# Direct Semiconductor Bonded 5J Cell For Space And Terrestrial Applications

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***Abstract* — Spectrolab has demonstrated a 2.2/1.7/1.4/1.05/0.73 eV 5J cell with an efficiency of 37.8% under 1 sun AM1.5G spectrum and 35.1 % efficiency for 1 sun AM0. The top 3 junction and bottom 2 junction were grown on GaAs and InP substrates respectively by metal organic vapor phase epitaxy. The GaAs and InP based cells were then direct bonded to create a low resistance, high transmissive interface. Both the space and terrestrial cells have high 1 sun $V_{oc}$ between 4.75-4.78 V. Initial tests of the terrestrial cells at concentration are promising with efficiencies increasing up to 10x concentration to a maximum value close to 41%.**

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

## I. Introduction

The most widely adopted cell for use in space and terrestrial applications is a three junction (3J) design where 1.9 and 1.4 eV cells are grown lattice-matched to a 0.67 eV Ge cell. Cell efficiencies for the upright Ge 3J cell have reached a maximum efficiency of near 30% for space and 41.6% for terrestrial [1]. While cell designs with 4 to 6 junctions present tantalizing opportunities for higher efficiencies, all such designs require near 1-eV bandgap materials. Three monolithic 4-6 junction approaches that incorporate a 1-eV junction include cells with InGaAsNSb, inverted metamorphic (IMM) cells, and direct bonded cells. InGaAsN cells have historically suffered from poor minority carrier lifetimes [2]. Although, recent work suggests that growth using molecular beam epitaxy (MBE) can improve material quality [3], MBE growth suffers from high cost and low growth rates. Inverted metamorphic (IMM) cells incorporating lattice mismatched InGaAs have been pursued, but growth of mismatched InGaAs results in degraded cell quality even with the use of thick grading layers [4].

An alternative approach is to grow infrared and visible bandgap cells on InP and GaAs respectively. The main benefit of this approach is that several high quality 0.73-1.4 eV alloys exist that are lattice matched to InP. The InP and GaAs cells can be bonded directly using a proprietary process at a relatively low temperature. The resulting bonded cell is termed a semiconductor bonded technology (SBT) cell that has been demonstrated previously as a 2 or 4 junction cell [5,6]. In this paper we have implemented a 2.2/1.7/1.4/1.05/0.73 eV 5 junction (5J) SBT cell. The top 3 junctions (T3J) are grown on GaAs and the bottom 2 junctions (B2J) on InP. The resulting SBT cells have achieved a 35.1% efficiency in AM0, and an NREL verified for terrestrial 1x AM1.5G of 37.8%. Initial concentration measurements indicate the technology is also promising for concentrator applications.

## II. Experimental

All III-V epitaxial layers were grown on a Veeco K475 MOVPE system. The top three subcells with bandgaps of 2.2/1.7/1.4 eV were grown inverted on GaAs substrates. The bottom two subcells with bandgaps of 1.05/0.73 eV were grown upright on InP substrates. The component wafers were chemical-mechanical polished (CMP) to a surface roughness of less than 0.5 nm. The direct bonding was completed in a Karl Suss wafer bonder. The bonding parameters such as temperature, pressure and bonding time were carefully optimized to achieve high mechanical strength and low electrical resistance across the bonded interface. Infrared transmission imaging was used to determine the uniformity and quality of the bonded interface. Following the direct bond, the GaAs wafer was substrate removed to yield a 5J stack ready for processing. The bonded pairs were full processed into 4 $cm^2$ cells for space. For terrestrial, the cells were processed into 1 $cm^2$ cells with grid pitches optimized for both 1 sun and 10 suns. The cells were characterized at Spectrolab by illuminated current voltage measurements (LIV) and quantum efficiency spectroscopy. For terrestrial cells, LIV measurements were confirmed by NREL using the OSMSS simulator system. Details of the OSMSS simulator system and the associated testing methodology have been described previously [5].

## III. Results and discussion

### A. Bonding process improvements

Significant progress has been made in direct bonding process at Spectrolab. Following a thorough optimization of bond parameters including bonding time, temperature and applied pressure, bonding yields have improved dramatically. We have achieved a fifty consecutive 100 mm GaAs epitaxy to

100 mm InP epitaxy bonds without mechanical breakage, demonstrating the stability and reliability of the process.

