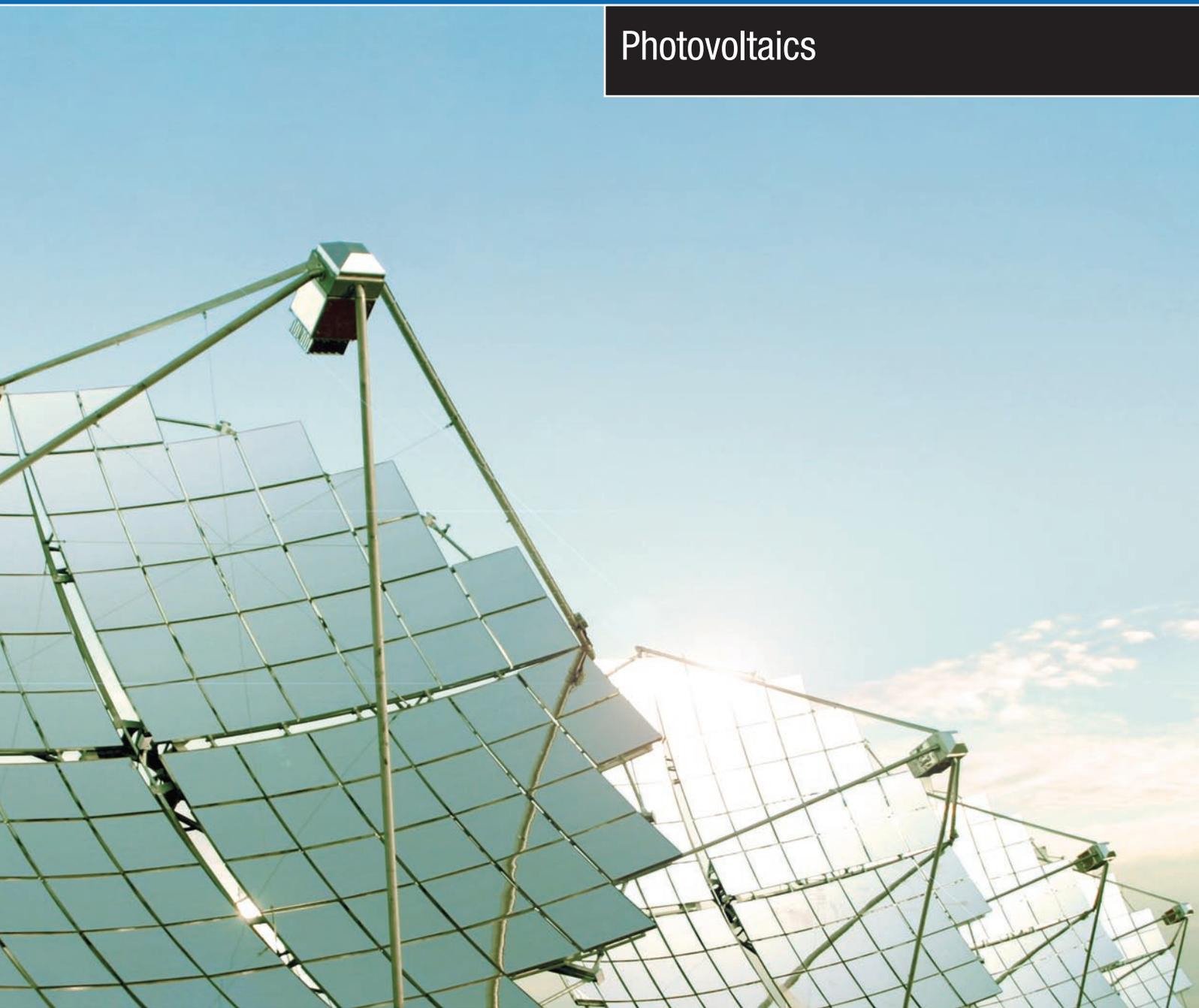


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Cover image

Highly efficient multijunction cells can be used in concentrator photovoltaic systems to bring down the cost of solar power.

[Industry Perspective p284](#)

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Playing catch-up

Considering how abundant the Sun's energy is, it is surprising that only 0.1% of the world's electricity is made using solar power. Even in Germany, the most enthusiastic supporter of solar power, this figure is only 0.2% (page 281). The reason for this huge disparity is that at present the cost of producing 1 kWh of electricity using solar power is much higher than using oil, coal or nuclear power. But times are changing.

The solar-power industry is experiencing growth rates that other industries can only dream about. Compound annual growth rates of around 30% until 2013 have been predicted by one market research company (page 290), and these predictions match the results of several key players in the market, with one even reporting an annual sales growth of more than 50%. Let's hope this growth continues because the industry has some serious catching up to do if it wants to become competitive. To become economical and therefore take a significant slice of the electricity market, the price per kWh must become comparable to that of a typical clean coal power station. Winfried Hoffmann, president of the European Photovoltaics Industry Association, believes that, despite healthy growth, this will still take around 20 years (page 292).

So what can the solar-power industry do to speed up this process? New technologies are helping to make solar cells cheaper, thinner and more efficient, thus bringing down the cost per kWh. Silicon-based solar cells dominate the market now, but will in the future lose market share to other technologies. Compound semiconductor systems are reporting record efficiencies of more than 40% (page 284), and developers of flexible polymer-based cells claim their technology has what it takes to bring costs down to a competitive level (page 287).

Only time will tell which technology will win in the end, but with such a lucrative market at stake, there will probably be room for everyone to have a slice of the cake.

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Payback time

Energy **33**, 224–232 (2008)

Using solar panels to generate electricity is ultimately an environmentally friendly process, despite the huge amounts of energy used to produce the panels, according to an Italian researcher who has carried out a detailed life-cycle assessment of electricity generation from photovoltaic cells.

Anna Stoppato, from the University of Padova, looked at mass and energy flows over the whole production process, starting from silica extraction to the final panel assembly, and considered the most advanced and consolidated technologies for polycrystalline silicon panel production. She found that the most critical phases are the transformation of metallic silicon into pure polysilicon and the panel assembly, which uses energy-intensive materials such as aluminium and glass.

“The most important results of the analysis are the calculation of a gross energy requirement of 1,494 MJ per panel (0.65 m² surface area) and of a global-warming potential of 80 kg of equivalent CO₂ per panel,” says Stoppato. “I also evaluated the energy pay-back time and I estimate it to be shorter than the panel operation life even in the worst geographic conditions.”

Stoppato also looked at the energy return factor, which is defined as the ratio between expected panel life (28 years) and the energy pay-back time. It represents how many times a typical photovoltaic plant with 36 cells pays back the energy needed for its production. She found that a photovoltaic plant can pay back this energy more than eight times.

Dipole alternative

Appl. Phys. Lett. **92**, 053507 (2008)

Researchers at the University of Toledo, USA, have developed an alternative way of creating the electric field required in photovoltaic cells to effectively separate the photo-generated electrons and holes. Instead of a field formed by the electric contact between p- and n-types of semiconductors, Diana Shvydka and Victor Karpov suggest that the electric field can be generated by aligned electric dipoles embedded in a photoconducting host.

These electric dipoles are simply semiconductor nanoparticles, such as wurtzite CdS and CdSe or similar materials that are pyro- and piezoelectric. Some ferroelectric nanoparticles may also be suitable.

