35.8% space and 38.8% terrestrial 5J direct bonded cells

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***Abstract* — Spectrolab has fabricated a direct semiconductor bonded space solar cell with an efficiency of 35.8% under the AM0 space spectrum. Using a similar technology, Spectrolab has achieved a 5-junction (5J) direct bonded terrestrial cell with a record efficiency of 38.8% under the one-sun AM1.5G terrestrial spectrum. Efforts to further improve the 5J cell efficiency have focused on development of the top 3 junctions (T3J) grown on GaAs. Experiments with top 3J isotype cells have yielded an improvement of 1% in current and 100 mV in voltage for the T3J. Spectrolab has also made significant improvements in its direct bonding process. The improved process has increased bond strengths by more than a factor of 5 and eliminated issues with large voids.**

***Index Terms* — direct bonding, semiconductor bonding, wafer bonding, multijunction cells.**

I. Introduction

Current state-of-the-art 3-junction (3J) cells grown on Ge have achieved efficiencies over 30% and at 41.6% under space and terrestrial spectra respectively. Increased efficiency is desired to reduce $/W costs and launch costs, to increase power generation in space satellites. While optimized 4-6 junction cells offer the potential of higher efficiencies, these designs require a ~1 eV bandgap cell. Previously Spectrolab has demonstrated a 5-junction (5J) cell where 3 top junctions lattice-matched to GaAs are direct semiconductor bonded (hereafter, direct bonded) to 1.0/ 0.73 eV cells grown on InP [1]. The advantage of this approach is that all 5 junctions in the stack are grown lattice-matched with excellent epitaxial quality. In particular, the 2 subcells grown on InP have average bandgap-voltage offsets (W_{oc}) that are far lower than that achieved using dilute nitrides [2] or inverted metamorphic cells [3], where lower W_{oc} is desirable. Largely as a result of the low W_{oc} values for the low bandgap cells grown on InP, very high efficiencies of 35.1% (1-sun, AM0) and 37.8% (1-sun, AM1.5G) have been previously reported [1]. In addition, Fraunhofer has recently announced a 44.7% efficient cell at a concentration of 297 suns under the AM1.5D spectrum with an analogous cell [4].

In this article we report on the continued development of 5J direct bonded cells. Spectrolab has achieved a 35.8% efficient 5J cell under the AM0 space spectrum and a 38.8% record cell under the one-sun AM1.5G terrestrial spectrum. Following these results, Spectrolab has made additional improvements to the top 3J cells grown on GaAs that should further increase 5J cell efficiencies in the future. Finally, we report on changes to the bonding process that have increased bond strengths and reduced large void densities.

II. Experimental

All III-V epitaxial layers were grown on a Veeco K475 MOVPE system. The top three subcells were grown inverted on GaAs substrates. The bottom two subcells were grown upright on InP substrates. The component wafers were chemical-mechanical polished (CMP) prior to bonding. Infrared transmission imaging was used to determine the uniformity and quality of the bonded interface. Following the direct bond, the GaAs growth substrate was removed to yield a 5J stack ready for processing. The bonded pairs were processed into 4-cm^2 and 1-cm^2 designs for 1-sun space and terrestrial cells, respectively. Internal quantum efficiencies of the cells were measured at Spectrolab. The light I-V (LIV) curves of both the space and terrestrial cells were measured at NREL using the one-sun multisource simulator (OSMSS). The OSMSS utilizes external quantum efficiency spectra and a spectral radiometer to tune the intensity of 9 filtered light sources. Additional details of regarding the OSMSS simulator system have been described previously [5].

III. Results and discussion

A. Space cell results

The latest 5J space cell results show an improvement from that reported previously, from 35.1 to 35.8% under the AM0 spectrum. The LIV curves of both cells were measured using the same OSMSS simulator at NREL. The LIV curve for a 4-cm^2 space cell is shown in Fig. 1. The voltage of the cell is nearly identical to that of the terrestrial cell at 4.76 V, since there are only small differences in subcell thickness and bandgap in the space and terrestrial devices. The measured current of 12.12 mA/cm^2 agrees within 1% with the J_{sc} calculated from measured spectral response, termed J_{sr}.

