool [4]. For the first time ultrasonic bonding with 25 µm diameter aluminum wires was applied on our thin film cells to contact the front metal grid.

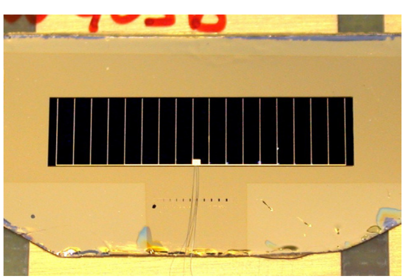

Figure 3: Photograph of a 1 cm^2 GaAs mirror cell.

3 RESULTS AND DISCUSSION

3.1 Metal mirrors

Fig. 4 shows the reflectance from the thin film InGaP test samples with the different metal mirrors. The oscillations in the reflectance are caused by interference of light reflected at the front and metal coated back side of the InGaP films. The copper mirror peak reflectance values are somewhat higher than for gold and silver (all above 0.9), whereas aluminum clearly reflects worse.

The reflectance is determined by the wavelength dependent complex refractive index values of the metals, and the interface quality of the metal-semiconductor interface. The samples do not have an anti-reflection coating, which means that already about 30% of the light is reflected at the incoming surface. The remaining 70% can be reflected by the mirror. For the case of a gold mirror, the reflectance with and without ARC was simulated (see fig. 5) using our calculation software [4]. Since the interference is suppressed by the application of an ARC, a coated sample shows reduced peak and valley values compared to a non-coated sample. The peak values with and without ARC are within 0.02 reflectance. Fig. 5 also shows that the measured reflectance values are about 5% lower than the simulation data. The optical parameters of the gold as deposited by e-gun evaporation are expected to be slightly different from the data used in the simulations which were taken from reference [5], leading to a small reflection loss. Still, 90% reflectance is an excellent value that justifies application of the mirror in our thin film cells.

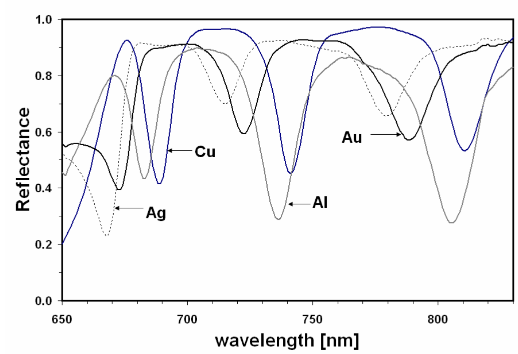

Figure 4: Reflectance at thin film InGaP samples with Cu, Al, Ag and Au mirrors at the back side.

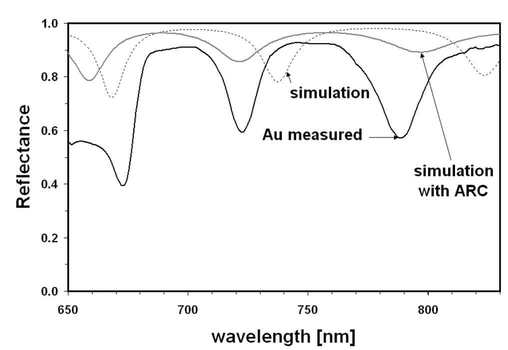

Figure 5: Reflectance at InGaP thin films with Au mirror: measured without and simulated with and without ARC.

In the ideal case, the mirror metal is also applied as a low-ohmic back contact. Unfortunately, a full-area low-ohmic contact is not possible for III-V's with copper. To obtain a sufficiently low contact resistivity gold or silver can be used on GaAs. Because silver is attacked by some of the wet etchants needed in the processing of the solar cell, the choice for gold as the preferred mirror was made. Only non-alloyed contacts can be applied, because a high temperature anneal treatment is expected to damage the interface between mirror and semiconductor, thereby reducing the reflectance. The contact resistivity between evaporated gold and two different semiconductor layers, the p-$(Al_{0.4}Ga_{0.6})_{0.5}InP$ BSF material and $1*10^{19}$ cm^{-3} p-GaAs, was measured using the TLM method. Values of $1*10^{-2}$ and $7*10^{-5}$ Ω cm^2 were measured, respectively. This indicates that a thin (20 nm) layer of GaAs is needed between the mirror and the BSF to obtain a sufficiently low contact resistivity. This results in a small loss of carriers generated in this p-contact layer.