“These dipoles do not even have to be in electric contact with the host material, which makes the system extremely flexible to implement,” says Karpov. “In contrast,

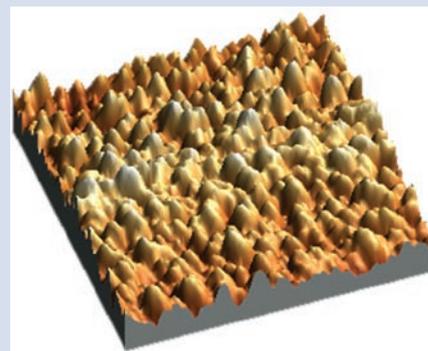
Increased efficiency

Appl. Phys. Lett. **92**, 053310 (2008)

Researchers in the USA have broadened the spectral response and increased the power-conversion efficiency in a single organic thin-film photovoltaic cell by creating simultaneously active, parallel heterojunctions with two donor materials.

The researchers used copper phthalocyanine (CuPc) and tin(II)-phthalocyanine (SnPc) as donor materials and a single C₆₀ acceptor. In previous work using this combination of materials, an ultrathin intermediate donor layer was grown in discontinuous islands. However, when thicker than 5 nm, this layer formed a continuous layer that blocks interactions between the acceptor and the other donor material.

In this new work, Fan Yang and colleagues from Princeton University and the University of Michigan, demonstrate a two-donor, one-acceptor cell. Controlled crystallization of the intermediate donor layer ensures the formation of nanocrystalline islands that allow the



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acceptor to form simultaneously active, parallel heterojunctions with both donors. Moreover, the spectral photoresponse of these multiple heterojunction cells is significantly broadened compared with the conventional single donor-acceptor heterojunction cell. The researchers anticipate that optimization of the choice of material and crystal size will further improve the efficiency of this type of solar cell.

p-n and similar junctions require a high-quality electric contact between the two materials, which sets major restrictions on the photovoltaic cell design.”

The researchers claim that this concept can be used with a variety of host materials that can be polymers, liquids, amorphous or polycrystalline. “We have shown that the generated field from these dipoles can be uniform and strong enough, around 3×10^4 V cm⁻¹, to separate electron-hole pairs and run significant drift currents,” says Shvydka. “Our suggested structure does not rely on p-n or Schottky junctions and can be tunable in a broad range of parameters.”

Shvydka and Karpov do not project extremely high absolute efficiencies for nanodipole photovoltaics and expect them to be at the level of the best existing thin-film photovoltaics (12–15%). “However the relative cost of their generated power (in dollars per watt) can be ten times lower than that of any of the existing photovoltaics,” says Karpov.

Nanotube hybrids

Nanotechnol. **19**, 115601 (2008)

Although research on the use of single-walled carbon nanotubes (SWNTs) as the acceptor in polymer photovoltaic cells is making great progress at present, their poor dispersion in a polymer matrix has greatly hindered the overall performance

of the devices. Researchers in China think they have come up with a solution. They have developed a bulk heterojunction structure based on a poly(phenyleneethynylene)/SWNT composite. They found that it achieved better dispersion and higher performance when compared with a common control device based on a poly(3-octylthiophene)/SWNT composite layer.

Qian Liu and colleagues from the Tianjin University of Technology and Nankai University claim that theirs is a new physical approach to the improvement of the dispersion of SWNTs in a polymer matrix based on the design of the polymer molecule.

Poly(phenyleneethynylene) is a class of rigid-rod conjugated polymer composed of aromatic rings and alkyne functional groups, which can form a hybrid with SWNTs. The good dispersion of the SWNTs in the poly(phenyleneethynylene) matrix makes this composite a potential candidate in photovoltaic applications. At present, a limitation of the donor material, the poly(phenyleneethynylene), is its narrow absorption band, which hinders its photovoltaic performance, especially in terms of its current density. The researchers believe this problem can be overcome by introducing other functional groups into the backbone or side chain to improve the ability of harvesting solar energy. By broadening its absorption band, a higher current density and energy-conversion efficiency can then be expected.



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MANUFACTURING TECHNOLOGY

Fabrication innovations

Advances at every stage of the manufacturing process are helping to reduce costs in the photovoltaics industry, but there is still a long way to go before photovoltaic cells reach their true potential.

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Despite the photovoltaics market growing at annual rates of 30–50% since the year 2000, less than 0.1% of global electricity production is from photovoltaic cells. In Germany, the country leading the world in photovoltaic installations and subsidy initiatives, photovoltaics still represents only 0.2% of electricity production. However, the potential is far greater, and it is estimated that up to 20% of electricity generation could be realistically supplied by solar power. In the future, on a timeframe of 2015–2025, initially in regions that receive high levels of sunshine, it is anticipated that the expansion of the industry will lead to cheaper installed systems and lower energy costs that will compete with retail electricity prices. In the longer term, photovoltaics will be able to compete with the rising costs of wholesale electricity from fossil fuels.

More than 90% of today's photovoltaic-cell production is based on crystalline silicon. In the early years, the silicon for photovoltaic cells came from recycled and off-specification material generated for the microelectronics industry. However, the recent growth in solar-cell production has been much greater than in the microelectronics industry, and today the demand for silicon for photovoltaic cells exceeds that for microelectronic products. Consequently, there has been insufficient off-specification silicon material available, and the photovoltaics industry has been forced to use prime-grade material at a higher cost.

In the photovoltaics industry, there has historically been a 20% reduction in price for each doubling of installed capacity, but the supply-constrained price rise in silicon feedstock has brought a temporary halt to this trend. As more silicon feedstock becomes available in the next few years



Quartz crucible containing polysilicon feedstock before loading into a crystal-growing furnace. Today, demand for silicon in the photovoltaics industry is greater than for the microelectronics industry.

the long-term historic cost-reduction trend is expected to resume. Nevertheless, the absolute cost of photovoltaics remains the major challenge to widespread deployment of the technology.

This article overviews the current innovations in crystalline silicon solar-cell technology that will result in lower-cost manufactured solar products over the next five years, and takes a brief look at the status of the competing thin-film and emerging technologies (see Box 1).

There are five basic sequential stages in the value chain for the manufacture of crystalline silicon solar cells: silicon-feedstock production, crystal growth, wafer slicing, cell fabrication and module (panel) assembly. Innovation at every stage is contributing to reducing manufacturing costs.

SILICON FEEDSTOCK

The first step in the production of high-purity silicon feedstock is the carbo-thermic reduction of quartz in an electric arc furnace to produce metallurgical grade silicon (MG-Si) used primarily for the production of aluminium-silicon alloys and silicones. Unfortunately, the purity of MG-Si, typically 99%, is too low for solar-cell applications, which require silicon with impurity levels of only a few parts per million and concentrations of electronically active impurities, such as boron and phosphorus, at parts-per-billion levels. A process known as the Siemens process is used for the purification of MG-Si to form electronic-grade silicon (known as polysilicon), suitable for photovoltaic

Box 1 Thin-film alternatives

In the wafer-based crystalline silicon solar-cell process described, the polysilicon feedstock today accounts for some 20% of the cost of the finished module. Thin-film solar cells offer a potentially lower-cost solution by reducing the amount of semiconductor needed. The approach deposits thin semiconductor films directly on to a glass support and optical window or on to a flexible metallic or metal-coated polymer substrate. In most thin-film photovoltaic products, the top electrical contact is a transparent conducting film of indium tin oxide (ITO) applied to the glass surface. Various semiconducting materials have been used in these devices with those offering the most commercial prospects being: amorphous silicon (a-Si), CdTe and copper indium gallium diselenide (CIGS).

