Lighting up CIGS PVs

Dr Mike Cooke reports on developments in producing lower-cost solar energy based on compounds of the elements copper, indium, gallium and selenium.

In the last couple of years, photovoltaics have moved from an interesting fringe activity to being one of the centers of high-tech attention. Apart from technological progress in the area, this attention results from an international focus on the benefits of renewable forms of energy production. Outside the USA, the main reason for this has been the increasing realization that non-renewable energy production and usage has contributed to climate changes across the planet. As part of its efforts to reduce carbon emissions, the European Union (EU) is calling for 20% of its energy to come from renewable sources, including solar, by 2020.

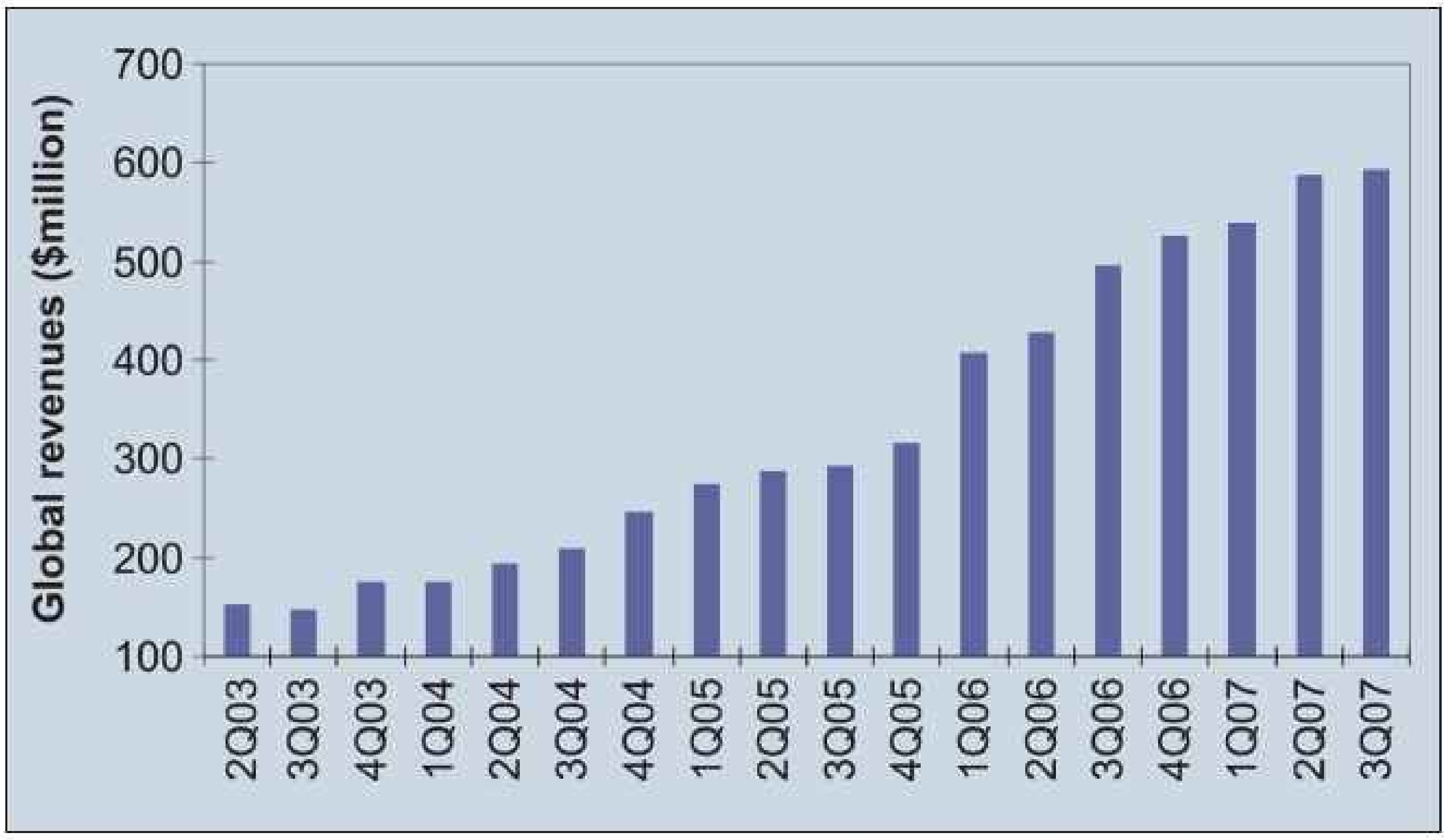

Figure 1. Revenues for polysilicon have been driven up by rising solar cell demand. Source: SEMI Silicon Manufacturers Group.

