Group-IV Subcells in Multijunction Concentrator Solar Cells

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Group-IV solar cells have great value for increasing conversion efficiency when integrated with III-V subcells in multijunction solar cells, as in today's 3-junction GaInP/ GaInAs/ Ge concentrator cells that have demonstrated over 40% efficiency. New types of Ge, Si, SiGe, and SiGeSn subcells show the potential to increase multijunction efficiencies to still higher values. Cells incorporating both dilute nitride GaInNAs and active Ge substrate cells can reach over 46% production average efficiencies at 50.0 W/cm^2 (500 suns), 25°C under the standard concentrated solar spectrum, with champion efficiencies over 48%.

Introduction

Germanium photovoltaic cells have been used in combination with III-V subcells in high-efficiency multijunction solar cells for many years (1-3). Three-junction GaInP/ Ga(In)As/ Ge solar cells with an active Ge bottom subcell have been the highest efficiency commercially available solar cells for space applications since 2000, and for terrestrial concentrator photovoltaic (CPV) applications since 2001. A metamorphic 3-junction GaInP/ GaInAs/ Ge concentrator solar cell, with III-V subcells grown at a different lattice constant than that of the Ge substrate was the first type of solar cell to reach over 40% efficiency (4), and this solar cell structure has now been independently verified at 41.6% efficiency.

Several happy circumstances of nature work together to make this a successful technology. The very close lattice constants and thermal expansion coefficients of GaAs and Ge make it possible to grow III-V semiconductors on Ge substrates with essentially the same high quality as on GaAs substrates – provided some attention is paid to the III-V nucleation on Ge and to lattice constant tuning – but with the advantages of lower cost, greater strength, and lighter weight that Ge substrates offer. Additionally, once high-quality p-type Ge substrates were developed in volume in the 1990s, the natural diffusion of group-V dopants into the Ge substrate from III-V semiconductor growth on top could be used to create an n-type emitter on the p-type Ge growth substrate, forming a Ge bottom cell (cell 3) and the 3-junction GaInP/ Ga(In)As/ Ge cell architecture.

In this paper we investigate the potential of new multijunction solar cell designs to substantially increase solar conversion efficiency, particularly those addressing the excess current density in present Ge subcells, and using new configurations and compositions of group-IV solar cells.

Previous Work

Although the Ge subcell in today's 3-junction cells results in a dramatic increase in voltage and efficiency relative to 2-junction GaInP/GaAs cells, the Ge cell 3 has substantial excess photogenerated current density that is wasted in these designs, for both space and terrestrial solar spectra. It was recognized early on that the potential exists to make better use of the infrared by adding a second epitaxial Ge or SiGe subcell in a 4- or 5-junction cell with two group-IV cells at the bottom of the stack (5,6). The excess current in the Ge bottom cell of conventional 3-junction cells has prompted many of the multijunction device innovations in recent years, such as mechanically-stacked III-V and Ge subcells with more than two terminals, removing the constraint of current matching (7). Approaches that have addressed excess Ge cell 3 current include the use of higher bandgap cell 3 semiconductors as in 3- and 4-junction inverted metamorphic (IMM) cells using metamorphic ~1-eV GaInAs as cell 3, and the study of dilute nitride GaInNAs(Sb) material, with a bandgap of ~1 eV lattice-matched to GaAs or Ge, in 4, 5, and 6-junction configurations (8,9). Recently, a 3-junction concentrator solar cell with a dilute nitride cell 3 reached a new efficiency record at 43.5% efficiency (10).

Group-IV subcells with a bandgap higher than the 0.67-eV indirect gap of Ge have also been proposed for this position in the multijunction stack, such as SiGe cells with indirect gap in the 0.7-1.0 eV range and active Si cells combined with III-V subcell layers (6), with provision made for the smaller lattice constant of these materials. Less fully-characterized semiconductors such as SiGeSn that can be grown lattice-matched to Ge or GaAs, for example, with an indirect gap of ~0.8 eV and direct gap of ~1.05 eV (11), may also be used for the bottom cell in a multijunction stack, or the subcell above the bottom cell, in order to make better use of the long wavelength photons in the solar spectrum.

Multijunction Cell Architectures

The light I-V curves for a standard 3-junction GaInP/ GaInAs/ Ge cell and its component subcells, calculated at 50.0 W/cm^2 (500 suns) for the standard AM1.5 Direct, ASTM G173-03 solar spectrum at 25°C, are shown in Fig. 1. Current density per unit incident intensity (responsivity) is plotted vs. voltage, since this is nearly independent of the optical concentration ratio for any given measurement. A schematic of the 3-junction cell with its subcell base materials and bandgaps is shown in the inset. These light I-V characteristics represent a production average 3J cell efficiency (η) of 39.2%, not champion cell performance. The large excess photogenerated current density in the Ge cell can be seen clearly in Fig. 1, as in the plot of calculated external quantum efficiency (EQE), internal quantum efficiency (IQE), and absorptance in Fig. 2. The photogenerated current density per unit incident intensity (J_{ph}/inten.) is printed for each subcell in Figs. 1 and 2.