In most thin-film processes a sequence of conductor and semiconductor layers is deposited using vacuum-coating processes. Cells are formed by isolating areas of the

multilayer film through laser ablation of the conductor or semiconductor layers, and monolithically integrating the series connection with a final conducting layer. This final layer connects the rear of one cell with the front of the adjacent cell through the intervening laser-ablated trench. The efficiency of today's commercial thin-film products approaches 10%, but laboratory results on small area CdTe and CIGS devices offer the potential for higher performance in the future. Nevertheless, the long-term prospects of thin-film products are not without significant challenges. Although the material consumption is lower than with crystalline silicon, the materials themselves are not as abundant or as low-cost as silicon. Indium is the most notable example. It is produced as a bi-product of metallic zinc and tin production. Its cost has increased more than 10 times in recent years due largely to its use in flat-panel displays. Its use in very high volumes for photovoltaic applications raises the prospects of having to establish

a mining and refining operation for photovoltaic indium.

Some of the materials used in thin-film products contain toxic heavy metals. For example, cadmium is gradually being removed from many manufactured components owing to environmental legislation. Manufacturers of CdTe thin-film products now offer end-of-life recycling of their product to accommodate future disposal restrictions, and this will add significantly to the initial product cost. All thin-film products are at an inherently greater risk of degradation than wafer crystalline silicon. By definition, the active layers are thin and at risk of electromigration of ions in the presence of an electric field over extended periods. Whereas crystalline silicon products have operated in the field for more than 25 years and continue to deliver electricity, the current thin-film products will need extensive field experience before customers can be confident of a high-performance life expectancy of 20–40 years.

and microelectronics applications. This process is expensive and increases the cost of silicon from around \$2 per kilogram for MG-Si to around \$40 per kilogram for polysilicon. There are a number of alternative processes for the purification of silicon. One that offers good prospects for significant cost reduction at present comprises the selective removal of key electronic impurities in molten MG-Si, followed by zone refining of solid silicon blocks. Successful pilot production trials have been reported, and output from the first production-scale units is expected over the next two years.

CRYSTAL GROWTH

Once the silicon has been purified, two forms of bulk silicon crystals for solar-cell manufacture can be made. The first form is monocrystalline silicon typically grown by the Czochralski process, where a seed crystal of silicon located on the end of a rod is dipped into molten polysilicon. The seed crystal's rod is pulled upwards and simultaneously rotated. By controlling the temperature gradients, the rate of pulling and the speed of rotation, it is possible to fabricate a large, single-crystal ingot (also known as a boules) of silicon from the melt. The second form is multicrystalline silicon, which is cast in a quartz crucible under controlled cooling. The presence



Germany has led the world in photovoltaic installations. Here a whole factory roof is covered with solar cells.

of grain boundaries and associated electronic defects in multicrystalline silicon means that the efficiency of the resulting solar cells is normally lower than those made with monocrystalline material. However, for multicrystalline silicon the unit investment cost for the manufacture is lower and the throughput is higher than for monocrystalline material. Current developments are focused around the casting process and increasing the throughput and ingot size. The standard production ingot mass today is around 260 kg, but experimental ingots of up to 600 kg have been reported

by the manufacturers Solar World and Photowatt. A significant innovation in this technology is the announcement by BP Solar of a process to grow monocrystalline-like material by a cast process, which offers the prospects of a higher-efficiency low-cost product.

WAFER SLICING

The bulk mono- or multicrystalline silicon is first sawn into bricks using a band-saw. A cutting fluid comprising silicon carbide particles in ethylene glycol medium and a 160- μm -diameter steel wire travelling at a velocity of 12 m s^{-1} slices the bricks into wafers. The process produces square wafers with a side length of 125 mm, 200 μm thick, but with an associated kerf loss of 50%. Over 4,000 wafers are produced in a typical five-hour saw cycle. Over the coming three to five years it is expected that wafers will be cut using wire with a diameter of 120 μm , to a wafer thickness of 150 μm , giving a 30% increase in the wafer yield per kilogram of brick. Sawn wafers that are just 80 μm thick have been demonstrated under laboratory conditions. This process offers the potential for further savings, provided that the yields in subsequent stages of the cell manufacture can be maintained. The growth of silicon ribbons directly from the melt is a process that

avoids wafer sawing completely. However, current ribbon growth rates are slow and their surfaces are uneven, requiring specialized techniques for cell production.

CELL FABRICATION

The most common photovoltaic cells comprise a p–n junction photodiode near the top surface of a silicon wafer, where light is incident. Metal contacts are applied to the top and bottom surfaces to extract the current, with the top surface requiring a fine-line metal grid to maximize the surface area that is exposed to the Sun. Screen-printing is used to apply aluminium and silver conducting layers to the top or bottom of the cells, which are then fired at 700–800 °C to form surfaces on which external copper conductor strips can be soldered.

The efficiency of typical commercial screen-printed photovoltaic cells ranges from 14% to 16%, but a number of notable high-efficiency cells have come to the market. One of the first was BP Solar's laser-grooved buried contact cell, which for almost a decade from 1992 was the world's highest-efficiency commercial product. One of the distinctive attributes of this cell was the top metal contact. This was produced by forming narrow but deep trenches in the top silicon surface (which incorporated a dielectric coating) using a laser, and electroless plating the silicon grooves with copper. These cells are produced on monocrystalline wafers and are typically 18% efficient. Sanyo has pioneered the development of a cell in which the junction is formed by doped amorphous silicon layers applied to both surfaces of an n-doped monocrystalline silicon wafer. Commercial cells of 20% efficiency are being produced. Most recently, SunPower has introduced a cell where both n and p contacts are integrated into the rear surface of the wafer, leaving the top surface completely free of shading by conductors. Commercial products containing 22% efficient cells are expected on the market in 2008. Efficiency improvements offer the



Photovoltaic cells are getting thinner thus saving on material costs. This laser-grooved buried contact cell is 140 μm thick. Wafer slices of 80 μm have been demonstrated.

greatest potential for reducing the unit cost per watt of solar power. However, cost reductions are also expected from economies of scale in high-throughput automated production lines and a transition from printed silver to plated base metal conductors.

MODULE ASSEMBLY

The assembly of the module, or panel, is the final stage in the production process. Under standard illumination test conditions, each 125 mm \times 125 mm crystalline silicon cell produces a typical current of 5 A at a potential of 0.5 V. In a module, cells are connected in series, with a typical 72-cell module delivering a power of 180 W at a potential of 36 V. The module is a laminate comprising a sheet of high-transmission glass, layers of ethylene vinyl acetate copolymer each side of the solar cells, a fibreglass matting layer and a back sheet of polyester or aluminium-coated Teflon as a moisture barrier. The assembly is placed in a vacuum laminator at a temperature of 130 °C, where the air and moisture are removed and the copolymer forms stable and durable crosslinked chains. A well-manufactured product should have a life expectancy of up to 40 years, and most quality manufacturers offer a

25-year warranty on their products. Long life expectancy is vital to low-cost solar electricity production. The fuel is free and maintenance costs are low, so the cost of energy (\$ per kWh) is governed by the manufacturing cost, conversion efficiency and operating period. Recent innovations in module assembly have included the application of a durable antireflection layer on the external glass surface, and bypass chip diodes on printed circuit boards incorporated into the laminate, thus avoiding external junction box circuits. In the future, low-cost miniature inverters may be attached at the individual module level to provide a.c. current output and enable lower connection costs to the electrical grid network.

