# Performance Study of Lattice-Matched Multijunction Solar Cells Incorporating GaInNAsSb Junctions with 0.7 – 1.4 eV Bandgap

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***Abstract* — We report on the progress made in the development of lattice-matched multijunction solar cells employing dilute nitride sub-cells. In particular, we report on upright four-junction architecture with bandgaps of 0.9 eV, 1.2 eV, 1.4 eV and 1.9 eV. The four-junction solar cell includes two dilute nitride sub-junctions. This structure exhibited an efficiency of 29% at 1-sun AM1.5D illumination, which is the highest level reported for such architecture so far. In addition, we report on the progress in developing lattice-matched solar cell materials with a bandgap down to 0.7 eV, which enable the fabrication of highly efficient five- or six-junction solar cells on GaAs. We estimate that under 1000 suns illumination these five- or six-junction cells could reach over 50% efficiencies.**

***Index Terms* — III-V solar cell, four-junction solar cell, dilute nitrides, molecular beam epitaxy.**

## I. INTRODUCTION

III-V semiconductor materials enable the fabrication of efficient multijunction solar cells. Currently, the best efficiencies have been reported for the bonded and inverted metamorphic four-junction (4J) cells. These cells exhibit up to 46% conversion efficiency [1]. Unfortunately, wafer bonding and inverted metamorphic approaches require complicated processes and handling of different type of wafers or carriers. Ideally, multijunction solar cell structure is monolithically fabricated on a single substrate. It is also beneficial to fabricate the structure in an upright architecture, which makes the epi-wafer processing simple, increases the yield, and involves handling of one wafer only.

Upright III-V triple-junction (3J) solar cells have been fabricated for more than a decade. The upright 3J solar cells have been fabricated in lattice-matched (LM) GaInP/ Ga(In)As/Ge and GaInP/GaAs/GaInNAsSb architectures, and by upright metamorphic architecture from GaInP/ Ga(In)As/Ge [2]-[4] Thus, the upright technology has evolved towards 4J solar cells with demonstrations and even commercial products reported for both metamorphic and LM approaches [2], [5]-[8]. The LM 4J approach is particularly interesting, since it does not require thick metamorphic buffer layers. In addition, the tunnel junctions perfected for the LM 3Js can be directly utilized for the formation of a high performance LM 4J solar cell. These properties make the LM approach the most efficient strategy for manufacturing. So far, LM 4J cells have been reported by implementing only one 1.0 eV dilute nitride junction on a Ge substrate [5]-[7], yet with modest performances. On the other hand, we have recently reported on an upright 4J solar cell monolithically grown on GaAs that incorporates two dilute nitride junctions [8]. The cell exhibited promising efficiency of up to 25% at one sun and 37% at 100 suns. In this paper, we focus on the progress made for the LM 4J approach. We also present new results concerning narrow bandgap (~0.7 eV) GaInNAsSb solar cells and estimate the practical usability of such narrow band-gap cells in a LM multijunction solar cell with more than four junctions.

## II. EXPERIMENTS

In this study, single-junction and 4J III-V solar cell structures were grown on GaAs substrates by molecular beam epitaxy (MBE). For the building blocks of the LM multijunction solar cells, first a set of single-junction solar cells were grown with bandgaps ranging from 0.7 eV to 1.9 eV. The narrow bandgap dilute nitride materials are pin-type cells, while the cells with over 1.4 eV bandgap are pn-type cells. After the performance analysis of the single-junction cells, experimental 4J solar cells were prepared, with the following combination of junction bandgaps: 0.95 eV, 1.2 eV, 1.4 eV, and 1.9 eV. The top most junction was either AlGaAs or GaInP, while the last two bottom junctions were based on GaInNAsSb, as shown in Fig. 1.

Subsequent to the growth, the solar cell processing was finished by fabrication of metal contacts, mesa isolation and a $Ti_xO/Si_yO$ antireflection coating (ARC). The photovoltaic performance of the solar cells was studied using a one sun solar simulator (OAI Trisol 7 kW simulator) and a self-made quantum efficiency (QE) measurement setup. The simulator was calibrated for AM1.5D (1000 W/m$^2$) spectrum using reference cells with different bandgaps. For the external quantum efficiency (EQE) measurements, the probe signal was calibrated with reference Si and Ge detectors.

