Deep junction III-V cells with enhanced performance

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Abstract

The influence of junction depth in III-V cell structures was investigated for GaAs and InGaP cells. Typical cells of this type employ a shallow junction design. We have shown that for both materials investigated a deep junction close to the back of the cell performs better than a shallow junction cell. The deep junction cells operate in the radiative recombination regime, whereas in the shallow junction cells non-radiative recombination is dominant. The steeper slope of the IV curve boosts the fill-factor by 3-4%, which is thereby the most improved cell parameter. In order to minimize collection losses in the upper part of the cell, the optimal active layer thickness of the GaAs deep junction cell is only two-thirds of a shallow junction cell. The associated lower cell current is however more than compensated by the higher fill-factor. The best deep junction GaAs cell shows a record efficiency of 26.5% for a GaAs cell on substrate. In the thinner InGaP deep junction cell the current loss does not occur, leading to 1.6% higher efficiency than for the shallow junction cell.

Keywords: III-V, junction depth, tandem cell

1. Introduction

In a typical GaAs single junction solar cell a shallow junction (SJ) design is applied consisting of a thin highly doped n-type emitter, usually between 50 and 200 nm, and a thick lightly doped p-type base of around 3500 nm, cladded by higher bandgap materials that operate as window and back surface field (BSF). The record efficiency of such a cell is 26.4% (Frauhofer ISE, 2010) [1]. A significantly higher efficiency of 28.8% has been achieved for a thin-film cell using a deep junction (DJ) design with a thick emitter and a thin base layer [2,3]. The increase in efficiency was mainly derived from an increase in open-circuit voltage V_{oc} . In a thin-film cell, the back-side mirror creates an optical thickness twice the active layer thickness, therefore an emitter thickness of 2 μm is sufficient to absorb photons with energy above the bandgap. In previous work we used the SJ design with reflector and obtained a 26.1% efficiency for the GaAs thin-film cell that was equal to that of the substrate cell [4]. In the thin-film only a minor increase in V_{oc} was found. This illustrates that both the cell design and reflector are crucial for a better use of the so-called photon recycling effect, where photons generated by radiative recombination are re-absorbed. The advantage of the DJ approach lies in the suppression of non-radiative Shockley-Read-Hall recombination that occurs mainly via mid-bandgap states in the depletion region. At the maximum power point the internal luminescence efficiency, given by the ratio of the radiative recombination rate and the total recombination rate, is raised [3]. In a thin-film cell where photons emitted through radiative recombination are more or less confined in the active layers of the cell, this results in an improved minority carrier lifetime and thus a higher V_{oc} .

The production of thin-film devices requires significantly more processing than a substrate cell which is therefore still the standard in industry. In this work the opportunity for

applying the deep junction cell design to substrate cells is explored. The light absorption rate and related carrier generation is maximal just below the top surface of the cell and decreases exponentially as the light travels further into the crystal structure. Hence, the collection efficiency of near the top surface generated minority carriers, which have to diffuse over a long distance to the junction to pass the pn-junction, has a strong impact on the short circuit current J_{sc} of such a cell. In this cell design the diffusion length of the holes in the n-type emitter and the recombination velocity at the window-emitter interface are the most critical parameters. The question is how thick the emitter can be to reach an acceptable cell current. To surpass the efficiency of a SJ cell, the DJ substrate cell's anticipated losses in J_{sc} need to be compensated by a higher V_{oc} and FF . In most III-V materials the absorption coefficient decreases with increasing wavelength which is why the bandgap of the active layer materials to a large extent determines the cell thickness. For an InGaP cell about 1 μm is sufficient, so beforehand, this opens better perspectives for a J_{sc} comparable to that of a SJ cell. In this work, both GaAs and InGaP cells have been investigated in order to assess if DJ cells can outperform the SJ design.

2. Experimental

GaAs and InGaP cells with deep and shallow junctions were grown with MOCVD under conditions describes in previous work [4]. All cells possess a 20 nm AlInP window, the BSF is either InGaP (GaAs cells) or $\text{Al}_{0.2}\text{GaInP}$ (InGaP cells). Initially, an active layer thickness of 3.2 μm was chosen for the GaAs cells, close to the thickness that is typically used for regular SJ GaAs cells. Based on the obtained hole diffusion length values the emitter thickness and doping level were varied for the DJ cell in a later stage. The InGaP

cell will eventually be used as a sub cell in a multi-junction structure. Therefore, the active layer thickness ($0.8 \mu\text{m}$) is tuned to deliver a cell current of about 14 mA/cm^2 .

