34% EFFICIENT InGaP/GaAs/GaSb CELL-INTERCONNECTED-CIRCUITS FOR LINE-FOCUS CONCENTRATOR ARRAYS

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ABSTRACT: While monolithic multi-junction cells are preferred for flat plate arrays, mechanically stacked multi-junction cells are superior for solar concentrator applications. Reasons for this are that the mechanical stacked configuration with high efficiency Gallium Antimonide cells allows utilization of a much wider range of the solar energy spectrum, and the ability to use voltage matched interconnects results in full use of low bandgap cell currents. Herein, data are presented for simple two terminal voltage-matched circuits using InGaP/GaAs/GaSb stacked cells showing 34% average circuit efficiency for a lot of 12 circuits given prismatic covers. These circuits have been designed to fit into the ultralight Stretched Lens Array being developed by NASA. With these new cell-interconnected-circuits, we project that the power density at GEO operating temperature can be increased from 296 W/m^2 to 350 W/m^2 while maintaining the specific power at 190 W/kg at the full wing level.

Introduction

In 1989, Fraas and Avery (1) demonstrated a world-record 31% efficient AM0 GaAs/GaSb mechanically stacked dual junction solar cell (measured at 25° C at 100 suns with prismatic cover). However, the GaAs/GaSb mechanical-stacked cell was designed to work with concentrated sunlight and at that time, the space community had no experience with concentrated sunlight solar arrays. So, the aerospace photovoltaic community continued to work primarily on improving flat plate cell efficiencies for satellite power systems. This work led to the adoption of the InGaP/GaAs/Ge monolithic dual junction cell with an efficiency of 23% (AMO, 25° C, 1 sun, no prismatic cover). Meanwhile in 1992, Fraas and Avery fabricated GaAs/GaSb cells and Entech supplied lenses for a concentrator mini-module that was flown on the Photovoltaic Advanced Space Power (PASP) satellite. This mini-module performed well with high power density, excellent radiation resistance, and with no problems tracking the sun. The success of the PASP module then led to the successful use of a 2.5 kW line-focus concentrator array as the main power source on Deep Space I. Deep Space I was launched in 1998.

Meanwhile, work on flat plate monolithic multijunction cells continued. It became clear that the GaAs/GaSb cell outperformed the dual junction InGaP/GaAs/Ge cell because it responded to a much wider spectral range. This led to efforts to put an active junction in the Ge wafer in order to create a monolithic triple junction cell. These efforts have been successful, leading to an improvement in efficiency to 26% for flat plate cells (AMO, 25° C, 1 sun, no prismatic cover). It has been observed that the efficiencies of these triple junction cells increases to 30% with concentrated sunlight (AMO, 25° C, 8 suns, with prismatic covers). This is almost as high as the GaAs/GaSb record efficiency recorded 12 years ago with the GaAs/GaSb dual junction mechanically stacked cell, but not quite. Unfortunately, the currents are not matched in the InGaP/GaAs/Ge cell. Millions of dollars have now been spent trying to rectify this problem by going to four junction monolithic cells. However, these efforts have not been successful to date.

Herein, we observe that the current matching problem that is inherent in the InGaP/GaAs/Ge monolithic triple junction cell does not exist in a triple junction InGaP/GaAs/GaSb mechanically stacked circuit where voltage matching can be used. We report here the design and fabrication of voltage matched circuits where InGaP/GaAs dual junction cells are stacked on GaSb cells. The InGaP/GaAs cells used here are made transparent in the infrared by growing the active layers on a thin GaAs substrate. Twelve circuits have been fabricated. The lot average circuit efficiency is 34% and the best of the lot circuit efficiency is 35% (AMO, 25° C, 15 suns, prismatic covers). Herein, we also observe that in the future by mechanically stacking a dual junction top cell on a dual junction bottom cell, efficiencies as high as 39% are achievable (AMO, 25° C, 15 suns, prismatic cover).