3.2 Thin film cell performance

As a result of reflection from the gold mirror on the back of the cell, the thickness of the cell can be reduced. This leads to improvements in optical absorption, collection efficiency and dark injection current J_o of the cell. A slightly higher short-circuit current J_{sc} can be obtained, which together with the lower dark current, enhances the open-circuit voltage V_{oc}.

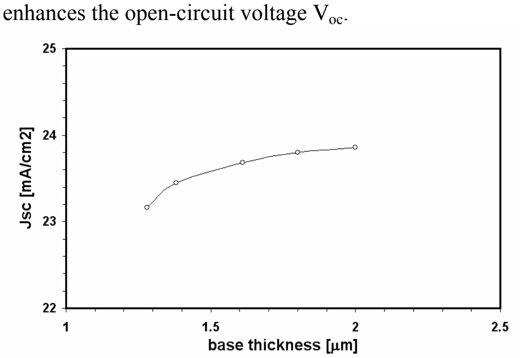

Figure 6: Short-circuit current as a function of the base thickness of thin film GaAs cell with Au mirror. Cell size is 7x8 mm^2 with a grid coverage of 20%.

In fig. 6 the short-circuit current of thin film cells is shown for a base thickness up to 2 µm. The curve flattens with increasing base thickness. An even higher base thickness would lead to lower V_{oc}, and only a marginal J_{sc} increase. Therefore, a base thickness of 2 µm was chosen for our thin film GaAs cells.

Solar cells with an area of 1 cm^2 (5x20 mm^2) were grown with and without release layer below the cell structure (see fig. 3). The substrate cells went through our regular processing sequence in which a rapid thermal anneal step at 450 °C to alloy the contacts is included. As already mentioned, annealing at these high temperatures is not possible after lift-off for a number of reasons: the glue under the cell cannot withstand these temperatures and the mirror would be alloyed to the contact layer which reduces the mirror function. The thin film cells were therefore annealed at 200 °C for one hour.

Fig. 7 shows the IV-characteristics of the thin film and substrate GaAs cells. These results might be compared with the best results obtained with regular and thin film GaAs cells as stated in the recently reported Solar Cell Efficiency Tables (version 25) [6]. This comparison indicates that with an efficiency of 24.9% the performance of our substrate GaAs cell is quite close to that of the 25.1% GaAs substrate cell produced by Kopin. With an efficiency of 24.5% the ELO GaAs cell clearly surpasses the 23.3% efficiency of the previously best thin-film GaAs cell, which was also produced by Kopin utilising the Cleavage of Lateral Epitaxial Films for Transfer (CLEFT) technique [7]. The open-circuit voltage of the thin film cell exceeds the substrate cell V_{oc} by 11 mV. Another of our thin film cells with an efficiency of 24.3% showed an even higher V_{oc} of 1.032 V. The current in the thin film cell is also higher than the substrate cell current. From the external quantum-efficiency (QE) data (fig. 8) it can be seen that for wavelengths above 700 nm the substrate cell QE is lower. This can be attributed to a deviation in the thickness of one of the layers in the ARC of the substrate cell. In potential the shape of the substrate cell external QE should be similar to the thin film curve (without the interference fringes), leading to a J_{sc} close to the thin film cell value.

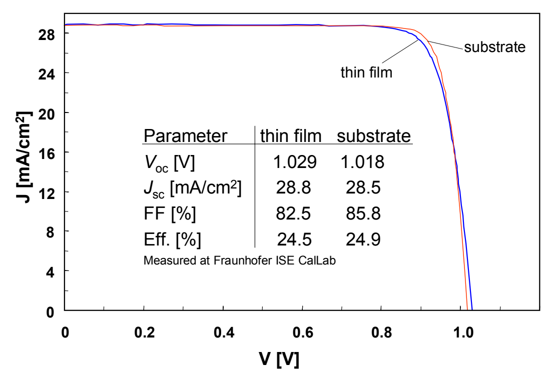

Figure 7: AM1.5G current-voltage curves of thin film GaAs cell with a gold mirror and a base thickness of 2 µm, and a GaAs cell on substrate with a base thickness of 3.5 µm.

