

Wafer-bonded Four-junction Solar Cell with 47.6% Conversion Efficiency for High Concentrating Photovoltaics

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Abstract—In high concentration photovoltaics (CPV) the solar cell only contributes less than 20 % to the overall system cost while most other costs are area related. Thus, solar cell performance is a key parameter to bring down levelized cost of electricity for CPV. In this work, we present a wafer-bonded 4-junction solar cell that was realized with the help of direct wafer-bonding. With this device, we reached a photovoltaic conversion efficiency of 47.6% at 665 suns, which demonstrates the potential of high concentration photovoltaics to contribute to the energy transition. It is the highest solar to electricity conversion efficiency that has been demonstrated up to date.

Keywords—Concentrating Photovoltaics, Direct wafer-bonding, III-V solar cells

I. INTRODUCTION

In the domain of high-concentration photovoltaics (CPV), the solar cell constitutes merely 10-15 % of the total system cost [1], while the majority of other expenses is associated with the module area. Consequently, optimizing solar cell performance emerges as a pivotal factor in reducing the levelized cost of electricity in CPV systems. Today's state-of-the-art technologies are multi-junction solar cells based on III-V semiconductors with three or more junctions. The best 3-junction solar cell based on GaInP/GaAs/GaInAs reached an efficiency of 44.4 % [2]. With an inverted metamorphic 6-junction solar cell recently an even higher efficiency of 47.1 % was demonstrated [3].

In this work, we present a new record solar cell, which is a wafer bonded GaInP/AlGaAs//GaInAsP/GaInAs 4-junction device with an efficiency of 47.6 %. We describe how it is realized with metal organic vapor phase epitaxy (MOVPE), subsequent direct wafer-bonding and standard microfabrication steps.

II. TECHNOLOGICAL REALIZATION

A. Metal Organic Vapor Phase Epitaxy

We fabricated a 4-junction solar cell following a wafer-bonding concept [4, 5]. Two separate dual-junction cell stacks were grown by metal organic vapor phase epitaxy (MOVPE) using an AIXTRON 2800G4-TM reactor. An $\text{In}_{0.85}\text{Ga}_{0.15}\text{As}_{0.65}\text{P}_{0.35}/\text{In}_{0.53}\text{Ga}_{0.47}\text{As}$ bottom tandem cell structure was grown upright and lattice-matched on a 4" InP

substrate. A $\text{Ga}_{0.51}\text{In}_{0.49}\text{P}/\text{Al}_{0.03}\text{Ga}_{0.97}\text{As}$ top tandem cell structure was grown invertedly lattice-matched on a 4" GaAs substrate. Target materials were defined by transfer matrix modeling of the absorptance aiming for current matching at standard testing conditions under the AM1.5d spectrum. Ternary and quaternary materials are modeled using an algorithm that morphs data between known compositions [6]. For the handover from modeling to epitaxial growth and iterative feedback, the bandgap energy was extracted from photoluminescence as well as from EQE measurements [7], following the approach published by Schygulla et al. [8]. Careful subcell absorber material characterization and optimization using X-ray diffraction analysis, spectrally and time-resolved photoluminescence, and atomic force microscopy along with precise MOVPE in-situ process control allowed to maximize the material qualities. A schematic representation of the final device stack is shown in Fig. 1 and a photograph of a fully processed wafer is displayed in Fig. 2.

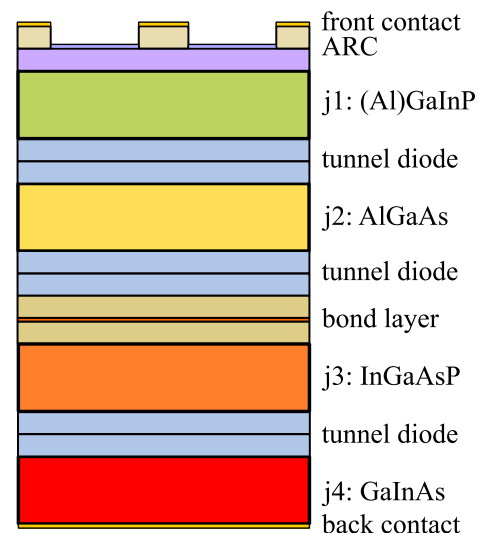


Fig. 1: Schematic representation of the 4-junction solar cell layer stack.