These very high cell conversion efficiencies can be very important for space satellites if the required concentrator array technology is developed and demonstrated. NASA has realized this and has been developing the ultralight Stretched Lens Array (SLA) for space power (2). In the following sections, we first describe in more detail why mechanically stacked cells outperform monolithic cells. We then present in more detail our triple-junction mechanical-stacked cell-interconnected-circuit (TJ-MS-CIC) design, fabrication, and performance results. Finally, we discuss the potential impact of higher performance TJ-MS-CICs on SLA space power.

Monolithic vs. Mechanical Stacked Multijunction Cells

Table I summarizes the various multijunction cell efficiency numbers discussed in the previous section.

Table I: Summary of AM0 Concentrator Cell Efficiencies

Cell Type	# Junctions	Efficiency	# Suns
Monolithic			
InGaP/GaAs/Ge	2	27.5%	15 x
InGaP/GaAs/Ge	3	30%	15 x
InGaP/GaAs/GaInAsN/Ge	4	< 20% QE in GaInAsN	
Mechanical Stack			
GaAs/GaSb	2	31%	100 x
InGaP/GaAs/GaSb	3	35%	15 x

Over the past ten years, monolithic tandem cells have been used exclusively because they are preferred over stacked cells for flat plate arrays. However, it is noteworthy that stacked cells still out-perform the monolithic cells by a substantial margin. First with reference to dual junction cells, the reason why the GaAs/GaSb stacked cell out-performs the InGaP/GaAs/Ge monolithic dual junction (DJ) cell is really quite straightforward. The monolithic DJ cell only uses the energy in the sun's spectrum between 0.4 and 0.9 microns while the GaAs/GaSb DJ cell uses the much larger spectral range between 0.4 and 1.8 microns.

Given the state of the art today, the most appropriate comparison to make is between the monolithic and mechanical-stacked triple junction cells. Table II shows this direct comparison.

Table II: Efficiency Comparison for Triple-Junction PV Cells at 15 Suns Concentration

	Monolithic InGaP/GaAs/Ge	Mechanical Stack InGaP/GaAs/GaSb
InGaP/GaAs Efficiency	27.5%	27.5%
IR Cell I_{mp}	15x16 mA/cm^2 (series limited)	15x30 mA/cm^2 (not limited)
IR Cell V_{mp}	0.25 V (Ge bandgap lower than GaSb bandgap)	0.35 V
IR Cell Efficiency	2.5% (from present SBIR contract)	6.5%
Triple-Junction Efficiency	<u>30%</u>	<u>34%</u>

Both the monolithic and mechanically stacked triple-junction (TJ) cells use the same InGaP/GaAs DJ top cell. In the monolithic cell case, the third junction is placed in the Ge and automatically connected in series with the DJ cell. In the mechanically stacked case, the third junction is in GaSb and the stacked cells allow voltage matching to be used instead of current matching. The most serious problem with the monolithic TJ cell is that the Ge cell is automatically series connected with the DJ cell. This means that while the DJ cell only produces a 1-sun current of 16 mA/cm^2, both the GaSb and Ge cells are capable of producing 33 mA/cm^2. In the series connected configuration, the current in excess of 16 mA/cm^2 is wasted. This is not a problem in the voltage-matched configuration used in mechanical-stacked circuits. A secondary problem with Ge vs. GaSb is that the lower bandgap of Ge leads to a lower voltage for the Ge cell and consequently worse performance at higher temperature relative to GaSb cells. Referring to table II, the result of the above two problems is that the boost efficiency from a Ge cell in the monolithic configuration is only 2.5% while the GaSb cell in the voltage matched configuration adds 6.5% to the final circuit performance. Thus, the 30% efficiency demonstrated for the InGaP/GaAs/Ge monolithic triple-junction (TJ) cell still falls short of the 34% efficiency achievable with a mechanically stacked TJ cell.

