Solar & Alternative Energy

Engineering the world's most efficient solar cells

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An inverted growth structure and improvements in lattice-mismatched materials enable over 40% of incident radiation to be converted to electricity.

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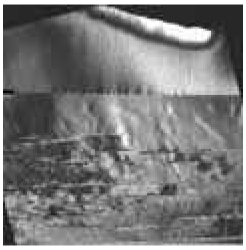

Extremely high efficiency solar cells are essential for space power, such as on satellites and the Mars rovers, and for terrestrial 'concentrator' power systems, which optically gather light from a large area. Yet effectively converting radiation to electricity is a difficult challenge. The range of photon energies (0 – 4eV) in the broad terrestrial solar spectrum limits conventional single-junction semiconductor solar cells, which fail to capture photonic energy that does not match the bandgap (E_g, the difference in energy between the ground and photoexcited states). A multi-junction cell overcomes this by using more than one sub-cell or junction, each of which is tuned to a different region.[1] In general, more junctions mean a more effective device overall, but using three represents a good practical tradeoff between efficiency and structural complexity.

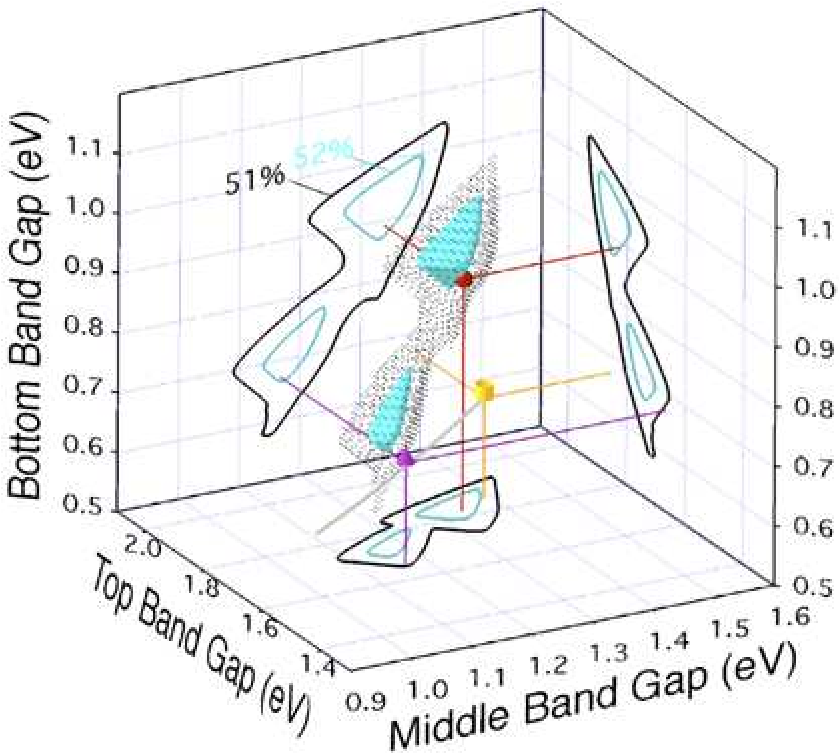

Figure 1. *Theoretical isoefficiency surfaces and their projected contours for series-connected triple-junction solar cells under the direct terrestrial solar spectrum at 500 suns concentration and 300K: 51% (black) and 52% (light blue). Bandgap combinations of actual champion devices are also shown: Spectrolab's 40.1% lattice-matched cell (yellow cylinder), the Fraunhofer Institute for Solar Energy Systems' 41.1% germanium-based metamorphic cell (purple cone), and National Renewable Energy Laboratory's 40.8% inverted metamorphic triple-junction (red sphere).*

The challenge is to create an actual cell that realizes these efficiency gains. The III-V semiconductor alloy system (Al,Ga,In)(As,P) made up of combinations of elements from groups three (aluminum, gallium and indium) and five (arsenic and phosphorus) of the periodic table is very attractive for multijunction cells because its characteristics can be tuned by varying the alloy composition. However, crystal defects such as dislocations reduce performance, and so these systems require very high crystalline perfection.

The semiconductor is grown on a substrate, and carefully choosing alloys to match the substrate and semiconductor lattice constants—parameters of the crystal lattice dimensions—can result in a negligible number of dislocations. However, this lattice matching restricts the choice of bandgaps and hence limits the maximum attainable efficiency, as can be seen from Figure 1, which plots calculated cell efficiency as a function of varying bandgaps of a three-junction cell. The efficiency is sensitively dependent on bandgap choice, with a global optimum of over 52% for the combination of bandgaps E_g ={1.86, 1.34, 0.93*eV*}. There is an additional local maximum at E_g ={1.75, 1.18, 0.70*eV*} with nearly as high efficiency. The yellow cylinder in Figure 1 represents a commercially available cell with two lattice-matched III-V junctions—gallium indium phosphide (GaInP) and gallium arsenide (GaAs) on a germanium (Ge) bottom junction.[2] Dislocations in lattice-mismatched III-V alloys, such as gallium indium arsenide (GaInAs), can be mitigated with strain-reducing compositionally-graded buffer layers between regions of different lattice constant.[3] This has the significant advantage of targeting optimal bandgap combinations for maximum efficiency. We have achieved very low dislocation densities using such buffer layers. Figure 1 shows the range of possible bandgap combinations using a single compositional grade on a Ge bottom junction (gray line). The purple cone represents a cell developed by the Fraunhofer Institute for Solar Energy Systems using this approach, which has attained 41.1% efficiency.[4]

