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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 efficiencies of 45–50%. 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 an inverted growth approach and (2) multijunction cells on wafer-bonded, layer-transferred epitaxial templates.

1. 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, 500 ×), the production cells have a rather mature distribution curve. Peak cell efficiencies of 39% were recorded on some of the 1 cm^2 cells.

2. Future III–V terrestrial concentrator cells

Recently, Boeing-Spectrolab's 3-junction concentrator cell reached an efficiency of 40.7% as shown in Fig. 2 [2,3]. Despite the high efficiency, it is well-known that the 3-junction cell bandgap combination compromises the ideal solar spectrum splitting in favour of subcell 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 with the 3-junction cell. The 4- and the 5-junction concentrator cell schematics are shown in Fig. 3.

Fig. 4 plots the iso-efficiency contours for a 4-junction terrestrial concentrator cell 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

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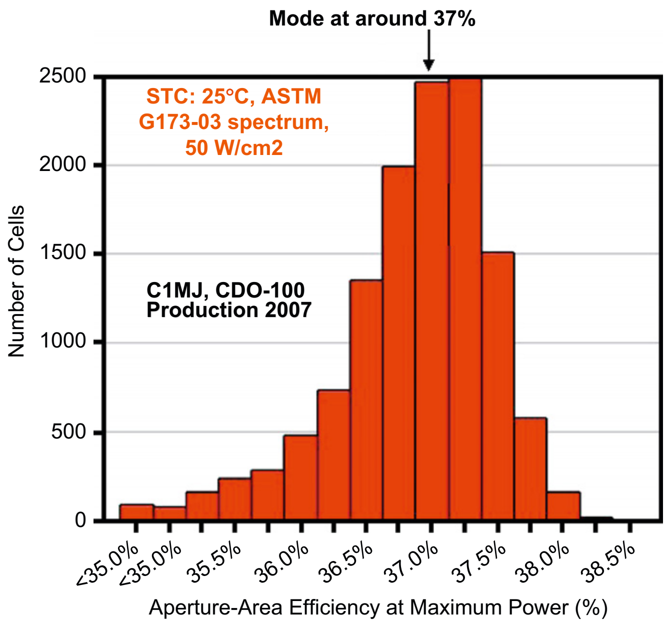

Fig. 1. Efficiency distribution of approximately 13,000 1 cm^2 Boeing-Spectrolab terrestrial concentrator cells tested at ~500 suns. The cells have a mode efficiency of 37%.

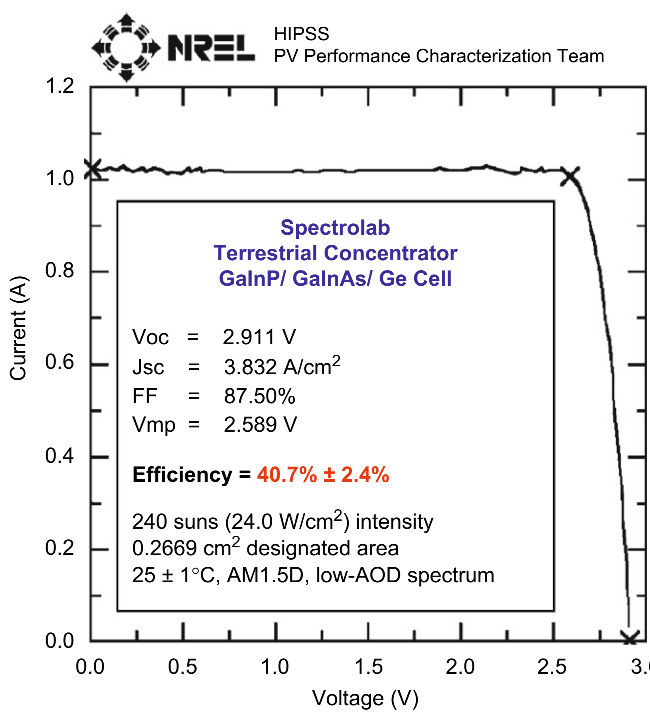

Fig. 2. Illuminated *I–V* curve of the 40.7% 3-junction cell certified at NREL.

concentrator cells. The unavailability of a lattice-matched ~1 eV subcell has limited the development of standard upright 4-junction cells from achieving the desirable bandgap combination for ultra-high conversion efficiency.