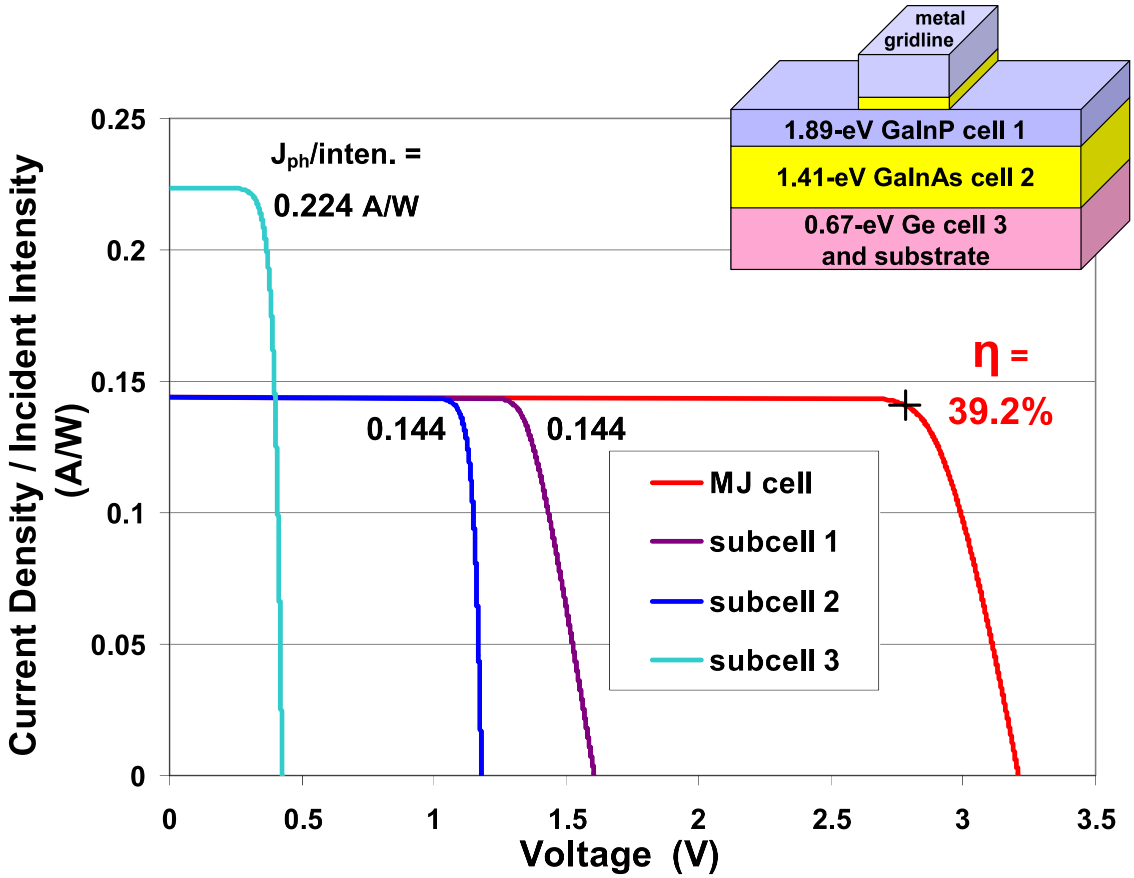

Figure 1. Calculated light I-V curves for a conventional 3-junction GaInP/ GaInAs/ Ge concentrator solar cell and its subcells at 50 W/cm^2 (500 suns).

