Future Technology Pathways of Terrestrial III-V Multijunction Solar Cells for Concentrator Photovoltaic Systems

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Abstract: Future terrestrial concentrator cells will likely feature four or more junctions. The better division of the solar spectrum and the lower current densities in these new multijunction cells reduce the resistive power loss (I^2R) and provide a significant advantage in achieving higher efficiency of 45% to 50%. The component subcells of these concentrator cells will likely utilize new technology pathways such as highly metamorphic materials, inverted crystal growth, direct-wafer bonding, and their combinations to achieve the desired bandgaps while maintaining excellent device material quality for optimal solar energy conversion. Here we report preliminary results of two technical approaches: (1) metamorphic ~1-eV GaInAs subcells in conjunction with inverted growth approach and (2) multijunction cells on wafer-bonded, layer transferred epitaxial templates.

I. INTRODUCTION

Terrestrial concentrator systems utilizing high efficiency III-V multijunction solar cells are becoming a viable technology for large scale generation of electrical power [1]. The III-V concentrator systems are unique in their high areal power density and offer rapid manufacturing scalability. With production cell efficiencies around 37% at about 500 suns, triple-junction GaInP/Ga(In)As/Ge terrestrial solar cells are enabling system manufacturers to produce concentrator systems competitive with other technologies and offering potential cost advantages.

Two types of III-V multijunction concentrator cells are now in large scale production at Boeing-Spectrolab. They are the C1MJ and the C2MJ. The efficiency distribution of the production C1MJ terrestrial cells is shown in Fig. 1. With mode efficiency and average efficiency at 37% (25°C, ASTM G173-03 spectrum, 500X), the production cells have a rather mature distribution curve. Peak cell efficiencies of 39% were recorded on some of the 1-cm^2 cells.

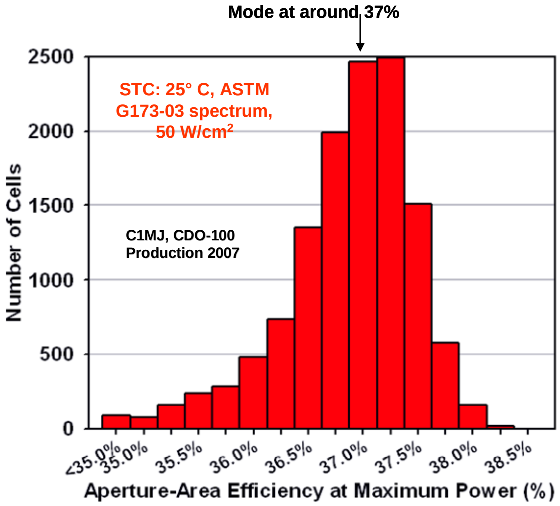

Fig. 1. Efficiency distribution of approximately 13,000 1-cm^2 Boeing-Spectrolab terrestrial concentrator cells tested at ~500 suns. The cells have a mode efficiency of 37%.

II. FUTURE III-V TERRESTRIAL CONCENTRATOR CELLS

Recently, Boeing-Spectrolab's 3-junction concentrator cell reached a record efficiency of 40.7% as shown in Fig. 2 [2,3]. Despite the record-high efficiency, it is well-known that the 3-junction cell bandgap combination compromise ideal solar spectrum splitting for subcells material quality, hence limiting the achievable efficiency. Future terrestrial cells will likely feature four or more junctions with performance potential capable of reaching over 45% efficiency at concentration. The 4, 5, or 6-junction concentrator cells trade lower current densities for higher voltage and divide the solar spectrum more efficiently. The lower current densities in these cells can significantly reduce the resistive power loss (I^2R) at high concentrations when compared to the 3-junction cell. The 4-junction and the 5-junction concentrator cell schematics are shown in Fig. 3.

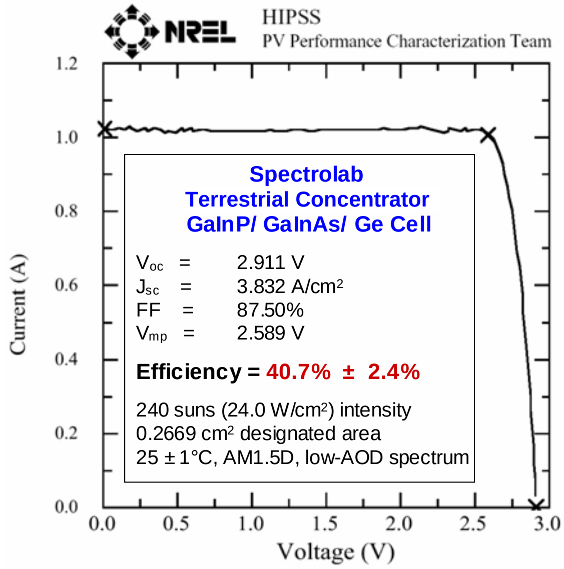

Fig. 2. Illuminated I-V curve of the record 40.7% 3-junction cell certified at NREL.