3. 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

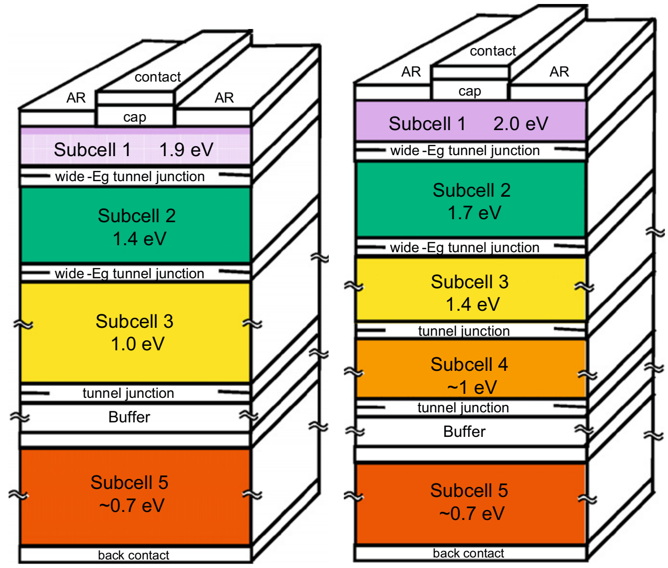

Fig. 3. Schematics of a 4- and a 5-junction concentrator cells.

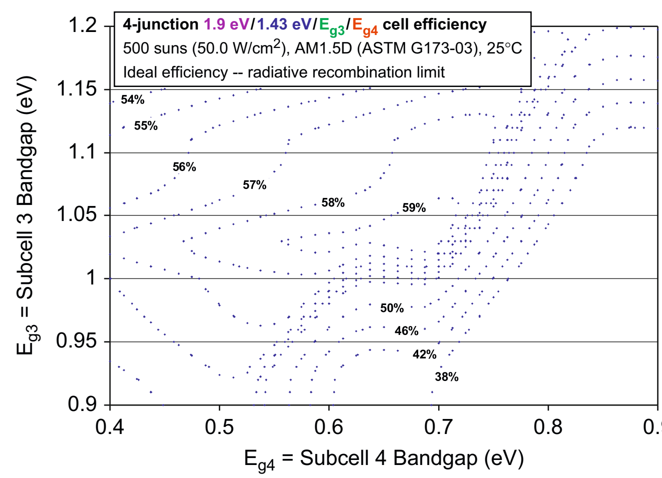

Fig. 4. Dependence of ideal efficiency on Subcell 3 and Subcell 4 bandgaps, E_{g_3} and E_{g_4}, for a 4-junction terrestrial concentrator cells limited by radiative recombination at ~500 suns.

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.

3.1. Highly metamorphic ~1 eV GaInAs subcells 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 $Ga_{1-x}In_xAs$. Figs. 5 and 6 present the quantum efficiency data and the open-circuit voltages (V_{oc}) of a series of metamorphic $Ga_{1-x}In_xAs$ 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

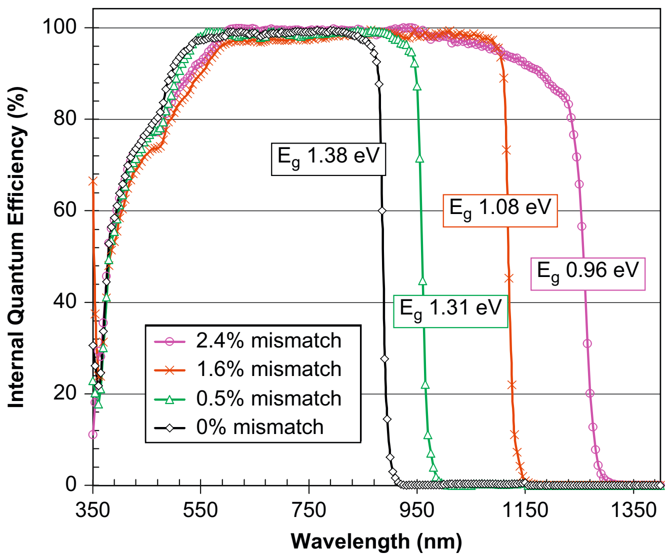

Fig. 5. IQE curves of metamorphic $Ga_{1-x}In_xAs$ single-junction cells with bandgaps ranging from 1.38 to 0.95 eV.