The cell structures were processed into test devices with an area of 1 cm^2 and an MgF_2/ZnS antireflection coating. Current-voltage (IV) curves were measured under AM1.5 conditions using a Keithley 2600 multimeter, an Abet Xe light source and a calibrated reference cell to correct for deviation from the 1000 W/cm^2 light intensity. The $2 \times 2 \text{ cm}^2$ reference cell was calibrated at ESTI, Italy under IEC 61836 test conditions. Dark IV curve characteristics were composed of a lower voltage part measured in the dark and a higher voltage part from J_{sc} - V_{oc} values measured under different light intensities to avoid series resistance effects at the higher current levels [5]. All IV measurements were performed at 25°C . The external quantum efficiency (EQE) was measured in 10 nm steps using a SpeQuest system calibrated with a reference photodiode. In all cases, excellent agreement was found between J_{sc} determined from the IV characteristics and J_{sc} as derived from the EQE measurements integrated over the AM1.5 spectrum.

3. Results and discussion

The current-voltage curves of GaAs and InGaP cells with SJ and DJ designs as described in the previous section were measured under 1 sun illumination and dark conditions. The relevant cell performance parameters together with the active layer thickness and carrier concentrations are collected in Table 1. For both types of material the DJ cells show a higher efficiency. In the InGaP case this is the most obvious as V_{oc} , J_{sc} and FF are all clearly higher resulting in a 1.6% (absolute) higher efficiency. As expected, for the GaAs cells, where the active layers need to be much thicker to absorb the lower energy photons,

the current is lower for the DJ cell. However, this is amply compensated by the significantly higher FF .

The dark current-voltage (J_d - V) curves of the four cells are shown in Fig.1. The curves are fitted to the two diode model expression [5]

$$J_d = J_{01} \left(e^{\frac{qV}{kT}} - 1 \right) + J_{02} \left(e^{\frac{qV}{2kT}} - 1 \right). \quad (1)$$

The first term in the equation accounts for the $n=1$ current (radiative recombination mainly in the neutral regions) which is dominant at higher bias voltages. The $n=2$ current is the result of non-radiative recombination mainly in the depletion region and at the cell perimeter and is dominant at lower bias voltages. The dark curves for the DJ and SJ cells depicted in Fig.1 show that for both GaAs and InGaP cells the magnitude of the dark current in the DJ (n - p^+) cells is smaller than that in the SJ (n^+ - p) cells in the voltage range of interest. The dark curve of the SJ GaAs cell deviates from the two diode model at intermediate voltages. We have used the lower voltage part for the determination of J_{02} . Comparison of the GaAs dark curve parameters in Table 1 shows that J_{01} of the DJ cell is close to that of the SJ cell. The SJ J_{02} value is one order of magnitude higher than that for the DJ. Choo treated $n=2$ recombination in the depletion region for the case of asymmetrical junctions [6] and found that, depending on doping levels, energy level of the recombination center(s) and capture symmetry, the $n=2$ current can vary significantly for n^+ - p or n - p^+ structures. The data show that this is also the case for these GaAs pn-junctions. In the n - p^+ case the $n=2$ recombination is suppressed compared to n^+ - p . This results in a steeper curve slope at the operating voltage of the cell, illustrated by an n value of 1.06 for the DJ cell compared to 1.86 for the SJ cell.

In the ideal case, the shape of the IV curve does not change under illumination, but is only shifted downwards by the short circuit current ($J_{ill} = J_d - J_{sc}$). The series resistance of the SJ and DJ cell is assumed to be similar, with about the same emitter sheet resistance (106 and 73 $\Omega/\square$ for SJ and DJ, respectively) and an identical top contact grid. It thus follows that the 4.5% higher FF for the DJ cell is a direct result of the lower $n=2$ current at the operating voltage.

A higher DJ FF is also found for the InGaP cells, where both J_{01} and J_{02} are lower in this cell type as compared to the SJ cell. The lower recombination currents have the effect that V_{oc} is raised by 38 mV. Geisz et al. [7] studied a 1 μm thick InGaP DJ and SJ design intended for application in thin-film cells. Their benchmark cells on substrate show a much lower (11.5 instead of 14.8 mA/cm^2) J_{sc} for the DJ cell and a similar V_{oc} and FF , resulting in a 4% lower (absolute) efficiency. This might be related to the, compared our DJ cell, thicker and five times higher doped emitter. We show in this work that also for InGaP cells the DJ cell design has the potential to be superior to the SJ in a substrate cell.