Practical triple-junction voltage-matched circuits

When there are two solar cell chips, one begins with 4 terminals, 2 per chip. How does one end up with a 2 terminal circuit? Figure 1 shows how this is done. When the cells are arrayed in a line, one simply connects the cells with the higher voltage in parallel while connecting the cells with the lower voltage in series until one obtains a voltage match. The example shown in figure 1 shows seven GaSb cells wired in series. In the circuit shown, the GaSb cells are wired in series to traces to the right of the circuit while the InGaP/GaAs cells are wired in parallel to traces at the left of the circuit. We refer to this as a 7 to 1 voltage match because it takes 7 GaSb cells in series to produce the voltage that 1 InGaP/GaAs cell produces. This is the appropriate interconnection for a circuit operating at 15 suns at room temperature. In that case, seven times the Vmp of GaSb (7 x 0.375 V = 2.63 V) slightly exceeds the Vmp of 2.4 V for the InGaP/GaAs cell.

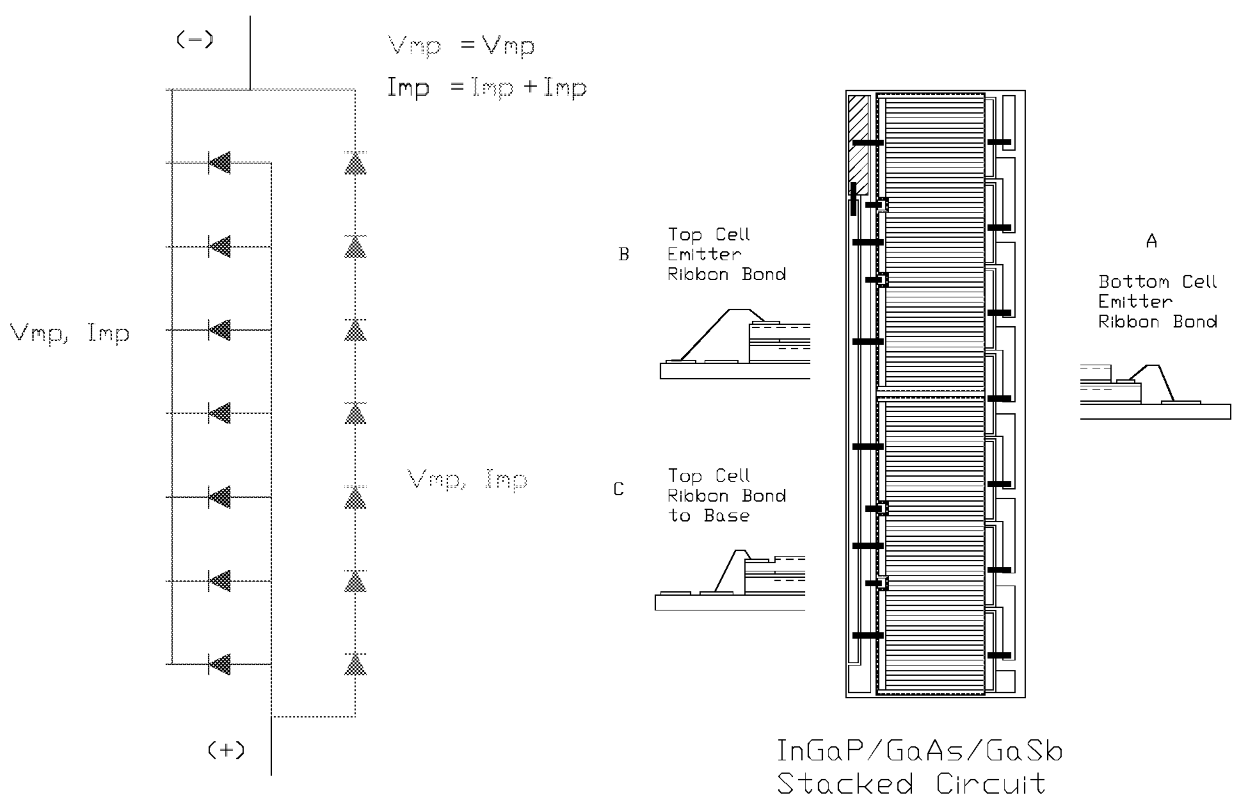
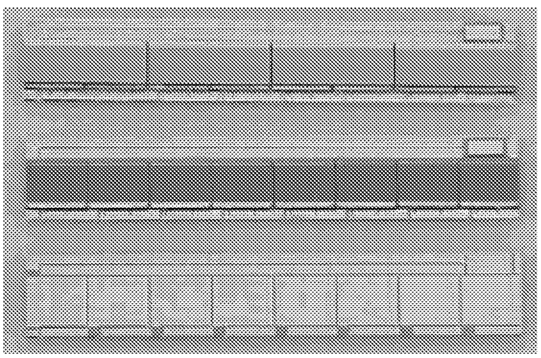


Figure 1. Voltage matching concept and mechanical circuit design.