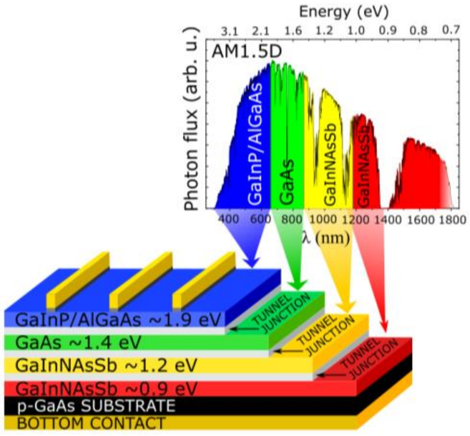

Fig. 1. Schematic illustration of the 4J solar cell structure studied in this work. The top cell can be AlGaAs or GaInP.

## III. RESULTS AND DISCUSSION

First, we measured the IV characteristics of the MBE-grown III-V solar cells. The determined open-circuit voltage ($V_{oc}$) values for MBE-grown LM solar cells are presented in Fig. 2. The $V_{oc}$ values were determined with full spectrum one sun AM1.5 1000 W/m$^2$ illumination. We see that below 0.55 V bandgap voltage offset values ($W_{oc}$) can be exhibited by using over 0.90 eV bandgap energies, and that the $W_{oc}$ increases to 0.65 V for the smallest bandgap values [9]. We note that in the best case, 1 eV dilute nitride cell can exhibit $W_{oc}$ value of 0.47 V. High current generation can be also achieved, owing to ~90% average EQE for the cells with over 0.9 eV bandgap. We believe that the narrow bandgap cells can be significantly improved by optimization, as it has also been possible earlier for 1 eV material.

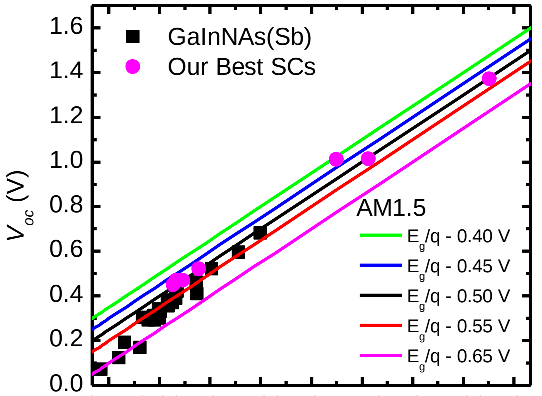

Fig. 2. $V_{oc}$ values for lattice-matched solar cells with different junction bandgap values determined using one sun AM1.5 (1000 W/m$^2$) illumination.

The wide range of available LM solar cell materials on GaAs with different bandgaps enable the fabrication of multijunction solar cells with more than three junctions. Thus, we have fabricated 4J solar cells incorporating junctions of 1.9 eV AlGaAs, 1.4 eV GaAs, 1.2 eV GaInNAsSb and 0.95 eV GaInNAsSb, as well as junctions of 1.9 eV GaInP, 1.4 eV GaAs, 1.2 eV GaInNAsSb and 0.95 eV GaInNAsSb. The LM 4J solar cell could achieve up to 34.7% efficiency at one sun, 43.2% efficiency at 100 suns and 46.4% efficiency at 1000 suns [8]. However, the bandgaps of the top cell pairs GaInP/GaAs and AlGaAs/GaAs in this configuration are not optimal; they are selected rather due to practical reasons. Firstly, thin top junctions enable fast epitaxial growth, and secondly it was easier to fabricate a high performance LM 4J benchmark demonstrator with well-known materials. Higher efficiencies could be achieved by replacing the top junction pair with junctions that have slightly higher bandgaps and $V_{oc}$.

The one-sun IV characteristics of the LM 4J cells are presented in Fig. 3. The LM 4J cells with AlGaAs top cell (red/SC1 and black/SC2 curves) exhibited up to 25% conversion efficiency. Using this data as an input for the structural optimization, we fabricated an improved LM 4J structure with optimized GaInP top junction. In addition, we refined also the design of the other junctions. As can be seen in Fig. 3, the improved LM 4J solar cell structure (blue/SC3) exhibited up to 29% conversion efficiency. The main improvement is due to the enhanced $V_{oc}$ from 2.94 V to 3.21 V and fill factor (FF) from 74% to 80%. We have estimated that the cell could exhibit a $V_{oc}$ of 3.39 V [8]. For the improved cell, we achieved 95% of this $V_{oc}$ limit. It is also estimated that balanced LM 4J cell could exhibit a $J_{sc}$ of 12.5 mA/cm$^2$ [8], of which up to 94% has been achieved. We expect further improvements by preparing the 4J with a more transparent top tunnel junction, by improving the ARC and by perfecting the current generation balance. We also expect that the improved LM 4J will set a new record for our LM 4J cells in CPV conditions.