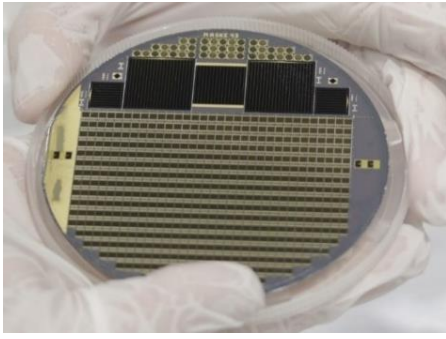


Fig. 2: Photography of a fully processed 4" wafer. The 5.4 mm^2 concentrator solar cells, which were used for IV-measurements under concentration, are positioned in the lower part of the wafer. The two large 4 cm^2 solar cells, which were used for EQE-measurements, are positioned in the upper part of the wafer.

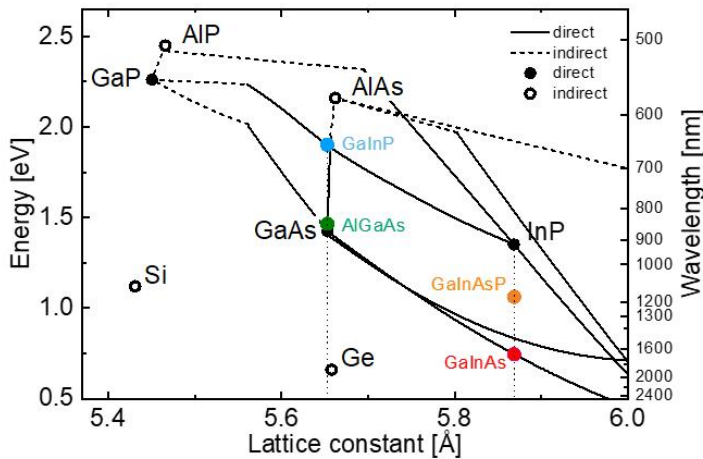
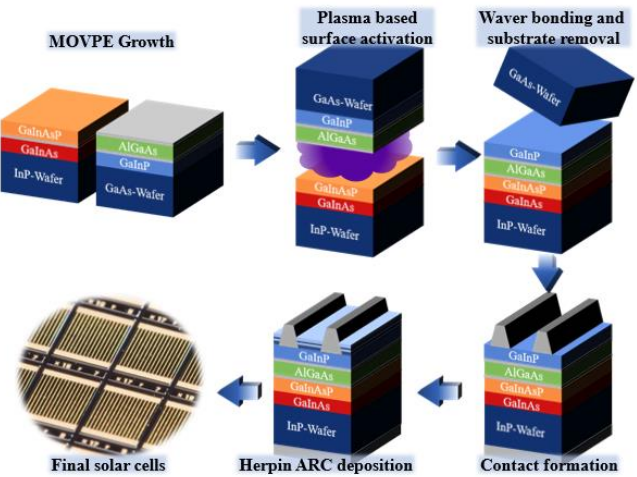


Fig. 3: (Left) The two tandem devices, grown on GaAs and InP, use different III-V compounds to form the sub-cells. High bandgap materials GaInP and AlGaAs are lattice-matched grown on the GaAs substrate, and low bandgap sub-cells made from GaInAsP and GaInAs are lattice-matched grown on InP. (Right) The process flow for a wafer-bonded 4-junction solar cell. After epitaxial growth of two tandem cells on their respective growth substrate, surfaces are cleaned and polished again, activated with an ion beam and then bonded with a direct wafer bond. Afterwards, contacts and a 4-layer antireflection coating are added with microfabrication steps.



III. RESULTS

The EQE of the solar cells are shown in Fig. 4. The excellent current match can nicely be seen as well as the high overall EQE, proving low parasitic absorbance in tunnel diodes, low reflectance and low finger shading.

The presented 4-junction solar cell reaches a maximum power conversion efficiency of 47.6 % under 665-fold concentration of the AM1.5d spectrum as can be seen in Fig. 5, which plots open circuit voltage V_{OC} , fill factor FF , and efficiency η against concentration ratio C . The concentration, at which the peak efficiency was reached, was increased as compared to the previous champion 4-junction device [9] from 508 suns to more than 665 suns due to a reduced series resistance, and consequently a reduced drop in fill factor at higher current densities. This is an important step towards highest efficiencies at high concentrations.