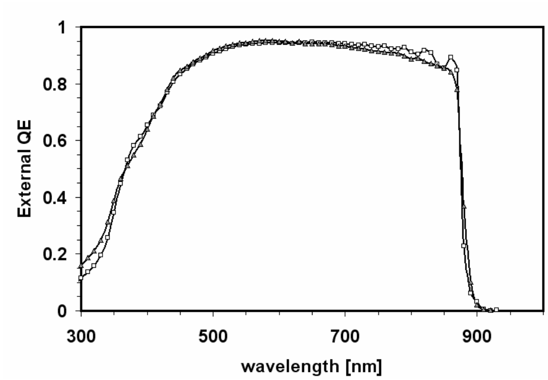

Figure 8: External quantum efficiency of the GaAs thin film and substrate cells.

The substrate cell has a lower series resistance, and therefore a higher fill factor FF, because it is equipped with alloyed contacts annealed at high temperature. The contact resistivity of our thin film p-type contact is sufficiently low (see §3.1). The n-type contact resistivity however, turned out one order of magnitude too high. Reducing this should improve the thin film FF.

The data clarify that the thin-film ELO cells are rapidly approaching the efficiency of the best substrate GaAs cells. Compared to our best substrate GaAs cell the ELO cell has a significantly lower base thickness (2 versus 3.5 µm), which results in a higher open-circuit voltage for the ELO cell. The present data indicate that once ELO cell processing is optimized the performance of the thin film cells can surpass that of the regular III-V cells.

3.3 Radiation resistance

The thin-film III-V cells will most probably first be utilized in space applications. As a result of the reduced cell thickness, ELO GaAs cells are expected to have a higher radiation hardness than regular GaAs cells. This is because in space the bombardment of high energy electrons and protons results in a degradation of the minority carrier diffusion length in the semiconductor material. The degradation of the cell performance will be less if the thickness of the cell is smaller than the diffusion length after irradiation. To verify this two thin film GaAs cells with a base thickness of 2 µm were prepared to be subjected to 1 MeV electron radiation tests with a dose of $3*10^{15}$ cm^{-2}. For this purpose the thin film cells were mounted behind 200 µm thick CMG glass plates (n=1.52) using optically transparent adhesive with a thickness of about 50 µm and a refractive index of 1.56. CMG cover glass is generally employed for space applications because it does not darken after irradiation, its thermal expansion is matched to that of GaAs and it exhibits an inherent UV radiation filter to protect the cell and the applied adhesive. Results of the power degradation in our cells compared to a reference GaAs cell on Ge are shown in fig. 9. These preliminary measurements indicate that at an electron fluence of $3*10^{15}$ cm^{-2} the radiation resistance for the thin film cells is better than that of the reference. More measurements will be done in the near future to investigate the radiation resistance in detail.

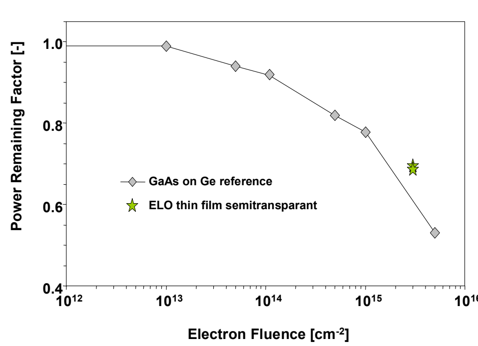

Figure 9: Normalized maximum power after 1 MeV electron irradiation of thin film GaAs cell compared to a reference cell on a Ge substrate.

4 CONCLUSIONS

Thin film GaAs cells, separated from their substrate using the epitaxial lift-off technique, were compared to GaAs cells on a substrate. The structure of the cells is identical, except for the base thicknesses which are 2 and 3.5 µm for the ELO thin film and substrate cell, respectively. A gold mirror layer on the back of the thin film cell reflects 90% of the high wavelength photons and additionally serves as a low-ohmic back contact.

A world record thin film single junction solar cell efficiency of 24.5% was obtained. The thin film cell showed a more than 10 mV higher open-circuit voltage compared to the substrate cell. In potential the efficiency of the thin film cell can be as good as or even better than the substrate cell efficiency while at the same time only half the thickness is required. Preliminary results show an increased radiation resistance for the thin film cell as a results of this lower base thickness.

5 ACKNOWLEDGEMENTS

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