Although optimization of bond time, temperature and pressure greatly enhances mechanical yield, there *was* a persistent high density (~7 per wafer) of large voids (defined as a void with a diameter greater than 1 mm). Large voids have a pronounced effect on the performance of direct bonded cells. The voids tend to burst during processing, resulting in reduced current, and or shunts through the top 3 junctions in stack. Based upon previous research of direct bonds, we attribute large void formation to particle contaminants with diameters on the order of a 1 μm [7]. Consequently, we have improved wafer handling and cleaning prior to the bonds to reduce the probability of particle contamination. The result is a decrease in the average large void density from 7 to 2 per 100 mm wafer. Infrared bonding images that demonstrate the improvement of large void density are shown in Fig. 1. We anticipate that further upgrades in the pre-bonding process will reduce the large void density to 0. This is the large void density achieved in SOI industry for 300 mm wafer direct bonds [8].

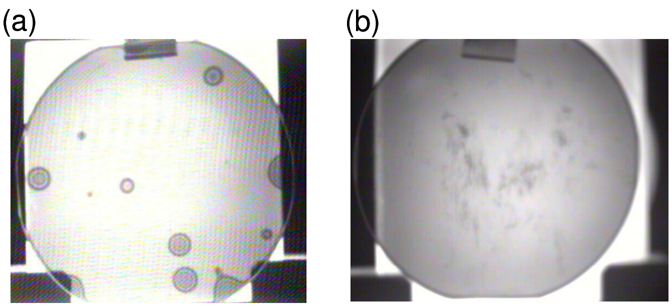


Fig. 1: Infrared bonding images of 100 mm GaAs epitaxy to 100 mm InP epitaxy (a) before and (b) after improvements to reduce particle contamination.

The mechanical strength of the direct bond with the updated and improved bonding process has been verified by thermal cycling tests. Several 4-cm$^2$ cells were cycled 5 times in liquid nitrogen (77 K) for 1 minute and a 423 K hot plate for 1 minute. The cells exhibited no signs of delamination. Moreover, as shown in Fig. 2, the LIV of the cells before after thermal cycling is identical to within measurement error.

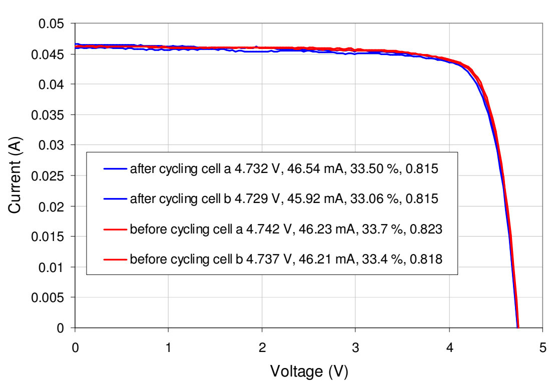


Fig. 2: LIV curves of two 4-cm$^2$ cells before and after 5 abrupt thermal cycles between 77 K and 423 K.

*Space cell results*

Due to the improvements in the bonding process that increased mechanical yield and reduced large void density, Spectrolab was able to produce multiple 20-cm$^2$ SBT5J cells with excellent performance under AM0 space irradiance. Large area cells are required for currently used 1 sun space arrays. A picture of one such 5J wafer is shown in Fig. 3a. The 5J wafer contains two large 20-cm$^2$ cells in the middle of the wafer, and eight 1-cm$^2$ test cells on the perimeter. The bond exhibits a single large void that reduces the performance of the top large area cell. The rest of the wafer is void free, including the bottom large area cell. The corresponding unfiltered forward bias electroluminescence (FBIR) image of the bottom large area cell is shown in Fig. 3b. As evident from Fig. 3b, there is no evidence of debonded areas or other defects in the FBIR image.

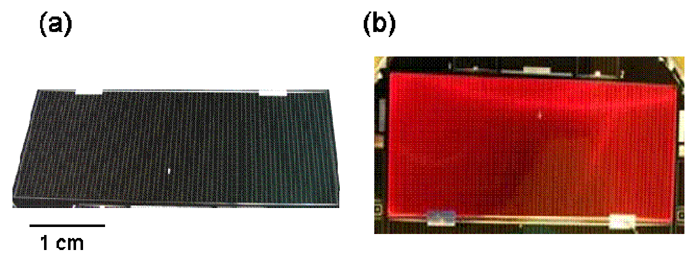


Fig. 3: (a) Picture and (b) unfiltered FBIR image of a bonded SBT 5J wafer optimized for space applications. Wafer contains 20-cm$^2$ and 1-cm$^2$ test cells on the perimeter.