In the USA, another factor has been more prominent in PV motivation — the perceived need to "reduce the dependence on oil", particularly with gas prices at the filling station reaching around $3 per gallon (approximately doubling over the price five years ago). Of course, these figures remain lower than the cost in much of the rest of the world. In much of Europe, gas costs around twice as much. In addition, crude oil is predominantly supplied by regions with populations, if not governments, hostile to the USA.

The stated aim of the US National Renewable Energy Laboratory's (NREL) Photovoltaic (PV) research is to focus on "decreasing the nation's reliance on fossil-fuel generated electricity by lowering the cost of delivered electricity and improving the efficiency of PV modules and systems." NREL's PV division carries out fundamental research on advanced materials and devices, as well as technology development work.

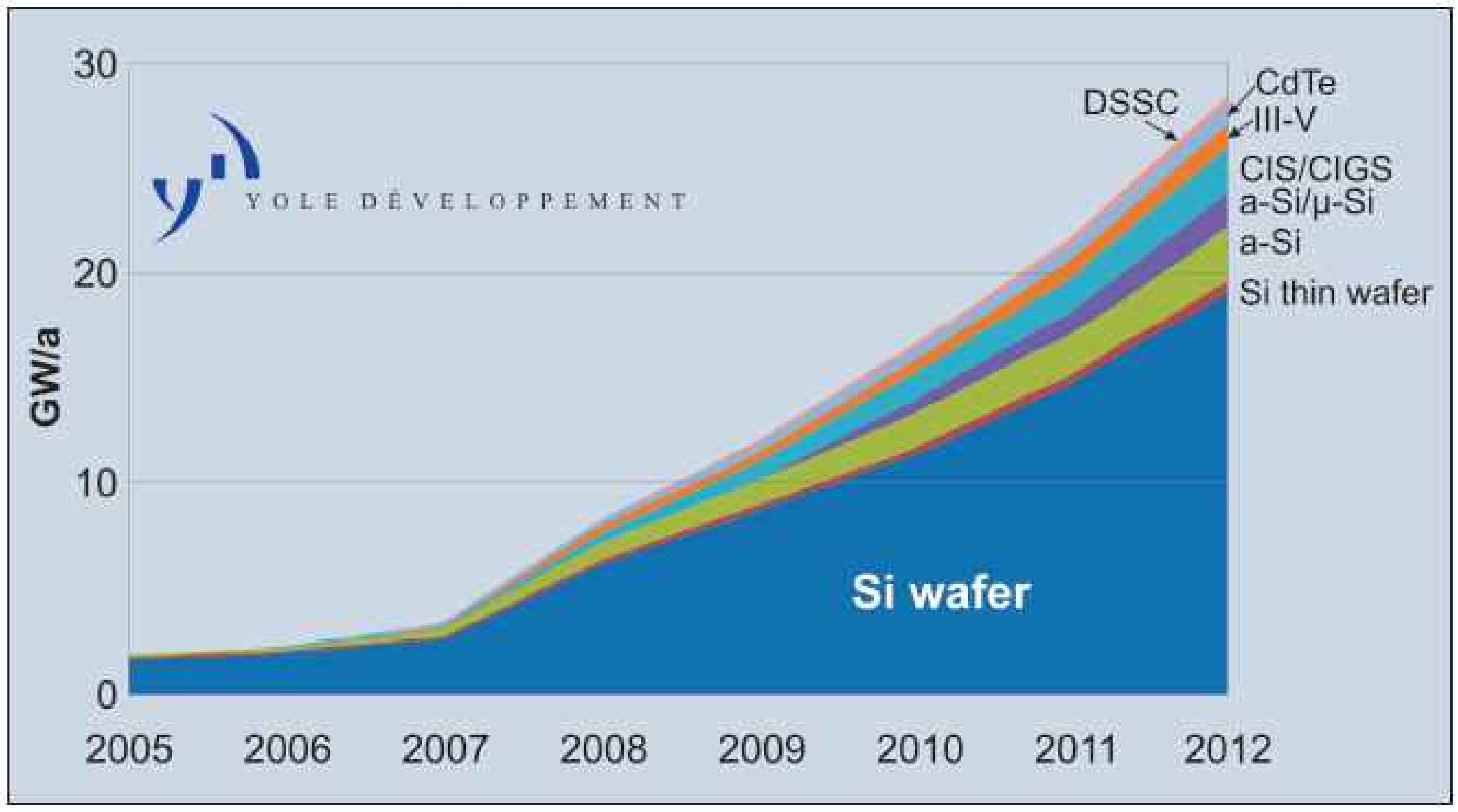

Figure 2. Yole's projection and historical data for production capacity for 2005–2012. Product types shown are silicon normal and thin wafer-based and the thin-film technologies using amorphous silicon (a-Si), amorphous and microcrystalline tandem/multi-junction silicon cells (a-Si/µ-Si), CIGS, III-V, cadmium telluride (CdTe) and dye-sensitized solar cells (DSSC).

Increased PV activity has put a strain on silicon wafer supplies — the predominant substrate in photovoltaic cell manufacturing. However, prompted partly by these difficulties, alternative 'thin-film' photovoltaics have been developed for mass production and are rapidly coming on-line, using different substrate materials that range from glass to flexible plastic or metal rolls. Being a late enthusiast on the PV scene, the USA is implementing the newer techniques most rapidly. The US is looking for technologies that operate in higher temperatures than the 25°C of silicon wafer cells. Apart from application in the higher-temperature conditions of some areas of the USA, such modules could find civilian and military use in places like Iraq. According to PV News (www.pvenergy.com/news.html), the 2006 market share for thin-film over traditional PV cells was 44% in the USA versus less than 6% globally.

