NEXT GENERATION OF WAFER-BONDED MULTI-JUNCTION SOLAR CELLS

M. Niemeyer, V. Klinger, F. Dimroth, F. Predan, P. Fuß-Kailuweit, D. Reinwand, D. Lackner, A. Wekkeli, E. Oliva, M. Schachtner, G. Siefer and A.W. Bett
Fraunhofer Institute for Solar Energy Systems ISE
Heidenhofstraße 2, 79110 Freiburg, Germany

ABSTRACT: The highest conversion efficiencies are reached by multi-junction III-V solar cells. Wafer-bonding offers new possibilities to advance beyond the industrial standard triple-junction cells and its efficiency limitations. Here we present for the first time results of two novel 4-junction device concepts based on direct wafer-bonding with a realistic efficiency potential of 50% under concentrated sunlight. In the first concept, an inverted grown GaInP/GaAs tandem cell is bonded to a metamorphic GaInAs/Ge tandem cell. Frist bonded 4-junction solar cell on Ge shows an efficiency of 34.5% under one sun AM1.5d. In the latter concept a GaSb cell will be bonded to an inverted metamorphic triple-junction solar cell. The main challenge in this approach is a conductive direct wafer bond between the two cell stacks. Here, bond characteristics between GaSb and $Ga_{0.29}In_{0.71}P$ and another between GaSb and $Ga_{0.79}In_{0.21}As$ are shown for the first time.

Keywords: III-V Semiconductors, Epitaxy, Gallium Arsenide Based cells, High-Efficiency, Multijunction Solar Cell, Simulation, Wafer bonding

1 INTRODUCTION

The standard lattice matched multi-junction solar cell made of GaInP/GaInAs/Ge (1.9/1.4/0.7eV) has reached efficiencies of 41% under concentration and is available as an industrial product from companies such as AZUR-Space, Germany [1], Boeing-Spectrolab, US [2] and Emcore, US [3]. In order to achieve higher efficiencies, more junctions with appropriate bandgaps have to be combined. This can be achieved in multiple ways as discussed elsewhere [4]. Today the most promising concepts are metamorphic growth on one standard substrate like GaAs or Ge and bonding of two wafers with different lattice constants.

Inverted metamorphic 3-, 4-, and even 5-junction cells have been successfully demonstrated [5-9]. Nevertheless, growing high quality metamorphic material remains a challenge. Further, especially the inverted metamorphic approach adds complexity to the processing technology as wafer lift-off and additional mechanical stabilizations of the epitaxial layers is required.

A transparent and conductive connection between two solar cells can be achieved by direct wafer-bonding (hence wafer-bonding). Direct atomic bonds are formed at the interface between the two materials. Therefore wafer-bonding enables a combination of materials with highly different lattice constants and offers an alternative to metamorphic growth. The two subsets of the bonded multi-junction stack consist of two separate epitaxial growths where the topmost cell-set is always grown inverted and its substrate is removed after bonding.

For the wafer-bonded GaInP/AlGaAs//GaInAsP/GaInAs cell high quality material by lattice matched growth of GaInP/AlGaAs and GaInAsP/GaInAs on GaAs and InP respectively, provides the basis for the current world-record efficiency of 44.7% [10]. Alternatives to this approach are wafer-bonded cells based on Ge or GaSb substrates which omit the relatively costly InP substrate. All three cell architectures are shown in Figure 1 and have a realistic energy conversion potential of 50% under concentrated sunlight. These four-junction solar cells are suitable for both space and concentrator photovoltaic applications.

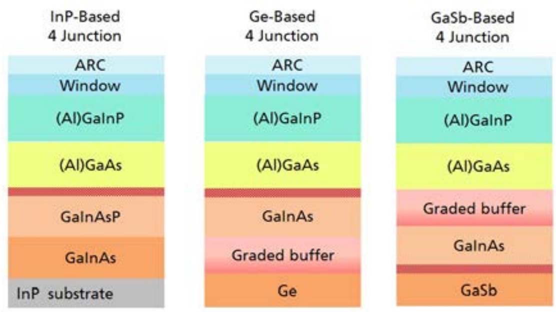

Figure 1: Different cell architectures for wafer-bonded 4-junction solar cells. The bond position is always indicated by the red line. Left: InP-based concept with wafer-bond between (Al)GaAs- and GaInAsP-junction. Center: Ge-based concept with wafer-bond between (Al)GaAs- and GaInAs-junction. The GaInAs junction is obtained by metamorphic growth on the Ge substrate. Right: GaSb-based concept with wafer-bond between GaInAs- and GaSb-junction.