The energy used in the production of a photovoltaic module, at present, takes between 1.5 years and 3.5 years to generate through sunlight energy conversion (depending on irradiance levels at the site of installation). The expected future reduction on material (largely silicon) consumption per module and higher-efficiency devices will reduce the current energy pay-back time over the coming five years. In terms of greenhouse-gas reduction, each installed kilowatt of solar power can avoid up to 40 tonnes of carbon dioxide emission during its operating life cycle.

OUTLOOK

The prospects for photovoltaic solar energy are exciting. Government targets for 20% of electricity production from renewable sources by 2020 will continue to provide market pull for the technology to establish the industry, and will drive costs down to the level of retail electricity prices over the near term. There is an opportunity for new photovoltaic technologies to demonstrate their merits, and existing technologies will continue to drive down costs in line with historic trends. In the longer term, new emerging technologies, based on materials such as organic and polymer chemicals or nanostructured or nanocomposite materials, may become competitive.

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.

Richard R. King

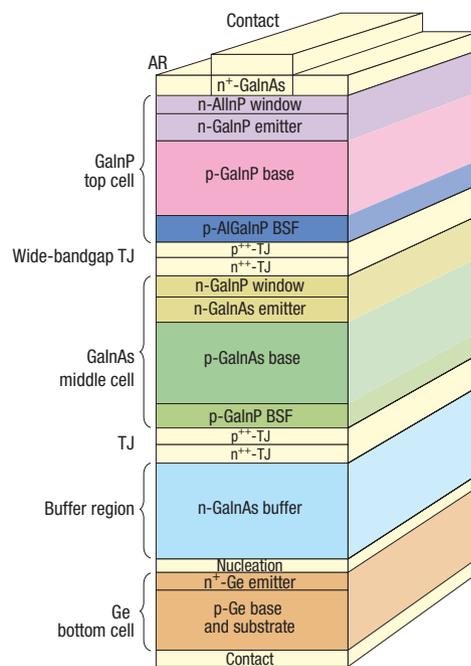
Spectrolab, 12500 Gladstone Avenue, Sylmar, California 91342, USA

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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 CO₂ 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

a Lattice matched



b Lattice mismatched or metamorphic

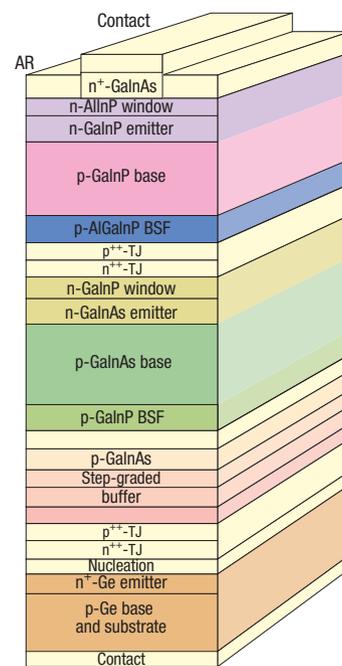


Figure 1 Schematic cross-sectional diagrams of three-junction cell configurations. **a**, Lattice-matched and, **b**, metamorphic GaInP/GaInAs/Ge, corresponding to efficiencies of 40.1% (lattice matched) and 40.7% (metamorphic) for concentrator cells. (AR: antireflection coating; BSF: back-surface field;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

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

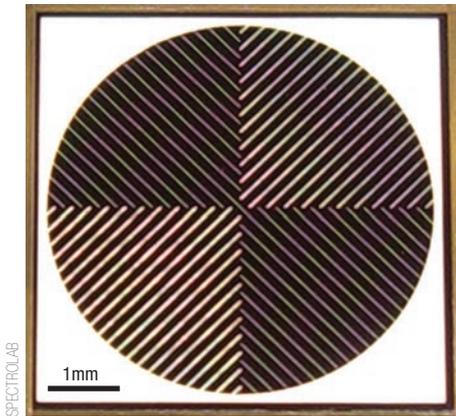


Figure 2 Photograph of a Spectrolab III-V multijunction concentrator solar cell, of the type that has reached a record 40.7% efficiency.

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 $\text{Ga}_{0.44}\text{In}_{0.56}\text{P}$ top subcells, and $\text{Ga}_{0.92}\text{In}_{0.08}\text{As}$ 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.



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.



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.

ORGANIC MATERIALS

Fantastic plastic

Polymer materials could bring down the cost of electricity production using photovoltaic technology to below \$1 per watt for the first time, and enable mass-market, portable applications for photovoltaic technology.

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Much of the early work on photoactive materials for photovoltaics focused on crystalline silicon, which dominates the commercial solar-energy field today. Several other materials, such as amorphous silicon (a-Si), cadmium telluride (CdTe) and copper indium gallium selenide (CIGS), are also now in various stages of commercialization, and are known as thin-film technologies. The lower manufacturing costs and higher production throughput of these materials potentially translate into lower electricity costs. Current thin-film technologies are expected to bring costs reasonably close to \$1 per watt of electricity produced at peak solar power.

There is, however, another technology that has the potential to bring this cost down even further. Bulk heterojunction technology, using organic semiconductors and roll-to-roll coating and printing techniques, could become the technology that makes solar energy affordable to the general public. The technology uses abundantly available non-toxic materials, is based on a scalable production process with high productivity, and requires low investment from the manufacturer.

A bulk heterojunction is a blend of p- and n-type semiconductors, which forms molecular p-n diodes all over the bulk layer. On light absorption, photo-induced charges are produced by ultrafast charge transfer (within a few femtoseconds) between the two semiconductor types. Various material systems have been suggested for bulk heterojunction solar cells, including: organic semiconductors, inorganic and organic semiconductor nanoparticles

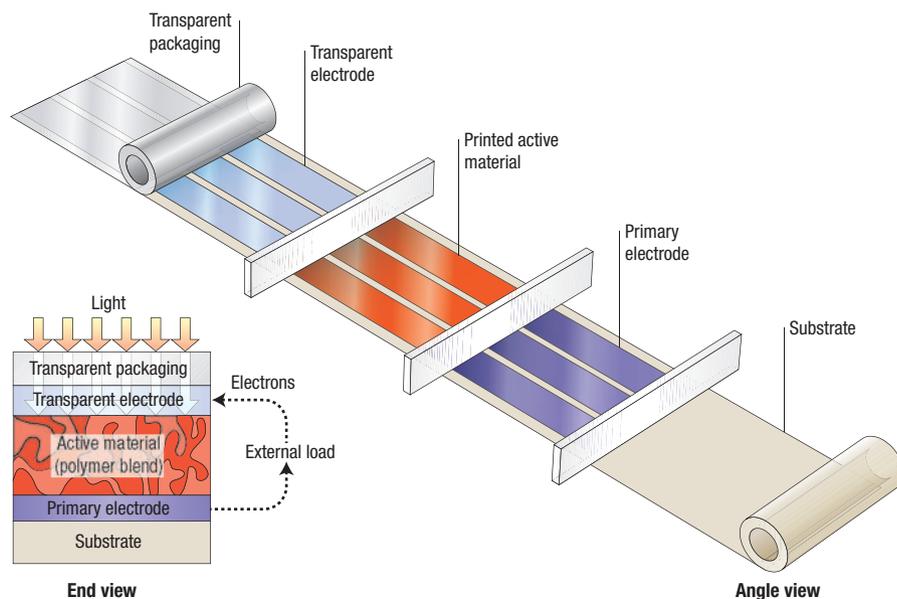


Figure 1 Polymer-based photovoltaic cells can be manufactured using standard printing processes.

and nanorods, metal oxides stained with dye molecules, as well as combinations of these.

