MULTIJUNCTION CELLS

Record breakers

Multijunction solar cells used in concentrator photovoltaics have enabled record-breaking efficiencies in electricity generation from the Sun's energy, and have the potential to make solar electricity cost-effective at the utility scale.

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Flat-plate solar panels for home-owner electricity generation have been popping up on rooftops at an ever-increasing rate in recent years. The solar photovoltaics industry is enjoying growth at present that few other industries have seen: global photovoltaic cell production has had a sustained increase of more than 30% each year for the past 10 years, with increases of more than 50% in some years. Solar-cell electricity generating capacity, measured in megawatts per year, exceeded 1 GW per year for the first time in 2004, about the equivalent of a conventional coal or nuclear power plant, and has been growing rapidly since. As the process of energy conversion from sunlight to electricity in a photovoltaic cell produces no CO_2 or other greenhouse gases, supplying our electricity and transportation needs with photovoltaics is one of our best hopes for developing a carbon-neutral form of power production, and staving off the perils of global climate change.

Within the field of photovoltaics, there is a new technology just coming out of the labs and onto the marketplace that is arguably growing even faster than the rest of the industry. The technology is multijunction concentrator solar cells based on III–V semiconductors. The striking feature of such cells, and the photovoltaic systems made from them, is their ability to convert sunlight to electricity with very high efficiency. This reduces the area of all components of the system and drives down cost. The cells achieve their high efficiency by combining several solar cells, or p–n junctions, into a multijunction cell. Each solar cell in the multijunction cell, called a subcell, is composed of a different semiconductor material, each with a different energy bandgap. The subcells are electrically connected in series as shown in Fig. 1. The subcells are also positioned in optical series such that the highest bandgap is in the subcell on top, which uses the highest energy photons in the solar spectrum. Photons with energy lower than the bandgap are transmitted to the subcell beneath, which has the second highest bandgap, and so on. In this way the multijunction solar cell divides the broad solar spectrum into wavelength bands, each of which can be used more efficiently by the individual subcells than in the single-junction case.

In the past eight years, the output power of terrestrial III–V multijunction cells used in a solar concentrator design (an approach where optics are used to focus and concentrate sunlight to achieve higher light intensities) has increased by 25%. The workhorse multijunction cell for terrestrial concentrator photovoltaics, which itself is the result of a great deal of innovation and vigorous refinement in the past decade, is the lattice-matched three-junction GaInP/GaInAs/Ge cell, shown in Fig. 1a.

But the efficiency of this type of cell can be improved still further, with an approach called metamorphic multijunction solar-cell design. The solar spectrum turns out to be best suited to different semiconductor bandgaps than those that are readily accessible

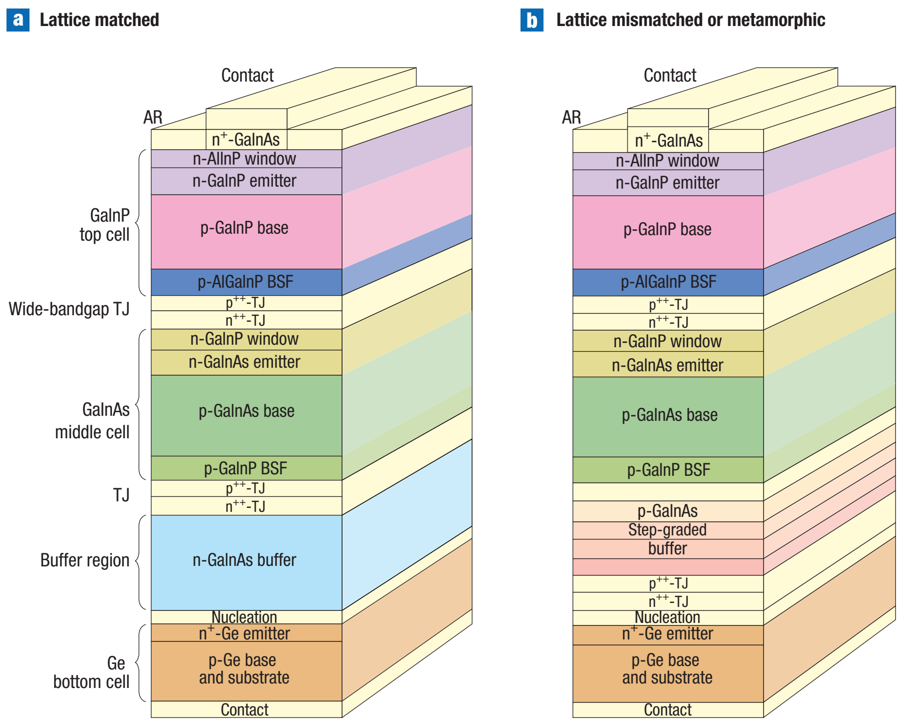
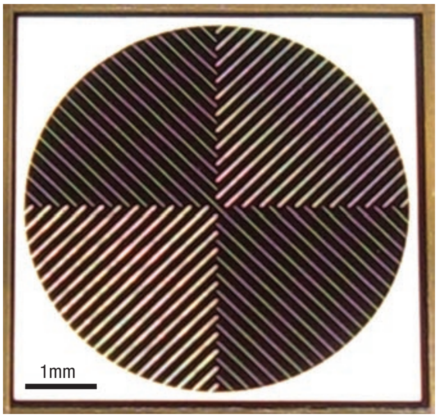