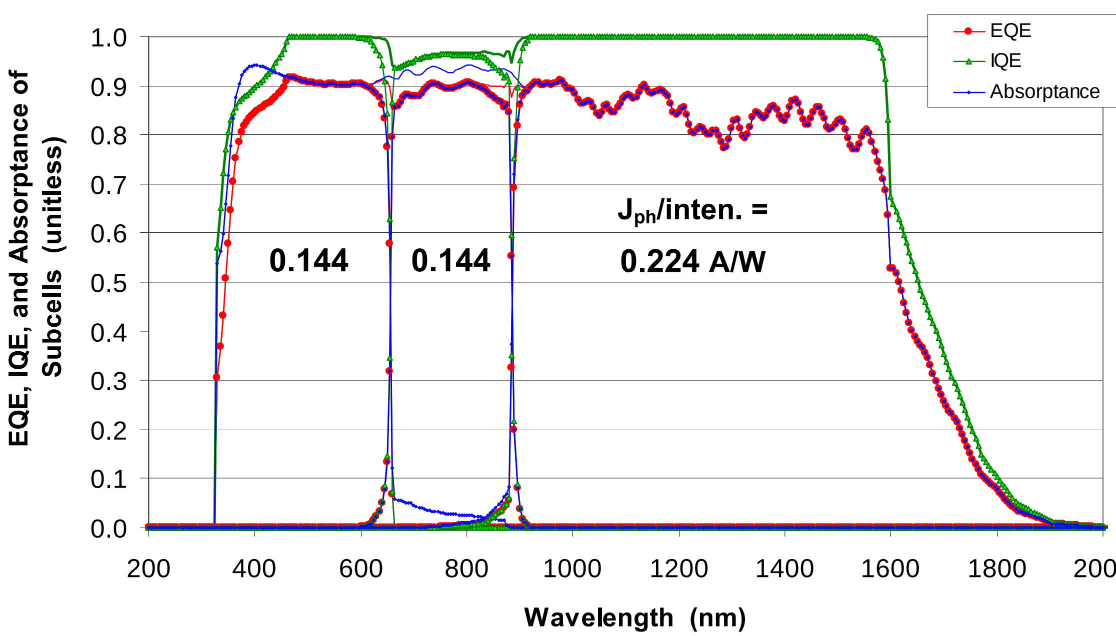

Figure 2. Calculated external quantum efficiency (EQE), internal quantum efficiency (IQE), and absorptance for the subcells in a standard 3-junction GaInP/ GaInAs/ Ge cell.

The light I-V curves for one type of multijunction cell that makes better use of infrared light in group-IV subcells, a 5-junction AlGaInP/ AlGaInAs/ GaInAs/ Ge/ Ge solar cell, and its subcells, are calculated and shown in Fig. 3 (5,6,12). The second to bottommost cell in this design, cell 4, is an epitaxially-grown germanium (Ge) cell, grown on top of the bottommost cell 5 formed from the Ge growth substrate. Thus, the multijunction solar cell includes a Ge/ Ge dual-junction combination, in which the voltages of the Ge cells add to each other, and which are current balanced due to the optically-thin construction of the upper Ge cell in the 2J Ge cell combination (5,6). A schematic of the 5-junction cell and its 2.0/ 1.65/ 1.41/ 0.67/ 0.67 eV bandgap combination is shown in the inset of Fig. 3. Each of the Ge subcells can be seen to contribute approximately 0.4 V in open-circuit voltage at the modeled conditions of 50.0 W/cm^2 (500 suns) for the standard AM1.5 Direct, ASTM G173-03 spectrum, at 25°C.