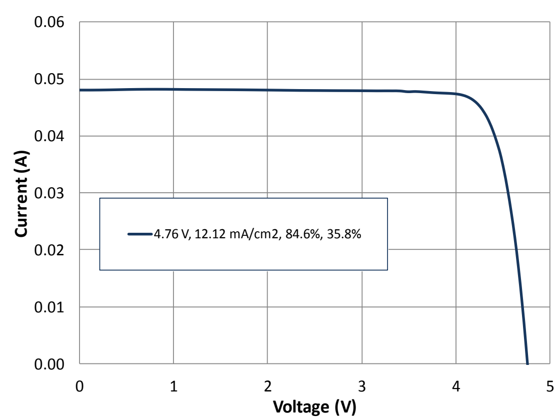

Fig. 1: Illuminated I-V curve for a 4-cm^2, 35.8%-efficient space direct-bonded 5J cell, measured at 1-sun, AM0, 25°C at NREL.

Spectrolab has completed processing several batches of cell-interconnect-coverglass (CIC) assemblies. To fabricate CICs, we have demonstrated that the front welding, back welding, and filtering (CICing) processes are compatible with direct-bonded cells. As shown in Fig. 2, no loss of cell performance was observed before and after the CIC process. The current axis in Fig. 2 is normalized to better compare the LIV curves. The CIC process substantially changes the J_{sc} due to the filtering step.

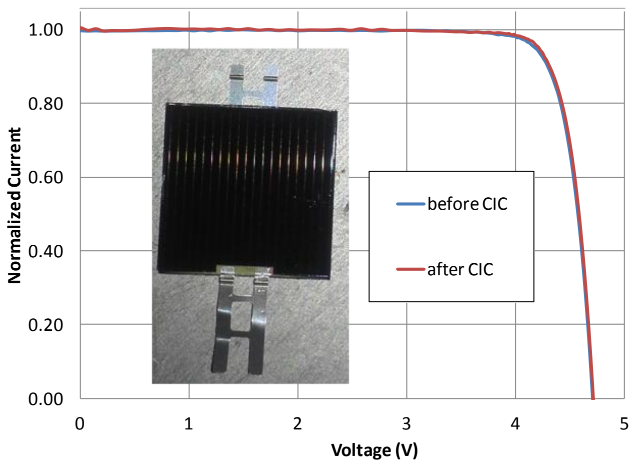

Fig. 2: Illuminated I-V curve for a 4-cm^2 cell before and after the CIC process. Inset shows a picture of a direct-bonded 5J CIC. Current is normalized for the purpose of comparison.

B. Terrestrial cell results

The terrestrial 5J results exhibited in the previous sections were based upon development of 5J cells for space. In Fig.3, we show a LIV curve of a 5J terrestrial cell measured at NREL. The cell achieves a record conversion efficiency of 38.8% under AM1.5G. This exceeds the previous reported 5J cell efficiency by 1 point absolute [1]. Similar to earlier reports, the cell has a voltage near 4.76 V. The cell voltage is comprised of 3.68 V from the top 3 junctions (T3J) on GaAs and 1.08 V from the bottom 2 junctions (B2J) on InP. The voltage contribution from the B2J is particularly high as evident from the low average W_{oc} of 0.35 V. The current density is 9.56 mA/cm^2. As exhibited in Fig. 4, the current density matches the J_{sr} 9.6 mA/cm^2, providing further confidence in the accuracy of the LIV measurement. The 5J cell is current limited by cell 2 (C2) of the multijunction stack (where cell 1 (C1) is the top cell that sunlight strikes first). Some optimization of the current balance between C2 and C3 offers potential for further gains in efficiency.