Of all these technology platforms, organic photovoltaics is generating considerable interest (Box 1). As the name implies, this technology comprises carbon-based materials as donor and acceptor molecules. The most popular class of organic donor molecules are conjugated polymers, such as polythiophenes, polyfluorenes or polycarbazoles. The material choice for acceptors is much narrower — for more than ten years substituted fullerenes have given by far the best photovoltaic performance.

The feature that differentiates this technology from all of the others is its compatibility with high-speed and low-temperature roll-to-roll processing. The processes are typical of those used in the printing and coating industry in that solutions of the active materials,

dissolved in organic solvents or water, are applied to a plastic sheet by means of a coating applicator.

Various printing and coating technologies have proven their compatibility with organic semiconductor processing, among them gravure printing, flexo printing, screen printing, slot die coating and, most recently, ink-jet printing. The printing solvent is evaporated when heated to moderate temperatures, producing a dried layer of the photoactive polymer. The modules are encapsulated between thin, flexible over-laminates, which protect the active layers from mechanical abrasion and the environment. Capital costs are very low, and the printing and coating processes can be done at high speed with no obvious limitation in the substrate width. The processing steps are summarized in Fig. 1.

The combination of low-temperature processing paired with high production

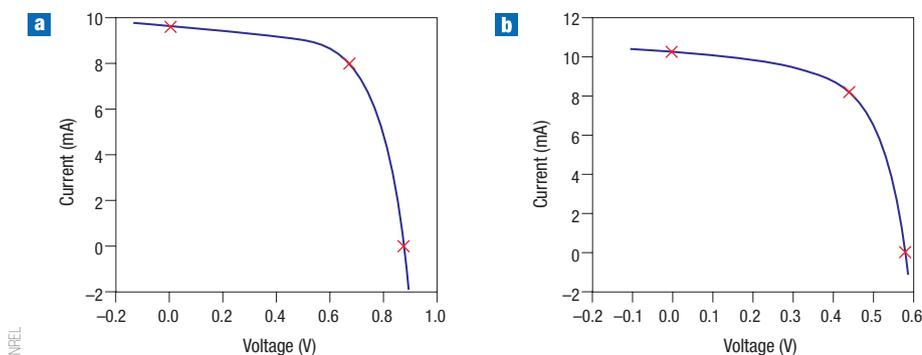


Figure 2 These plots show record efficiencies achieved with organic photovoltaic technology as certified by the National Renewable Energy Lab (NREL). **a**, Results for a device with an active area of 1.024 cm² and an efficiency of 5.21%. **b**, Results for a device with an active area of 0.685 cm² and an efficiency of 5.24%.

throughput suggests that attractive energy payback times — the time it takes to generate energy equivalent to that outlaid during fabrication — should be possible. With large-volume manufacture and reasonable efficiencies of 5% to 10%, these printed solar cells should have the potential to go significantly below \$1 per watt of electricity. So far,

no complete life-cycle analysis has been completed, but expectations are that the energy payback time can be as low as a few weeks.

The efficiency of organic photovoltaic technology is low when compared with silicon or compound semiconductor technologies. However, many significant modifications and improvements have

been made to the polymer structures over the past few years (Fig. 2). These modifications include the incorporation of comonomers that withdraw electrons from the sea of electrons on the polymer backbone, causing a large shift in the absorption band towards the infrared. Some of these modifications result in absorption at wavelengths as long as 1,000 nm and more, enabling the cell to absorb more than 50% of the total radiation from the Sun. In addition, the structures are versatile enough, from a molecular architecture standpoint, that the entire visible spectrum can be covered as well. Modelling indicates that some of these polymers, when combined with fullerene, will exhibit cell efficiencies between 7% and 10%.

Even higher efficiency values are expected for tandem or multiple junction geometries, where solar cells of different bandgaps are stacked on top of each other and interconnected in series. Each cell absorbs at a different wavelength, reducing the amount of uncaptured radiation that is lost as heat and enabling higher efficiencies. The materials for tandem cells can come from a variety of

Box 1 The structure of an organic photovoltaic cell

All photovoltaic cells have several common features: they must have two electrodes and a layer of photoactive material that absorbs light (a photon) and generates current (an electron). The key to the success of organic photovoltaics is its two-component active layer, which on coating and drying forms a very unique morphology (shown schematically in Fig. B1) referred to as a bulk heterojunction. The main feature of this heterojunction morphology is the intertwining of phases of each of the components, which spontaneously occurs when the solvent is evaporated. In current designs of polymer photovoltaic cells, one of the components is a polymer that has three functions: to absorb light; to inject an electron into the second component; and to carry the resultant hole to one of the electrodes. The other component is a fullerene derivative. Its function is to accept an electron and carry it to the other electrode. The primary advantage of the bulk heterojunction is the very high surface area that is formed between the two phases, which directly affects the efficiency of charge transfer between the polymer and the fullerene phases.

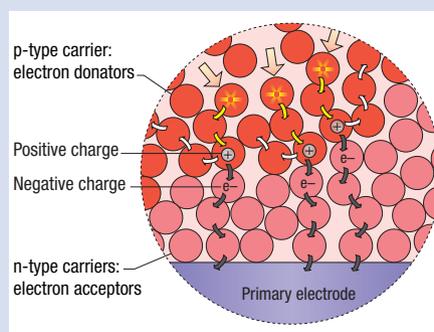


Figure B1 The mechanism of charge transfer and transport in a bulk heterojunction structure.

External quantum efficiencies of up to 80% have already been demonstrated, though today's power-conversion efficiency is only in the regime of 5–6%.

The current generated by the cell is related to the absorption spectrum of the polymer, which is determined by its molecular structure. The structural design of these molecules is adjusted to absorb broadly across the solar spectrum from the blue to

the near infrared. As the active-layer coating is a fraction of a micrometre thick (100–200 nm), the polymers must have a very high absorptivity as well. When choosing which polymers to use as the donor and acceptor molecules, material scientists must look at the different energy states of the molecular electrons in the donor and the acceptor molecule. All charge carriers need to be transported across the bulk to the electrodes before recombination takes place. At typical carrier lifetimes of a few microseconds, charge-carrier mobilities of 10^{-3} cm² V⁻¹ s⁻¹ or higher are required for loss-free carrier collection.

These selection criteria significantly narrow down the polymeric structures that have potential for efficient photovoltaic energy conversion. Finding suitable polymers for this application is challenging because a compromise must always be reached between the choice of bandgap (which dominates the short-circuit current) and the position of the electronic levels (which dominates the open-circuit voltage). The product of the short-circuit current and the open-circuit voltage dominates the efficiency.

conjugated polymers, always combining a narrow-bandgap semiconductor with a wide-bandgap one. Efficiencies over 6% have already been reported for a tandem architecture based on polymer and fullerene composites (Kim, J. Y. *et al. Science* **317**, 222–225; 2007).

Although still low compared with silicon and compound semiconductor technologies, these efficiencies represent a big step forward in polymer photovoltaic technology. Polymer systems also have many advantages over conventional photovoltaic technology. For example, organic photovoltaic modules are lightweight, have a high power-to-weight ratio (more than 100 mW g^{-1} at 5% efficiency) and they are mechanically flexible (Fig. 3). This makes them particularly useful for portable applications, which represent the first target markets for the technology. Potential uses include battery chargers for mobile phones, laptops, radios, flashlights, toys, and almost any handheld device that uses a battery. The modules can be adhered to the outside face of a briefcase or a piece of clothing, or they can be incorporated into the housing of a device. They can also be rolled up or folded for storage in a pocket when not in use. The first products serving this market should be available later in 2008.