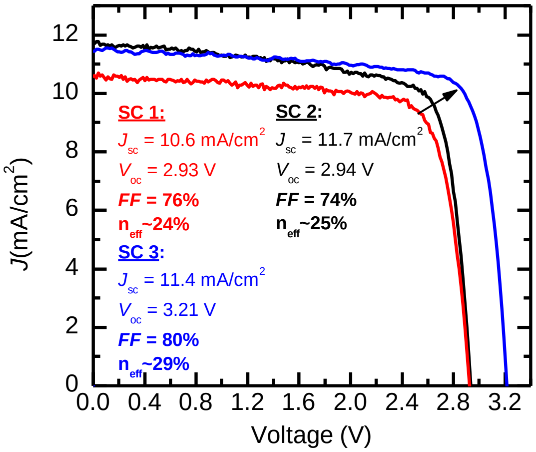

Fig. 3. IV characteristics of 4J solar cells under one sun illumination.

Fig. 4 shows an EQE measurement for an AlGaAs/GaAs/GaInNAsSb/GaInNAsSb solar cell and for a GaInNAsSb bottom cell with 0.75 eV bandgap. Here, the EQE curve of the 0.75 eV cell is filtered with the experimental 4J solar cell. For simplicity, we assume that the bottom cell in the 4J has negligible collection losses for the absorbed photons. This assumption is motivated by the fact that the bottom cell of the 4J has rather long minority charge carrier lifetime of 2 to 4 ns [8], as verified by PC1D modelling. By using these conditions, the prototype 0.75 eV bottom junction could generate 3.7 mA/cm$^2$ current density under AM1.5D (1000 W/m$^2$) spectrum.

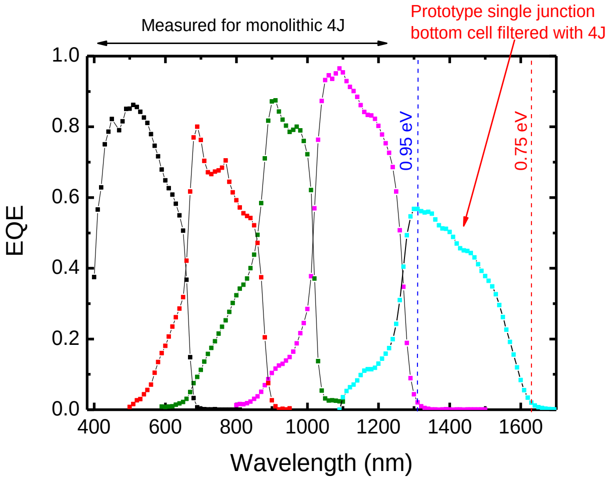

Fig. 4. EQE measurement of an AlGaAs/GaAs/GaInNAsSb/GaInNAsSb solar cell [8] and the new 0.75 eV bottom cell [9]. The EQE of the 0.75 eV bandgap bottom junction is calculated to be incorporated under the experimental 4J cell.

This current density is far too low for a high efficiency 5J. Because of this, we used the data of Fig. 2, Fig. 3 and Fig. 4 as an input for the calculation of an optimal LM 5J and LM 6J cells that incorporate the prototype 0.75 eV bottom cell. The structure is optimized by finding an optimal bandgap configuration for the 5J and the 6J cells, when optically thick junctions are used on top of the 0.75 eV junction. By using top cell bandgaps of 2.1 eV and 2.0 eV for the 5J and 6J cells respectively, the cells could exhibit 50.0% and 50.4% efficiencies at 1000 suns. The corresponding current densities would be 9.7 A/cm$^2$ and 8.2 A/cm$^2$. It is also interesting to note that the optimal 6J could be made by using three dilute nitride junctions. It is clear that the efficiencies are currently just projections, but since all the experimental junctions are lattice-matched on GaAs, the road-map for the 5J and 6J cell implementation is rather straightforward. One of the main challenges that needs to be solved include the fabrication of high quality AlGaInP junctions with over 2 eV bandgap on top of the LM 5J and 6J stack.