The LIV results for the cells in Fig. 3b are shown in Fig. 4. The LIV was measured using SBT 5J Learjet standards to calibrate the simulator. The spectral mismatch factors using the new standards are limited to 1% or less for each of the 5 junctions. The $J_{sc}$, $V_{oc}$, and FF of the best large cell is 12.0 mA/cm$^2$, 4.78 V, and 83.5% respectively. This results in an AM0 efficiency of 35.1%. The efficiency of the large area cell is actually 0.2% absolute higher than the 1-cm$^2$ cells on the same wafer. The difference in efficiency is direct result of a 70 mV increase in $V_{oc}$ going from 1-cm$^2$ to 20-cm$^2$ cell. We tentatively attribute the increase in $V_{oc}$ to a reduction in perimeter recombination for the larger area cell [9]. In general, the high $V_{oc}$ of both the large and small area 5J cells is a demonstration of the high quality lattice matched components grown on GaAs and InP substrates. Previous data collected on cell fabricated from GaAs T3J and InP B2J wafers in the same epitaxial runs had $V_{oc}$ of 3.68 and 1.08 V respectively. In particular, we note that the average voltage bandgap offset of the B2J is 0.335V, attesting to the high quality of the B2J grown on InP. The near ideal agreement 5J cell voltage with that of the GaAs and InP components indicates little to no loss in cell quality due to the direct bonding process.

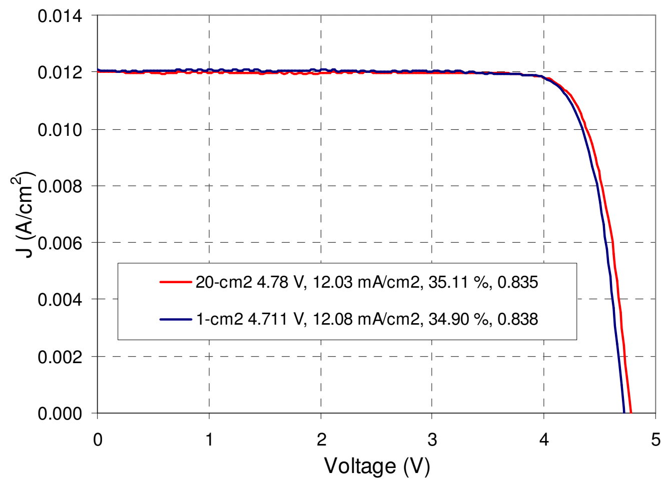


Fig. 4: Illuminated IV curves 1-cm$^2$ cells and >20 cm$^2$ cells for the 5J wafer shown in Fig. 3a. The large area cell measures at 35.1% space at 1 sun AM0 spectrum (1366 W/m$^2$), 28°C. The simulator was calibrated using SBT 5J Learjet standards.

The quantum efficiency curves for the 5J space cell are shown in Fig. 5. The integrated EQE currents (after accounting for busbar loss) are also given in red in Fig. 5. The limiting cell from EQE is C3 at 11.9 mA/cm$^2$. This EQE current agrees within 1% of the measured $J_{sc}$ of 12.0 mA/cm$^2$. The excellent agreement between the EQE and simulator currents provides further confidence in the accuracy of the 35.1% efficiency value.

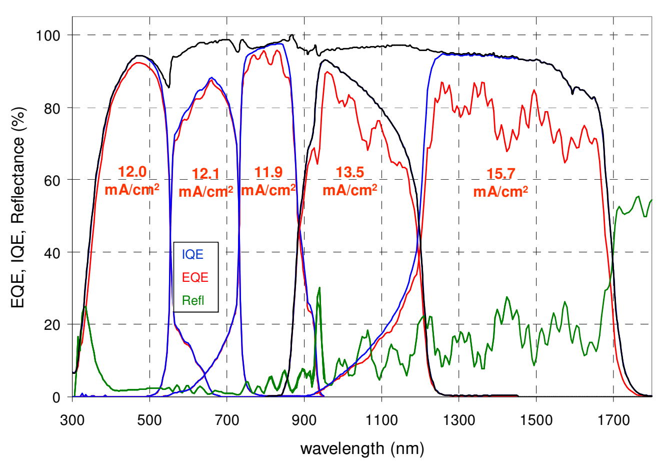


Fig. 5. EQE, IQE and reflectance curves for space SBT 5J cell. EQE, IQE, and reflectance are given by the red, blue, and green curves respectively. IQE CUM is given by the black curve. Integrated EQE values after busbar correction are shown in the red numbers.