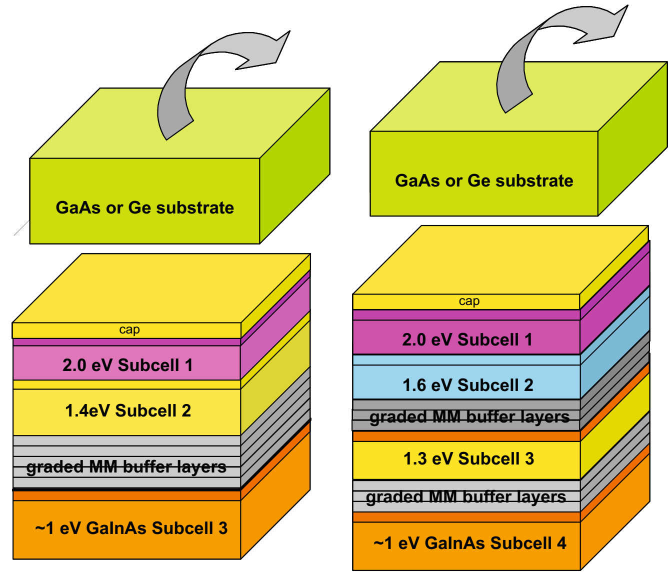

Fig. 7. Schematics of an IMM 3-junction and an IMM 4-junction concentrator cells.

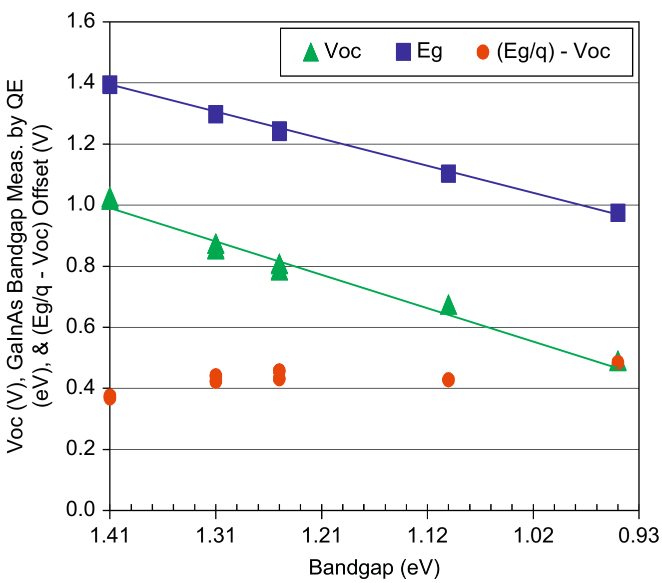

Fig. 6. Measured open-circuit voltages, bandgap energies, and $(E_g/q-V_{oc})$ offsets of various metamorphic GaInAs single-junction cells.

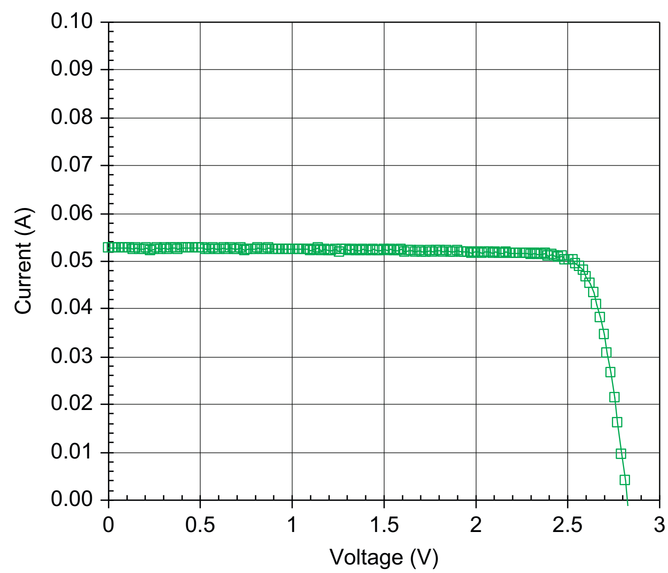

Fig. 8. Illuminated *I–V* characteristic of an IMM 3-junction cell tested at 7 suns under the AM1.5D spectrum.

