# 34.1 % Efficient GaInP/AlGaAs//Si Tandem Cell

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***Abstract*— III-V/Si tandem solar cells are investigated as a promising solution to increase the power output of photovoltaic modules under terrestrial sunlight conditions. Over the last years, we have developed a wafer-bonded GaInP/AlGaAs//Si triple-junction solar cell with a recently calibrated conversion efficiency of 34.1% under AM1.5g. This is the highest efficiency of any Si-based 2-terminal tandem device and it shows the potential of this technology to reach significantly higher performances than any single-junction devices.**

***Keywords—III-V on Si, multi-junction solar cells***

## I. INTRODUCTION

As silicon solar cells reach the theoretical limit of performance, tandem devices are more intensively investigated for terrestrial photovoltaic applications. Silicon is a suitable low cost bottom cell and substrate material for tandem cells with two or three junctions and the two most promising top absorbers are currently made either of Perovskites or III-V compound semiconductors. We are developing combinations of III-V and silicon absorbers and follow a process of wafer bonding to transfer the 3-5 µm thin III-V layer stack onto a pre-processed silicon bottom cell. With this, we combine III-V top solar cells with very high material quality with a Silicon tunnel-oxide-passivated bottom cell. This concept has already led to excellent passivation for the Si cell and therefore high voltages of nearly 690 mV. In 2018 we have published results of a GaInP/GaAs//Si triple-junction cell with 33.3% efficiency [1] which already included a photonic rear side grating in SU8 resist coated with silver to enhance absorption in the Si bottom cell [2]. This cell was processed by growing the layer structure for the GaInP/GaAs top absorbers inverted and bonding them to the silicon bottom cell.

Now we have adapted the process flow by growing the III-V absorbers upright, then temporarily attaching the film to a sapphire wafer before removing the GaAs substrate and bonding the III-V layers onto the Si bottom cell. The two different processes are described schematically in Figure 1 and Figure 2. The new process route has advantages for the GaInP top cell which experiences less exposure to high temperatures above 600 °C during MOVPE growth. Additionally, a rear-hetero design could be successfully implemented resulting in improved device voltages.

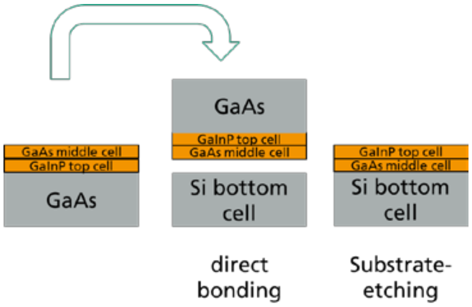

*Figure 1: Process flow for a GaInP/GaAs//Si triple-junction cell by wafer bonding of an inverted top tandem cell structure to silicon.*

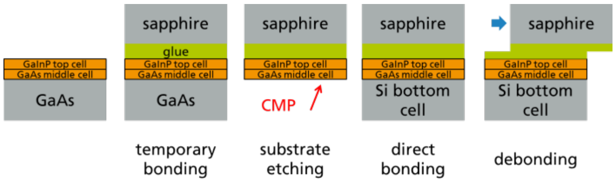

*Figure 2: Advanced process flow for a GaInP/Gas//Si triple-junction cell by wafer bonding in which the III-V layers are temporarily attached to a sapphire wafer before bonding them to silicon.*

## II. EXPERIMENTAL

All III-V layers were grown by MOVPE using an Aixtron G4 planetary reactor. Cell processing for the best devices followed the route described in Figure 2. The cell structure is illustrated in Figure 3. $Al_{0.06}Ga_{0.97}As$ was used for the middle cell with a thickness of 2.65 µm. The top cell was made of GaInP with an n-doped absorber and a p-doped AlGaInP back surface field. High bandgap tunnel diodes were introduced between the top and middle cell as well as between the middle and bottom cell. The III-V layers were bonded to the silicon bottom cell using surface activated direct wafer bonding. This required CMP polishing of both, the poly-Si and GaAs bond layers before the bonding to achieve sufficiently low surface roughness.

The Si bottom cell has tunnel-oxide passivating contacts (TOPCon) on both sides [3]. A rear side grating in SU8 resist coated with silver helps to enhance absorption. The cell has a 2-layer anti-reflection coating and metal contacts on top and bottom.

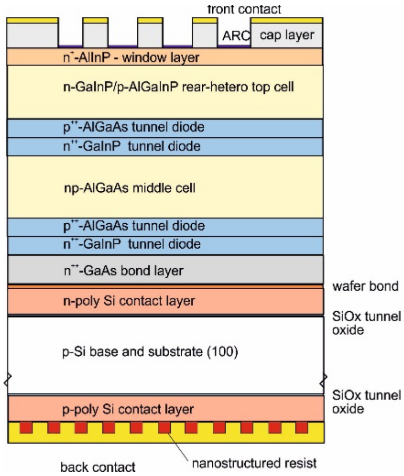

*Figure 3: Full layer structure of cell X610-6 with a GaInP/AlGaInP rear-hetero top cell and an AlGaAs middle cell.*

Figure 4 shows images of the 5 µm thin GaInP/AlGaAs tandem solar cell structure on sapphire before wafer bonding (left) as well as a scanning acoustic microscope image after bonding the layers onto the silicon bottom cell (right). One can see that the layers were well bonded in the middle of the wafer. Towards the edge, the film was partially removed during the etching of the GaAs substrate which is mainly caused by strain.

