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NEXT GENERATION RADIATION HARD IMM SPACE SOLAR CELLS

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ABSTRACT

High efficiency space solar cells based on the $GaInP_2$/InGaAs/Ge triple junction lattice matched device with 1 sun, AM0 efficiencies of approximately 30% are commercially available from several companies. Multiple approaches have been suggested for significantly surpassing the 30% efficiency level, but achieving this in a commercially viable cell has not been easy. We review those approaches, pointing out the advantages and challenges of each. SolAero has been focused on developing the inverted metamorphic multi-junction (IMM) solar cell, and has recently demonstrated a radiation hard version. We present the most recent performance data, including the response to particle radiation. The IMM cell can be used in a number of rigid or flexible configurations, and considerable effort has been focused on cell packaging and panel integration. The IMM device is ready to start qualification to the ECSS and AIAA standards.

1. INTRODUCTION

The $GaInP_2$/InGaAs/Ge triple junction lattice matched solar cell is the primary source of space satellite power. Several vendors provide commercially available cells, with performance of approximately 30% under 1 sun, AM0 illumination [1]. While silicon solar cells were initially used for space power, they were replaced by III-V based devices, first by the GaAs single junction cell [2] and then eventually by the previously mentioned triple junction cell. While the III-V devices were more expensive ($/Watt) than silicon on a bare cell level, at the array and panel level the III-V devices were a lower cost option [3, 4]. This was due to the III-V device higher efficiency and superior radiation hardness compared to silicon, which led to smaller area arrays, with fewer cells.

The current situation is in some ways similar to the transition from silicon to III-Vs. Surpassing the 30% efficiency level for space cells requires a new cell architecture. Higher efficiency cells require either additional junctions or a better match of the junctions to the solar spectrum, or a combination of both. Added growth and processing increases the cost at the bare cell level. The question is how much additional bare cell cost is acceptable. If the higher cell performance is mission enabling, or if the $/W at the spacecraft level are equal or lower than current technologies, then a higher bare cell cost will be acceptable. The decision needs to be made at the mission level.

2. HIGHER EFFICIENCY CELL OPTIONS

Options for higher efficiency cells have been discussed previously [5], with pros and cons for each approach. Since that time progress has been made with several of the approaches, notably wafer bonding, dilute nitrides, upright metamorphic, and IMM. While the wafer bonding approach has achieved very high terrestrial efficiencies [6], it will not be considered due to the very high expense of growths on two substrates (one being very expensive InP) and subsequent processing, which includes chemi-mechanical polishing as well as chemical treatments to ensure good high quality bonding with no voids. It is simply too expensive for 1 sun space applications. Updates on the other approaches will be provided in the next few sections.

2.1 Dilute Nitrides

The dilute nitride approach involves inserting a lattice matched GaInAsN 1.0 eV junction between the second junction and the bottom Ge junction (Figs. 1). The approach was first presented in 1998 [7] and created considerable interest as a way to create a four junction, lattice matched higher efficiency device.

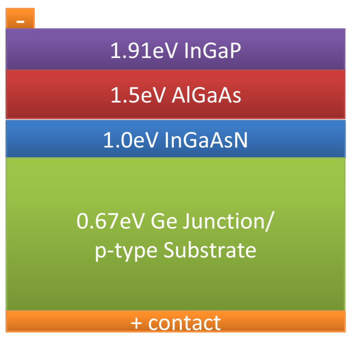

Figure 1. Cross section schematic of a four junction device incorporating a GaInAsN 1 eV junction.

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Unfortunately, poor material quality due to short minority carrier diffusion lengths and high carbon background for MOCVD grown GaInAsN [8] led to poorly performing devices, and interest in the dilute nitride approach waned. Several years after this MBE grown GaInAsSbN demonstrated lower background carbon doping which allowed for p-i-n junctions with a high internal field to be used to counter the still poor minority carrier diffusion lengths and low voltages. Triple junction $GaInP_2$/InGaAs/GaInAsSbN devices were demonstrated. Efforts are currently being made to commercialize both triple and quadruple junction devices [9]. While the MBE grown dilute nitride junction is improved over a MOCVD grown junction, there are still issues with poor minority carrier diffusion lengths. The dilute nitride junctions have yet to achieve the voltages expected for the corresponding band gaps. Another challenge is that while MBE grown dilute nitride material is better quality than MOCVD grown material, MOCVD is the better option for growing high quality phosphide materials such as $GaInP_2$. Growing a three or four junction device with optimized performance would require two separate growths, since neither growth option is best for the complete structure. Another issue with MOCVD grown dilute nitrides is the high quantity of nitrogen precursor required and the associated high precursor costs [8]. The growth/performance/cost issue needs to be resolved.