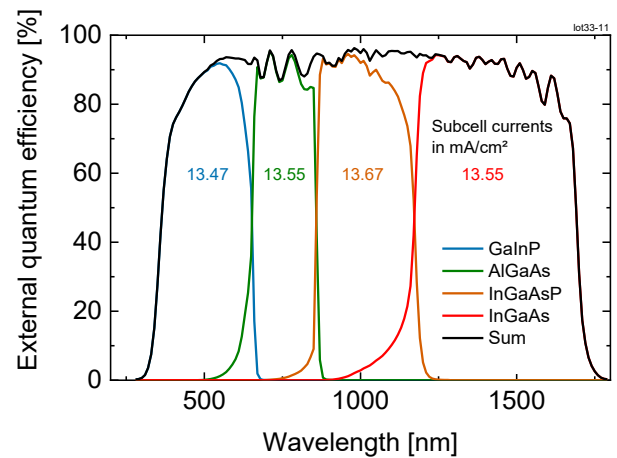


Fig. 4: External quantum efficiency EQE of the four subcells (colored lines) plotted against wavelength. The black line represents the sum of the subcell EQEs. Resulting subcell currents under the AM1.5d norm spectrum are stated inside each subcell EQE plot.

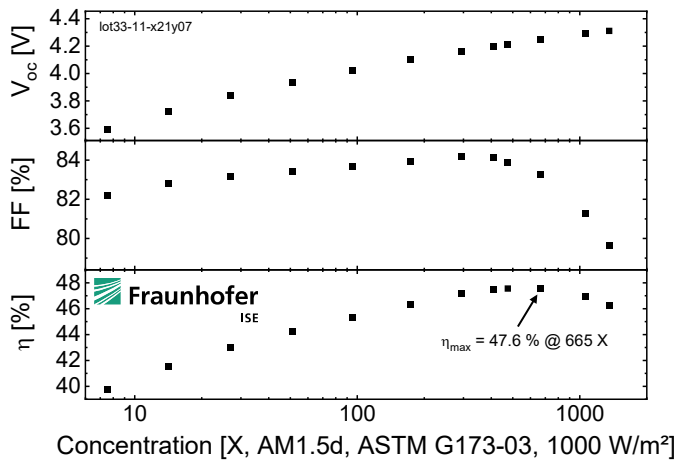


Fig. 5: Performance metrics of the wafer-bonded 4-junction concentrator solar cell plotted against concentration; open-circuit voltage V_{OC} , fill factor FF and conversion efficiency η . The record efficiency of 47.6 % was reached at a concentration of 665 suns.

The I - V characteristics of the champion device are shown in Fig. 6. The cell shows a high parallel resistance and a low specific series resistance of around $20 \text{ m}\Omega \text{ cm}^2$, which allows for the operation of the device at high concentrations of more than 500 suns.

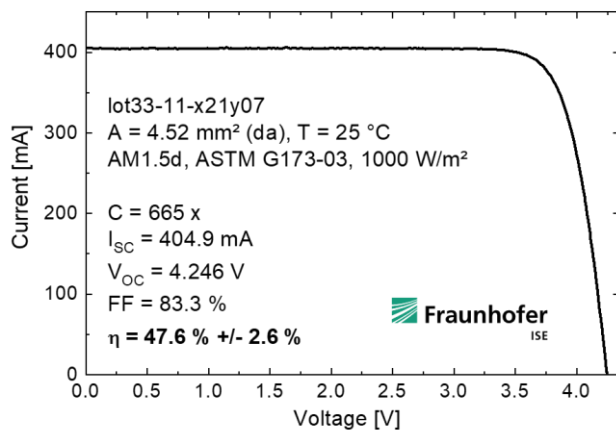


Fig. 6 Current-voltage (I - V) curve of the champion device measured under a spectrally adjustable flash based solar simulator with four different light channels (QuadFlash [10]) in the ISE calibration laboratory. The aperture area was defined by a shadow mask which covered the edges of the chip with an opening of 4.52 mm^2 .

IV. CONCLUSION

We presented a wafer-bonded 4-junction solar cell that was realized following a direct wafer-bonding approach. The champion device achieved an unprecedented power conversion efficiency of 47.6 % at 665 suns, which clearly demonstrates the potential of high concentration photovoltaics to contribute to the energy transition.

V. REFERENCES

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