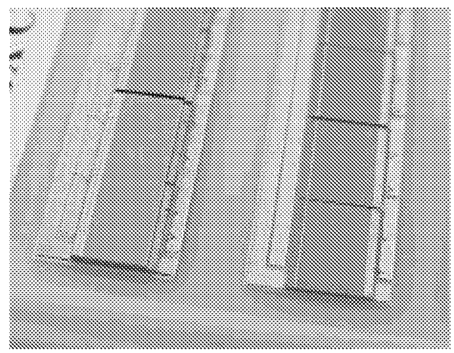
In addition to the voltage match concept, figure 1 also shows some detail related to mechanical assembly. There is a challenge in mechanical stacked circuits. How does one connect to the hidden base layer for the top cell? Figure 1 shows a drawing of a CIC assembly with schematic details of the wire bonds for each of three contact types.

The (a) interconnect connects the front GaSb cell contact, the positive contact, to an appropriate circuit board trace. The (b) interconnect is from the top surface contact of the InGaP/GaAs cell, also positive, to the circuit board. The (c) interconnect is the negative GaAs to circuit connection. Notice that (c) is shown on the frontside of the InGaP/GaAs cell. This is a new approach for front cell interconnects that allows all lead bonding to be done from the top side down, with no need to flip the top cells over as we have done previously to connect to the GaAs backside contact. A window is etched in the frontside epi layers and an isolated metal bonding pad is formed that electrically contacts the GaAs substrate. In this configuration, current is collected as usual by a grid on the backside of the GaAs wafer and transported to a bus underneath the topside base contact pad. This current then flows through the GaAs wafer thickness to the topside base contact pad. Since the electron mobility in N-type GaAs is high, for a wafer doping density of 3×10^{17}/cc and a pad area of 1 mm^2, the through-the-wafer resistance is only 2 milliohms. At 15 suns AMO, the top cell current will be 0.23 Amps per cm^2. So the voltage drop through the wafer will be less than 1 mV.

In actuality, we have used an 8 to 1 voltage match in our fabricated circuits because we have designed for an operating temperature of 80° C for GEO. Photographs of these InGaP/GaAs/GaSb circuits are shown in figure 2.



Top: Completed InGaP/GaAs/GaSb Circuit
Middle: Circuit with GaSb IR Cells
Bottom: Substrate with Metal Traces



Close-up showing ribbon bonds
(Patent pending)

Figures 2a and 2b. Mechanically stacked triple junction cell-interconnected-circuits.

TJ-MS-CICs are made simply as follows. First, thin GaSb cells (0.8 cm x 1 cm) are positioned. This is done rapidly with an automated pick-and-place machine which first writes a solder pattern on the evaporated metal pattern on the alumina substrate. The diode is placed followed by furnace solder attach. Then these cells are connected to the circuit traces shown at the right of the circuits in figure 2b using an automated ribbon bonder. The DJ cells are supplied with the backside negative contacts fed through to front side bonding pads, enabling front top bonding of both polarity contacts. These cells are adhesive-bonded on top of the GaSb cells with silicone adhesive and are then ribbon bonded to the circuit traces shown to the left on the circuits in figure 2b.

The DJ cell lead bonding is done with the same automated ribbon bonder that was used previously for the GaSb cell ribbon bonding. While the TJ-MS-CICs shown here in figure 2 is novel, this assembly procedure is similar to that used in fabricating the first concentrator PASP module flown in space in 1994. However, there is one notable improvement. Note that all of the ribbon bonds are made to the top side of the stack.