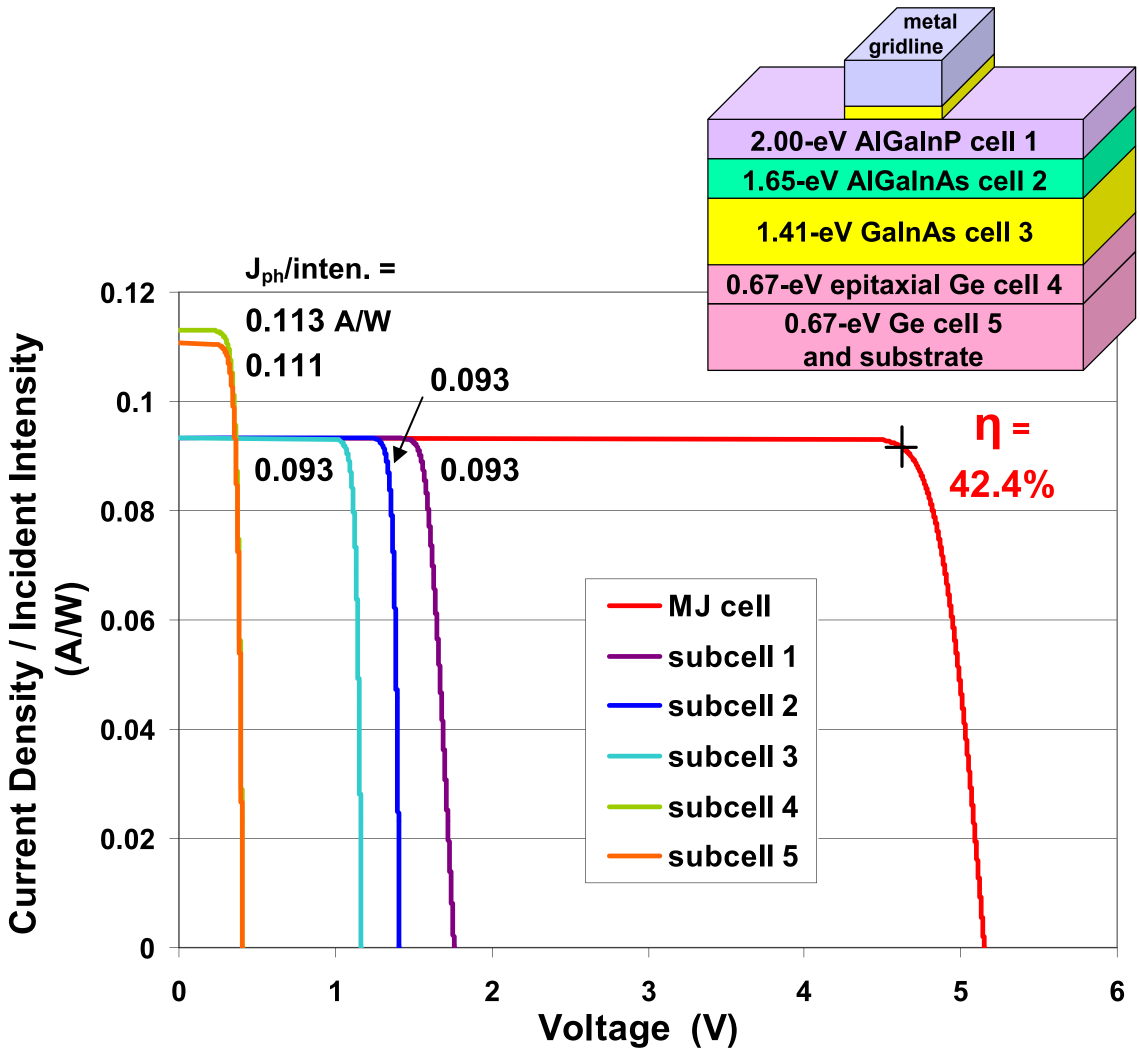

Figure 3. Calculated light I-V curves for a 5-junction concentrator solar cell with an AlGaInP/ AlGaInAs/ GaInAs/ Ge/ Ge construction and its subcells at 50 W/cm^2 (500 suns), using an optically-thin, epitaxial germanium cell 4 (5,6,12).

The spectrum above the 1.41-eV bandgap of the GaInAs cell 3 is divided into three portions with equal current density, while the spectrum below that photon energy is divided into two portions used by the two Ge subcells, as can be seen in Fig. 3 and in the plot of EQE, IQE, and absorptance of the 5-junction cell in Fig. 4. This allows ample current in the bottom two Ge cells to current balance the top three cells, with some left over to ameliorate the lower fill factor of these low-bandgap bottom cells. The calculated production average efficiency for this type of 5-junction cell with an epitaxial Ge cell 4 is 42.4%, directly comparable to the 39.2% efficiency of the standard 3J cell in Figs. 1 and 2, a gain of 3.2% in absolute efficiency, or a relative gain of 8.2% in cell power.