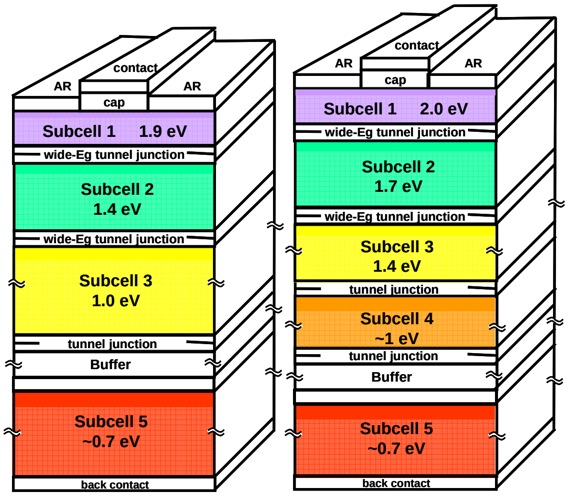

Fig. 3. Schematics of a 4-junction and a 5-junction concentrator cells.

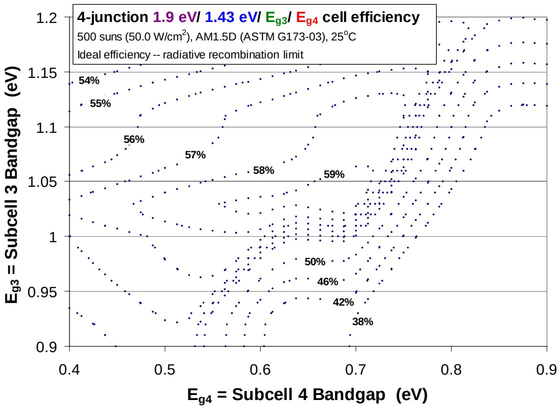

Fig. 4. Dependence of ideal efficiency on Subcell 3 and Subcell 4 bandgaps, Eg_3 and Eg_4, for a 4-junction terrestrial concentrator cells limited by radiative recombination at ~500 suns.

Figure 4 plots the iso-efficiency contours for a 4-junction terrestrial concentrator cells as a function of Subcell 3 and Subcell 4 bandgaps (with Subcell 1 and Subcell 2 bandgaps held constant) under the AM1.5D (ASTM G173-03) solar spectrum at 500 suns. Ideal conversion efficiencies of over 59% for the 4-junction cells are possible, and for the 5- or 6-junction terrestrial concentrator cells, efficiencies over 60% are achievable in principle. With the effects of series resistance, grid shadowing, and other real-world effects included, practical cell efficiencies of 47% are within reach for 4-junction cells with a bandgap combination of 1.9/1.4/1.0/0.7-eV.

Previous work has focused on the development of GaInNAs materials lattice-matched to the GaAs or the Ge substrate as the 1-eV subcell material for solar cell applications [4-7]. So far, limited success has been reported and most GaInNAs materials do not meet the performance requirements for high performance concentrator cells. The unavailability of a lattice-matched ~1-eV subcell has limited the development of standard upright 4-junction cell from achieving the desirable bandgaps combination for ultra-high conversion efficiency.

III. TECHNOLOGY PATHWAYS FOR III-V MULTIJUNCTION CONCENTRATOR CELLS

The 4-, 5-, and 6-junction terrestrial cells will likely utilize new technologies to build some of the subcells with the desired bandgaps and material quality. Two technology pathways are presented here: 1) highly metamorphic GaInAs subcell materials in conjunction with inverted growth and 2) multijunction cells on wafer-bonded, layer transferred epitaxial templates are reported.

