INFLUENCE OF BASE THICKNESS ON FRONT AND BACK SIDE EFFICIENCY OF THIN FILM GaAs SOLAR CELLS

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ABSTRACT

Compared to conventional solar cells on a substrate, thin film GaAs cells show a higher efficiency at a lower thickness due to back surface reflection. The optimal cell thickness is 1.7 µm. Thin film cells can also be illuminated from the rear side with an efficiency only 15% (relative) lower than for front side illumination.

1. INTRODUCTION

Thin films III/V solar cells offer a number of very interesting advantages compared to cells on substrate, e.g. they can be mounted on any carrier material to reduce the weight or to remove heat. For large area devices like solar cells, the main motivation for using thin films is the demand for low cost, high efficiency solar cells, which can be obtained by a substrate reuse. The most successful method for obtaining a III-V thin film is epitaxial lift-off (ELO), in which the cell structure is separated from the substrate by selective wet etching of a thin AlAs release layer with an HF solution. This leaves the expensive GaAs substrate completely intact, offering the possibility of reuse for the growth of new solar cell structures. The area of the thin films released with the ELO method, as proposed in the late 1980s [1], was limited to a few mm² which is too small for solar cells. The weight-induced ELO (WIELO) procedure, as developed in our laboratory, does not show this limitation. The application of a plastic support foil combined with a variable weight and the further optimization of working temperature, release layer thickness \( d \) and carrier concentration results in the release of large area thin films at high etch rates. A drawing of the WIELO setup is shown in Fig.1. Details of the WIELO procedure have been described in other papers [2-4].

In contrast to a cell on a substrate, a thin film cell can be illuminated from the front as well as the rear side. This requires a contact grid with low cell coverage on both sides of the cell. A mirror can be used to couple the light in on both sides. The thickness and doping concentration of the \( n- \) and \( p- \)layers that form the \( p-n \)-junction of the solar cell play an important role in the efficiencies that can be obtained with front or rear illumination. The base layer is normally lower doped and has a thickness of 3-4 µm. In case of rear illumination, when the base layer operates as the emitter, this layer is too thick. In the present work, the \( p- \)layer thickness was varied between 0.25 and 2.5 µm to determine the optimal thickness for front and rear illumination.

Another factor influences the optimal cell thickness, because the energy conversion efficiency of a thin film III-V cell is expected to improve due to reflection from the rear surface. Unabsorbed photons have another chance of creating an electron-hole pair, thus increasing the spectral response. This allows the use of thinner cells, thereby saving time and costs in the growth process. In the present work this effect is also examined.

2. EXPERIMENTAL

The solar cells were grown by low pressure metal organic vapor phase epitaxy (MOVPE) on 2 inch GaAs wafers. The AlAs release layer with a thickness of 5 nm was grown first, followed by the layers for the solar cell in reverse order. The solar cell structure used in this work was originally designed for front illumination as an \( n \)-on-\( p \) cell. The thicknesses and doping concentrations are: InGaP window layer: 0.03 µm, \( n=2*10^{18} \) cm⁻³; GaAs emitter: 0.1 µm, \( n=1*10^{18} \) cm⁻³; GaAs base: thickness varied, \( p=1*10^{17} \) cm⁻³ and InGaP back surface field (BSF)
layer: 0.07 µm, \( p = 6 \times 10^{17} \text{ cm}^{-3} \). The p-type GaAs layer thickness was varied between 0.25 and 2.5 µm, leading to a total cell thickness in the range 0.45-2.7 µm. The cells on a substrate, which were grown to compare them to the thin film cells, have an identical layer structure with the same varied base layer thickness. It should be noted that an optimized GaAs cell structure on a substrate has a thickness of around 4 µm [5,6].

The cell structure is released from the substrate by WIELO. After WIELO the thin film on a plastic support foil is processed further into a solar cell with metal grid contacts and glass covers on both sides of the cell (see Fig. 2). A ZnS anti-reflection coating (ARC) was evaporated solely on the front side. An optically transparent glue with a thickness of about 50 µm and a refractive index of 1.56 is used to bond the thin film to the 200 µm thick coverglasses \((n=1.52)\). Both glass and glue are fully transparent in the wavelength region between 300 and 900 nm, which is the part of the solar spectrum of interest for GaAs. The rear contact grid is positioned entirely on the cell area as can be seen in Fig. 2. The contact grid on the front with identical shape as the rear contact grid has the bond flap outside the cell area to enable further interconnection.