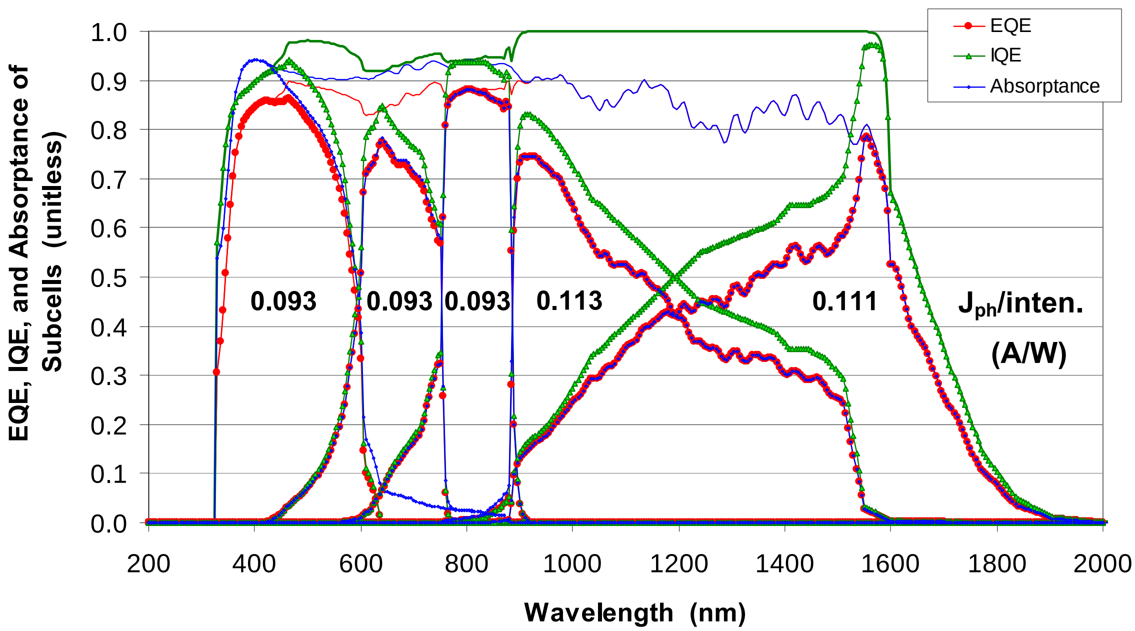

Figure 4. Calculated EQE, IQE, absorptance, and current densities per unit intensity for each subcell in a 5-junction AlGaInP/ AlGaInAs/ GaInAs/ Ge/ Ge concentrator solar cell, using an optically-thin, epitaxial germanium cell 4, and a Ge substrate cell 5 (5,6,12).

Other examples of multijunction cell structures employing group-IV subcells with potentially even higher efficiency include those using SiGeSn subcells. SiGeSn is a semiconductor alloy that is not yet fully characterized, with the ability to reach higher bandgaps than Ge while remaining at the Ge lattice constant. Fundamental studies of this material indicate that a indirect gap of ~0.8 eV and direct gap of ~1.05 eV may be achieved in SiGeSn lattice-matched to Ge (11). Calculated light I-V curves for a 5-junction AlGaInP/ AlGaInAs/ GaInAs/ SiGeSn/ Ge cell with 0.8-eV indirect-gap epitaxial SiGeSn cell 4 are plotted in Fig. 5. A schematic of this type of cell is shown in the inset. The higher bandgap of the SiGeSn cell results in greater voltage than for a Ge cell 4, giving a modeled production average efficiency of 43.5% for this type of 5-junction cell with a SiGeSn cell 4, 1.1% higher in absolute efficiency than for comparable 5-junction cells with Ge cell 4 in Figs. 3 and 4.