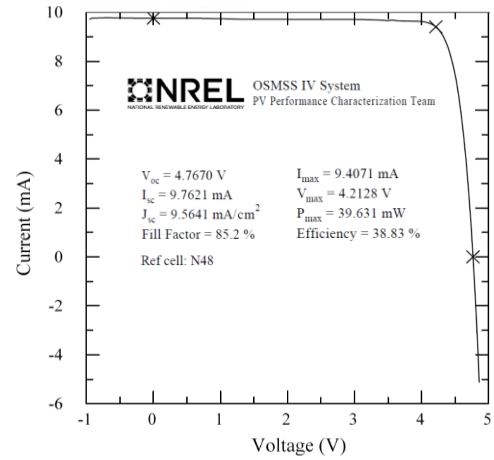

Fig. 3: Illuminated IV curve for a record 38.8%-efficient terrestrial 1cm^2 5J direct bonded cell. The cell was measured at 1 sun under the AM1.5G spectrum, 25°C at NREL.

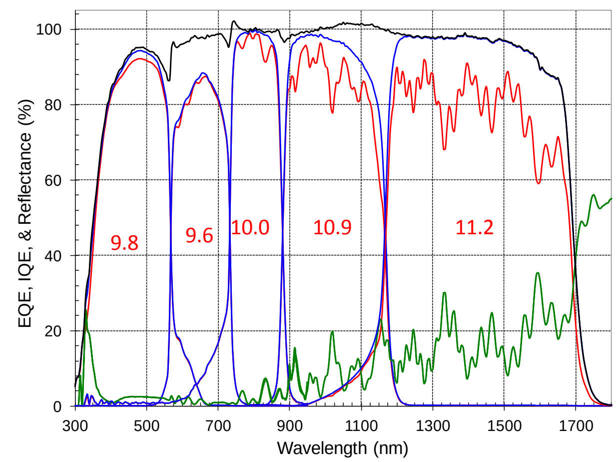

Fig. 4: EQE, IQE and reflectance curves for record SBT 5J cell. EQE, IQE, and reflectance are given by the blue, red, and green curves respectively. Cumulative IQE, the total obtained by summing the IQE from every subcell at each wavelength, is given by the black curve. Integrated Jsc values calculated from EQE for each cell are shown by the red numbers.

C. Improvements in T3J epitaxy

While the space and terrestrial 5J cells shown in Figs. 1-3 have achieved record efficiencies, there is still an opportunity for additional enhancements in cell performance. In particular, the cumulative IQE in Fig. 4 exhibits a pronounced dip between C1 and C2. It should be noted that the cumulative IQE for the corresponding space cell exhibits a similar decrease between C1 and C2. Since the current of the T3J limits the entire 5J stack, any increases to the cumulative current in the T3J would increase the current of the 5J. By improving the cell growth parameters of C1, Spectrolab has achieved a significantly improved cumulative IQE between C1 and C2 (see Fig. 5). Under the AM0 spectrum, the increase in IQE results in a 0.36 mA/cm^2 increase in current, leading to a 1% increase in 5J cell current with proper current balancing.

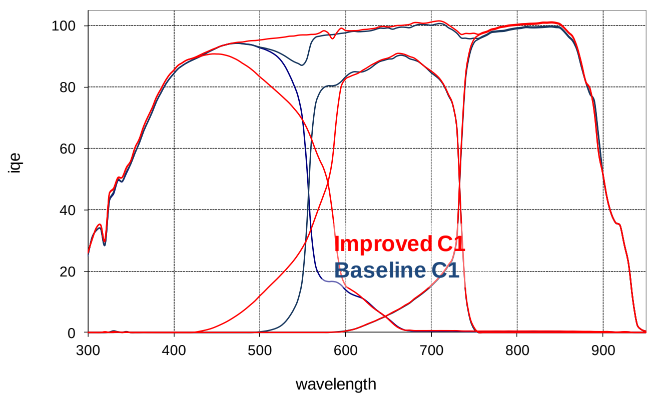

Fig. 5: IQE for GaAs T3J cells. Red and blue curves correspond to the IQE of the T3J with improved and baseline C1 growth conditions, respectively.