### *B. Terrestrial cell results*

SBT5J terrestrial cells were based upon the space structure discussed in the previous section because the bulk of the development such cells was for space applications. Small adjustments to the bandgap and thickness were required to improve the current matching in an AM1.5G spectrum. The LIV results for the 1.02-cm$^2$ SBT 5J cells optimized for 1 sun AM1.5G performance are in Fig. 6. The LIV measurements were performed by NREL on the new OSMSS simulator. As evident in Fig. 6, the cell has a $V_{oc}$ of 4.76 V. Similar to the space 5J cells, the $V_{oc}$ of the 5J closely matches the sum of the GaAs and InP components. The $J_{sc}$ of the cell is 9.4 mA/cm$^2$. The limiting junction from the EQE curves in Fig. 7 is C1 at 9.6 mA/cm$^2$. Therefore the $J_{sr}$ (defined as the limiting current density as measured by EQE) and $J_{sc}$ (measured by NREL) agree reasonably to within 2%. The fill factor of 84.4% is limited by a non-linearity in between 0.5-3.5 V. The non-linearity is attributed to current matching between the cells with two lowest integrated EQE: C1 and C2. The difference in current between C1 and C2 is 0.3 mA/cm$^2$. We note that the current matching between C1 and C2 could only cause a characteristic non-linearity in the IV curve if limiting junction, C1 also had poor reverse bias breakdown.

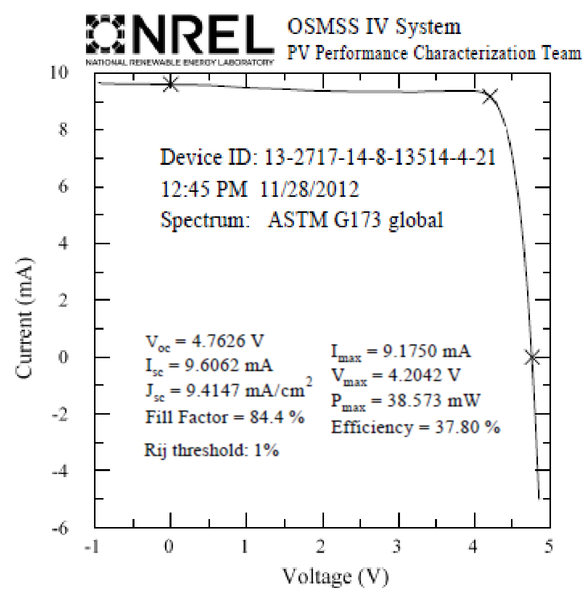


Fig. 6: Illuminated IV curve for 37.8% terrestrial 5J SBT cell. Cell was measured at 1 sun under AM1.5G spectrum, 25°C by NREL.

While the 1x AM1.5G efficiency of 37.8% is encouraging, the SBT 5J cell has opportunities for improvements in cell efficiency that are evident from the QE curves. Fig. 7 plots the IQE cumulative (CUM) in black. The CUM is 95% for C1, nearly 100% for C2 and C3, and ~97% for C4 and C5. The 3% loss in CUM in C4 and C5 is not due to an issue with cell quality but rather transmission losses through the bond interface. However, the peak IQE of C1 could be enhanced, resulting in a direct increase in $J_{sc}$ (as C1 is limiting). Moreover, increase in C1 current would reduce current imbalance between C1 and C2, resulting in an increase in FF.

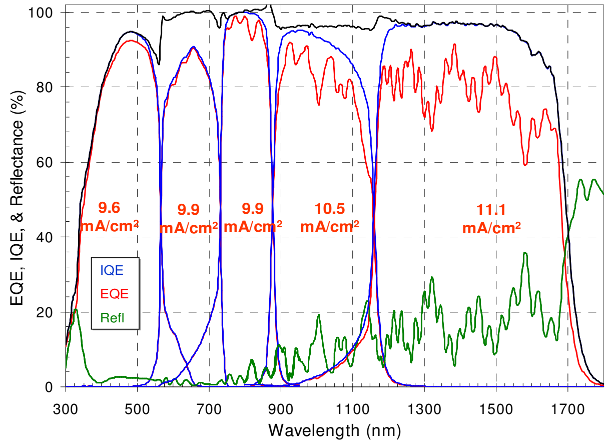


Fig. 7. EQE, IQE and reflectance curves for terrestrial SBT 5J cell. EQE, IQE, and reflectance are given by the red, blue, and green curves respectively. IQE CUM is given by the black curve. Integrated EQE values after busbar correction are shown in the red numbers.