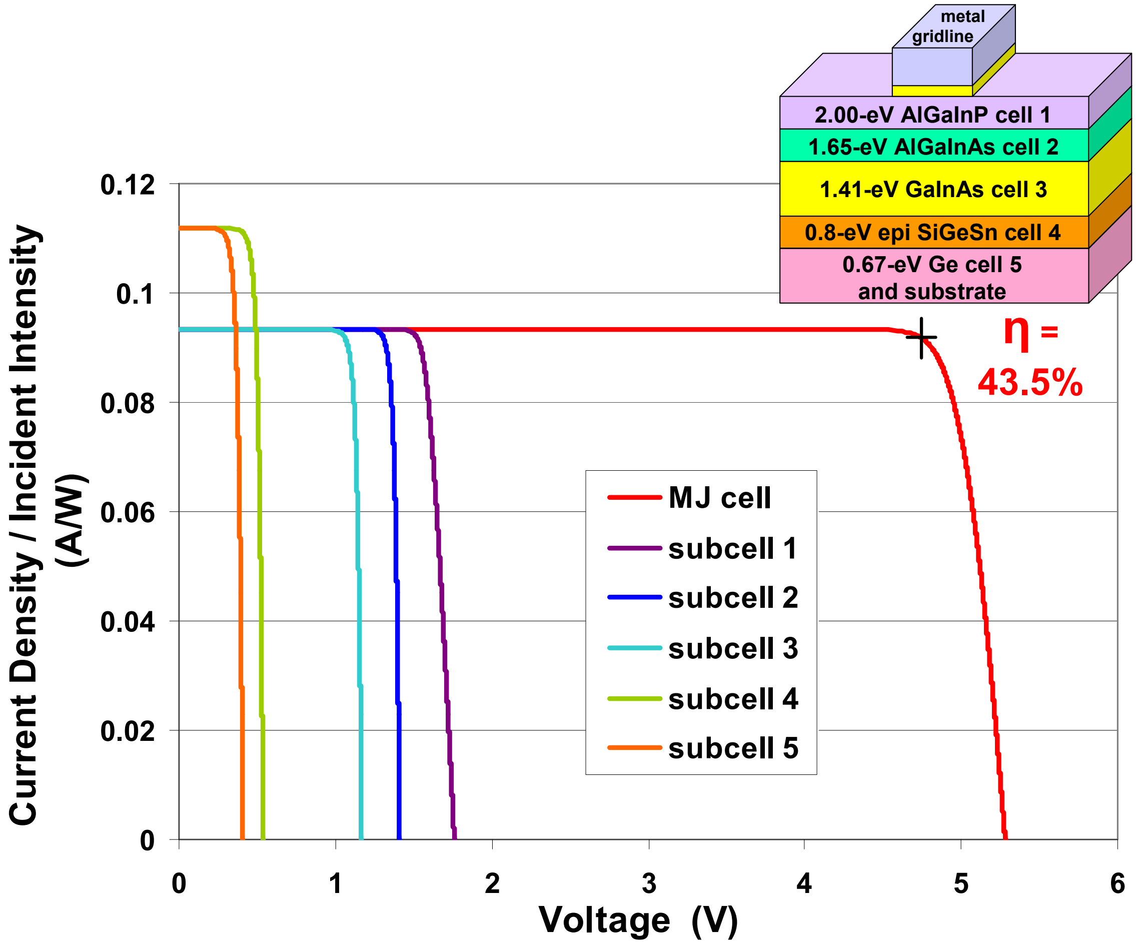

Figure 5. Calculated light I-V curves for a 5-junction AlGaInP/ AlGaInAs/ GaInAs/ SiGeSn/ Ge cell with a 0.8-eV indirect-gap epitaxial SiGeSn cell 4, at 50.0 W/cm^2 (500 suns), 25°C.

If the bandgap of cell 4 can be made still higher, for instance by combining a dilute nitride GaInNAs(Sb) cell 4 with an active Ge cell 5 formed from the Ge growth substrate, then even higher efficiencies can be reached. Fig. 6 plots the light I-V curves of an example 5-junction AlGaInP/ AlGaInAs/ GaInAs/ GaInNAs(Sb)/ Ge concentrator cell (5,9,12) and its subcells at 50.0 W/cm^2 (500 suns), 25°C, and Fig. 7 plots the EQE, IQE, and absorptance for each subcell in this structure. A GaInNAs(Sb) subcell 4 with direct bandgap of 1.12 eV, at a composition lattice matched to the active Ge substrate and subcell 5 is used in the model, where the parentheses indicate the incorporation of antimony (Sb) is optional. As shown in Figs. 6 and 7, the group-IV substrate subcell still contributes significantly to the voltage and current of the overall multijunction cell, while the higher bandgap and voltage of a dilute nitride GaInNAs(Sb) cell 4 results in a projected production average efficiency of 46.1% for this type of cell, capable of reaching champion cell efficiencies of 48% or higher.

