Presented at the 29th European PV Solar Energy Conference and Exhibition, 22-26 September 2014, Amsterdam, The Netherlands

NEW EFFICIENCY FRONTIERS WITH WAFER-BONDED MULTI-JUNCTION SOLAR CELLS

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ABSTRACT: Triple-junction (3J) solar cells will soon be history. The next generation of multi-junction (MJ) devices are now reaching efficiencies far beyond the record levels of 3J cells on Germanium. In this paper we present results of a 4J wafer-bonded solar cell with bandgaps 1.88 / 1.45 // 1.10 / 0.73 eV measured with an improved efficiency of 46.5% at 324x by Fraunhofer ISE. Design for cost has, from the outset, been a priority with the development of engineered substrates to replace costly and low yielding InP substrates, a product building on Soitec's proprietary SmartCut® technology. Wafer bonding enables the electro-mechanical combination of lattice and thermal expansion mismatched materials with electrically conductive, transparent bonds, enabling concentrator solar cells to be built from high quality 2J GaInP/GaAs absorbers lattice-matched to GaAs bonded to high quality 2J GaInPAs/GaInAs absorbers lattice matched to InP that operate well at high concentration.
Keywords: III-V Semiconductors, Wafer-bonding, Concentrator cells, High-efficiency, Multijunction solar cell.

1 INTRODUCTION

As the now well-known lattice matched GaInP/GaInAs/Ge triple-junction concept reaches the practical limit of its commercial development, namely around 29% to 40% conversion efficiency in space and under concentrated light respectively [1] [2] [3], research into high efficiency III-V based solar cells is exploring a number of new approaches to further increase efficiency. Unconstrained by bandgap, the optimum detailed balance [4] efficiency and corresponding bandgaps for 3, 4 and 5 junction devices is shown in Figure 1 [5].

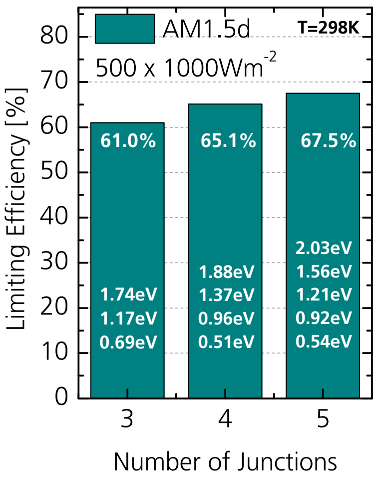

Figure 1: Detailed balanced limit calculations for 3J, 4J and 5J MJ cells under concentrated light, with the optimum bandgap combination shown [5].

4J solar cells combining bandgaps of 1.9 / 1.4 / 1.1 / 0.7 eV are very close to the optimum bandgap combination, with realistic efficiency potential of over 50% under concentration of 500 – 1000x. In order for 4J and 5J solar cells to achieve these projected performance levels, junctions with bandgap energy between 0.9 - 1.1 eV are required, requiring materials that are not readily available lattice matched to GaAs or Ge. Metamorphic [6] and inverted metamorphic [7] approaches, where subcells in the multi-junction (MJ) stack are grown with mismatched materials, gives access to bandgaps typically less than that of GaAs (1.42 eV). However, these devices are challenging to grow with sufficient material quality to avoid voltage losses associated with increased non-radiative recombination, and require additional relatively thick buffer layers to transition from one lattice constant to another. Other approaches include the dilute nitrides [8], which give lattice matched bandgaps ~1 eV, though appear to be restricted to molecular beam epitaxial growth.

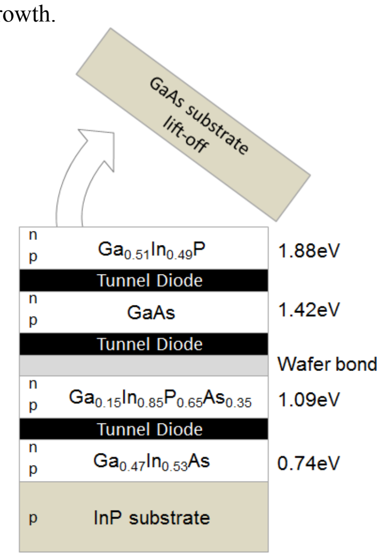

Figure 2: Schematic of a wafer-bonded GaInP/GaAs//GaInPAs/GaInAs 4J solar cell.