The LIV curves for a 1.328-cm$^2$ SBT 5J cell optimized for 10x concentration were measured at Spectrolab. The LIV curves at 1x, 5x, 10x, and 20x are shown in Fig. 8. Plots of the efficiency, FF and $V_{oc}$, as a function of concentration are given in Fig. 9. Although the cell was measured internally at Spectrolab, the internal efficiency of 38.2% agrees reasonably well with that measured by NREL for a similar cell. As shown in Fig. 9a, the efficiency increases from 1x-10x to a maximum of 40.7% at only 10x concentration. The efficiency decreases from 10x-20x due to a drop in FF (see Fig. 9b) or specific resistance. Using the multiple light intensities method [10], the specific resistance of the cell is 2 Ω-cm$^2$. Grid, top layer, and contact resistance contributions to the specific resistance should only be of the order of 0.56 Ω-cm$^2$. The difference in specific resistance is presumably in the tunnel junctions or at the bond interface that were developed and optimized for only 1 sun space applications. In particular, further studies regarding bond resistance with respect to the identity and doping of the bonding layers, chemical pre-treatment and substrate miscut would be required to optimize the bond resistance.

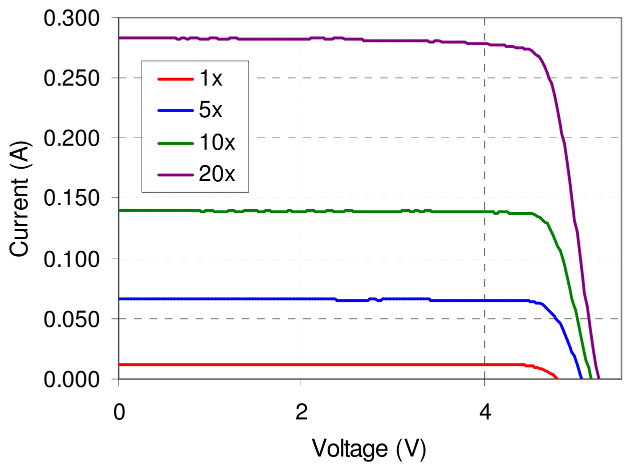


Fig. 8: LIV curves measured at concentrations between 1x and 20x for a 1.328-cm$^2$ SBT 5J cell optimized for low concentration.

As expected, the $V_{oc}$ is linear with respect to the log concentration as in Fig. 9c. The slope of this plot is related to the ideality factor of the cell. According to the Voc vs. concentration dependence, the ideality factor 5.6. This is reasonably close to the predicted value for 5 ideal diodes in series, and is a further indication of the high quality of the junctions in the 5J SBT cell.

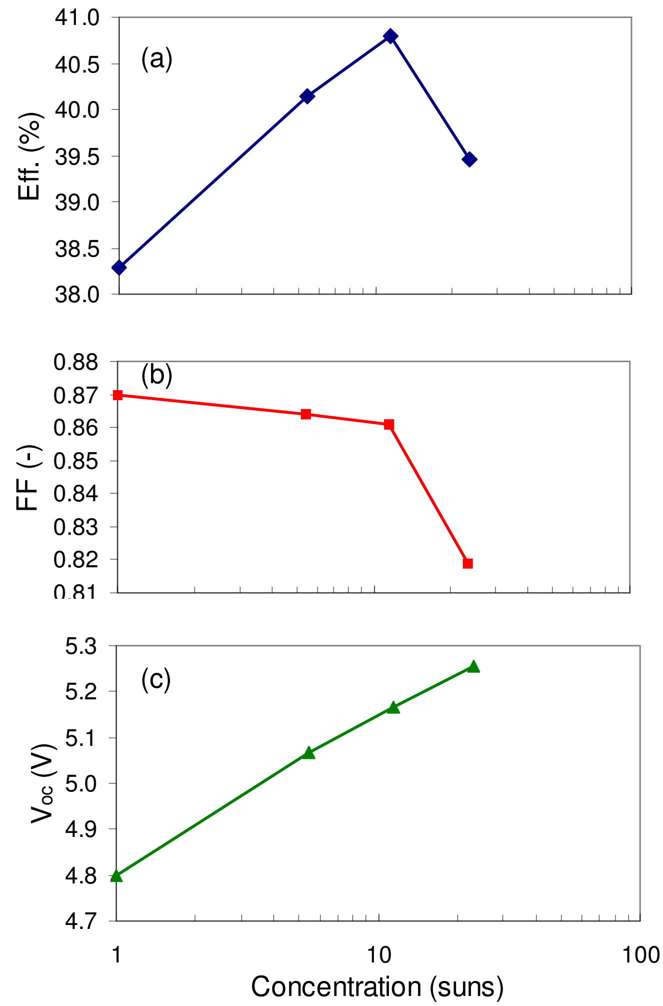


Fig. 9: (a) Efficiency, (b) FF, and (c) $V_{oc}$ as a function of concentration for terrestrial SBT5J cell.

