Dilute Nitride Triple Junction Solar Cells for Space Applications: Progress Towards Highest AM0 Efficiency

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Abstract

We report a detailed performance assessment of triple junction dilute nitride solarcells fabricated by a combined molecular beam epitaxy–metal organic chemical vapor deposition process and designed for space applications. The experimental sample exhibits an efficiency level of 30.8% under AM0 illumination. Analyses of the isotype single junction dilute nitride bottom cells reveal a band gap voltage offset of 0.49 V at one sun illumination and a value as low as 0.47 V for full spectrum excitation without filter layers. The analyses point out the limitation of the design in terms of current balancing. With optimized design, an efficiency of 32.1% is possible, revealing the maturity reached by dilute nitride technology in the quest for improving the efficiency of lattice-matched multijunction solar cells.

Introduction

Lattice-matched GaInP/Ga(In)As/Ge solar cells have been continuously improved largely due to the need to reach higher efficiency for space applications. Such devices are an industry standard and typically exhibit a maximum beginning-of-life efficiencies of 30%. To further increase the efficiency, one needs to deploy materials with improved spectral match to AM0 spectrum. Among the most attractive approaches, lattice-matched 1-eV dilute nitride (GaInNAs) junctions, with lower thermalization losses than Ge bottom junctions, have the potential to increase the beginning-of-life conversion efficiency by up to 3 percentage points. [1-3] Typical band gap voltage offsets for dilute nitride cells range from 0.5 to 0.6 V at one sun, while down to 0.4 V can be achieved for GaAs-based compounds.3 Dilute nitride triple junction (3 J) cells with approximately 30% efficiency at one sun excitation have been reported by using molecular beam epitaxy (MBE) [4,5] or a combined MBE–metal organic chemical vapor deposition (MOCVD) method. [6] In particular, the MBE-MOCVD approach combines the advantage of high-performance dilute nitrides grown by MBE with mature high-throughput MOCVD process for the growth of GaInP/GaAs cells. This paper focuses on providing a detailed analysis of the performance of triple junction cells made with the combined MBE-MOCVD process aiming to define its full potential for AM0 operation. The analysis includes measurements of state-of-the-art 3J space solar cells and a diode model used for pointing out optimization path and extrapolating the performance potential.

Experiments

The solar cell structures were fabricated on 100-mm p-GaAs substrates following the procedure described in Tukiainen et al [6] and in Figure 1. For dilute nitride cells, the MOCVD-grown part was either fully electrically active 3J cell or isotype cells with n-type doped optical filter layers mimicking the absorption of the 2 top junctions. In addition, GaAs isotype and GaInP single junction cells were grown on p-GaAs substrates without GaInNAs junction or other underlying junction(s). MOCVD-grown single junction GaAs isotype solar cell was incorporated with n-type filter layers on top. The epitaxial structures were processed in cells with a size of 2 cm × 2 cm. For testing, we used 3 different solar simulators: a dual-source WACOM simulator, a multi-band simulator, and an OAI TriSOL simulator. Different solar simulators were used to ensure reliable results. Secondly, the measurements with different systems enables understanding the cell dynamics, which are needed for accurate modelling. The dual-source WACOM simulator was calibrated for AM0 illumination using a secondary working standard set for the GaInP/GaAs/Ge triple junction cells at Spasolab (Spain). The other 2 solar simulators were calibrated with known single junction cells with band gaps of 1.9, 1.4, and 1.0 eV and with a GaInP/GaAs AM0 cell measured at Fraunhofer ISE. In addition, external quantum efficiency (EQE) measurements were performed with an EQE system based on a monochromator and a quartz tungsten halogen lamp. [5-7] The EQE system was calibrated using NIST traceable Si and Ge detectors. Light-emitting diodes were used for optical biasing of the subjunctions of the triple junction cells. Additional details on the EQE system and the biased illumination used are reported elsewhere.5 For AM0 reference, we used ASTM E490 spectrum. [8] The performance of the solar cells was modelled using diode equations adapted for dilute nitride cells as described in previous studies. [3,9,10]