Experimental Results

As of this writing, Tecstar has just delivered 138 top cells, 24 with efficiencies over 26% (AM0) and 87 with efficiencies in the 25% to 26% range. JX Crystals had previously designed the circuit substrates and fabricated GaSb cells and populated circuits with GaSb series strings. JX Crystals has now fabricated 12 circuits complete with GaSb series strings and InGaP/GaAs parallel strings. Circuit outputs measured for these cell-interconnected-circuits range from 3.07 W to 3.25 W. Given an input power of 0.6 x 8 x 0.1353 x 15 = 9.74 W, the resultant circuit efficiency for the best circuit with an output of 3.25 W should be 33.4%. Given that the top cell grid shading is 7%, this efficiency could potentially increase to over 35% with the use of prismatic cover slides. Validation of these efficiency measurements at NASA is still required. However, it should be noted that NASA verified GaSb cell boost efficiencies (1) behind GaAs as high as 7% in flight experiments in 1990. Given this and the fact that the dual junction cell is a well-characterized cell, these high circuit efficiencies follow, and should not be surprising. The surprising fact is really that these high efficiency stacked concentrator cells have been ignored for so long.

Figure 3 shows the illuminated current vs. voltage curve for one of these circuits and tables III and IV summarize the performances for these 12 circuits.

Table III: TJ MSCIC Performance Summary

	Without prismatic cover	With prismatic cover*
Best Circuit Pmax	3.25 W	3.41 W
Best Circuit Effic	33.4%	35.1%
12 Circuit Ave Pmax	3.15 W	3.31 W
12 Circuit Ave Effic	32.5%	34.1%

*Projection

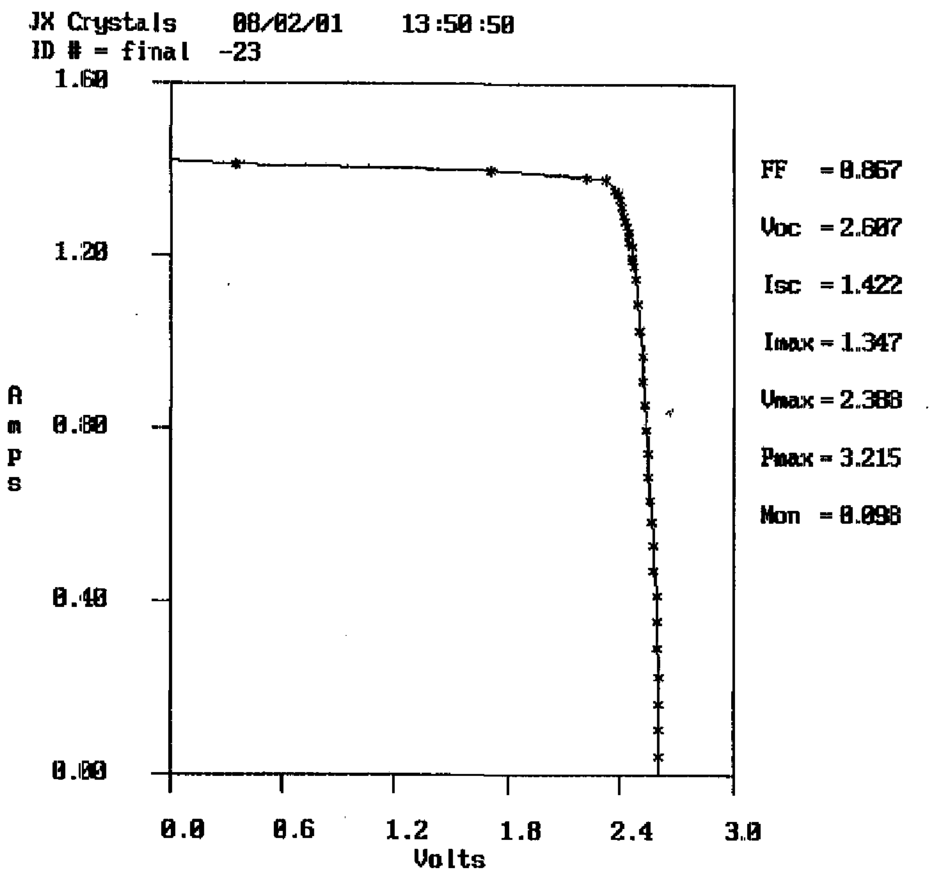


Figure 3. The illuminated current vs. voltage power curve for one of JX Crystals' satellite power circuits.