Next we model the performance of the SBT 5J cell at 500x, assuming that the specific resistance of the tunnel junctions and bond interface could be reduced to a negligible amount (<5 mΩ-cm$^2$). The purpose of the modeling is to demonstrate the tantalizing potential of the SBT5J cell in terrestrial concentrator application. The assumptions used in the model are realistic, based largely upon measured SBT5J data. For example, the cell quality in terms of current collection and voltage bandgap offset of all 5Js is assumed to be equal to that shown in Figs. 5 and 7. We have also utilized tunnel junctions that absorb more than those used in the 1x SBT5J design, but have been proven to operate with peak currents significantly higher than the 500x operating currents. In order to improve current matching only the bandgap and thicknesses of the cells were adjusted for an AM1.5D spectrum. The one major assumption in the model is a total specific resistance of 25 m$\Omega$-cm$^2$, a number that is readily achievable of tunnel junction and bond interface resistances are suppressed <5 m$\Omega$-cm$^2$ . It should be noted that a similar resistance has been previously achieved in direct bonded cells, as evident by high FF in a 4J cell tested at >300 suns [11]. The results of the modeling are shown in Figs. 10a and b. The modeled IV curve has a $J_{sc}$, $V_{oc}$, and FF of of 4.96 A/cm2, 5.56 V, and 84.7% respectively. This results in a theoretical 500x efficiency of 46.7%.

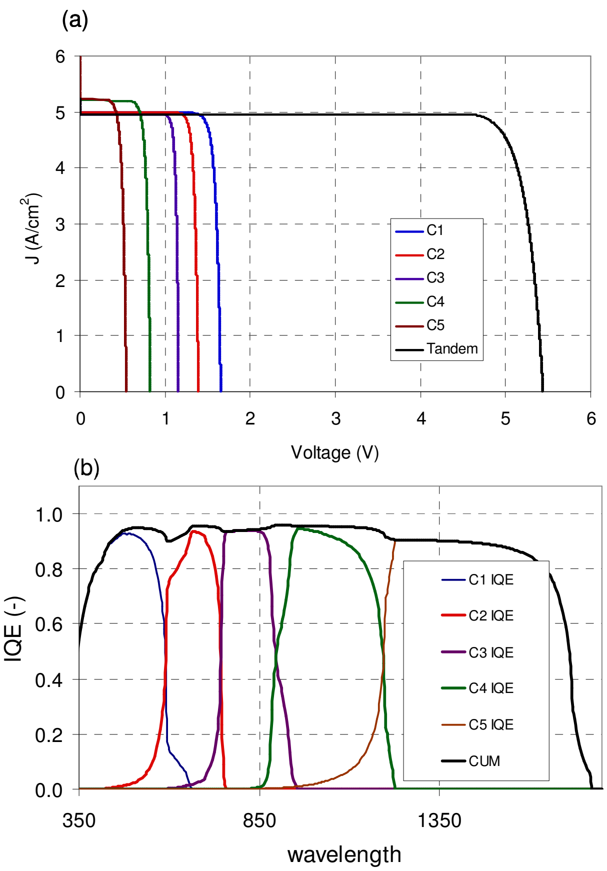


Fig. 10: Modeled (a) IV and (b) IQE curves of an SBT5J cell optimized for 500x AM1.5D.

## V. Conclusions

Spectrolab has demonstrated high quality 5J cells optimized for space and terrestrial irradiance. The 5J cells were fabricated by direct bonding high quality, lattice matched, T3J cells grown on GaAs and B2J cells grown on InP. A 20-cm$^2$ space cell achieved an efficiency of 35.1% for AM0 1 sun. A terrestrial cell reached an efficiency of 37.8% that was verified independently by NREL. Both the space and terrestrial efficiencies are among the highest the highest measured at 1 sun. Cell measurements at concentration indicate efficiencies approaching 41% at low concentration. Modeling indicates the potential to reach close to 47% at 500 suns. This demonstrates the potential of using direct bonding to couple lattice matched GaAs and InP cells to form a single multijunction stack.

## V. Acknowledgements

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