In many ways, increasing PV production in recent years saved the suppliers of silicon raw materials and wafers from a squeeze on prices that they had been subjected to for many years by integrated circuit manufacturers (Figure 1). While this new outlet for silicon wafers could be short lived, for example if PV manufacturing goes thin-film en masse, the industry analyst Yole Développement expects silicon wafer products to dominate the solar market up to at least 2012 (Figure 2).

Yole's Gaetan Rull believes that while, thin-film technologies may reach 30% by 2015, there is still significant potential for reducing the manufacturing costs of traditional silicon wafer-based production. The balance is between potentially lower manufacturing costs but higher investment costs for thin-film production. At this stage, the investment risks are much higher for the newer technologies.

As always, a technological breakthrough could disrupt this established landscape. But, even then, there will be a significant time delay between discovery and mass production.

Solar structures

Thin-film PV cells (Figure 3) use a wide range of semiconducting materials: crystalline and amorphous silicon, cadmium telluride, cadmium sulfide, and materials based on the copper, indium, gallium diselenide quaternary system (which is variously represented as $CuIn_{1-x}Ga_xSe_2$, $Cu(In,Ga)Se_2$ or 'CIGS'). These materials are used to create absorber and buffer layers in various solar cell configurations (Figure 4). A photon hitting the absorber layer excites an electron across the bandgap, creating an electron–hole pair. A pn junction between the absorber and buffer layers creates a selective valve for separating the pair, avoiding immediate recombination (conversion back to either photons/light or phonons/heat) and allowing access to the solar energy for practical use.

In addition to substrates and semiconducting materials, one needs top and bottom contact materials. If a transparent substrate is being used with the intention that it is to let the sunlight into the system, the bottom contact should also be transparent. Conversely, if the substrate is opaque, the light comes in from the top and thus the top contact instead should be transparent. Indium tin oxide (ITO) and zinc oxide (ZnO) are two popular materials for transparent contacts. The transparent contact can also have a layered structure to electrically match with the buffer layer. Non-transparent contacts range from silver/stainless-steel substrates to molybdenum (most widely used for CIGS cells).