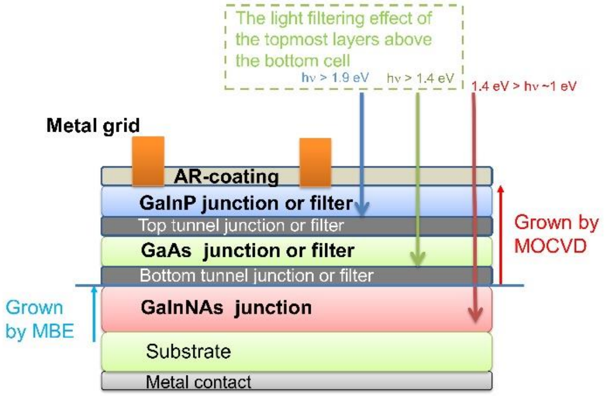

Figure 1. *Schematic illustration of the sample structure(s).*

Results and discussion

The current-voltage (IV) characteristics of the best 3J cells measured with the WACOM solar simulator are shown in Figure 2. The figure includes also the data of the first high-performance dilute nitride cell fabricated by the MBE-MOCVD method [6] as well as the simulated IV characteristics. In particular, the black curve corresponds to the improved 3J cell with on an efficiency of 30.8% while the red curve reveals a simulated potential of 30.7% modelled with cell parameters based on Aho et al. [9] The blue curve in Figure 2A represents the best-fit diode model for a cell with efficiency of 30.8%. The performance parameters used in the model are obtained from single junction isotype cells and are presented in Table 1.

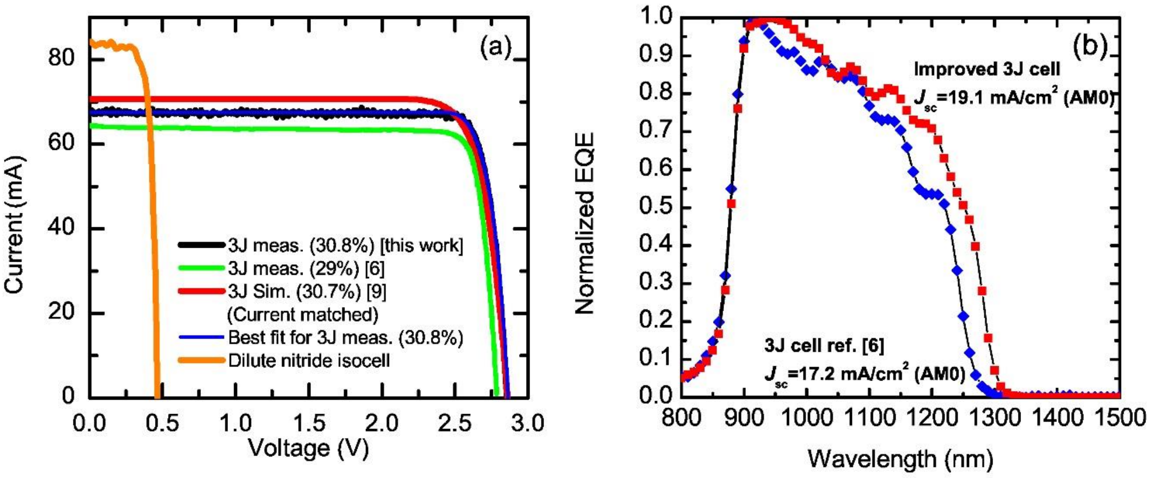

Figure 2. *(a) Experimental and simulated current-voltage characteristics at AM0 for dilute nitride cells. (b) External quantum efficiencies for bottom cells of GaInP/GaAs/GaInNAs triple junction solar cells.*

Table 1. J_{sc} values for triple junction cells, sub-cells and corresponding isotype cell measured with different solar simulators.

	WACOM solar simulation or ***diode modelling***			J_{sc} values from multiband simulator measurement or ***sub cell J_{sc} values used in the diode modelling***			$J_{sc\text{-}EQE}$ (mA/cm2) from EQE of bottom junction	Estimated solar cell efficiency (%)
Cell	V_{oc} (V)	J_{sc} (mA/cm^2)	η (%)	$J_{sc\text{-}GaInP}$(mA/cm^2)	$J_{sc\text{-}GaAs}$(mA/cm^2)	$J_{sc\text{-}GaInNAs}$ (mA/cm^2)		
GaInP/GaAs/GaInNAs [6]	2.827	16.2	29.2	16.3	17.0	17.4	17.2	29.2
GaInP/GaAs/GaInNAs improved [this work],	2.815	17.1	30.1	17.2	17.7	21.4 (multiband)	19.1	29.8
GaInP/GaAs/GaInNAs *optimized* [this work]	2.856	16.9	30.8	-	-	-	-	30.8
GaInP/GaAs/GaInNAs *simulated, all junctions current matched [3]*	***2.860***	***17.7***	***30.7***	***17.7***	***17.7***	***17.7***	-	-
GaInP/GaAs/GaInNAs simulated with sub-cell parameters	***2.865***	***16.9***	***30.9***	***16.9****	***18.1****	***21.1*** (multiband)***	-	-
GaInP/GaAs/GaInNAs simulated potential	***2.869***	***17.7***	***32.1***	***17.7***	***18.1***	***20.5***	-	-
GaInP ISO	1.41	16.9*		-	-	-	-	-
GaAs ISO	1.00	18.1*		-	-	-	-	-
GaInNAs ISO	0.46	24.5		-	-	21.1* (multiband)	19.1	-

*The measured J_{sc} values from isotype cells were used for modelling. For the sub-cell modelling, we used a diode model with 1.5 ideality factor for each of the sub-cells. The dark current density (J_0) was calculated using J_{sc} and V_{oc} data. The total series resistance for the experimental solar cell components of this paper can be approximated to be 2 Ω cm^2. Here we treat the tunnel junctions as very low resistance (<< 2 Ω cm^2) resistors. See [3] for more detailed construction of the model.