Highly Metamorphic ~1-eV GaInAs Subcell in Conjunction with Inverted Growth

Recent work on highly metamorphic GaInAs materials has demonstrated standard "upright" ~1-eV 1-junction cells on Ge (or GaAs) substrates through the use of transparent graded buffer layers [8-10]. The compositionally graded buffer layer gradually alters the lattice constant from the Ge (or GaAs) lattice constant to that of the 1-eV $Ga_{1-x}In_xAs$. Figure 5 and Fig. 6 present the quantum efficiency data and the open-circuit-voltages (V_{oc}) of a series of metamprphic $Ga_{1-x}In_xAs$ cells with bandgaps ranging from 1.38 to 0.95-eV. The metamorphic GaInAs cells reached nearly 100% in internal quantum efficiency (IQE) over the majority of the wavelength range. The IQE remains remarkably high for the 1.08-eV and the 0.95-eV cells given the extreme lattice mismatch with the Ge substrates. The measured V_{oc} values and the bandgap energies of the metamorphic GaInAs cells are 1.03V, 0.87V, 0.69V, and 0.48V for the 1.41, 1.31, 1.08, 0.95-eV GaInAs cells. These results showed that the highly metamorphic GaInAs cells even at ~1-eV meet the requirements of high performance multijunction concentrator cells.

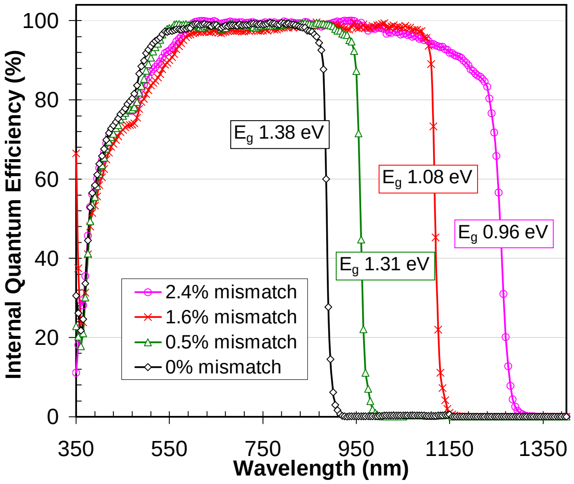

Fig. 5. Internal quantum efficiency curves of metamorphic $Ga_{1-x}In_xAs$ single-junction cells with bandgaps ranging from 1.38 to 0.95-eV.

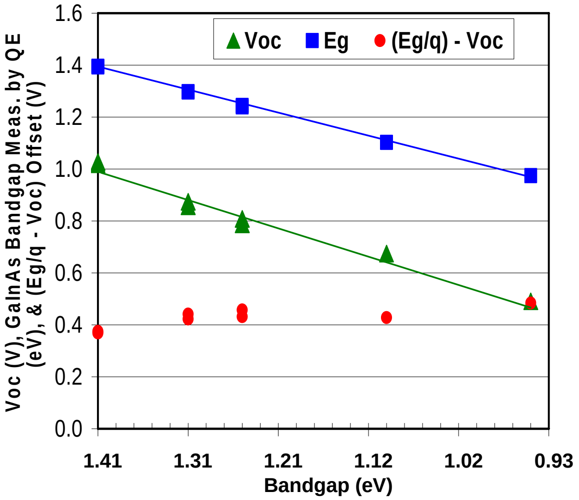

Fig. 6. Measured open-circuit-voltages, bandgap energies, and (Eg/q - V_{oc}) offsets of various metamorphic GaInAs single-junction cells.

The integration of the highly metamorphic 1-eV GaInAs subcell in standard upright multijunction cell structures is not trivial. As mentioned previouly, the highly metamorphic material has a rather large lattice mismatch (~1.7-2.4%) with the Ge (or GaAs) substrate. Hence it is inherently challenging to grow the 1-eV GaInAs material and even more difficult to grow the high bandgap subcells above it at the new lattice constant. One way to mitigate this challenge is to combine highly metamorphic material with inverted growth [11]. The inverted growth approach allows the high bandgap subcells (e.g. GaInP) to be grown first, lattice-matched to the substrate lattice-constant, followed by the transparent graded buffer layer and the highly metamorphic ~1-eV subcell. In this way, the material and device quality of the high bandgap junctions can be preserved, thereby minimizing or shielding them from the defects of the metamorphic layers. Schematics of inverted metamorphic 3-junction and 4-junction terrestrial concentrator cells are shown in Fig. 7.

The inverted metamorphic (IMM) solar cells demand more complex device fabrication than conventional solar cells. The inverted cell structure must first be either temporarily mounted or permanently bonded to handle substrate before the original growth substrates is removed to reveal the terrestrial cells in the "sun-side-up" direction. Standard fabrication techniques are then used to process the device materials into solar cells.