At the National Renewable Energy Laboratory (NREL), we have used lattice-mismatched GaInAs but with a key difference: the junctions with the largest mismatch are grown last, thus mitigating the effect of strain and dislocation on the full device structure.[5–7] We chose this approach, commonly referred to as the inverted metamorphic triple-junction solar cell, because with it we could target the higher-bandgap E_g ={1.86, 1.34, 0.93*eV*} efficiency maximum point in Figure 1.

We grew the lattice-matched, high-bandgap GaInP junction first and the most lattice-mismatched, low-bandgap GaInAs junction last, in an inversion of the conventional procedure. We used transparent graded buffer layers between the mismatched layers. Using this approach, we have been able to produce GaInAs bottom junctions with remarkably low $10^6 cm^{-2}$ threading dislocations, in spite of the high mismatch. A small amount of In in the middle junction with a second graded buffer brings us close to the optimal bandgap combination and introduces only $10^5 cm^{-2}$ dislocations in the middle junction. The final step in the fabrication of this inverted structure is the removal of the substrate. This is necessary so that light can enter the cell through the high-bandgap junction, where the highest energy photons are absorbed. Low energy photons pass through to subsequently lower bandgap junctions. The resulting device structure, which has achieved 40.8% efficiency,[7] is shown in Figure 2. We have characterized the low dislocation densities by transmission electron microscopy and plan-view cathodoluminescence.

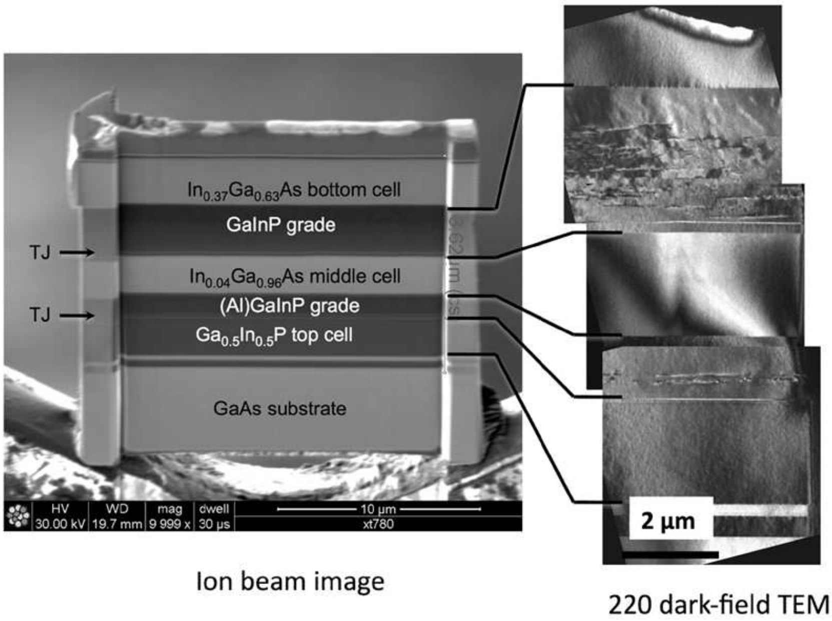

Figure 2. *Ion beam image and composite 220 dark-field transmission electron microscopy (TEM) of a cross-section of an unprocessed inverted triple-junction solar cell structure. Plan-view cathodoluminescence indicates threading dislocation densities of* $2\times10^{6}\,cm^{-2}$ *in the bottom cell,* $1\times10^{5}\,cm^{-2}$ *in the middle cell, and none observed in the top cell. TJ: Tunnel junction.* $In_xGa_yAs_z$*: Indium gallium arsenide alloy.* $Ga_xIn_yP_z$*: Gallium indium phosphide. (Al) GaInP: (Aluminum) gallium indium phosphide. GaAs: Gallium arsenide.*

The inverted approach presents some interesting advantages over the Ge-based triple-junction approaches. The higher bandgaps of the inverted design result in better high-temperature performance. There is significant room for improving efficiency up to 45 – 50% by improving material quality, reducing internal resistances, and possibly adding a fourth junction. The thin transparent nature of the design can result in a high power-to-weight ratio for space applications and reduced heating from unused IR absorption. Flexible, cheap, and thermally conductive substrates can be considered in the final device independently from the epitaxial template. Finally, the necessity of removing the substrate can be turned into an advantage by enabling reuse or recycling of the expensive substrate.

Conventional III-V multijunction cells have exceeded 40% solar power conversion efficiency, and have achieved commercial success in the space and terrestrial-concentrator markets. Lattice-mismatched and inverted triple-junction approaches have demonstrated even higher efficiencies of 41%, and efficiencies of 45 – 50% appear possible with further development.

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