Direct semiconductor wafer bonding (hereafter wafer bonding) is an alternative technique enabling two semiconductors possessing different lattice constants and coefficients of thermal expansion to be joined with an electrically conductive, mechanically strong bond. The main challenge of wafer bonding is the mating surface preparation: the two wafer faces must have a very low surface roughness and be free of particles, native oxides, and surface states must be well controlled to achieve high conductivity. Having achieved these conditions, the two materials may bond together and stay bonded. This enables the joining of two materials that would otherwise be difficult to combine through epitaxy owing to lattice or thermal expansion mismatch. Boeing-Spectrolab published the first account of successful wafer bonding to combine high quality III-V materials lattice matched to GaAs and InP into a 4J solar cell [9]. A schematic of such a solar cell is shown in Figure 2. This cell design enables the visible and near infra-red parts of the spectrum to be absorbed by the 2J device lattice matched to GaAs, and the infra-red light is then absorbed in materials lattice matched to InP.

In this paper we report on further progress made in the development of this concept building on the initial report of a 44.7% 4J wafer bonded solar cell [10]. Owing to the expense of brittle InP substrates, one challenge of wafer bonding is to combine the proven high material quality on InP with an acceptable yield and cost point for use in the terrestrial CPV market. To this end, Soitec has developed an engineered substrate based on their SmartCut® technology [11], whereby an ultra-thin single crystal layer of InP is provided on a robust carrier substrate. This technology can enable the more widespread application of InP based semiconductors principally by reducing the cost and increasing the mechanical strength of an InP substrate. A schematic of this is shown in Figure 3.

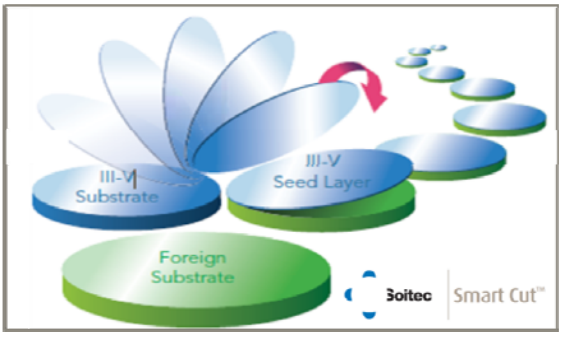

Figure 3: Graph showing the principle of InP-based engineered substrate production.

2 EXPERIMENTAL SETUP

2.1 Epitaxial Growth

All III-V epitaxial layers were grown using an Aixtron 2800-G4™ MOVPE reactor, configured for 8 x 4" wafers. The same reactor was used for both the GaAs based and InP based sub-cells. The top two GaInP/GaAs cells were grown inverted on GaAs wafers, with release and etch stop layers allowing for the removal of the GaAs substrate after bonding. Conventional sources of AsH_3, PH_3, TMGa, TEGa, TMAl, TMIn, were used for group V and III elements respectively, and DMZn, CBr_4, SiH_4, DETe and DTSe for p and n dopants respectively. The same sources were employed for the growth of the InP based bottom two junctions, grown upright. Special care is taken in operating the reactor such that wafer bow after growth and surface particle density is minimized, fundamentally to ensure higher bonding yield.

2.2 Wafer Bonding

Wafers were prepared after epitaxy for wafer bonding with surface treatments (chemical mechanical polishing) followed by the bonding process. This process is proprietary to Soitec. Post-bonding quality is ensured through semiconductor acoustic microscopy (employing ultrasound) which has sub-mm resolution and shows clearly areas where the bonding is complete (black) and leaves voids (white), see Figure 4.

2.3 Post-Bonding processing

The wafers were processed into conventional III-V solar cells after wafer bonding and GaAs substrate removal. Ohmic contacts were deposited on the front and back sides of the wafers, and an optimised 2-layer anti-reflection coating was applied of MgF_2 / Ta_2O_5 . Cell sizes vary from ~5.42 mm^2 for concentrator test cells, with a front grid optimized for ~500x operation, to 4 cm^2 for large area cells for 1 sun and EQE measurements.