Compared with the cells reported in Tukiainen et al [6], the band edge of the bottom cell was shifted towards longer wavelengths, which is apparent in the EQEs shown in Figure 2B. The main motivation for this was to increase the device fill factor and, therefore, enable higher efficiencies. The band edge was shifted by increasing In and N compositions of GaInNAs from 0.09 and 0.033 to 0.10 and 0.036, respectively. The J_{sc} of the bottom cells calculated from EQEs were 17.2 and 19.1 mA/cm^2 for the benchmark and the improved cell, respectively. On the other hand, there is a possible drawback in terms of band gap penalty resulting in lower V_{oc} for the improved cell. However, in practice, the reduction in the operation voltage of the 3J cell is small due to the excess current generation in the bottom cell; the V_{oc} of the 3J cell decreased only by 12 mV when the dilute nitride band gap decreased by 29 meV. In addition, compared with the reference cell, the top cell of optimized 3J generated a higher current (16.9 mA/cm^2 instead of 16.3 mA/cm^2) and showed V_{oc} increase of 29 mV. As a result of the optimization, the total efficiency of the cell was improved by 1.7 percentage points, from 29.1% to 30.8%.

To estimate more precisely the limiting subcell and the current generation capability, the triple junction and isotype cells were measured with the multiband simulator. For both triple junction cells, the top cell was found to limit the current. The middle junction was found to be the second limiting, and the highest generation was measured for the bottom cell. The cell IV characteristics, measured with different solar simulators, and J_{sc} values calculated for the bottom cells from EQEs are summarized in Table 1.

The match between the different measurements is excellent, except for the isotype GaInNAs cell where there is some difference between the Jsc values. Jsc values determined from EQEs, and the multiband results are the closest to each other. The maximum difference of 2 mA/cm^2 between the multiband J_{sc} and J_{sc} calculated from the EQE can be explained partly due to EQE measurement range, which is limited to 800 nm and partly due to the small signal measurement nature of EQE, when compared with full IV measurement. One possible explanation is also considered to arise from luminescent coupling of the top layers into the bottom junction. [11-13] The highest J_{sc} for the bottom cell, of 24.5 mA/cm^2, was measured from an isotype type cell with the WACOM solar simulator tuned to AM0. We estimate the current density for the bottom cell to be 21 mA/cm^2. This current density was measured for the GaInNAs isotype cell with the multiband measurement system and with the OAI TriSOL simulator. The WACOM calibration value can be ruled out by the fact that even unity values of the EQE starting from the short wavelength edge of GaAs SC to 1300 nm could give only 23.3 mA/cm^2. This would mean that the bottom cell would need to operate at 105% EQE on average. The J_{sc} values calculated from the TriSOL simulator, multiband simulator, and EQE measurements result in more realistic average EQE values of 90%, 91%, and 82%, respectively. As a final remark, we want to note that due to the nature of the Xenon-based single lamp spectrum in the TriSOL system with tailored AM0 spectral filter, each of the 3 subbands under simulation has spectral dips and peaks. For this case, the spectral purity of the system was evaluated with single junction cells, and it needs to be considered case by case. This means that for the best simulation for every type of cell, the AM0 spectral filter would need to be tailor made and fine-tuned according to the simulator performance.

Since there is some deviation for the bottom cell J_{sc} values between different methods, we made simulations for the cell efficiencies for different values of the current generated by the bottom cell. The simulation results are shown in Figure 3A. In this simulation, we used the measured performances for the GaInP and GaAs isotype cells. From the simulated data, we see that when the bottom cell current is over 16.9 mA/cm^2, one can achieve over 30% efficiencies. Using the isotype bottom cell Jsc of 21.1 mA/cm^2, the simulation yields 31.0%, and for the cells with J_{sc}, 19.1 mA/cm^2 estimated from EQE, one achieves

30.8%. The upper limit of the efficiency, considering bottom cell generating a J_{sc} of 23.3 mA/cm^2 and unity EQE, is 31.3% for the structure under investigation.