with the Ge substrates. The measured V_{oc} values and the bandgap energies of the metamorphic GaInAs cells are 1.03, 0.87, 0.69, and 0.48 V 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.

The integration of the highly metamorphic 1 eV GaInAs subcell in standard upright multijunction cell structures is not trivial. As mentioned previously, 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 [11,12]. The inverted growth approach allows the high bandgap subcells (e.g. GaInP) to be grown first, lattice-matched to the substrate, 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 (IMM) 3- and 4-junction terrestrial concentrator cells are shown in Fig. 7.

The IMM solar cells demand more complex device fabrication than conventional solar cells. The inverted cell structure must first be either temporarily mounted onto or permanently bonded to a 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 IMM solar cells [13]. Fig. 8 shows the illuminated IV characteristic of a "proof-of-concept" IMM 3-junction cell tested under the AM1.5D 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 IMM 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 IMM multijunction concentrator cells.

3.2. 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 and the challenges associated 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 optimal bandgap combinations of 4-, 5-, and 6-junction concentrator cells [14].

Recently, we have demonstrated GaInP/GaAs 2-junction solar cells on wafer-bonded, layer-transferred Ge-on-Si templates [15]. Fig. 9a shows the schematic of the bonded device structure. Overall, the photovoltaic performance of the dual-junction solar cell devices was comparable to that of 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 (Figs. 10 and 11).

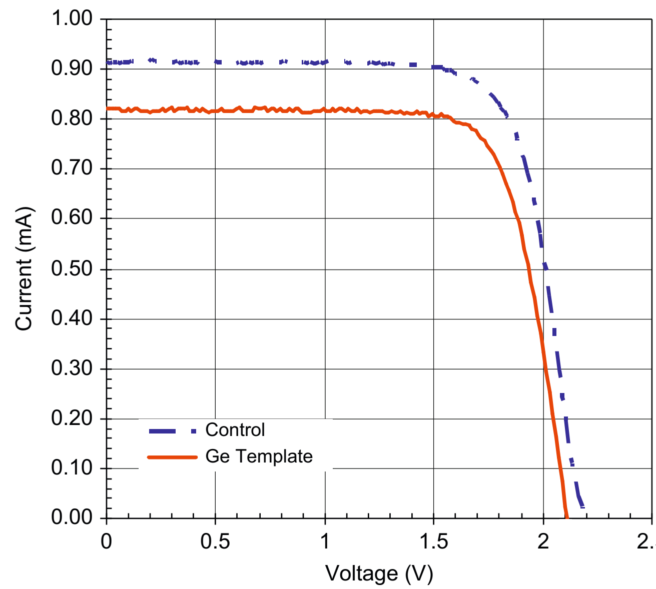

Fig. 10. Measured *I–V* characteristic of a control 2-junction cell and a wafer-bonded, layer-transferred 2-junction cell under the AM1.5G Spectrum (cell size = 7 mm^2).