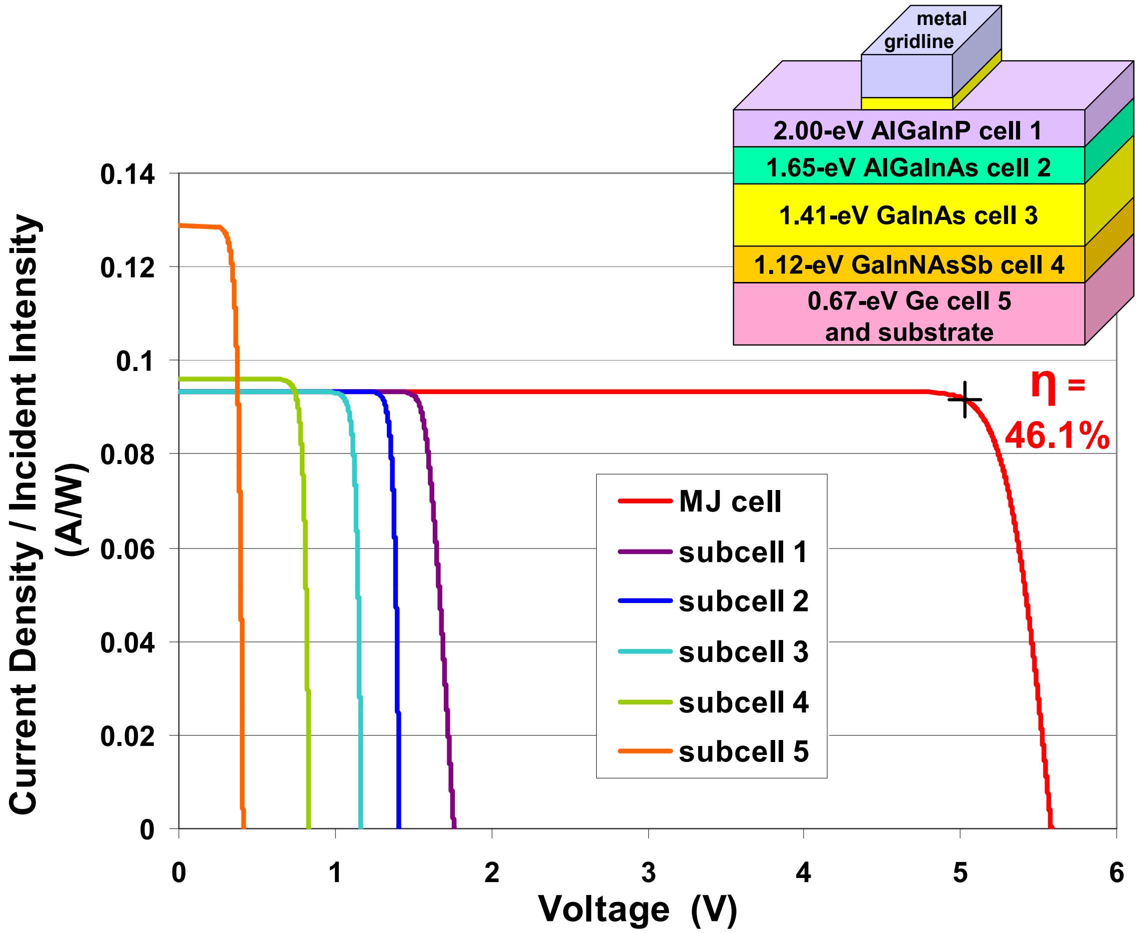

Figure 6. Calculated light I-V curves for a 5-junction AlGaInP/ AlGaInAs/ GaInAs/ GaInNAs(Sb)/ Ge cell with a 1.12-eV direct-bandgap dilute-nitride GaInNAs(Sb) subcell 4, at 50.0 W/cm2 (500 suns), 25°C.

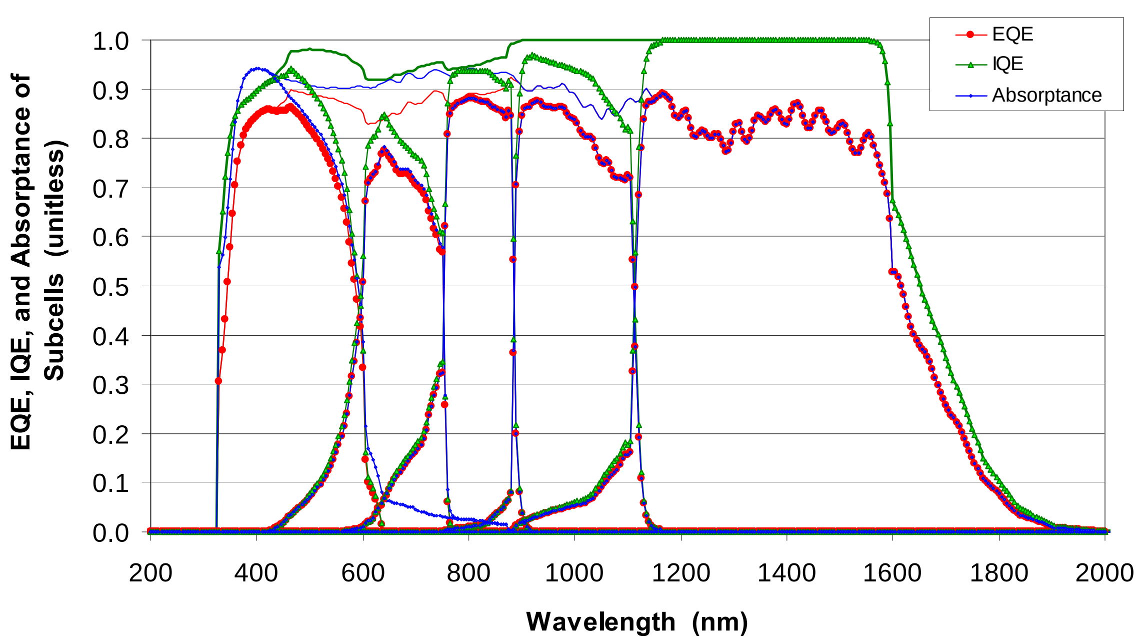

Figure 7. Calculated EQE, IQE, and absorptance for each subcell in a 5-junction AlGaInP/ AlGaInAs/ GaInAs/ GaInNAs(Sb)/ Ge concentrator solar cell, using a 1.12-eV dilute-nitride GaInNAs(Sb) cell 4, and a Ge substrate cell 5 (5,9,12).