Figure 1 Schematic cross-sectional diagrams of three-junction cell configurations. **a**, Lattice-matched and, **b**, metamorphic GaInP/GaInAs/Ge, corresponding to efficiencies of 40.1% (lattice matched) and 40.7% (metamorphic) for concentrator cells. (AR: antireflection coating; BSF: back-surface field; TJ: tunnel junction.)



SPECTROLAB

Figure 2 Photograph of a Spectrolab III–V multijunction concentrator solar cell, of the type that has reached a record 40.7% efficiency.

in the lattice-matched three-junction cell. Specifically, the solar wavelength distribution favours lower bandgaps for the upper two subcells than nature has provided for GaInP and GaInAs grown at the lattice constant of a germanium substrate. The lower bandgaps can be reached by increasing the indium content, but this increases the lattice constant, typically causing the formation of dislocations in the crystal lattice when grown on a germanium substrate. This in turn has a detrimental effect on the voltage in the subcells.

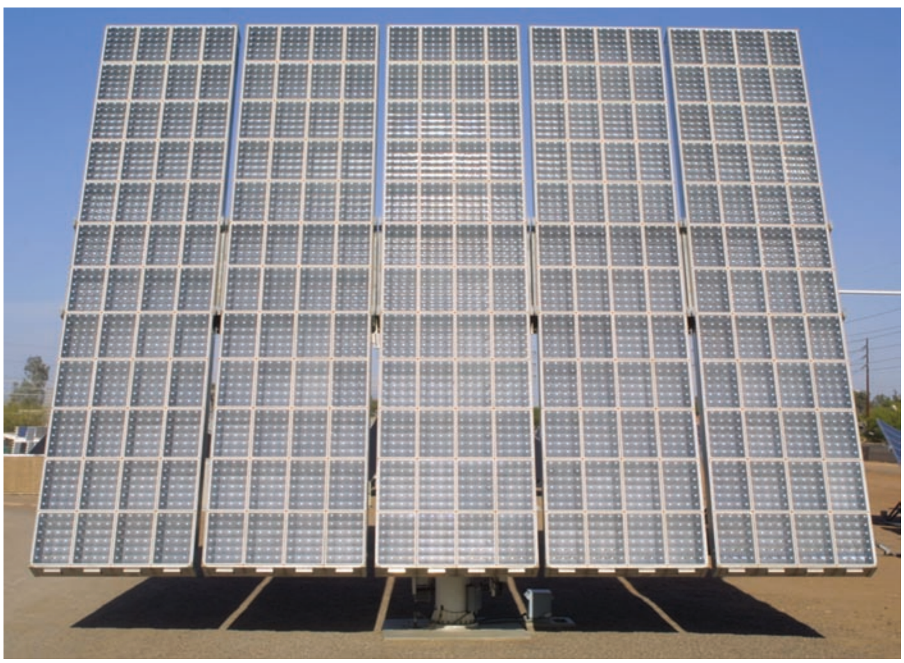
In the metamorphic multijunction solar cell (Fig. 1b) the crystal dislocations are allowed to form in a metamorphic buffer — a region with a graded semiconductor composition, grown first on the substrate. The crystal structure relaxes, so that by the end of the metamorphic buffer growth, a new, larger lattice constant has been reached, which can be used as a virtual substrate for growth of semiconductors with high crystal quality at the larger lattice constant. The central challenge with metamorphic solar cells is keeping the dislocations that propagate upward into the active cell layers to a minimum, through careful buffer design.