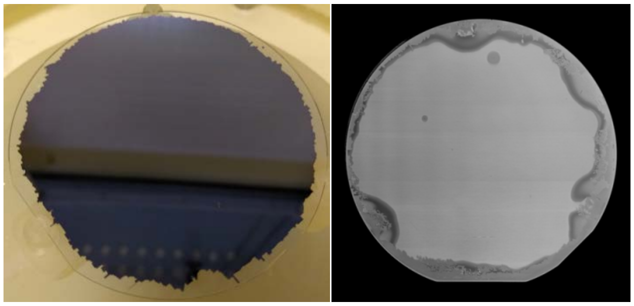

*Figure 4: GaInP/AlGaAs top cell structure after temporary bonding to sapphire and removal of the GaAs substrate (left). SAM image of the bond interface between the GaInP/AlGaAs top cell and Si. Continuous light grey areas in the center of the wafer indicate good bond quality.*

## III. Results and Discussion

Solar cells with an area of 4 cm$^2$ were processed and characterized in the Fraunhofer ISE CalLab. An apparent sign of quality is visible red luminescence emitted by the top GaInP cell when illuminated under the lamp of a solar simulator. The cells in the center of the wafer emit homogeneous red light (see photograph in Figure 5). Cells closer to the wafer edge show a dark contrast, which corresponds to unbonded areas or areas with increased defect density. The red luminescence was not visible in previous batches of triple-junction solar cells and confirms that non-radiative recombination in the GaInP top cell was significantly reduced by integrating a rear-heterojunction design.

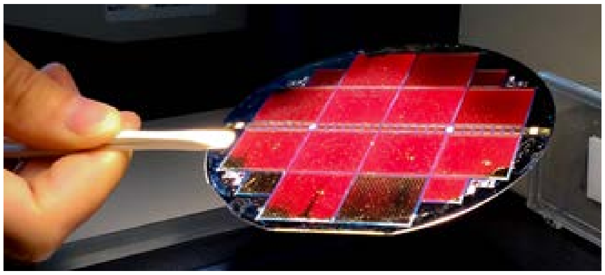

*Figure 5: Image of the best GaInP/AlGaAs//Si wafer X610-6 with 4 cm$^2$ devices shining red under the solar simulator due to luminescence from the GaInP top cell.*

IV-characteristics under AM1.5g are shown in Figure 6 and the EQE in Figure 7. An efficiency of 34.1% is reached under AM1.5g conditions [4]. The current is limited to 12.4 mA/cm$^2$ by the AlGaAs middle cell. Both, the Si cell with 13.1 mA/cm$^2$ and the GaInP top cell with 13.7 mA/cm$^2$ generate >5.6 % relative higher photocurrents. The additional current cannot be utilized in this series-connected 2-terminal device, therefore re-adjustment of the top and middle cell bandgaps/thicknesses will further improve the performance of this device. The open-circuit voltage of the current cell generation is 50 mV higher compared to our previous GaInP/GaAs//Si tandem with 33.3% efficiency [1]. Table 1 shows how this improvement in voltage is distributed. The voltage of the GaInP top cell could be improved by 38 mV which is explained by better material quality (longer carrier lifetime) and the implementation of a rear-heterojunction cell design. The AlGaAs middle cell has a 12 mV higher voltage than the previous GaAs cell but the bandgap was increased by 80 mV. This shows that the expected gain in voltage could not yet be fully harvested. This is explained by a lower quality of Al-containing subcells. The voltage of the Si bottom cell is unchanged.

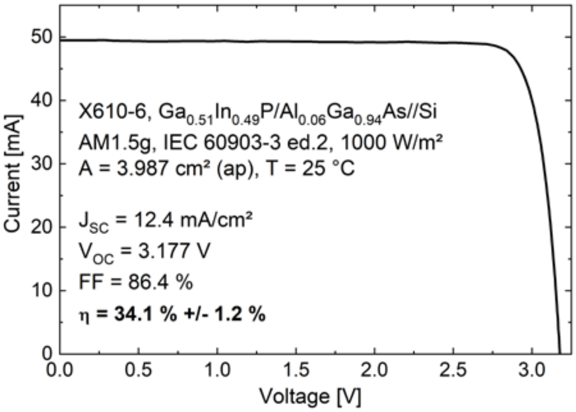

*Figure 6: IV-characteristics of the currently best GaInP/AlGaAs//Si triple-junction solar cell under AM1.5g spectral conditions. The measurement was performed in the Fraunhofer ISE CalLab.*