Recently, Boeing-Spectrolab has demonstrated large-area inverted metamorphic solar cells [13]. Figure 8 shows the illuminated IV characteristic of a "proof-of-concept" IMM 3-junction cell tested under the AM1.5G spectrum at 7-suns. An open-circuit-voltage of 2.8 V, a current-density of 52.7 mA/cm^2, and a fill factor of 85% are recorded for the 1-cm^2 inverted metamorphic 3-junction cell. Despite the less-than-optimal performance, the results clearly demonstrate the capability to grow, handle, fabricate, and test IMM solar cells. Focused development efforts are underway to improve the conversion efficiency and cell yield of the inverted metamorphic multijunction concentrator cell.

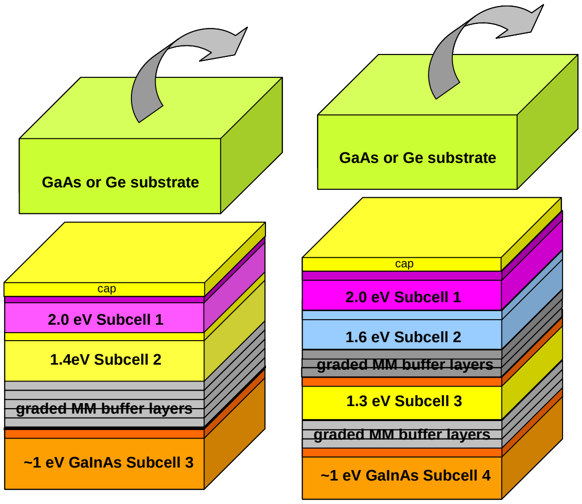

Fig. 7. Schematics of an inverted metamorphic 3-junction and an inverted metamorphic 4-junction concentrator cells.

Terrestrial Multijunction Cells on Wafer-Bonded, Layer-Transferred Epitaxial Templates

California Institute of Technology (Caltech) and Boeing-Spectrolab have teamed together to conduct experiments on wafer bonding and layer transfer processes for potentially lower-cost, higher-performance terrestrial concentrator cells. Wafer bonding provides the ability to integrate subcells from dissimilar substrates into a single device structure. This relieves the constraint of lattice-matching or the challenges associate with integrating highly metamorphic subcells. Thus, materials such as, GaInPAs and Si can be used for the ~1-eV subcell in high-performance terrestrial cells. Concentrator cells may also utilize a 0.73-eV GaInAs subcell on InP as the low-bandgap junction. Ion implantation induced layer transfer further allows thin layers of crystalline films to exfoliate from their original substrate and bond to a lower-cost handle. Combining wafer bonding and layer-transfer capabilities can enable low-cost, high-performance terrestrial multijunction cells with lattice-matched subcell materials from dissimilar substrates to approach the more optimal bandgap combinations of 4-, 5-, and 6-jucntion concentrator cells [14].

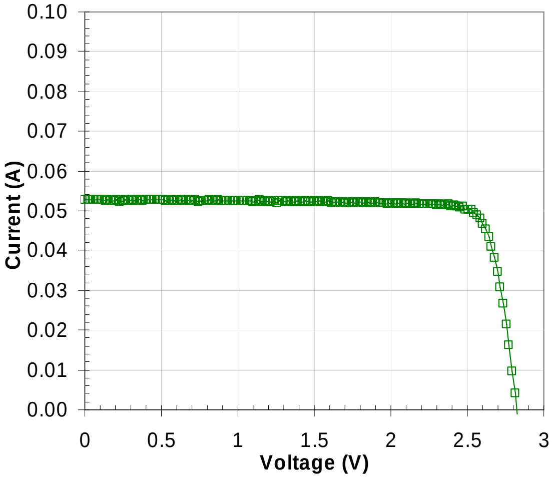

Fig. 8. Illuminated I-V characteristic of an inverted metamorphic 3-junction cell tested at 7-suns under the AM1.5G spectrum.

Recently, we have demonstrated GaInP/GaAs 2-junction solar cells on wafer-bonded, layer-transferred Ge-on-Si templates [15]. Figure 9a shows the schematic of the bonded device structure. Overall, the photovoltaic performance of the dual-junction solar cell devices was comparable to those deposited on bulk Ge substrates. The bonded 2-junction cells showed slightly lower short-circuit current-densities, open-circuit-voltages, and external quantum efficiency than a control device (Fig. 10 & 11). The preliminary results are encouraging and demonstrate the feasibility of integrating solar cell architectures through wafer bonding and layer-transfer of key subcell materials.