2.4 Device characterization

Devices were measured under conventional flash-based wafer mapping tools, details can be found in [12], as a qualitative indication of wafer performance, with cells being further characterized under a 3-source solar simulator [13]. Flash measurements are then carried out under a series of different irradiances to give a performance as function of concentration. Quantum efficiency measurements are also made.

3 RESULTS AND DISCUSSION

3.1 Bonding yield

Since October 2013 significant effort has been spent in improving the bonding, principally through particle density reduction on the post-epitaxial wafer surface. Figure 4a and b shows a scanning acoustic micrograph of the 44.7% wafer reported in [10] and a more recent wafer pair bonded in April 2014.

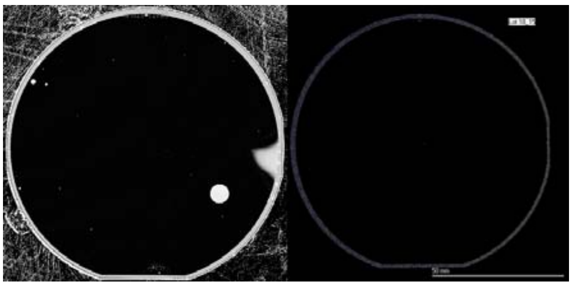

Figure 4a & 4b: Left: (a) 44.7% wafer bond showing voids in white where bonding has not been successful owing to particle contamination on the surface of the wafer; Right: (b) More recent wafer bonding showing almost perfect bonding with very few microvoids. Both wafer-pairs are 100 mm diameter.

3.2 Solar cell quantum efficiency and light IV performance

The solar cell with 44.7% efficiency reported in [10] hereafter referenced as cell A in this paper has a number of deficiencies which are reported in [14] and Figure 5 compares the external quantum efficiency of this 44.7% solar cell with a more recent device referenced as cell structure B.

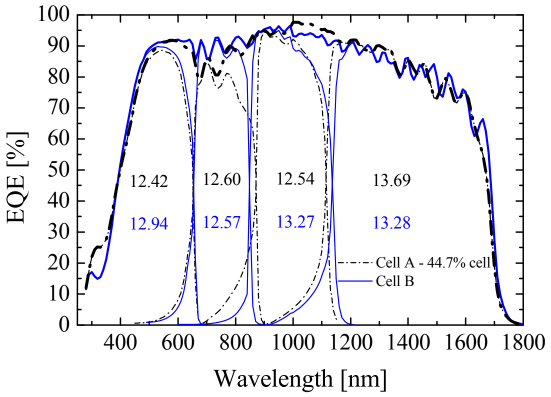

Figure 5: Comparison of EQE of two CPV cells A (published in [10]) and a recently improved design B. The sum of the EQE across all wavelengths is also shown in bolder lines. The current densities under AM1.5d at 1000 Wm^{-2} are shown for all junctions in both devices (upper: cell A, lower: cell B [$mAcm^{-2}$]). Cell A = C1509-1//C1548-5, cell B = C2075-6//C2124-4).

The main improvements resulting from the recent developments are (moving from short to long wavelengths)

- An improved emitter response in the GaInP cell, resulting in higher photocurrent
- A transparent GaInP/AlGaAs tunnel diode between the top two cells has been successfully implemented
- The GaAs-based subcell bandgap and thickness has been increased. This subcell is now providing more photocurrent at a higher voltage
- The GaInPAs cell bandgap has been reduced in order to achieve better current matching between the bottom two cells

The photocurrent mismatch has been reduced from 1.27 $mAcm^{-2}$ in device A to 0.71 $mAcm^{-2}$ in the improved device B, which must be further reduced to obtain maximum efficiency potential from this design.