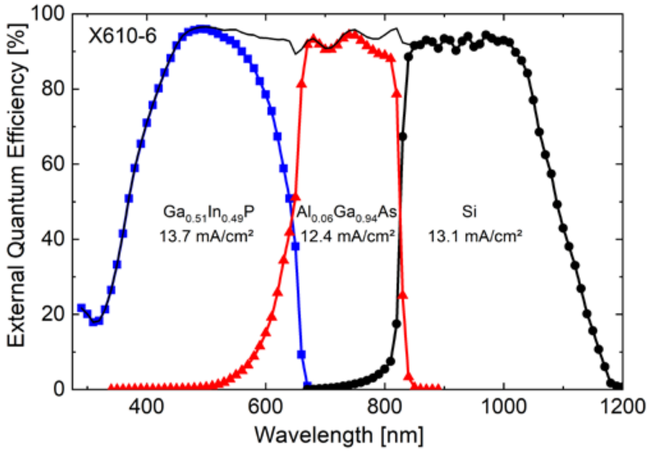

*Figure 7: Ext. Quantum Efficiency of the currently best GaInP/AlGaAs//Si triple-junction solar cell*

*Table 1: Subcell voltages determined by spectral electroluminescence and quantum efficiency measurements.*

| **Subcell voltage** | **EX8-11 (η=33.3%)** | **X610-6 (η =34.1%)** | **Subcell voltage gain** |
|---|---|---|---|
| J1 | 1.412 V | 1.450 V | +38 mV |
| J2 | 1.026 V | 1.038 V | +12 mV (but $E_g$+80mV) |
| J3 | 0.689 V | 0.689 V | unchanged |
| Total | 3.127 V | 3.177 V | + 50 mV |

We have recently realized another III-V/Si triple-junction solar cell in which the AlGaAs middle cell was replaced by GaInAsP. Details of the GaInAsP middle cell development are discussed in [5] where it is shown that both, the current generation and voltage are superior for this material. The sum of the subcell EQEs and photocurrents in Figure 8 increased from 39.4 mA/cm$^2$ (13.7+12.5+13.2 mA/cm$^2$) to 40.2 mA/m$^2$ (13.8+13.4+13.0 mA/cm$^2$) for this new GaInP/GaInAsP//Si triple-junction cell. Unfortunately, the cell had technological issues with the rear side contact which resulted in a loss in fill factor and therefore did not lead to a new efficiency record.

Figure 8 also shows the EQE of a mono-crystalline silicon solar cell with random pyramids on the front and a planar back side. This cell has a conversion efficiency of 25.8% and an outstanding current density of 42.9 mA/cm$^2$ [6]. One can see that the quantum efficiency of the silicon solar cell outperforms all III-V/Si tandem devices in the wavelength range between 300-1200 nm. Some of this current is still accessible for the III-V/Si tandem cells in the future by optimizing the III-V layer structure towards lower parasitic absorption in window, barrier and tunnel diode layers. And further by introducing a more efficient light trapping at the rear side of silicon which allows optimum absorption close to the bandgap.

Besides the potential to increase the current density of our III-V/Si tandem solar cells, also the voltage can be improved by better material quality and slight bandgap increase of the GaInP top and GaInAsP middle cell. And finally passivation of the sidewalls of the silicon bottom cell will be another development target in the future which may add 0.5-0.8% absolute in efficiency. This analysis shows that the presented efficiency of 34.1 % for the currently best 2-terminal III-V/Si tandem solar cell still leaves significant room for further research and development.

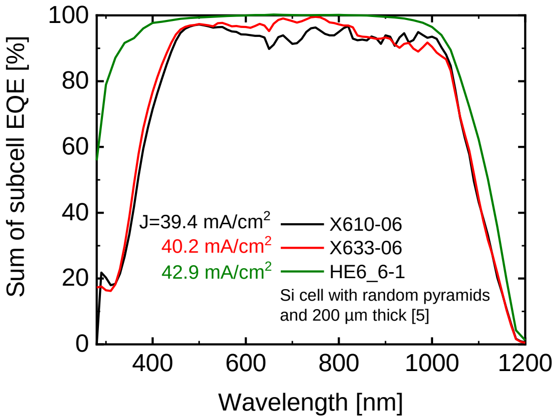

*Figure 8: Comparison of the sum of subcell EQEs for the GaInP/AlGaAs//Si cell X610-06 with 34.1% efficiency and a new GaInP/GaInAsP//Si cell X633-06 with improved middle cell. Furthermore, the EQE of a silicon solar cell with random pyramids and outstanding current density is displayed as reference.*

## IV. SUMMARY

We have developed GaInP/AlGaAs//Si triple-junction solar cells for the application under 1-sun AM1.5g conditions and reached a new efficiency record of 34.1% (AM1.5g, 1000 W/m$^2$, Area = 4 cm$^2$). The cell was calibrated in the Fraunhofer ISE CalLab. Further improvements in current generation are reached by exchanging the middle cell material from AlGaAs to GaInAsP. This change together with further improvements in current collection, silicon absorption, material quality and edge passivation will allow reaching conversion efficiencies above 36% in the future.

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