The external quantum efficiency measurement data are used to analyze the collection of current in the cells. Using the so-called Hovel model [8-11], it is possible to differentiate between the contributions to the internal quantum efficiency of the depletion zone (QE_d) and the neutral regions of the emitter and base (QE_e and QE_b). The output parameters of a fit to the measurement data are the minority carrier diffusion lengths L_n and L_p and the interface recombination velocities S_n and S_p , which are to a large extent the parameters that determine the cell current. The input parameters used for the calculations are listed in Table 2. The diffusion coefficients D_p , D_n and neutral emitter and base thickness X_e , X_b were calculated from carrier concentration data in Table 1 in combination with the corresponding mobilities from the PC1D5 simulation package [12]. The data for the

absorption coefficient α (the only wavelength dependent input parameter) were taken from Kurtz et al. [10] for InGaP and Aspnes et al. [13] ($E < 1.7\text{eV}$) and Sturge et al. [14] ($E > 1.7\text{eV}$) for GaAs. EQE is calculated using

$$EQE = (1 - A)(1 - R)(QE_e + QE_b + QE_d) \quad (2)$$

with A the absorption in the anti-reflection coating and window, and R the surface reflection of the cell. A and R are calculated using the transfer-matrix method (n-k data taken from the Sopra database [15]).

Fig. 2 shows the modeled EQE together with the measured EQE of the InGaP and GaAs DJ and SJ cells. The graphs reveal that for the SJ cells all three parts of the cell contribute significantly to the total EQE . For the DJ cells the situation is different: almost all the current is collected in the thick emitter. For the InGaP cell this fraction is 95%, in the GaAs cell 99.8%. In the middle part of the wavelength range of the DJ GaAs cell, the measured EQE is almost flat, overlapping with the calculated emitter external quantum efficiency $(1-A)(1-R)QE_e$ which is at a constant level up until wavelengths close to the band edge. QE_e is described by:

$$QE_e = \left[\frac{\alpha L_p}{\alpha^2 L_p^2 - 1} \right] \left[\frac{\frac{S_p L_p}{D_p} + \alpha L_p - e^{-\alpha X_e} \left[\frac{S_p L_p}{D_p} \cosh \frac{X_e}{L_p} + \sinh \frac{X_e}{L_p} \right]}{\frac{S_p L_p}{D_p} \sinh \frac{X_e}{L_p} + \cosh \frac{X_e}{L_p}} - \alpha L_p e^{-\alpha X_e} \right]. \quad (3)$$

For the DJ cells, in the wavelength range considered here, the first term of (3) reduces to $1/\alpha L_p$ and the second term to $\alpha L_p/C$, with C the denominator of the second term:

$$C = \frac{S_p L_p}{D_p} \sinh \frac{X_e}{L_p} + \cosh \frac{X_e}{L_p} \quad (4)$$

which does not depend on α and is therefore a constant. Multiplying the two terms leads to $QE_e = 1/C$. For DJ cells grown under the same conditions with the same emitter doping and window layer, two of the three parameters (S_p and L_p) that determine C do not change

if the third parameter X_e is varied. The EQE of a set of DJ GaAs cells with different emitter thicknesses of 1.1, 2.1 and 3.1 μm was measured to determine the values of S_p and L_p . Fig. 3 shows that the $1/C$ flat EQE level increases with decreasing X_e as expected from calculations. We obtained a value of $S_p < 50 \text{ cm/s}$ from these calculations. Below this value the sinh term is negligible compared to the cosh term, which means that C is reduced to $\cosh(X_e/L_p)$ and thus interface recombination does not play a role in QE_e . For these three DJ GaAs cells the L_p found is $8.4 \pm 0.2 \mu\text{m}$. The low value for S_p obtained here can also be found in literature [16, 17] and is indicative for excellent surface passivation. Lush [17] deduced the lifetime τ for cladded n-GaAs layers with different thicknesses and doping levels. For 2.5 μm , $1.3 \times 10^{17} \text{ cm}^{-3}$ material a lifetime of 210 ns was found. The corresponding L_p value, derived from $L_p = (D_p \tau)^{1/2}$, is 12.3 μm , which is somewhat higher than the modelled value found for our emitter.

The low S_p found for the DJ GaAs cell was also used in the calculations of the diffusion lengths for the other cells given in Table 2. The influence of S_n on the fits for the SJ cells is negligible for considerably higher values than found for S_p . Since the interface for the BSF to base is comparable to the window-emitter interface, the S_n value for our cells can be assumed to be clearly below this level. In the InGaP DJ cell the value of L_p is almost three times lower than for GaAs, caused by a lower τ in this material. The value of 2.5 μm is in good agreement with the 3 μm previously reported in literature [8].

The graphs in Fig.3 show that the maximum EQE for the 3.1 μm thick emitter DJ GaAs cell is lower than for the SJ cell with the same active area thickness, which is reflected by the 1 mA/cm^2 lower J_{sc} . A small percentage of the minority carriers generated in the upper part of the cell is not collected. There are two possible routes for increasing the cell current. The first is improving the diffusion length by improving the emitter material

quality or adjusting the doping level. For this purpose a cell with a V/III ratio of 120 (normally 60) for the emitter layer was grown, meant to improve the material quality. Also a set of cells with emitter doping levels 3×10^{16} , 7×10^{16} and $1 \times 10^{17} \text{ cm}^{-3}$ has been grown. L_p improved slightly to $8.8 \text{ } \mu\text{m}$ for the higher V/III ratio sample, for the doping series L_p remained in the range $8.4\text{-}8.6 \text{ } \mu\text{m}$.