## IV. CONCLUSIONS

We report the progress in the development of III-V solar cells LM on GaAs substrate with bandgap energies down to 0.7 eV. In addition, progress for the development of LM 4J solar cells incorporating two dilute nitride sub-cells is reported. Since the recent report published in [8], we have been able to increase the AM1.5D one sun efficiency of the 4J solar cell from 25% to 29%. The increase is mainly due to an improvement of $V_{oc}$ from 2.9 V to 3.2 V. We also presented preliminary results for a LM 0.75 eV GaInNAsSb bottom cell. It was estimated that the $J_{sc}$ value of 5J or 6J cells incorporating the 0.75 eV junction could reach 9.7 A/cm$^2$ and 8.2 A/cm$^2$ at 1000 suns, respectively. In turn, such cells could reach 50.0% (5J) and 50.4% (6J) efficiencies. Due to the early stage of the development for the narrow bandgap GaInNAsSb junctions, we believe that it is possible to increase the cell performance significantly.

## ACKNOWLEDGEMENTS

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## REFERENCES

[1] M.A. Green, Y. Hishikawa, E.D. Dunlop, D.H. Levi, J. Hohl-Ebinger, M. Yoshita and A. Ho-Baillie, "Solar cell efficiency tables (Version 53)," Prog Photovolt Res Appl, vol. 27, pp. 3-12, 2019.

[2] W. Guter, F. Dunzer, L. Ebel, K. Hillerich, W. Köstler, T. Kubera, M. Meusel, B. Postels and C. Wächter, "Space Solar Cells – 3G30 and Next Generation Radiation Hard Products," E3S Web Conf., vol. 16, 2017.

[3] M.A. Green, K. Emery, Y. Hishikawa, W. Warta, and E. D. Dunlop, Solar cell efficiency tables (Version 41). Prog. Photovolt: Res. Appl., vol. 21 pp. 1-11, 2013.

[4] A. Aho, R. Isoaho, A. Tukiainen, V. Polojärvi, T. Aho, M. Raappana and M. Guina, "Temperature coefficients for GaInP/GaAs/GaInNAsSb solar cells," in 11TH International Conference on Concentrator Photovoltaic Systems: CPV-11, pp. 050001, 2015.

[5] R.R. King, P.C. Colter, D.E. Joslin, K.M. Edmondson, D.D. Krut, N.H. Karam and S. Kurtz, "High-voltage, low-current GaInP/GaInP/GaAs/GaInNAs/Ge solar cells," in Photovoltaic Specialists Conference, pp. 852-855, 2002.

[6] S. Essig, E. Stammler, S. Ronsch, E. Oliva, M. Schachtner, G. Siefer, A.W. Bett and F. Dimroth, "Dilute nitrides for 4-and 6-junction space solar cells," in 9th European Space Power Conference, 2011.

[7] M. Ochoa, I. García, I. Lombardero, L. Ayllón, I. Rey-Stolle, C. Algora, A. Johnson, J.I. Davies, K.H. Tan, W.K. Loke, S.

Wicaksono, S.F. Yoon, E. Ochoa-Martínez and M. Gabás, "Modelling of lattice matched dilute nitride 4-junction concentrator solar cells on Ge substrates," AIP Conference Proceedings, vol. 1766, pp. 080003, 2016.

[8] A. Aho, R. Isoaho, L. Hytönen, T. Aho, M. Raappana, V. Polojärvi, A. Tukiainen, J. Reuna, S. Mäkelä and M. Guina, "Lattice-matched four-junction tandem solar cell including two dilute nitride bottom junctions," Prog Photovolt Res Appl, vol. 0, 2018.

[9] R. Isoaho, A. Aho, A. Tukiainen, T. Aho, M. Raappana, T. Salminen, J. Reuna, M. Guina,"Photovoltaic properties of low-bandgap (0.7–0.9 eV) lattice-matched GaInNAsSb solar junctions grown by molecular beam epitaxy on GaAs", Solar Energy Materials and Solar Cells, vol. 195, pp. 198-203, 2019.