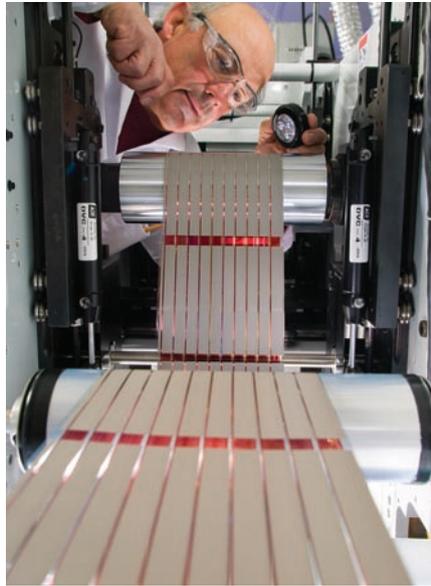


Figure 3 Polymer photovoltaic technology has a high power-to-weight ratio, which allows thin modules that have the added advantage of being lightweight and flexible, making it ideal for portable applications.

Organic photovoltaic modules will probably also be used in architectural or building-integrated applications.

Potential applications are in electricity-generating awnings that can be rolled up for storage or windows in office buildings and greenhouses, where two transparent electrodes are used so that the module is semitransparent.

The biggest market for organic solar panels is large-area rooftop applications in residential and commercial buildings. This will require efficiencies between 7% and 10% and lifetimes of 7–10 years. Konarka is now running extensive lifetime investigations, and the company's cells regularly pass more than 1,000 hours under accelerated degradation. To verify the lifetime of 7–10 years, the degradation over around 3–5 years must be measured and then extrapolated. So far, Konarka has been measuring the lifetime of its cells for more than one year (extrapolated out to three years) with no degradation observed.

This shows the enormous progress that has been made over the past few years in designing environmentally stable organic materials and interfaces. Until recently it was thought that organic solar-cell lifetimes were restricted to 1–2 years, but today it is clear that the technology could reach lifetimes of 5–10 years, making it a strong contender for consumer solar-cell applications.

Giant solar plant for Arizona



ABENGOA SOLAR

Abengoa Solar has signed a contract with Arizona Public Service Company (APS) to build, own and operate what would be the largest solar power plant in the world if operating today.

The plant, called the Solana Generating Station and scheduled to go into operation by 2011, is located 70 miles southwest of Phoenix, near Gila Bend, Arizona, USA. It will sell the electricity

produced to APS over the next 30 years for a total revenue of around \$4 billion.

The plant will have a total capacity of 280 MW, enough to power 70,000 homes. It will use proprietary concentrating solar power (CSP) trough technology developed by Abengoa Solar, and will cover a surface of around 1,900 acres.

The solar trough technology uses trackers with high-precision parabolic mirrors that follow the Sun's path and concentrate its energy, heating a fluid to over 371 °C and using that heat to turn steam turbines. The solar plant will also include a thermal-energy storage system that enables electricity to be produced as required, even after the Sun has set.

Abengoa Solar is now operating the world's first commercial CSP solar tower plant in Spain, and is building three more in the country with a total capacity of 120 MW.

of making solar energy more competitive and sustainable. Principal investigator Ken Durose highlights the price of indium (\$660 per kilogram) as a particular cost barrier. "At present you would need tens of tonnes of very rare and expensive materials for large-scale production of solar cells to produce sizeable amounts of power," he says. "Some of the materials currently used may not be sustainable in 20 years time, which is why we have to conduct research into alternative materials that are cheaper to buy and more sustainable."

Thin-films to eat into silicon's dominance



BCC RESEARCH

The global market for photovoltaics is expected to be worth more than \$16 billion by the end of 2008, according to a market report by BCC Research. This is expected to increase to over \$32.2 billion by 2013, a compound annual growth rate of 14.9%.

According to the report, the energy produced by photovoltaic cells and modules from global shipments reached 2,875.1 MW in 2007. This is projected to grow by 28.6% to reach 3,697.3 MW by the end of 2008, and with a compound annual growth rate of 30% it will reach 13,724.4 MW by 2013.

Silicon technology, which accounted for about 89% of the market in 2007, will continue to dominate in the near future, with shipments of multicrystalline silicon cells growing by 285% by 2013. Recent improvements in this traditional technology and its reliability will keep it in the forefront, and BCC predicts that silicon will still represent 79% of the market in 2013.

That said, thin films, which only have 10% of the market at present, will grow by 45% to account for 19% of the market in 2013. Improvements in efficiencies and the use of these materials on flexible substrates will account for their rapid growth.

New technologies, such as nanostructured thin films and silicon and dye-sensitized solar cells, accounted for just under 0.5% of the market in 2007, but will grow by 34% to reach an energy production of 19.2 MW in 2008, and then exhibit 50% annual growth to achieve 145.7 MW by 2013.

Ersol and Schott to develop thin-film technology

German companies Ersol Thin Film and Schott Solar have agreed to jointly develop so-called micromorphous technology for thin-film solar cells. The two companies will be combining their resources in the area of research and development, and will exchange staff between the two sites. In contrast to the amorphous version, a micromorphous thin-film module has a double-layer structure consisting of an amorphous and a microcrystalline silicon film. The arrangement results in improved exploitation of sunlight, because the two silicon layers convert the whole light spectrum into power. "We believe that this so-called micromorphous tandem cell can achieve up to a 50% increase in the module efficiency, and therefore also in the module yield in comparison with amorphous technology," explains Christian Koitzsch, managing director of technology for Ersol Thin Film.

Q-Cells becomes 'world's largest manufacturer of solar cells'

German company Q-Cells claims it is now the world's largest manufacturer of solar cells, after reporting a 54% increase in production in 2007 to 389.2 MW. In 2007, sales rose by 59% to €858.9 million (\$1,300 million) compared with €539.5 million (\$830 million) for the previous year. Earnings before interest

and taxes grew by 52% to €197.0 million (\$300 million), compared with €129.4 million in 2006 (\$200 million). For fiscal year 2008 as a whole, Q-Cells continues to expect total sales of approximately €1.2 billion (\$1.85 billion).

To allow rapid growth to continue, Q-Cells has decided on further expansion in its production capacity. In its core business, the production of monocrystalline and polycrystalline solar cells based on silicon wafers, Q-Cells has completed the ramp-up of the first two phases of expansion of production line 'V' and is now starting work on the construction of production line 'VI' in Bitterfeld-Wolfen, Germany. The first phase of expansion with a production capacity of 130 MW is to start production in the fourth quarter of 2008. The company has also decided to construct its seventh production line in Malaysia.

Sustainable cell manufacture

A team of scientists from eight universities across the UK is embarking on one of the UK's largest ever research projects into photovoltaic solar energy.

Led by Durham University, the £6.3 million (\$12.5 million) PV-21 programme will focus on making thin-film light-absorbing cells for solar panels from sustainable and affordable materials. The eight universities will work together with nine industrial partners towards a "medium- to long-term goal"

A flexible system for making flexible photovoltaic cells

SOLAR COATING MACHINERY

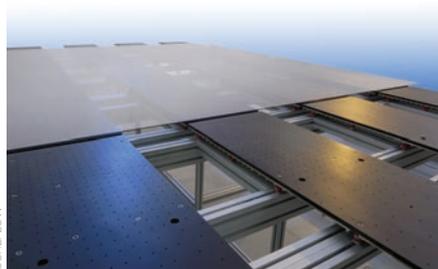


www.solarcoating.de

German company Solar Coating Machinery has developed a modular pilot line for the production of flexible solar cells. Called Click&Coat, the system is made up of 12 units, which click together to form a pilot line. These are a winder unit, coating unit, infrared dryer unit, flotation unit, sintering unit, vacuum unit, bath unit, another winder unit, edge-guiding unit, slitting unit, laminating unit and an edge-sealing unit. The company claims its pilot lines can be used to scale up from research to production volumes and suit a variety of photovoltaic technologies, including amorphous silicon, dye-sensitized cells, organic, copper indium selenide (CIS) and copper indium gallium selenide (CIGS). The company says that its products are particularly suitable for manufacturing flexible solar cells, performing encapsulation, packaging and substrate bonding.