No special attention was paid to optimize the grid contact for this thickness series. The metal coverage used for the back contact is close to 20% of the 7x8 mm² cell area, the thickness of the evaporated contacts is only 0.3 µm (see Fig. 3). The thin film cells are illuminated either from the front or the rear side to determine the IV- and quantum efficiency (QE) curves. A direct comparison can be made between the IV- and QE results of the front illuminated thin film cells and the cells on a substrate. No special attention was paid to optimize the grid contact for this thickness series. The metal coverage used for the back contact is close to 20% of the 7x8 mm² cell area, the thickness of the evaporated contacts is only 0.3 µm (see Fig. 3). The thin film cells are illuminated either from the front or the rear side to determine the IV- and quantum efficiency (QE) curves. A direct comparison can be made between the IV- and QE results of the front illuminated thin film cells and the cells on a substrate.

In a later stage of the research, a larger thin film cell of 20x10 mm² was realized with the optimal p-GaAs thickness (see Fig. 3). For this cell the front and rear contact grid were improved and the metal contacts were thickened to 3 µm by galvanisation.

3. RESULTS AND DISCUSSION

Because all measured 7x8 mm² cells, thin film as well as on substrate, show an open circuit voltage \( V_{oc} \) and Fill Factor (FF) in the ranges 0.97-1.00 V and 0.76-0.78 respectively, the differences in solar cell efficiency are mainly determined by the short circuit current density \( J_{sc} \). For the 10x20 mm² thin film cells the metal contacts were thickened from 0.3 µm to 3 µm, which enhances the FF upto 0.84.

Fig. 4 shows \( J_{sc} \) as a function of the p-type GaAs layer thickness for the front and rear illuminated thin film cells and the cells on a substrate. \( J_{sc} \) increases monotonically with the p-GaAs thickness for cells on a substrate. At 2.5 µm thickness \( J_{sc} \) amounts 23.30 mA/cm². A further increase of the base thickness will only lead to a minor increase of \( J_{sc} \). The front illuminated thin film cell has a maximum \( J_{sc} \) of 23.85 mA/cm² at 1.5 µm p-GaAs thickness, which is above the highest substrate cell current. The high \( J_{sc} \) values indicate that the WIELO process has not damaged the material quality. The results of thin film cells from the same wafer show a larger cell to cell difference than for substrate cells. This is due to the thin film cell processing, in which a number of steps should be improved by the development of dedicated thin film handling techniques.
The maximum $J_{sc}$ for rear illumination is also found at a $p$-GaAs layer thickness of 1.5 µm. Although the cell was designed for front illumination, $J_{sc}$ for rear illumination is only 4 mA/cm$^2$ lower at the optimal $p$-type GaAs layer thickness. This difference is even smaller if the lack of an ARC at the rear side and a significantly larger metallized area (the bond flap is on the cell area, see Fig. 2) are taken into account. Correcting for the additional shadowing of 14% relative, the difference in $J_{sc}$ with the front illuminated cell decreases to 2.3 mA/cm$^2$. The total current in a 7x8 mm$^2$ cell illuminated from both sides is 42.7 mA/cm$^2$. For the 10x20 mm$^2$ cell, which has a lower metal coverage, the total current amounts 46.8 mA/cm$^2$.

![Fig. 5](image)

**Fig. 5** Light reflection in thin film cell.

The internal reflection of photons at the back interface of a thin film cell, which results from the difference in refractive index of the III-V material and the glass/glue, traps part of the photons in the cell. There are two possibilities: total reflection (shown in Fig. 5 for front illumination) and reflection of a fraction of the light (shown for rear illumination in Fig. 5). The critical angle $\theta_{cr}$ calculated from Snell’s law for total reflection at the rear surface is 27° for the glass / III-V interface. All photons with a higher angle of incidence are reflected. At lower angles only part of the photons are reflected. At normal incidence the reflection at the rear interface is 17%. As a comparison for the cell on a substrate these values are 79° and 0.01%, respectively, for the GaAs substrate / BSF interface. An even higher reflection can be obtained in the case of a thin film with open back side (no glass). Then, $\theta_{cr}$ is only 17° and the normal incidence reflection increases to 33% due to the even higher refractive index difference. The consequence is however also a 33% reflection for incoming photons if the cell is illuminated from the rear side. So, an open back side is only favorable if the thin film cell is not used for additional rear illumination.