Table IV: Measured* JX Crystals' TJ MSCIC Performance Parameters**

ID	FF	Voc	Isc	Imax	Vmax	Pmax	Effic
23	0.872	2.617	1.424	1.356	2.397	3.252	33.4%
24	0.848	2.607	1.412	1.3	2.402	3.122	32.1%
25	0.864	2.617	1.34	1.256	2.412	3.03	31.1%
26	0.86	2.607	1.385	1.32	2.354	3.106	31.9%
3	0.862	2.617	1.397	1.307	2.412	3.152	32.4%
10	0.879	2.602	1.391	1.324	2.402	3.181	32.7%
11	0.87	2.602	1.385	1.321	2.373	3.136	32.2%
12	0.866	2.593	1.415	1.321	2.407	3.18	32.7%
13	0.881	2.603	1.386	1.322	2.402	3.176	32.7%
14	0.87	2.613	1.394	1.328	2.388	3.171	32.6%
15	0.87	2.598	1.394	1.31	2.407	3.153	32.4%
18	0.878	2.593	1.394	1.32	2.402	3.172	32.6%

*Without prismatic covers
**BMDO/NASA contract

As of this writing, we have sent the lowest performance circuit, #25, and the highest performance circuit, #23, to ENTECH for incorporation into mini-modules for further testing. In order to check out assembly procedures, ENTECH has initiated testing using the lowest performance circuit first. Figure 4 shows a photograph of this circuit in outdoor testing. Their initial performance testing on a very hot day showed a module efficiency of 27.3%. The outdoor temperature during this test was 42° C. Based on these results, a mini module efficiency of 30% should be achievable in the very near future.

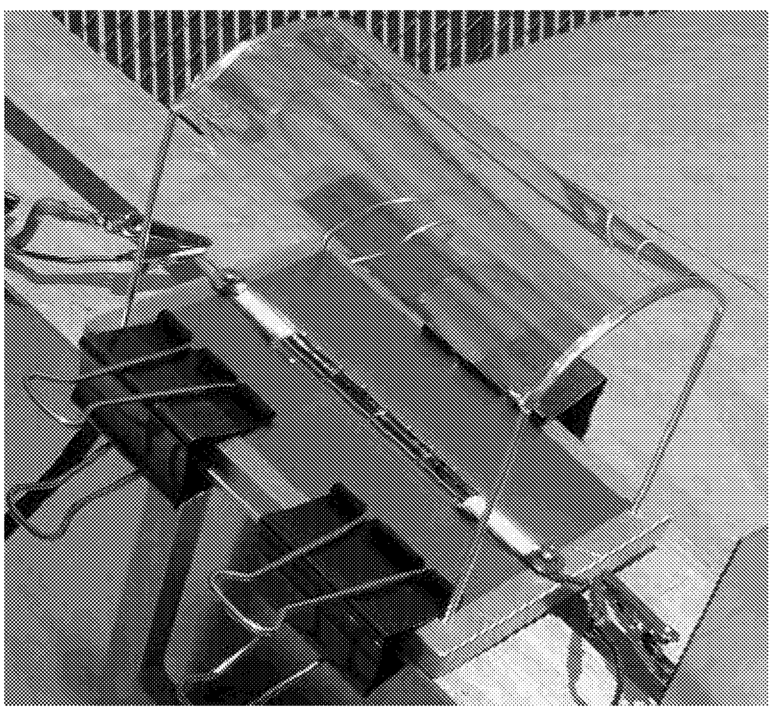


Figure 4. Mini-module with stretched lens and InGaP/GaAs/GaSb circuit.

Improved array performance

NASA has been developing the ultralight Stretched Lens Array (SLA) for space power (2). The baseline cell for this array to date has been the monolithic TJ cell. Very respectable array performance has been predicted for this SLA, as is shown in the first column in table V. In this section, we discuss the potential impact of mechanically stacked multijunction cells and circuits on the performance of this array. There will be an impact on both array weight and array power.