Non-contact solutions for handling crystalline wafers and solar glass

COREFLOW



www.coreflow.com

Israeli company CoreFlow has developed a number of non-contact solutions for the transport, handling, and processing of crystalline wafers and solar glass substrates. CoreFlow's air-cushion solutions enable high-speed handling and transport (up to 100 m per minute) for large thin-film solar substrates. This non-contact procedure enables very high

process speeds and reduced vibration during the manufacturing process, resulting in improved throughput and higher manufacturing latitude. CoreFlow's Pressure Atmosphere technology floats substrates with an air gap of up to 300 μm in size to ensure non-contact, and is ideal for most inline and offline transport applications. The Pressure Vacuum system is ideal for critical process zone applications, such as laser-scribing and surface-inspection stations. The company claims its systems can enable higher material throughput and minimize glass stress and damage during manufacturing.

Metallization furnace combines solar-cell drying and firing in one unit

www.btu.com

The company BTU International has introduced a metallization furnace that combines solar-cell drying and firing in one unit for optimized throughput and reliability. The most recent addition to the PVD-600 Series furnaces, the PVD624, combines the rapid thermal processing of a 600 Series Solar Cell Firing Furnace and a D-900 Series Dryer as an integrated system. By combining drying and firing in one unit, the solar cells transfer directly from the dryer into the furnace without additional handling. This improves efficiency by saving factory floor space and reducing automation costs. In addition, the PVD-624 offers greater throughput with the use of a wider, 24-inch belt. The PVD-624 also features highly effective, closed-loop convection cooling, which enables precise control of cooling rates. This new design also provides a significantly advanced water cooling system. Quartz tubes set in a herringbone pattern maximize thermal uniformity throughout the PVD624. Individually removable, sliding side ports in each zone allow easy cleaning below the belt, and an enhanced exhaust design helps to provide superior uptime.

Flexible laser system processes thousands of silicon wafers per hour

www.innolas.de

The ILS 700 laser system from German company Innolas is a dedicated tool for processing monocrystalline and polycrystalline silicon solar cells. Examples of the laser-processing techniques available with the system are: laser edge isolation, laser-fired contacts processes, micro through-hole drilling,

SiN and SiO₂ ablation, downsizing, surface modification, laser scribing and surface structuring.

This gantry-type machine enables the processing of wafer sizes ranging from 100 mm \times 100 mm to 210 mm \times 210 mm, selected using a software program. Process performance does not degrade as the wafers increase in size, and automatic laser treatment of pseudo square formats is also possible. The machine can be supplied in various configurations, including a version that suits integration into fully automatic manufacturing lines.

The system offers the possibility of integrating up to two laser sources in one machine for processing two wafers simultaneously or for subsequent processing with different laser sources and wavelengths. This guarantees flexibility and a very high throughput of up to 2,000 wafers per hour, depending on the application.

System combines water and laser cutting in one operation



SYNOVA

www.synova.ch

Swiss company Synova claims its Laser MicroJet can cut photovoltaic cells without affecting electrical efficiency or inducing chips, burrs, mechanical stress or damage from heat. This technology enables omnidirectional cutting, drilling, scribing, grooving, edge grinding, thinning, marking and other specific applications for thin photovoltaic cells.

The Laser MicroJet combines the advantages of both water and laser cutting in one operation. Using the difference in the refractive indices of air and water, a laser beam is guided to the workpiece within a thin jet of water, which acts as a light guide.

Laser MicroJet technology enables the beam to be guided over a distance of up to 10 cm. The water jet cools the substrate while removing the molten material from the cut and avoiding contamination. The result is accurate cutting of porous or layered materials, with minimal thermal and structural distortion and a finely cut edge.

Accelerating adoption

The photovoltaics industry is growing fast, but it still needs to bring down costs before it can reach its true potential. **Nadya Anscombe** talks to Winfried Hoffmann, president of the European Photovoltaics Industry Association, to find out more.

Why is so little of the world's electricity generated by solar power?

Cost is the one and only limitation this industry has had to its growth. Until recently, it simply has not been economical for the average householder to buy a solar-power system for electricity generation. But this will change dramatically in the next 20 years. The cost of generating power using solar cells has been decreasing by 5% every year, and I believe the industry is able to maintain this trend. In 1991, the electricity production cost from a 1-kW residential rooftop system under German sunlight conditions was €1.1 per kWh. Today, this is more like €0.40 per kWh. In 20 years time, electricity production costs will be comparable to those of a 500-MW clean coal power station, and this is when solar power will finally take a considerably larger market share of the energy market.

Can the industry survive without the heavy subsidies it receives at present?

There are already certain places in the world, such as California and Japan, where a liberalized utility market exists, and in these places an investment in solar power would pay off, even without subsidies. But at the moment, most of the industry is reliant on subsidies. This has been necessary to get volume up and to get us through the price–experience curve as quickly as possible so we can get to the next stage. All these subsidies are doing is speeding up the process. Without them, the industry would still have progressed, but more slowly. Germany is a particular success story. Ten years ago, there were about 5,000 people working in the photovoltaics industry in Germany. Today this figure is more than 40,000. It is predicted that in 20 years time, the photovoltaics industry will have a turnover similar to that of the semiconductor industry, so the German government has been wise to invest so heavily in this area.

But the subsidies cannot go on forever. The cost of electricity production from



Winfried Hoffmann is president of the European Photovoltaics Industry Association.

solar cells depends a lot on the amount of sunlight available in a particular location. In 5–8 years, sunny parts of the world will be able to survive without subsidies, but in other areas, such as the UK and Germany, this will take closer to 20 years. Once the cost of making electricity from solar cells is comparable to that from a large power plant, the industry will not need any subsidies.

How has the silicon shortage affected the photovoltaics industry?