2.2 Upright Metamorphic

The upright metamorphic approach (Fig. 2) has also been studied since 1997 [10]. The challenge has been growth of high quality, lattice mismatched material with good minority carrier properties. All of the epitaxial junctions, which provide a high percentage of the power conversion, have threading dislocations and recombination centers, which increases the junction dark current. For 1 sun applications the metamorphic devices have never surpassed lattice matched devices. In addition, the metamorphic grades add growth time, and the mechanical strain due to the lattice mismatch requires a thick germanium substrate, which adds weight as well as further cost. Weight reduction requires thinning the substrate, and ensuring that the final solar cell assembly is attached to a rigid coverglass or carrier.

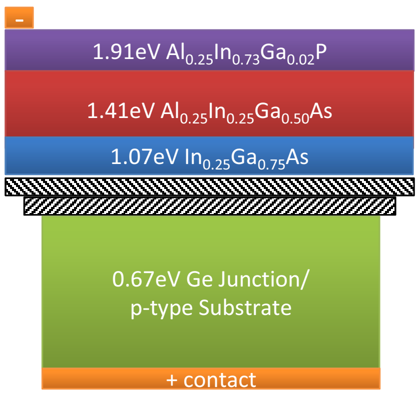

Figure 2. Cross sectional schematic of an upright metamorphic four junction device. All epitaxial junctions are grown lattice mismatched with respect to the Ge junction.

2.3 Inverted Metamorphic

The IMM space cell (Fig. 3) has been studied since about 2007 [11, 12], and devices with up to 6 junctions have been demonstrated [13]. The device is grown inverted, with lattice matched high band gap junctions grown first, followed by two lattice mismatched junctions. Subsequently the structure is inverted, mounted on a carrier, and the growth substrate removed. While readily surpassing the 30% efficiency level, the challenge has been the added costs associated with growth and processing. In addition, there have been some questions about the radiation hardness of the lower band gap junctions. These two issues have been overcome, and in the following sections we address first the performance concern and then secondly the cost and manufacturability concern.

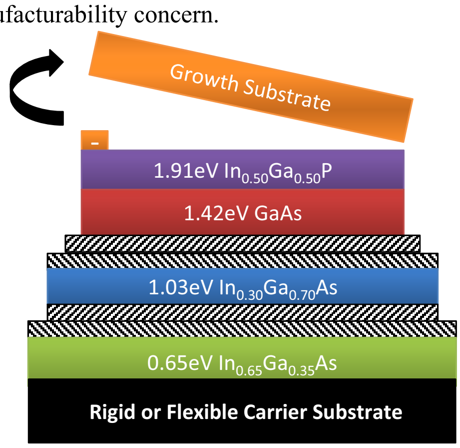

Figure 3. Cross sectional schematic of the IMM four junction device.

3. IMM PERFORMANCE

Recent development efforts at SolAero on the IMM cell have resulted in very high radiation hardness. While some beginning of life (BOL) performance has been sacrificed, the end of life (EOL) performance has been much improved. Fig. 4 shows a comparison between SolAero's $GaInP_2$/InGaAs/Ge ZTJ efficiency and the IMM efficiency as a function of exposure to 1 MeV electrons. The IMM shows a marked improvement over the ZTJ cell over a wide fluence range. In addition, a curve for an "annealed" or "healed" IMM cell is also shown. Radiation damage in a solar cell can be

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annealed due to a number of factors, including thermal load, light soaking, and reverse bias exposure [14]. For thermal healing, the amount of efficiency restoration is dependent on the time at a given temperature. In Fig. 4 the improvement was based on the ECSS post radiation exposure testing procedure. Fig. 5 shows the relative improvement in IMM efficiency for both the AIAA S-111 and ECSS post radiation testing procedures, after exposure to 1 MeV electrons to a fluence of 1 x 10^{15} e/cm^2. With the AIAA standard there is an absolute 0.5% efficiency improvement, and with the ECSS standard the improvement is 0.8% absolute. With radiation damage annealing in the IMM accounted for, the efficiency is 28.3% for 1 sun (135.3 mW/cm^2), 28°C, AM0 conditions after exposure to 1 MeV electrons to a fluence of 1 x 10^{15} e/cm^2. This is a 12% relative improvement over the ZTJ cell, and 87% EOL/BOL for these conditions.