2 SIMULATIONS OF EFFICIENCY POTENTIALS

The concepts of the three wafer-bonded 4-junction cells have been simulated in order to determine their realistic efficiency potentials. Details of the simulation can be found elsewhere [11]. For the simulations mentioned here, models of the cell designs have been created and optimized with regard to the efficiency under concentration of 500 suns (AM1.5d). The first concept based on InP (Figure 1, left) shows an efficiency potential of up to 53.8% [11]. A very similar approach has been already experimentally investigated and is discussed in [10].

The next concept discussed in this paper is a Ge-based 4-junction cell (Figure 1, center). A metamorphic GaInAs junction is grown on a Ge substrate. This tandem cell is then combined with a high-bandgap (Al)GaInP/(Al)GaAs tandem solar cell grown inverted but lattice matched on GaAs by wafer-bonding. This concept has a calculated efficiency of 49.5 % under 500x concentration [11].

For the other concept discussed in this paper (Figure

1, right), an inverted AlGaInP/AlGaAs/GaInAs 3-junction solar cell is bonded to a 0.73 eV GaSb cell, thereby forming a 4-junction solar with a calculated efficiency of 51.5% at a concentration of 500 suns [11].

3 EXPERIMENTAL APPROACH

All structures mentioned in this paper were grown on a multi-wafer AIX2800-G4TM MOVPE reactor at Fraunhofer ISE using standard organometallic precursors and hydrides. For the Ge based concept a GaInP/GaAs (“cell 1”) and a GaInP/$Al_{0.04}Ga_{0.96}As$ (“cell 2”) tandem cell were grown inverted on a 4” GaAs wafer. The Ge/GaInAs tandem cell was grown on a 4” Ge wafer. After diffusing the Ge cell, the lattice constant was changed by a metamorphic buffer. On top of the buffer a $Ga_{0.71}In_{0.29}As$ (“cell 1”) and $Ga_{0.82}In_{0.18}As$ (“cell 2”) cell was grown, respectively.

For the second concept a metamorphic GaInAs buffer was grown on a 4” GaAs substrate to simulate the IMM structure. As a bond layer $Ga_{0.79}In_{0.21}As$ and $Ga_{0.29}In_{0.71}P$ were used. All layers and substrates were negatively doped by Si.

Microscopic surface roughness is a crucial parameter for the bonding process [12-14] and should be kept below 1 nm RMS [14], which is challenging especially for metamorphic growth. Therefore both wafers were treated by chemical mechanical polishing (CMP). On the GaInAs/Ge wafer surface roughness was reduced from 0.7 nm to 0.1 nm.

For all structures bonding was performed in a SAB-100 bonder from Ayumi by fast atom beam activated wafer-bonding. Oxides and other contaminants were removed from the surface by argon fast atom beams (FAB) at low pressure (< 3 E-6 Pa). After FAB cleaning, the wafers were immediately brought into contact with each other and a force of 10 kN was applied for 5 min.

In the first concept GaAs substrate was removed by etching before processing. The cells were processed with a standard front and back side contact, mesa etched and an anti-reflection coating was evaporated, optimized for the cell structure.

In the second concept the structures on GaAs were bonded to a 2” GaSb wafer. For conductivity measurements ohmic contacts were evaporated on both sides of the bond and the bond was diced in pieces of 3x3 mm².

4 RESULTS AND DISCUSSION

4.1 Ge-based 4-junction cells

The bond quality was tested by scanning acoustic microscopy (SAM). A bonded structure of a GaAs 4” wafer and a Ge 4” wafer with the metamorphic buffer on top can be seen in Figure 2. Nearly no non-bonded areas (white) are visible. This is a sign for high mechanical quality of the bond. It was not possible to divide the two wafers with a blade in order to measure the bond strength as proposed in [15]. This implies that the bond strength is comparable to the atomic bonds in the crystals.

The internal and external quantum efficiency of the first bonded 4-junction solar cell on Ge, cell 1, is shown in Figure 3. This cell shows the high potential of the concept and reveals several possibilities for optimization. To harvest the full potential improved current matching between the sub-cells is necessary. Therefore cell 1 was used as a calibration for further simulations of the absorption using the transfer matrix method.

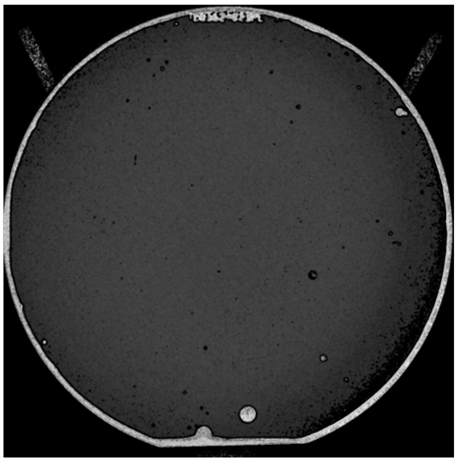

Figure 2: Scanning Acoustic Microscope (SAM) image of a bonded structure of a 4” GaAs wafer and a 4” Ge wafer with a metamorphic buffer on top. Bonded areas are black, non-bonded white. The wafers are completely bonded, except for some small bubbles. The wafer laser marking can be seen on top of the bond.