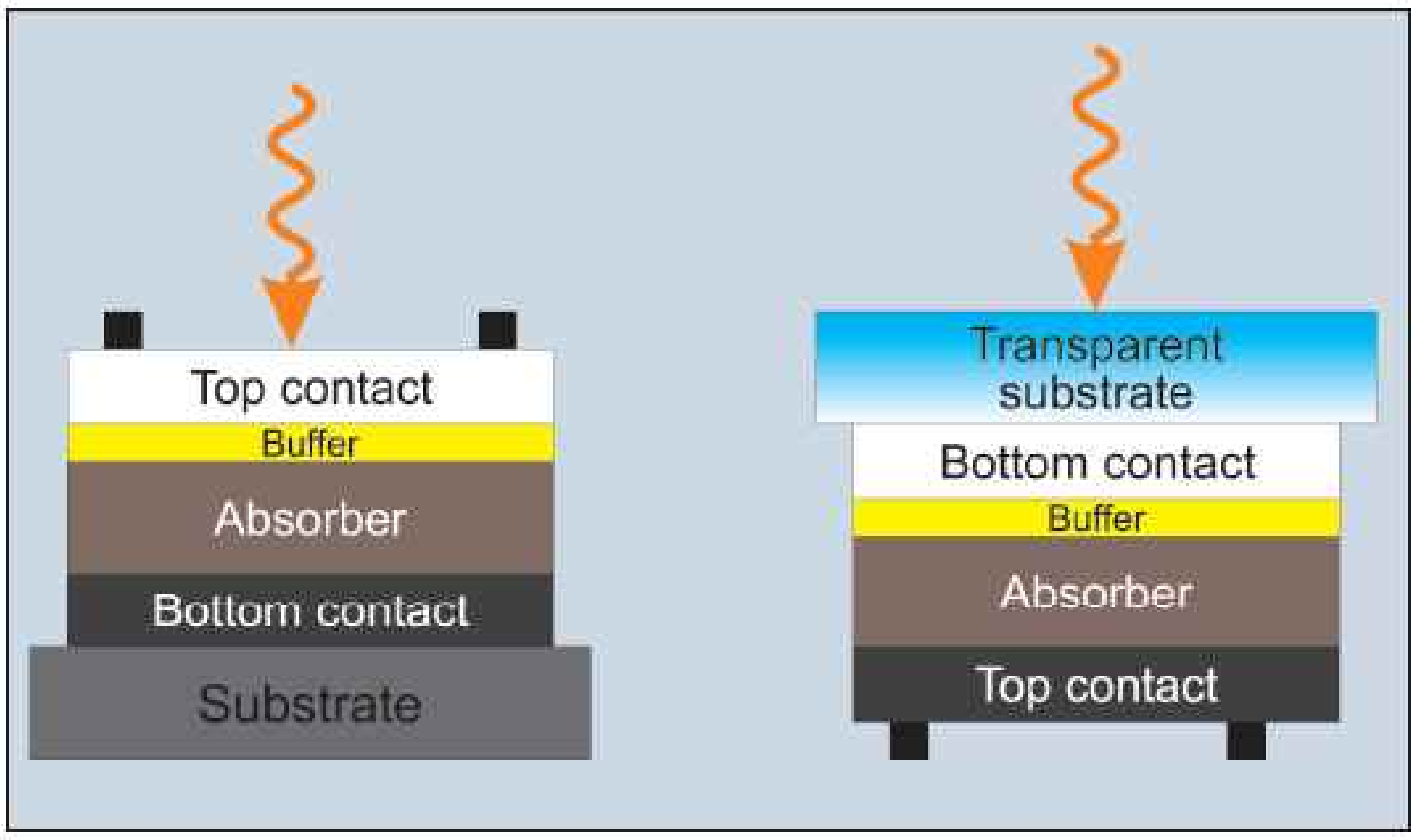

Figure 3: For CIGS-based cells (left) the absorber material is the CIGS itself. The buffer layer is typically CdS, although alternatives such as In(OH,S) and $Zn(Se,OH)_x$ have been used. For opaque substrates, the top contact is a transparent conducting oxide (TCO) such as of indium tin (ITO) or zinc (ZnO). In CIGS production, the non-transparent contact is most often molybdenum. Transparent substrates allow the alternative configuration on the right. The CIGS layer is generally p-type, while the buffer and TCO are n-type, allowing separation of the liberated charges after photon absorption.