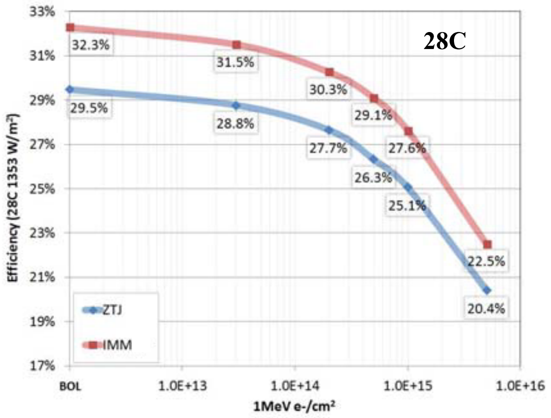

Figure 4. Efficiency (135.3 mW/cm^2, 28°C) as a function of 1 MeV fluence for the ZTJ cell and the IMM cell, post radiation and healed post radiation.

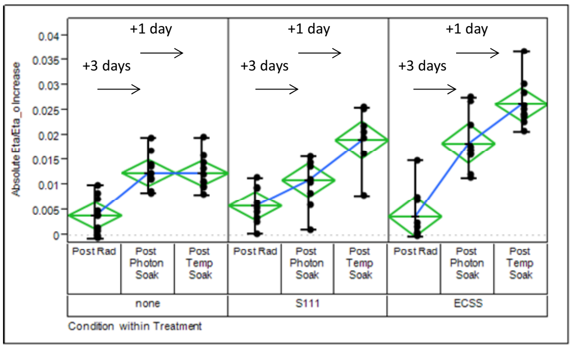

Figure 5. Improvement in efficiency for the IMM cell after exposure to 1 MeV electrons to a fluence of 1 x 10^{15} e/cm^2, for the AIAA S111 and ECSS standards post radiation test procedure.

4. COST AND MANUFACTURABILITY

A major step forward in reducing IMM costs has been the reduction in MOCVD growth time and the incorporation of a number of automated steps in the IMM process flow. The reduction in growth time was achieved through a simplification of the growth structure, particularly the metamorphic buffer layers. Automation, an example of which is shown in the wet bench in Fig. 6, increases throughput and yield, and reduces labor costs.

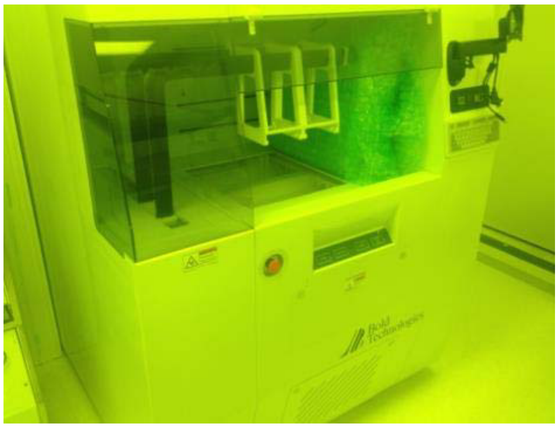

Figure 6. Automated etching bench that includes robotics for cassette handling of wafers.

A step by step analysis of the IMM growth and process steps have indicated the major cost drivers. We have worked on a number of our process steps as well as with a number of vendors to determine lower cost process and materials alternatives that will still provide the same final solar cell performance. In one case the process/material costs were reduced by 70%, and in another by 55%, all without compromising performance. We are working through a process step cost pareto to ensure that we are working on areas that will provide the best return for our efforts.

Cell size has a large impact on panel integration costs through reduction in piece part count and touch labor on a per Watt basis [15]. Large area IMM devices on 4" wafers of ~60 cm^2 have been demonstrated. In addition, IMM manufacturing on 6" wafers to achieve even larger cell form factors has begun at SolAero. A comparison of ~27.5 cm^2, ~60 cm^2 (4" substrate), and 73.5 cm^2 (6" substrate) form factors is shown in Fig. 7.

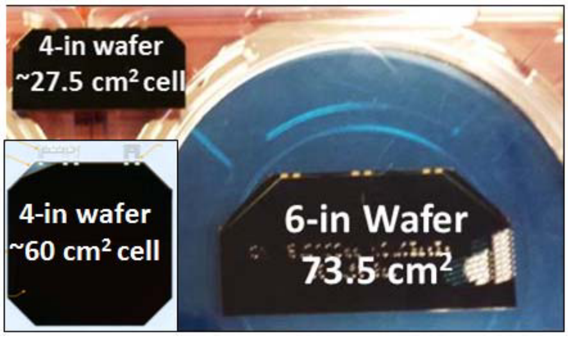

Figure 7. A comparison of cell form factors for 6 inch and 4 inch wafers.

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Based on the IMM cell performance and manufacturing status it is ready to start qualification to the AIAA S-111 and ECSS-E-ST-20-08 cell standards.