In addition to the T3J cumulative current, there is also opportunity for improvement in the T3J voltage. The average W_{oc} for the top 3J is 0.44V. This far exceeds that achieved for the bottom 2 junctions on InP. To determine which junctions could be optimized for higher voltages, Spectrolab grew a series of top 3J component cells, in which only one subcell is active, and the other subcell layers are inactive, isotype filter layers (hereafter termed isotype cells). The V_{oc} and W_{oc} values corresponding to each of the C1-3 isotype cells are given in Table 1. As shown in Table 1, the sum of the baseline V_{oc} values is 3.66 V. This agrees well with typical V_{oc} values achieved for the T3J. From Table 2, it is evident that the C2 W_{oc} is the highest at 0.484 V. Moreover the W_{oc} of C3 at 0.439 V is also high given that the cell material is GaAs. GaAs subcells with W_{oc} values as low as 0.36 V have been measured even without the benefit of photon recycling. Given these results, we have performed extensive optimizations on the growth conditions of C2 and C3. W_{oc} values for C2 and C3 have been reduced by 50 and 49 mV respectively. The increase in C2 and C3 voltage should increase overall 5J cell voltage by 2% relative. Between the current and voltage increases achieved in T3J and isotype studies, an additional increase in 1% absolute in 5J efficiency is expected. We expect integration of these improvements in a full 5J stack to occur in the near future.

Table 1: Summary of GaAs T3J isotype cell results. Bandgap-voltage offset (W_{oc}) values are reported before and after growth optimization.

Cell isotype	**W_{oc} baseline**	**W_{oc} improved**
C1	0.422	-
C2	0.484	0.434
C3	0.439	0.388

D. Improvements in bonding process

Concurrent with our efforts in improving the T3J epitaxy, Spectrolab has continued to improve the direct bonding process. Previously we had reported an average of 2 large voids (>1 mm) per 4-inch GaAs-InP epitaxial pair. While a significant improvement to the large void densities was achieved in 2012, 2 large voids per wafer still presented a challenge to achieving high yields for large-area space cells. To further improve the areal yield per direct bond for large-area space solar cells, Spectrolab has worked extensively to improve the critical pre-bonding process. Recently, *no large voids* have been observed over four 4-inch GaAs-InP epitaxial bonds. Typical IR bond images of 4-inch bonded GaAs-InP bonded pairs are shown in Fig. 5a for the new and the previous pre-bonding methods. In addition, we have measured the force required to break the direct bond. As shown in Fig. 5b, the new pre-bond method also results in a high bond pull force that is nearly 7 times that achieved using the previous pre-bond method. These bonding process improvements are anticipated to significantly increase the yield and reliability of direct-bonded space solar cells.

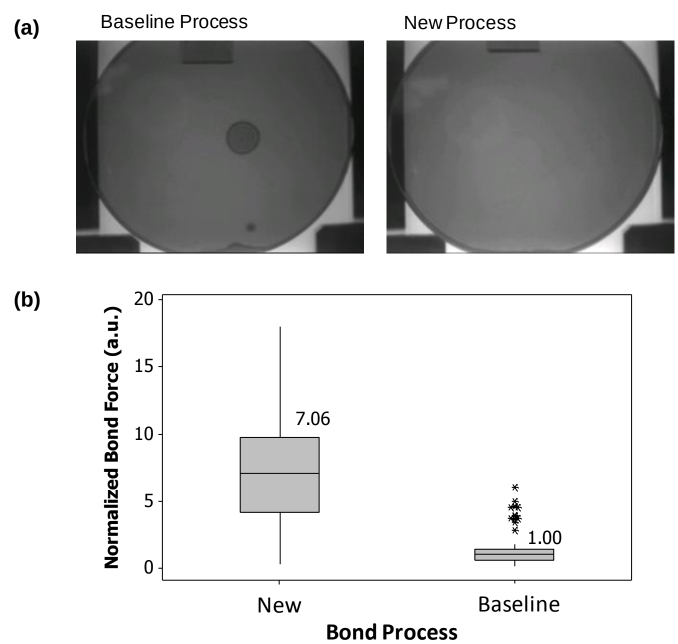

Fig. 6: Comparison of (a) IR bond images (b) normalized bond pull force between baseline and new bond processes.

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