Here we will focus on CIGS developments that are expected to increase rapidly over the next couple of years (Figure 5). There is a bewildering variety of firms involved in developing CIGS-based cells and modules. One expects that the investment lottery will weed this profusion in the next year or so. A number of CIGS projects are planning to start volume production in 2008, so it will be very interesting to see which of them deliver on their promises to investors. On the negative side, in the past year a number of reports have come out that some of these companies have laid-off staff. These reports are often vehemently denied by the firms involved. Other reports are of start-up companies

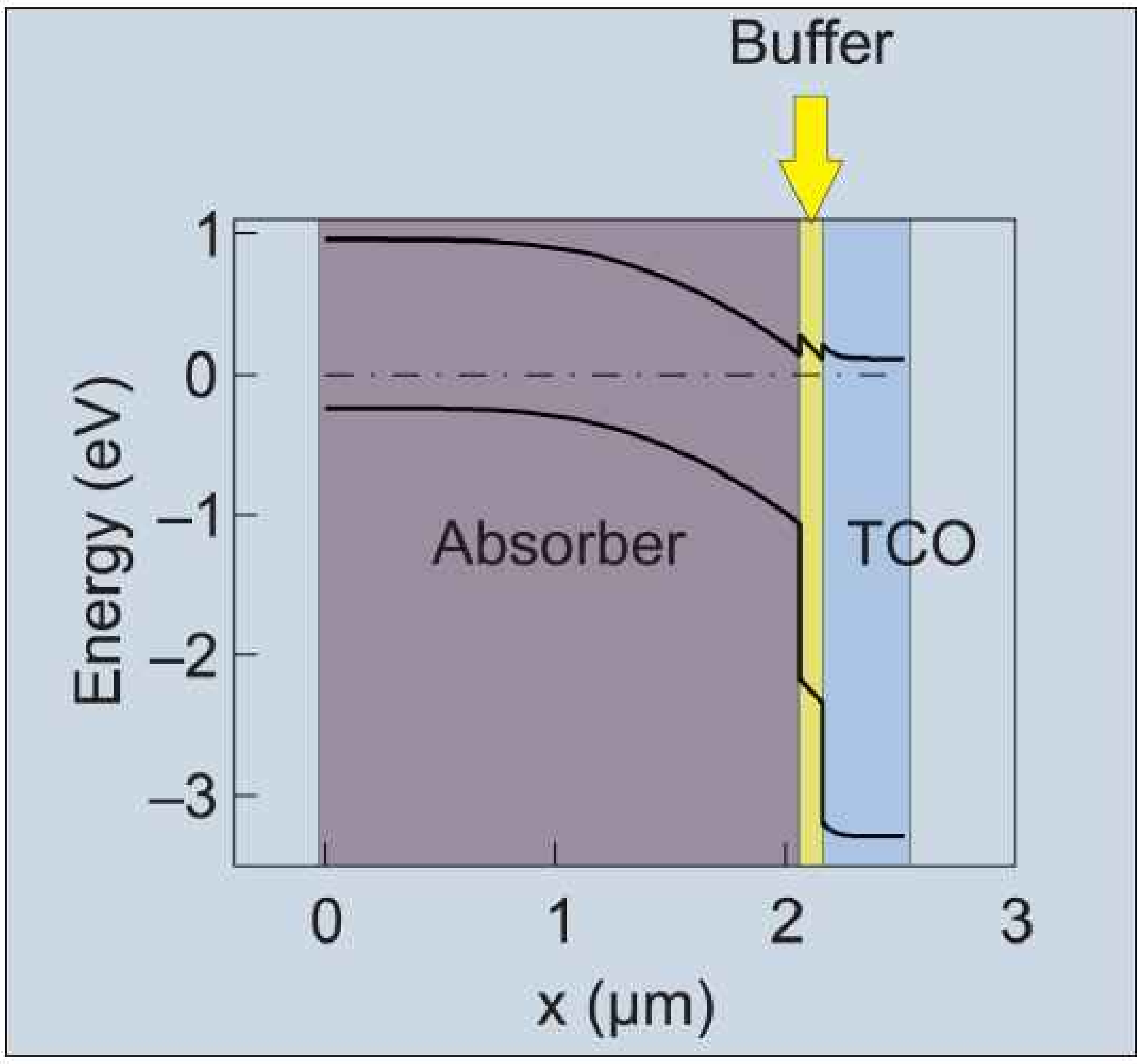

Figure 4. PV band-structure diagram of CIGS cell based on Igalson and Urbaniak, Bull. Pol. Ac.: Tech. vol.53(2), p.157, 2005. Curve is based on CIGS absorber, CdS buffer and ZnO as TCO.