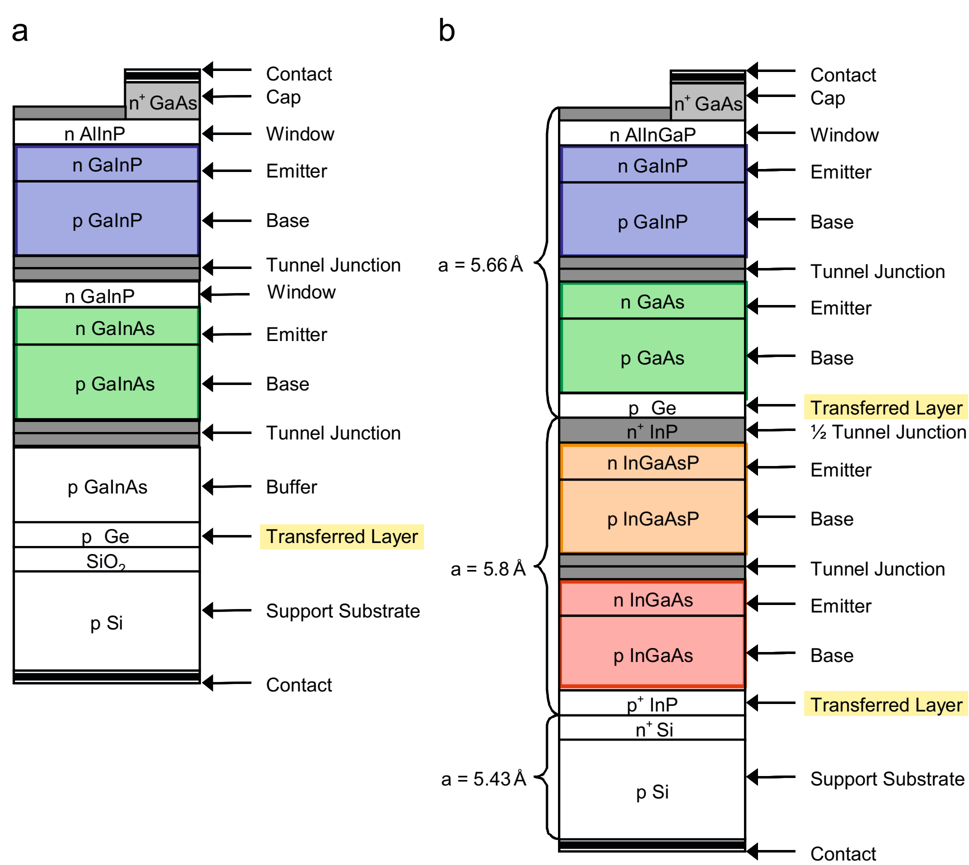

Fig. 9. (a and b) Schematics of the demonstrated 2-junction cells and the final wafer-bonded, layer-transferred 4-junction cell.

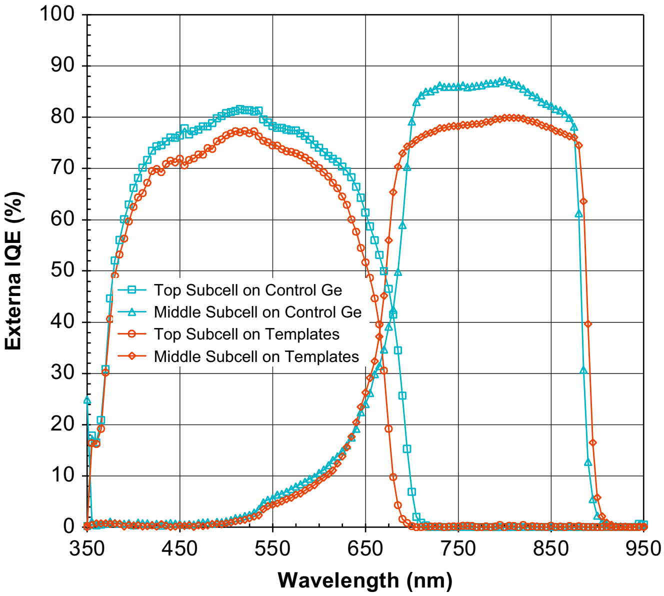

Fig. 11. External quantum efficiencies of a wafer-bonded, layer-transferred 2-junction cell and a control 2-junction cell.

The preliminary results are encouraging and demonstrate the feasibility of integrating solar cell architectures through the 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 wafer-bonded, layer-transferred GaInP/GaAs–GaInPAs/GaInAs 4-junction terrestrial solar cells. The final cells will have the highly desirable bandgap combination of 1.9, 1.42, 1.05, and 0.72 eV (Fig. 9b) as discussed in the previous section.

4. 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.

Acknowledgments

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