The reflection of light will lead to a higher absorption rate, and thus a higher $J_{sc}$. Low-energy photons, which are absorbed deeper into the cell benefit most from the back surface reflection. At the maximum power point, the collection probability which is the probability of generated minority carriers to contribute to the cell current, decreases exponentially with increasing distance to the depletion region around the $pn$-junction [7]. Re-absorption therefore becomes more efficient if the base layer is thinner. In the substrate cell without any significant rear reflection, a thick base layer is desired to absorb all photons. The decrease in collection probability at increasing base thickness is expressed in the flattening of the substrate cell curve in Fig. 4.

The thin film cell current is expected to exceed the substrate cell current at any thickness, because light reflection provides an addition to substrate cell current. From Fig. 4 is can be seen that this is not the case for all data points. As mentioned previously, it is expected that optimization of the thin film cell processing will lead to an increase in cell performance.

The difference in cell current between the thin film and the substrate cell is most significant at a base thickness of 1.5 µm (front illumination). The QE data of these two cell types are shown in Fig. 6. The contribution of back surface reflection in the thin film cell compared to the substrate cell is clearly visible. At 550 nm the QE of the thin film starts to rise above the substrate QE and this difference increases at higher wavelengths.

![Fig. 6](image)

**Fig. 6** External QE of front illuminated thin film (dashed line) and substrate cell (solid line). The base layer thickness is 1.5 µm for both cells.

If the cell is illuminated from the rear side, the short circuit current is influenced by the $p$-GaAs layer thickness in two ways. For this $p$-on-$n$ configuration, where the front illuminated base operates as the back illuminated emitter, the junction depth varies with $p$-GaAs layer thickness. Since absorption of photons decreases exponentially with the distance from the surface, most of the (especially high energy) photons are absorbed close to the incoming surface. If the distance between the surface and the $pn$-junction becomes larger, a considerable amount of the minority carriers recombines before contributing to the cell current. Thus, a higher emitter thickness decreases the blue response (short wavelengths). This is shown in the QE data of Fig. 7 for a 2.5 µm emitter thickness. On the other hand, if the $p$-GaAs emitter is thin, the total cell thickness is too low to absorb the low-energy photons. The red response (long wavelengths) is poor in this case, which is clearly seen for a cell with a 0.25 µm thick emitter (Fig. 7). At the intermediate thickness of 1.5 µm an optimum is obtained, resulting in a relatively high QE for short as well as long wavelength photons. It should be
noted that the rear illumination response of the cells can be improved in the whole wavelength range by applying a rear ARC and a contact grid with lower coverage.

Fig. 7  External QE of rear illuminated thin film cells with p-GaAs thickness 0.25 (■), 1.5 (◊) and 2.5 µm (▲).

4. CONCLUSIONS

In this work thin film GaAs solar cells were compared to cells on a substrate. Apart from a small cell to cell variation originating from the non-optimized processing of the thin film to a working device, no degradation was found for the thin film cell efficiency. Thin film cells show a number of advantages over substrate cells. First, the short circuit current of thin films cells is raised by reflection on the rear surface of the cell. This reflection offers non-absorbed photons a second chance to generate an electron-hole pair, which results in a better red response. Second, a lower cell thickness is required to profit optimally of this effect, which saves time and costs in the MOCVD growth process. The optimal thin film cell thickness is 1.7 µm, compared to >3 µm for a conventional cell on substrate. Third, a thin film cell can be used for front and rear illumination at the same time. The optimal p-GaAs thickness for rear illumination is also 1.5 µm. For our 20x10 mm² sized thin film cells, the short circuit current is 48.92 mA for front and 44.76 mA for rear illumination. The efficiencies are 19.7% and 16.7%, respectively. For a comparable cell on substrate, an efficiency between these two values is found. We believe that the desired improvements in cell processing and cell configuration will easily raise the efficiency above 20%.

6. ACKNOWLEDGEMENTS

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