5. INTEGRATION

Integration of the IMM cell offers more possibilities than the standard upright triple junction cell. The carrier substrate in the schematic in Fig. 3 can be rigid or flexible. Preliminary work has been done to verify the ability of the IMM cell to survive space conditions for some of these integrated configurations. Fig. 8 shows an IMM cell string on a rigid panel before and after 12,000 LEO thermal cycles. The cells are forward biased into electroluminescence, and there are no indications of damage to the cells. The coupon pre/post measurements showed no change in performance. An additional 6 coupons have been tested to a similar level with no performance degradation seen. While a full qualification is needed, both the radiation performance and the survivability to thermal cycling indicate that the IMM cell can be used as a “drop in replacement” for the traditional multi-junction cell.

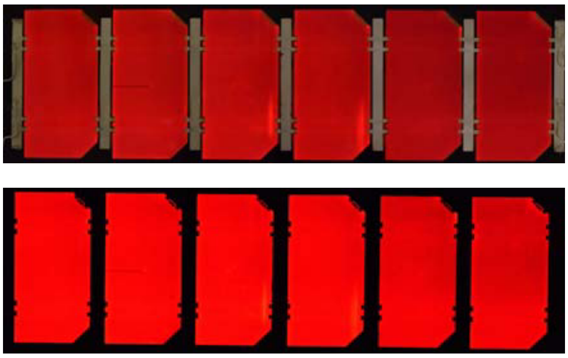

Figure 8. Pre (top string)/post (bottom string) luminescent pictures of an IMM string on a rigid substrate which underwent 12,000 LEO thermal cycles. Performance testing indicated no change in efficiency.

In addition to a rigid panel configuration, the IMM cell can be used on a flexible panel. Fig. 9 shows two 8 cell IMM strings on kapton, which are mounted on flexible mesh scrim. This configuration can then be rolled or folded into a more compact array.

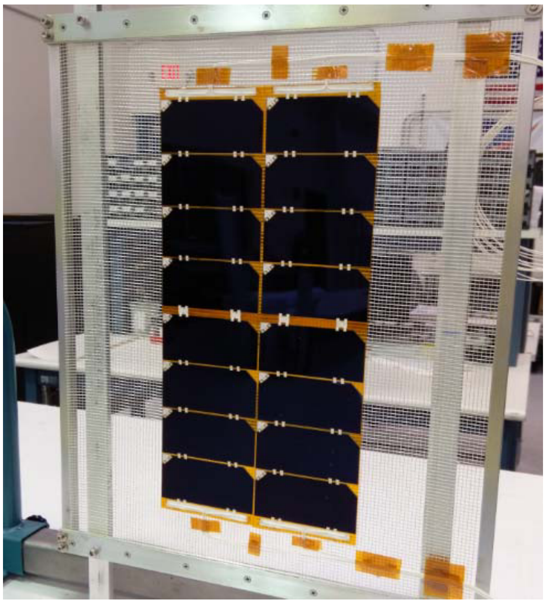

Figure 9. Two 8 IMM cell strings connected and mounted on mesh scrim.

Initial confidence testing has been done on the flexible mounted strings, and consisted of 20x roll and unroll at room temperature, 5 day soaks at ± 60 °C, multi-axis vibration testing intended to mimic stowed flight conditions, thermal vacuum exposure (80 °C for a minimum of 24 hours in a vacuum of <10-5 torr, 8 thermal vacuum cycles from -137 to 120 °C), and finally hot GEO thermal cycling (2000 cycles from -175 to +140 °C). The mounted strings exhibited essentially no loss of output power as measured by large area pulsed solar simulator (LAPSS) measurements during and after the confidence test suite (Fig. 10), indicating excellent survivability of these string assemblies.

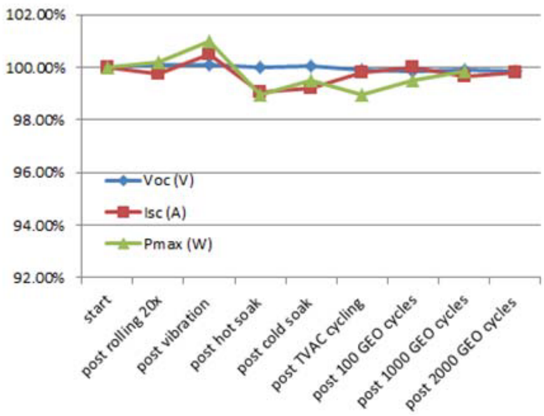

Figure 10. % remaining factors through confidence testing, as measured by LAPSS

6. CONCLUSIONS

The IMM cell developed at SolAero demonstrates superior performance at BOL and EOL compared to current state of the art triple junction technologies as well as other proposed next generation technologies. The cell is capable of being made in a high volume. There is a roadmap to cost parity ($/W) with heritage triple junction cells at the panel level. The cell is ready to start qualification to the AIAA S-111 and the ECSS-E-ST-20-08 cell standards.

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