Low-electrical resistance bonded interfaces fabricated from epitaxial materials were discussed previously [16]. In addition, InP-on-Si templates similar to the Ge-on-Si demonstrated in this work are also available [17]. Thus one can assemble the GaInP/GaAs dual junction on Ge templates with the GaInPAs/GaInAs dual-junction on InP templates to achieve a wafer-bonded, layer-transferred GaInP/GaAs-GaInPAs/GaInAs 4-junction terrestrial solar cells. The final cells will have a highly desirable bandgaps combination of 1.9, 1.42, 1.05, and 0.72-eV (Fig. 9b) as discussed in previous section.

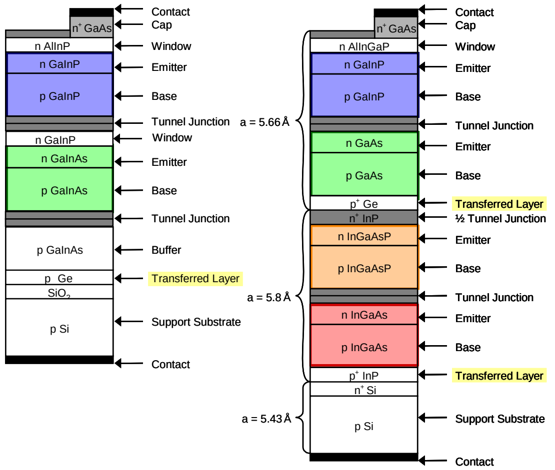

Fig. 9a and 9b. Schematics of the demonstrated 2-junction cells and the final wafer-bonded, layer-transferred 4-junction cell.

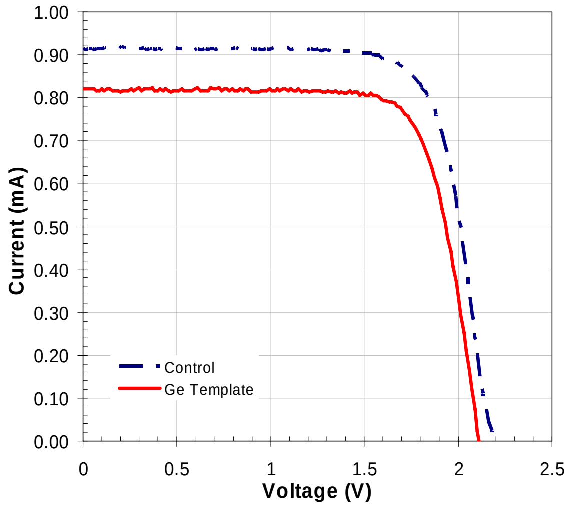

Fig. 10. Measured I-V characteristic of a control 2-junction cell and a wafer-bonded, layer-transferred 2-junction cell under the AM1.5G Spectrum (Cell size = 7 mm^2).

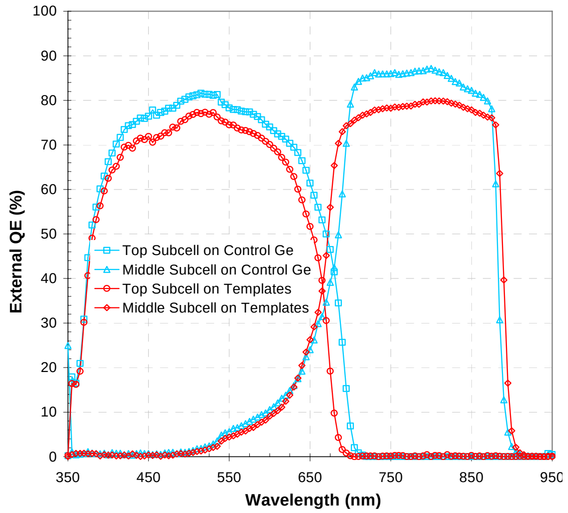

Fig. 11. External quantum efficiencies of a wafer-bonded, layer-transferred 2-junction cell and a control 2-junction cell.

IV. CONCLUSION

Boeing-Spectrolab continues to provide high performance terrestrial photovoltaic products for concentrator photovoltaic systems. Research work now focuses on advancing cell architectures and technology pathways that will enable us to reach 45-50% conversion efficiency. Preliminary results of two technical approaches: (1) metamorphic ~1-eV GaInAs subcells in conjunction with inverted growth, and (2) multijunction cells on wafer-bonded, layer transferred epitaxial templates are reported. Further development efforts in component subcell improvements and integration capabilities will allow future terrestrial concentrator cells to reach the efficiency goal. If successful, these very high efficiency cells can reduce the cost of all area-related components of a photovoltaic system, such as glass, encapsulation materials, metal support structures, semiconductor material themselves, opening wide market areas for concentrator photovoltaics.

V. ACKNOWLEDGEMENTS

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