We first discuss the impact on array power density. The baseline SLA is designed to operate at 8 suns concentration and in GEO with cells operating at 80° C. Given a lens optical efficiency of 92%, the array efficiency using Monolithic TJ cells is anticipated to be 22% (column 1 in table V). For this reason, we measured the efficiency of circuit #15 at 8 suns and 80° C. We measured an efficiency of 27.2%. With lens losses, we anticipate an increase in array efficiency at operating temperature using mechanically stacked TJ cells from 22% to 25%. This will increase the array power density from 296 W/m^2. to 336 W/m^2. We also measured the efficiency for circuit #15 at 15 suns and 80° C and found the efficiency to increase from 27.2% to 28.1%. The array power density could then increase to 350 W/ m^2. However, operation at 15 suns would require a tighter pointing tolerance (perhaps 1 degree instead of 2 degrees).

In the last two columns in table V, we note that still further improvements are theoretically possible. These improvements include improvements in the DJ and GaSb cells as well as the potential realization of four active junctions by making a stack consisting of 2J + 2J. This 2J + 2J will be much easier to achieve than a monolithic 4J because of relaxed material constraints.

What about the impact of our InGaP/GaAs/GaSb circuits on array weight? In a real array, we would not use the alumina substrates but we would use flex circuits instead. Given this, then the additional weight for the stacked cell comes about through the additional bottom cell and an increase in thickness in the DJ cell. If we assume 200 micron thick top and bottom cells as opposed to a 140 micron monolithic TJ cell, we find that additional weight is added to the array. However, because of the small sizes of the cells, this additional weight is not large and is compensated by the increase in power density such that the mass specific power at 8 suns remains nearly unchanged at 191 W/kg. As one goes to 15 suns, the mass specific power actually improves.

Finally, we briefly discuss costs. Without going into detail, if we assume an array final cost of $500 per Watt, then the additional value associated with each GaSb cell would be approximately $30 per cm^2. GaSb cells are made via simple diffusions without toxic gases and can easily be made at costs well below this value.

Table V: Stretched Lens Array Performance Projections

Cell Type	3J Mono	2J+1J Mech	2J+1J Mech	2J+1J Mech	2J+2J Mech
Cell supplier	Spectrolab	JXC	JXC	JXC	Tecstar
Conc. Ratio	8x	8x	15x	15x	15x
Cell Effic.(RT)*	Demo	Demo	Demo	Theory	Theory
2J	27.5%	27.5%	28%	30%	30%
Boost	2.5%	6.0%	6.5%	7%	9%
Total	30%	33.5%	34.5%	37%	39%
Operational @ 80° C Array Efficiency	22%	25%	26%	28%	30%
Areal Power (W/m^2)	296	336	350	377	403
Areal Mass (kg/ m^2)	1.54	1.76	1.54	1.54	1.54
Specific Power (W/kg)	192	191	227	245	262

*With prismatic cover

Conclusions

Transparent InGaP/GaAs Dual Junction solar cells were fabricated at a qualified aerospace solar cell production company. Efficiencies of over 26% were measured. These concentrator cells were mechanically stacked on top of GaSb booster cells that added over 6% efficiency for a total of over 32% at 15 suns. This high number results from the benefits of mechanical stacking. The solar energy spectrum is utilized out to 1.8 microns and the full current potential of the lower bandgap back-cells is realized by voltage matched interconnects.

A new stacked cell CIC design is being implemented that provides for voltage matching and bypass diode protection in a basic two-terminal array building block configuration. This Triple-Junction Mechanically-Stacked configuration can increase the real power density for the Stretched Lens Array dramatically to 350 W/m^2 without a penalty in the mass specific power density.

References:

1.) J.E. Avery, L. M. Fraas, et. al. 21st IEEE PVSC (1990) p. 1277.
2.) Mark J. O'Neill, Michael F. Piszczor, et. al., 36th IECEC (2001) IECEC2001-AT-39.