Recent advances in III–V metamorphic multijunction solar-cell design for terrestrial use have resulted in ever greater photovoltaic efficiency. Metamorphic three-junction cells have been demonstrated in the lab with high-indium-content $Ga_{0.44}In_{0.56}P$ top subcells, and $Ga_{0.92}In_{0.08}As$ middle subcells, at a lattice mismatch of 0.5% with respect to the germanium substrate, which also serves as the third and bottom subcell. Such metamorphic three-junction concentrator cells developed at Spectrolab have reached a record efficiency of 40.7% under the terrestrial solar spectrum, when the sunlight was concentrated by a factor of 240 (Fig. 2). This is the highest solar-energy conversion efficiency yet achieved for any type of photovoltaic cell under standard spectral conditions, and is the first solar cell to reach over the 40% milestone. The lower bandgaps of the top two subcells result in a more optimal division of the solar spectrum among the subcells, pushing the efficiency higher for this type of cell. Lattice-matched three-junction GaInP/GaInAs/Ge concentrator cells developed at Spectrolab are not far behind, with independently confirmed efficiencies of 40.1%.

The shape of the solar spectrum also favours a higher bandgap than that of the germanium bottom subcell in the lattice-matched three-junction design. In another type of metamorphic cell, under investigation in several labs around the world, the germanium third subcell is replaced with a metamorphic GaInAs subcell that has a bandgap of around 1 eV, grown in an inverted configuration with a transparent graded buffer region. This type of metamorphic cell design has given the best performance (33.8% efficiency) under unconcentrated sunlight in cells developed by the National Renewable Energy Laboratory.

In photovoltaics, efficiency has a direct impact on the cost per watt of electricity delivered. A high cost per watt in the past is the basic reason why solar electricity has not displaced conventional electricity production so far. Cost per watt has been steadily declining, and is nearing the tipping point at which photovoltaic technology may be deployed on a very broad scale, replacing a significant fraction of the electricity-generation infrastructure, but it is still not low enough. A large part of the cost of photovoltaic systems is in the semiconductor material of the silicon or other types of solar cells used, but the dominant cost is that of more conventional materials, such as glass, metal and plastic. Solar energy is a fairly dilute energy resource, and requires collectors with a large surface area to generate useful amounts of power. If the efficiency of the system is doubled, then only half the collector area is needed for the same power production, halving not only the amount of expensive semiconductor material required for the solar cells, but also those conventional materials that contribute so much to the system cost.

Through a combination of higher light concentration and better use of the solar spectrum due to its multijunction design, III–V three-junction concentrator cells with 37–40% efficiency can easily enable overall concentrator photovoltaic system efficiencies greater than 30%, roughly double that of the typical silicon flat-plate solar module.



AMONIX

Figure 3 Example of one type of concentrator solar photovoltaic system from Amonix, using a parquet of Fresnel lenses to form an array of many small light foci on passively cooled solar cells.

SOLAR SYSTEMS PTY

Figure 4 Examples of another type of concentrator solar photovoltaic system from Solar Systems Pty, using a large reflective dish to focus onto a dense array of photovoltaic cells.

In concentrator systems like those shown in Figs 3 and 4, with concentration ratios of around a factor of 500, the cell area required can be approximately 500 times smaller than the aperture area of the primary concentrating optics. The dramatic reduction in cell area allows III–V multijunction cells, which are costly per unit area, to be used effectively in a concentrator system. These III–V multijunction solar cells have become the cell architecture of choice for most concentrator photovoltaic systems being designed today because of their higher efficiency. Although III–V multijunction cells are more complex and expensive than conventional silicon cells, the reduced system cost that their high efficiency brings more than makes up for their cell cost. This lower system cost and corresponding drop in cost per kWh of solar electricity is expected to enable photovoltaics to compete not only in the residential market, but also in the more challenging commercial rooftop and utility markets, where prices paid per kWh are very low.

The production levels of III–V multijunction concentrator photovoltaic cells are projected to reach several gigawatts per year in the next decade, catching up with and augmenting the burgeoning market for its sister technology, flat-plate silicon solar cells. Continuing research in advanced multijunction cell architectures around the globe, many of which incorporate metamorphic semiconductor materials, can be expected to increase practical concentrator-cell efficiencies to 45% or even 50%. By using efficiency as a powerful lever to bring down the cost, it will become possible to deploy solar-cell technology on a larger scale than ever before. This will fundamentally change the way we generate electricity, and form a key part of the solution to the energy-security and global climate-change perils that we face today.