Several optimizations were realized in cell 2. In respect to current matching the bandgap of the GaInAs cell (Figure 4, (3)) was increased. This also increases the voltage and the quantum efficiency of the GaInAs cell. The latter happens as this cell suffers from low diffusion length due to dislocations introduced by metamorphic growth. A lower lattice constant misfit between the GaInAs cell and Ge should therefore decrease the threading dislocation density. In cell 1 current matching between GaInP/GaAs (24.75 mA/cm²) and GaInAs/Ge (26.70 mA/cm²) was sufficient. In cell 2 the voltage of the stack was also increased by using a fully absorbing $Al_{0.04}Ga_{0.96}As$ cell instead of a partly transparent GaAs cell (Figure 4, (1, 2)).

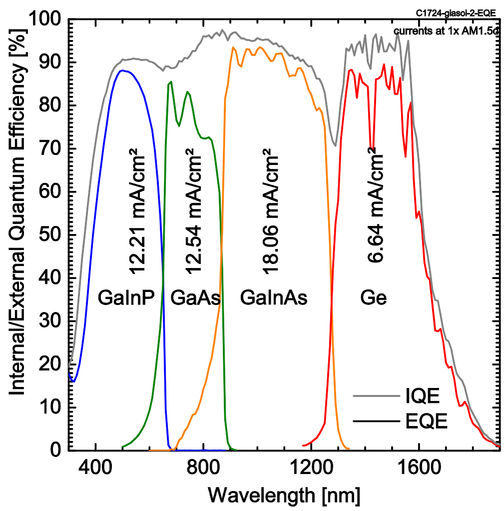

Figure 3: External Quantum Efficiency of the sub-cells and sum of the Internal Quantum Efficiencies of the first

bonded 4-junction solar cell on Ge (cell 1). Currents are calculated under AM1.5d spectrum.

The transparency of the metamorphic buffer between the Ge and GaInAs sub-cells can be further increased as some layers in cell 1 have a lower bandgap than the GaInAs cell. This increases the quantum efficiency of the Ge cell (Figure 4, (4)) in cell 2. Replacing the absorbing tunnel diode between GaInP and GaAs cells by a transparent one will also increase the quantum efficiency of the GaAs cell. All these optimizations were realized in cell 2, shown in Figure 6.

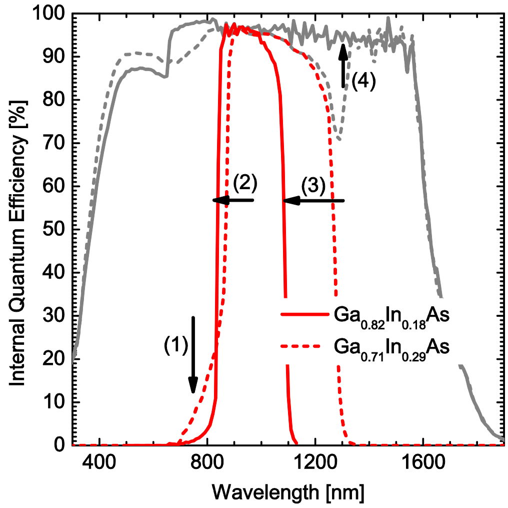

Figure 4: IQE of cell 1, the first 4-junction cell on Ge (gray-dashed), its GaInAs sub-cell (red - dashed) and the optimized version, cell 2. A fully absorbing $Al_{0.04}Ga_{0.96}As$ cell improved the voltage while keeping the current matching (1, 2). Both, changing the bandgap of the GaInAs cell (3) and using a transparent buffer (4), increased the IQE of the cell.

Increasing voltage and current led to an efficiency of 34.5% under one sun AM1.5d. The corresponding I-V characteristics are shown in Figure 5. An increased serial resistance needs further investigations.

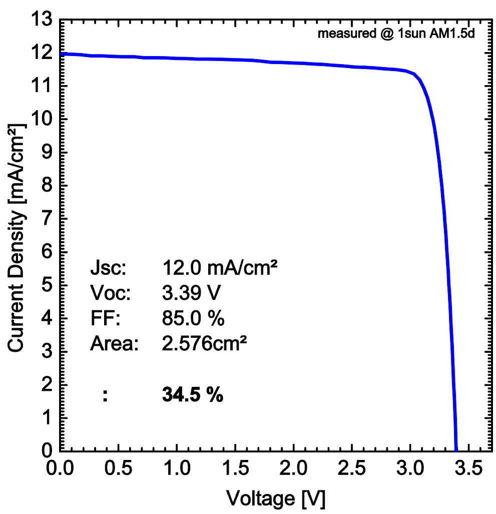

Figure 5: I-V characteristics of cell 2, a bonded 4-junction cell on Ge. An efficiency of 34.5% was measured under one sun AM1.5d illumination.