The second option is to optimize the emitter thickness for maximum J_{sc} . For this purpose an additional set of three cells with emitter thicknesses of 2.2 , 2.4 and $3.0 \text{ } \mu\text{m}$ were grown. The Hovel model was used to calculate J_{sc} from the EQE curves as a function of the emitter thickness. The results are shown in Fig.4 together with measured J_{sc} data. The measured J_{sc} values are about 0.5 mA/cm^2 lower than the calculated curve, caused by deviations between the fit and measured curves in the lower and higher wavelengths (also visible in Fig.2). Apart from this, the measured J_{sc} 's follow the same trend as the calculated curve. According to the calculations the optimal emitter thickness is between 1.8 and $2.3 \text{ } \mu\text{m}$. For the measured cells, the maximum J_{sc} is found for an emitter thickness of $2.2 \text{ } \mu\text{m}$. Due to a higher FF , in our cells the $2.4 \text{ } \mu\text{m}$ emitter cell shows the best efficiency of this series and is therefore also listed in Table 1 and 2. Compared to the SJ GaAs cell, the J_{sc} loss is reduced to 0.5 mA/cm^2 in this DJ cell. With an efficiency of 26.5% this cell surpasses the best GaAs on substrate cell efficiency obtained so far [1], which is remarkable result since the cell thickness is only two-thirds of a typical SJ GaAs cell.

4. Conclusions

Typical III-V cells with a shallow junction (emitter thickness $70\text{-}150 \text{ nm}$) have been compared with cells with a junction positioned near the back of the cell structure. For both GaAs and InGaP cells the deep junction cells achieve a higher efficiency. At the maximum

power point they operate mostly in the $n=1$ regime, which means that recombination is mainly radiative. This results in higher FF and V_{oc} values than for SJ cells. For a high bandgap material cell as InGaP also J_{sc} is higher for the same active layer thickness, but for lower bandgap material as GaAs, where a much higher thickness is necessary to absorb the low energy photons, J_{sc} is limited by losses close to the cell surface.

The diffusion length of holes in the DJ emitter can be determined from EQE measurements, which allows for optimization of emitter thickness and doping level. We have shown that the optimal thickness of the active material is between 1.8 and 2.4 μm , compared to 3.5-4 μm for SJ GaAs cells. For this thickness the DJ cell current is only slightly lower, but since mainly the FF is much higher, the efficiency of 26.5% surpasses that of the best substrate based GaAs cell reported so far.

A DJ cell design is even more suited for application in a thin-film cell with a back-side mirror [3, 6]. The mirror increases the optical thickness by a factor of two and thus the current loss from the substrate DJ cell can be prevented. As a bonus, the open-circuit voltage can be raised due to a more efficient photon-recycling.

In a multi-junction cell the InGaP DJ is preferred over the SJ. For the underlying GaAs cell the optimization of the thickness differs from the method used here, because the wavelength range that delivers the highest EQE is used by the top cell. In a thin-film cell this would not be a problem, but in a substrate cell the overall cell current is reduced. Therefore a SJ GaAs sub cell would be preferred in a substrate tandem cell.

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Figure and Table Captions

Fig. 1: Dark IV measurements of GaAs (black) and InGaP (blue) deep and shallow junction cells. The continuous curves are DJ cells, the dashed curves SJ cells. The operating voltages for 1 sun are indicated by the markers.

Fig. 2: External quantum efficiency graphs of (a) GaAs SJ, (b) GaAs DJ, (c) InGaP SJ and (d) InGaP DJ cells. In each graph the contributions to the EQE of the emitter (blue), base (red) and depletion region (green) are visible. The black line represents the sum of these three contributions to the EQE. The cell's reflection and absorption losses in the coating and window are shown in grey. Measured external quantum efficiencies are indicated by the markers.

Fig. 3: External quantum efficiency measurements for GaAs DJ cells with different emitter thicknesses of 1.1, 2.1 and 3.1 μm (base thickness 0.1 μm). The dashed line indicates the EQE of the GaAs SJ cell with a total thickness of 3.2 μm .

Fig. 4: Short-circuit current density J_{sc} as a function of the emitter thickness in a GaAs DJ cell (base thickness 0.1 μm). The dashed line shows the curve from the calculated EQE integrated over the AM1.5 spectrum for $L_p=8.5 \mu\text{m}$, the square markers represent the measured data.

Table 1: Structural and operational parameters of SJ and DJ InGaP and GaAs cells. The bottom line in *italic* shows the results for the best cell with a lower emitter thickness.

Table 2: In- and output parameters of the EQE model analysis for the cells appointed in table 1.