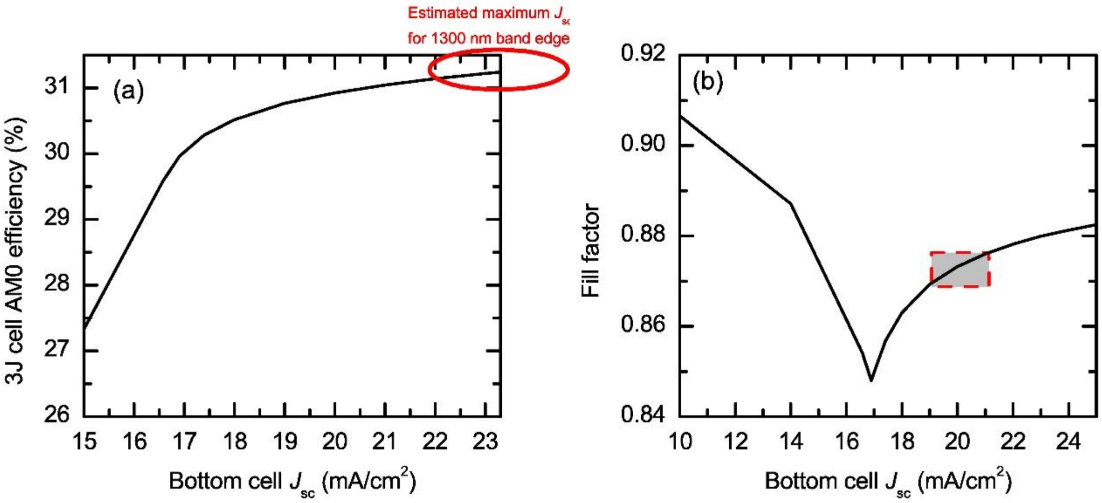

Figure 3. *(a) Calculated efficiency for the triple junction cell with different bottom cell J_{sc} values. (b) Calculated fill factor values for the same simulation. The grey area represents the possible J_{sc} range of the bottom cell.*

The high current of 24.5 mA/cm^2 measured with the WACOM solar simulator can be explained by the fact that this simulator was not in particular calibrated or optimized for the spectral range of the dilute nitride bottom junction. However, our simulation analysis shows that this system can be used for dilute nitride triple junction solar cells if the bottom junction is over generating current. In fact, we made a direct comparison of the same cells measured with WACOM and OAI TriSOL simulators, and we obtained efficiencies of 30.1% and 29.8%, respectively. The efficiency difference of 0.3 percentage points between the different simulators can be partly explained by the differences in the simulator spectrum in the GaInP and GaAs spectral bands. For the short wavelength bands calibration of the TriSOL simulator, we used the GaInP/GaAs cell calibrated at Fraunhofer ISE; in this case, the same limiting current was measured for the triple junction cell. Based on the measurement uncertainties, we estimate the error bar for the efficiency measurement to be ±0.3 percentage points.

As a proof for the accuracy of the simulation, the simulated fill factor values for 3J cell are presented in Figure 3B. If the bottom cell J_{sc} would be less than 19 mA/cm^2, it would be unlikely to have over 0.87 fill factor, which was measured for the cell under broadband excitation. For the future increase of the cell efficiency, we calculated that by slightly increasing the J_{sc} value of the GaInP top cell to 17.7 mA/cm^2, an efficiency of 32.1% can be obtained. In this calculation, we assumed that the J_{sc} increase is taken away from the overgenerating bottom cell.

Moreover, a band gap voltage offset of 0.49 V was achieved when the dilute nitride cell was integrated in the triple junction cell, while the corresponding value for full spectrum excitation of GaInNAs isotype cell was 0.47 V. This result represents the best band gap voltage offset achieved for any type of dilute nitride cell, and the value is approaching the ones achieved for GaInAs. [14] For such a low band gap voltage offset, we estimate that the minority carrier lifetimes should be in the range of a few nanoseconds and the background doping level under 10^{16} cm^{-3}.

Conclusion

Performances of the state-of-the-art dilute nitride triple junction solar cells fabricated by combined MBE-MOCVD method were analyzed using 3 different solar simulators, EQE system, and modelling results. The analysis reveals that the bottom dilute nitride cell is overgenerating a significant amount of current and that the best 2 × 2-cm^2 cell has efficiency of 30.8 ± 0.3% at AM0. The uncertainty for the efficiency arises from the current generation range of the bottom cell, which is 19 to 21 mA/cm^2, while the limiting top cell has a current density of 16.9 mA/cm^2. With optimal current balancing, up to 32.1% efficiency could be achieved when using the band gap combinations presented in this paper. We also achieved down to 0.49-V band gap voltage offset for a dilute nitride cell integrated in a full triple junction structure.

Acknowledgements

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