As shown in Figure 6, current matching was strongly improved compared to cell 1 shown in Figure 3. Further steps, such as increasing the current of the GaInP cell and optimizing the tunnel diodes, are under investigation at the moment. However, these first results look quite promising on the way to the efficiency potential of 49.5% [11] under concentration.

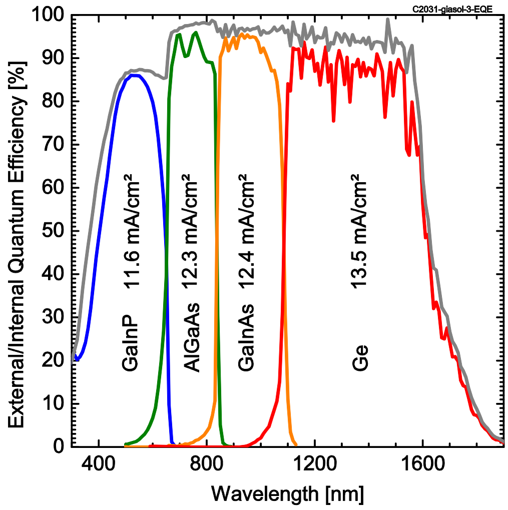

Figure 6: Summed IQE of cell 2 and the EQE of the sub-cells. Currents are calculated with the AM1.5d spectrum under one sun.

4.2 GaSb-based 4-junction cells

Solar cells with an Inverted Metamorphic (IMM) structure have a high potential regarding efficiency [8]. This potential can even be increased by putting a fourth junction with a low bandgap beneath the 3-junction stack. Also GaSb photovoltaic cells have shown excellent performances, e.g. [16]. The missing link for this 4-junction cell is a bond between the metamorphic 3-junction cell and GaSb. This linkage is investigated and discussed here.

The Scanning Acoustic Microscope (SAM) picture in Figure 7 shows a nearly completely bonded (dark grey) area.

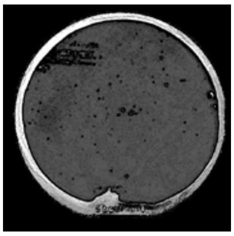

Figure 7: SAM image of a bond between a 2” GaSb wafer and a 4” GaAs wafer with a metamorphic buffer and a $Ga_{0.79}In_{0.21}As$ bond layer. Only the 2” GaSb wafer is visible. Black areas arise from rough backside of the GaSb wafer.

The I-V characteristics of the whole stack (contacts, wafers, bond) are shown in Figure 8. The $Ga_{0.79}In_{0.21}As$/GaSb bond shows ohmic behavior, the $Ga_{0.29}In_{0.71}P$/GaSb bond has a slightly diode like behavior. The voltage loss over the bond itself in a 4-junction cell under 300 suns with a current of approximately 3.7 A would be 5-12 mV in both cases, which is only about 0.3% of the expected V_{OC}.

These results show that a bond between an IMM cell and a GaSb cell with negligible voltage loss can be produced by fast atom beam activated wafer bonding. In a next step the 4-junction cell itself has to be developed.

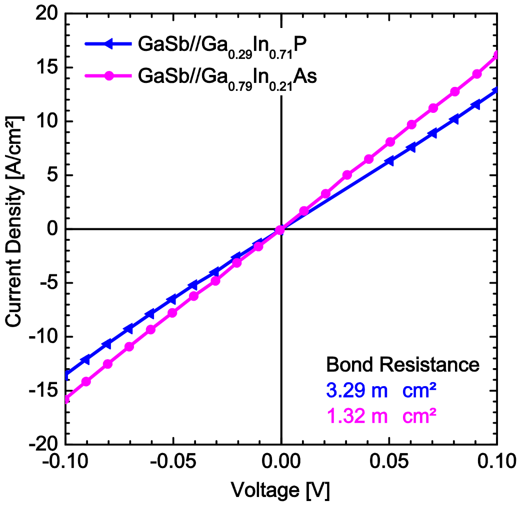

Figure 8: I-V characteristics of bonded structures between GaSb and GaInP (blue) and GaSb and GaInAs (purple).

4 CONCLUSION

As realistic simulations reveal, bonded solar cell structures have the potential to reach efficiencies in the range of 50% under 500 suns. In this paper we report in first experimental results. A Ge-based bonded 4-junction solar cell achieved already an efficiency of 34.5% under one sun. Combining metamorphic material and GaSb with a bond resistance below 5 mΩcm² enables us to close the gap between metamorphic 3-junction cells and GaSb. Therefore 4-junction solar cells with those components are feasible in the future.

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