3.3 Cell Performance under high intensity

The most promising cell has been carefully characterized under spectrally matched 1 sun AM1.5d spectrum and under a flash at Fraunhofer ISE. The cell performance data is shown in Figure 6. Although the limiting one sun photocurrent is only $1.2\%_{rel}$ higher than cell A, cell B performance is significantly enhanced owing to the improved voltage and fill factor performance. The improved voltage performance can be attributed to the higher sum of bandgaps of subcells, and the fill factor has improved because of reduced parasitic series resistance in the device. Figure 7 shows IV curves for the two solar cell devices A and B taken at very similar intensities (~300x) for a visual comparison of the curves. The inset shows the detail near V_{OC}, where R_{series} can be compared. The result of the measurements is a peak efficiency of 46.5% at 324x concentration.

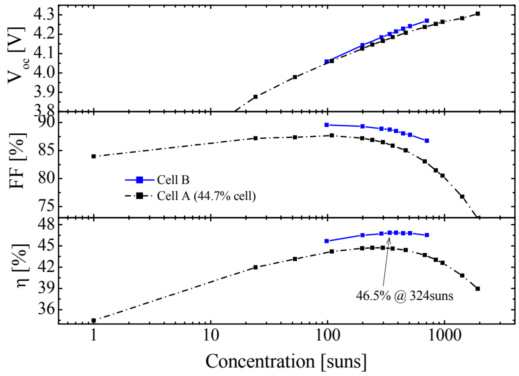

Figure 6: Performance metrics for cell structure B compared with the previous record cell A. The peak efficiency measured at 324x is now 46.5%.

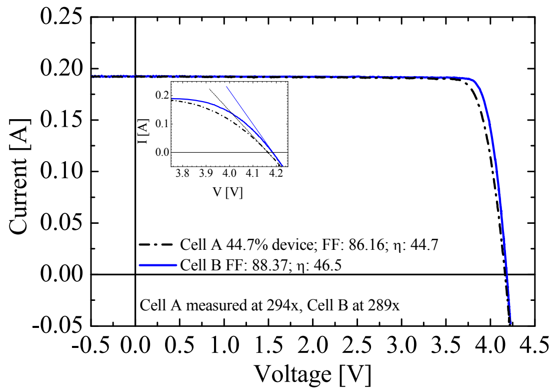

Figure 7: Flash IV curves for solar cell devices A and B, taken at very similar concentrations (~300x). The inset shows the detail at V_{OC} with the gradient at V_{OC} highlighted with additional lines. Hero cell B has a lower R_{series} of 49.0 $m\Omega cm^2$ versus 63.5 $m\Omega cm^2$ for cell A.

3.4 Outdoor performance in concentrator modules

Cells from the same design as the 44.7% design have also been built into CPV modules of the FLATCON® [15] design and tested outside. Notably the CSTC result (Concentrator Standard Testing Conditions, 1000Wm^{-2}, T_{cell} = 25°C) obtained from over 871 eligible and stable IV curves measured is 36.7%, an excellent module conversion efficiency [16].

4 SUMMARY AND CONCLUSIONS

A wafer-bonded 4J concentrator solar cell has been presented with an efficiency of 46.5% at 324x. These results represent to date the highest efficiency of any cell measured here at Fraunhofer ISE. The cell architecture is two-fold: a GaAs lattice-matched inverted GaInP/GaAs 2J device is wafer-bonded to an upright GaInPAs/GaInAs 2J device lattice matched to InP. Bonding yield is very high across 4" wafers, and series resistance in the devices has been reduced, leading to even higher performance when compared to the previous record cell with 44.7% [10]. This performance is significantly better than the traditional 3J Ge-based devices, due mainly to the additional fourth junction, the bandgaps being close to the ideal values for maximum efficiency and high material quality available with lattice matched material growth.

5 ACKNOWLEDGEMENTS

The authors would like to acknowledge and thank M. Scheer, K. Wagner, A. Panamatschuk, K. Mayer, and I. Semke for device processing, and for device characterisation E. Fehrenbacher, G. Chistiakova, and E. Schäffer.

We also like to thank Thierry Salvetat (CEA), Emmanuelle Lagoutte (CEA), David Lackner (FhG-ISE) and Alexis Drouin (Soitec) for valuable discussions. LETI and SOITEC would like to acknowledge support from the French Environment and Energy Management Agency through the "Investissement d'Avenir" program GUEPARD.

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