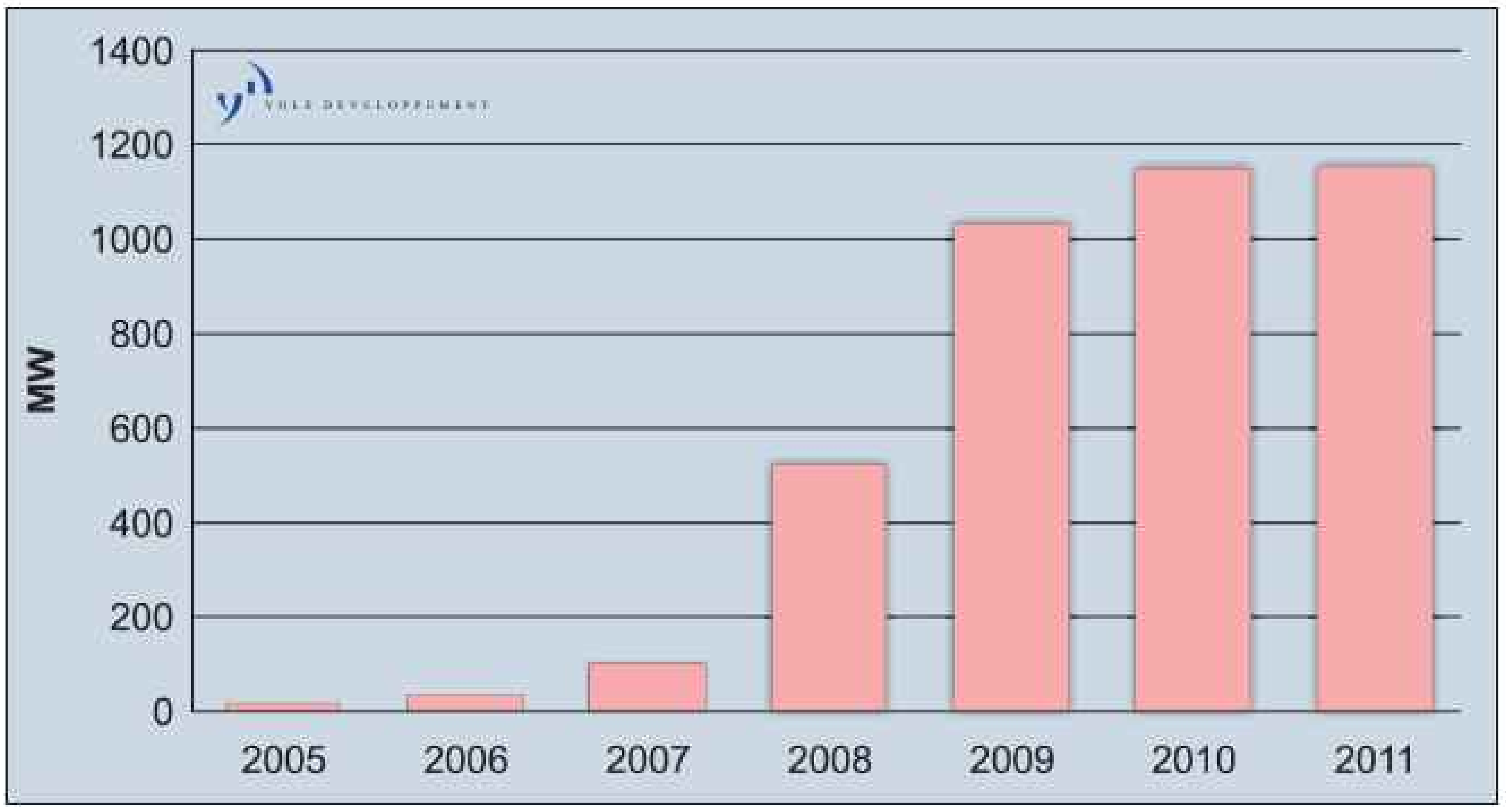

Figure 5. Yole Développement's projection for increased CIGS production capacity up to 2011.

set up by former founders of the older companies and staffed by some ex-employees of the original company. Such activities express tensions between finance and technological delivery of mass production. One would not be surprised to see acquisitions of the less successful start-ups by the more successful start-ups, or even by corporations wanting to buy into and dominate the market. Some may fail outright.

Print run

Vacuum deposition has been used extensively in production of all PV types up to now, in some ways a transfer from semiconductor production. However, more recently, printing-type techniques have been applied with a view to lower production costs.

One firm promoting printing of solar cells is Nanosolar, which has in addition won a contract to supply CIGS-based photovoltaic panels for a solar power plant located on a former landfill site owned by one of the largest waste management companies in east Germany. The project will be based on Nanosolar's 'Utility Panel' in combination with systems technology and services from Beck Energy. The initial size of the plant is planned at 1MW (an amount sufficient to power about 400 homes).

The Utility Panel is the first product in Nanosolar's PowerSheet product line. The company has designed the product line as a 'solution' for solar power plants on free fields at the outskirts of towns and cities.

"After five years of product development — including aggressively pipelined science, research and development, manufacturing process development, product testing, manufacturing engineering and tool development, and factory construction — we now have shipped first product and received our first check of product revenue," said Nanosolar's CEO Martin Roscheisen on the company's 'blog'.