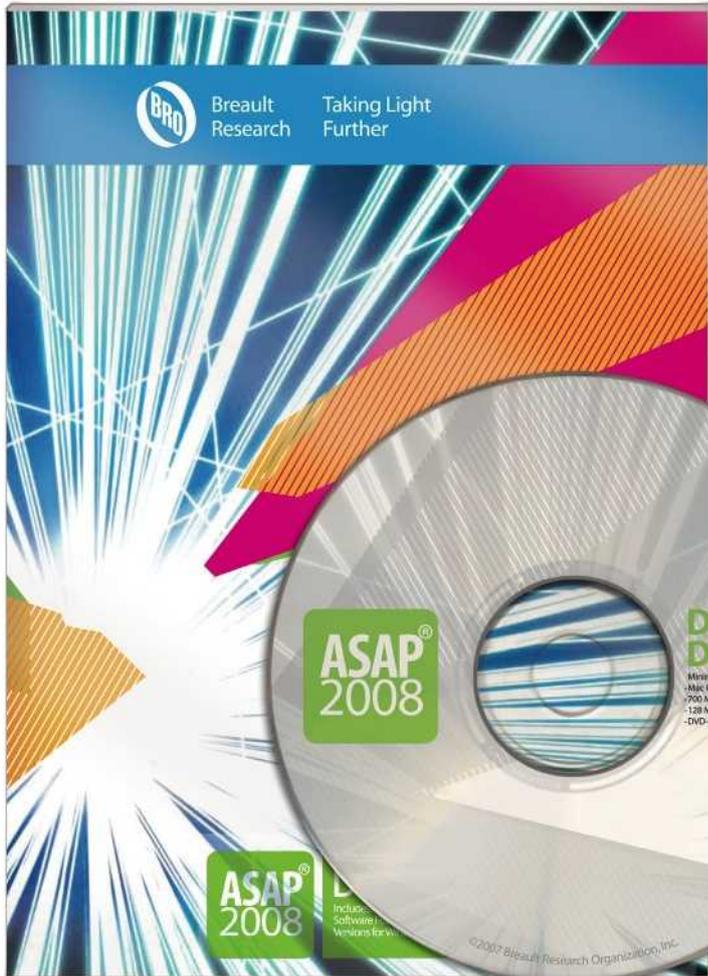
When an industry is growing as fast as the solar-cell industry is, there will inevitably be shortages in some materials. The shortage in solar-grade silicon has been a huge challenge for the industry to overcome. Making polysilicon takes chemical expertise that cannot be learned overnight. Rectifying the shortage has taken 2–3 years of investment and over the course of 2008 much greater quantities of silicon feedstocks have become available. By 2010 we will have three times more

polysilicon than we had two years ago. Although the shortage has been painful, it has also had some good points. Necessity is the mother of invention and the industry's engineers have been very inventive during the shortage. A few years ago no-one would have believed that you can make solar cells with wafers just 200 μm thick, but today this is a reality.

Will silicon technology always dominate the market?

Other technologies, such as thin-film, polymer and III–V semiconductor systems, will take an ever-increasing market share in the future, but I believe crystalline silicon will continue to dominate the market over the next 20 years. Thin-film technologies are growing fast: every 5 years, they increase their market share by 5%. I have always believed it is the applications that choose the technologies and not the other way around. So if you have limited space but plenty of sunshine, silicon is the most appropriate technology to use. If the application is in partial shade or, for example, a photovoltaic system is being integrated into a semitransparent window, then thin-film technologies are more appropriate. Organic photovoltaics will be particularly suited to applications where their shorter lifetimes are not an issue. For example they can be used in mobile devices, where a lifetime of less than five years is not a problem. I believe that, while the efficiencies of silicon solar cells are continuously increasing, they will never match the efficiencies of III–V semiconductor multijunction systems. So, although these systems are expensive, for some applications they are the systems of choice because of their higher efficiency. It all comes down to the intelligent use of technology for each specific application, but for the foreseeable future I believe silicon-based systems will still dominate the market.

Nadya Anscombe is a freelance science and technology journalist based in the UK.



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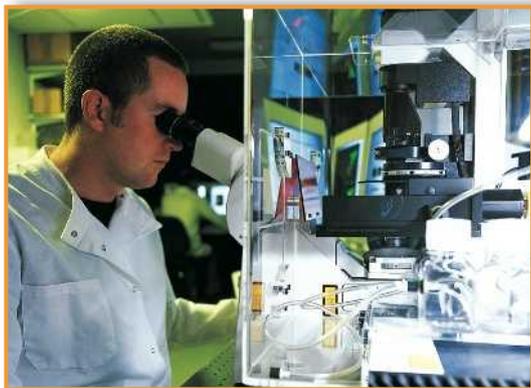
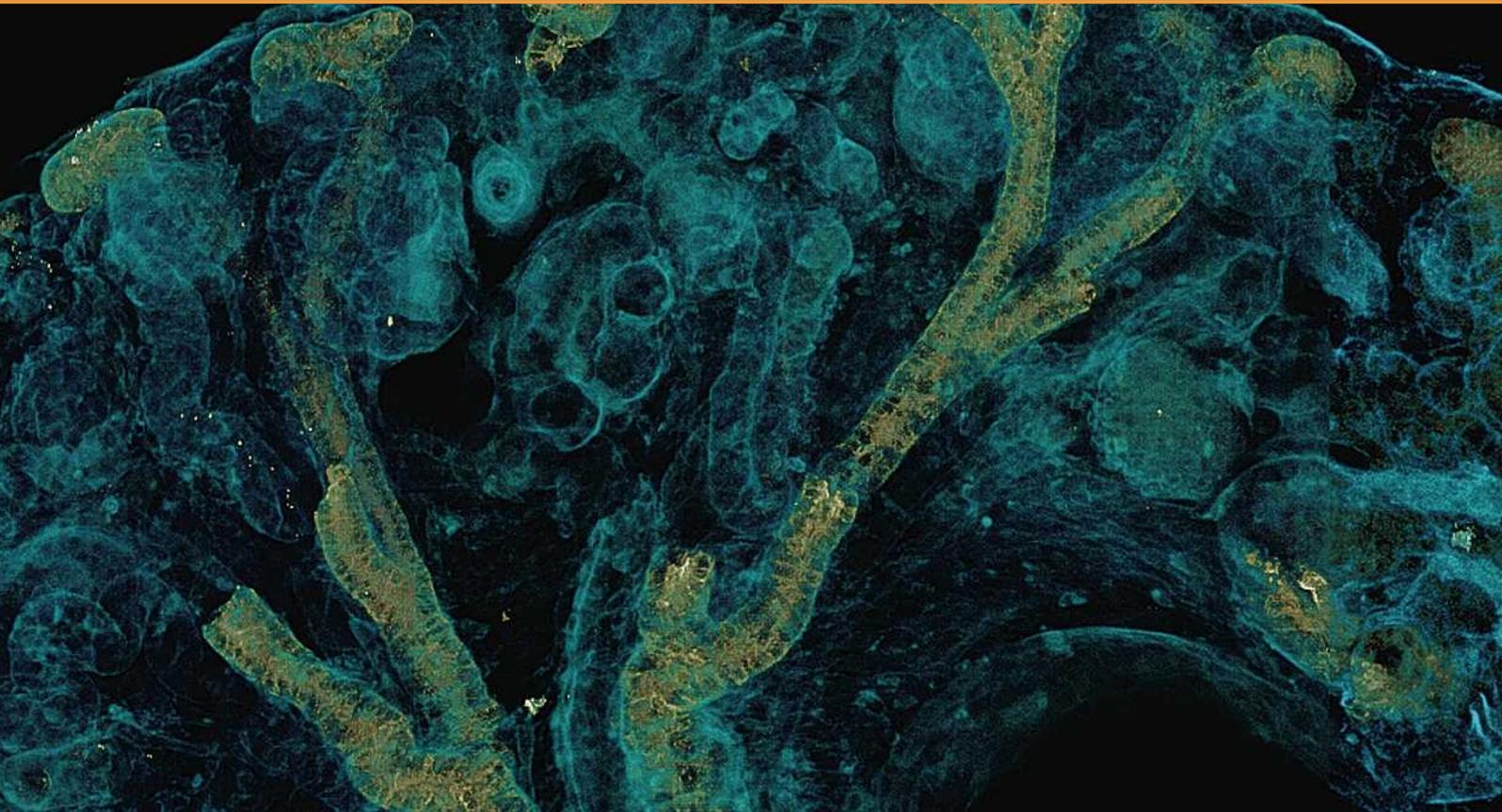
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