Summary

Group-IV solar cells such as Ge, Si, SiGe, and SiGeSn subcells can provide a path toward higher multijunction solar cell efficiencies. Ge subcells formed from a Ge growth substrate contribute greatly to the 3-junction GaInP/ GaInAs/ Ge cell architecture that was the first type of solar cell to reach over 40% efficiency. Group-IV solar cells continue to show their value when integrated with III-V subcells in new multijunction cell architectures that allow better use of photon energies below 1.4 eV than in conventional 3-junction cells, with production average efficiencies of about 39.2% at 50.0 W/cm^2 (500 suns). Such multijunction cell structures can achieve over 46% projected production average efficiencies, with champion cell efficiencies capable of reaching over 48%.

Acknowledgments

The authors would like to thank Jim Ermer, Daniel Law, Russ Jones, Shoghig Mesropian, Xing-Quan Liu, Dimitri Krut, Kent Barbour, Mark Takahashi, Andrey Masalykin, and the entire multijunction solar cell team at Spectrolab. This work was supported by Spectrolab IR&D funding.

References

1. D. L. Miller and J. S. Harris, Jr., "Molecular beam epitaxial GaAs heteroface solar cell grown on Ge," Appl. Phys. Lett. 37(12), 1104, 15 December 1980.
2. S. P. Tobin, S. M. Vernon, C. Bagjar, V. E. Haven, L. M. Geoffroy, and D. R. Lillington, "High-Efficiency GaAs/Ge Monolithic Tandem Solar Cells," IEEE Elect. Dev. Lett. 9(5), 256, May 1988.
3. N. H. Karam, R. R. King, B. T. Cavicchi, D. D. Krut, J. H. Ermer, M. Haddad, L. Cai, D. E. Joslin, M. Takahashi, J. W. Eldredge, W. T. Nishikawa, D. R. Lillington, B. M. Keyes, and R. K. Ahrenkiel, "Development and Characterization of High-Efficiency Ga0.5In0.5P/GaAs/Ge Dual- and Triple-Junction Solar Cells," IEEE Trans. Elect. Dev. 46(10), 2116, Oct. 1999.
4. R. R. King, D. C. Law, K. M. Edmondson, C. M. Fetzer, G. S. Kinsey, H. Yoon, R. A. Sherif, and N. H. Karam, "40% efficient metamorphic GaInP / GaInAs / Ge multijunction solar cells," Appl. Phys. Lett., 90(18), 183516, 4 May 2007, doi: 10.1063/1.2734507.
5. U.S. Pat. No. 6,316,715, "Multijunction Photovoltaic Cell with Thin 1st (Top) Subcell and Thick 2nd Subcell of Same or Similar Semiconductor Material," R. R. King, D. E. Joslin, N. H. Karam, filed Mar. 15, 2000, issued Nov. 13, 2001.
6. U.S. Pat. No. 6,340,788, "Multijunction Photovoltaic Cells and Panels Using a Silicon or Silicon-Germanium Active Substrate Cell for Space and Terrestrial Applications," R. R. King, N. H. Karam, M. Haddad, filed Dec. 2, 1999, issued Jan. 22, 2002.
7. Flamand et al., Sep. 2009, IMEC press release, http://www2.imec.be/be_en/press/imec-news/archive-2009/mechanically-stacked-gaas-ge.html.

8. D.J. Friedman, J.F. Geisz, S.R. Kurtz, J.M. Olson. "1-eV solar cells with GaInNAs active layer," J. Crystal Growth, 195, 409, 15 Dec. 1998.
9. R. R. King et al., "Metamorphic III-V Materials, Sublattice Disorder, and Multijunction Solar Cell Approaches with Over 37% Efficiency," Proc. 19th European Photovoltaic Solar Energy Conf., Paris, France, June 7-11, 2004 (WIP-Munich, Munich, Germany, 2004), pp. 3587-93.
10. Solar Junction press release, April 14, 2011, Diandra Weldon, http://www.sjsolar.com/downloads/ Solar_Junction_World_Record_%20Efficiency_14April11.pdf .
11. V.R. D'Costa, Y.-Y. Fang, J. Tolle, J. Kouvetakis, J. Menéndez, "Ternary GeSiSn alloys: New opportunities for strain and band gap engineering using group-IV semiconductors," Thin Solid Films, 518(9), 2531, 26 February 2010.
12. R. R. King, D. Bhusari, D. Larrabee, X.-Q. Liu, E. Rehder, K. Edmondson, H. Cotal, R. K. Jones, J. H. Ermer, C. M. Fetzer, D. C. Law, and N. H. Karam, "Solar Cell Generations Over 40% Efficiency," Prog. Photovolt: Res. Appl., published online 4 Apr. 2012 at wileyonlinelibrary.com, doi: 10.1002/pip.1255, and 26th European Photovoltaic Solar Energy Conf., Hamburg, Germany, Sep. 5-9, 2011.