Nanosolar describes itself as being in the 'third wave' of solar power development. The 'first wave' refers to the silicon-based solar cells of 30 years ago. The second was the development of commercial thin-film technology a decade or so ago. Nanosolar believes that it has tackled the shortcomings of previous solar technologies with seven innovations: the use of nanoparticle inks, semiconductor printing, conductive substrates, roll-to-roll processing, low-cost top electrode, sorted cell assembly into modules, and creating a high-current panel.

The ink contains the CIGS semiconductor material. According to Nanosolar, the four elements have to be in just the right atomic ratios to each other, locking in a uniform distribution. The homogeneous mix of nanoparticles in the ink in just the right overall amounts ensures that the atomic ratios of the four elements are correct wherever the ink is printed, even across large areas of deposition. This enables a low-cost roll-to-roll printing process in contrast to the usual vacuum deposition processes where, due to the four-element nature of CIGS, one has to atomically synchronize various material sources.

The ink is printed onto a conducting metal foil substrate rather than having to deposit an additional metal thin-film bottom electrode on a non-conducting substrate such as glass or polymer. Nanosolar claims that its metal substrate is 20 times more conductive than the stainless steel used by some competitors. Nanosolar also claims a low-cost transparent top electrode that supports an order-of-magnitude higher current than attained previously.

The company also claims to have dealt with problems of the electrical mismatches between cells in assembled panels that lead to significant power losses. All told, the company claims that its products deliver 5–10 times higher current compared with other thin-film solar panels on the market today. However, more detailed specs seem to be hard to find.

Nanosolar was founded in 2002 and says that it is building the world's largest solar cell factory in California and the world's largest panel-assembly factory in Germany. The US facility in San Jose covers an area of 140,000ft^2 and that in Berlin covers 507,000ft^2.

Global Solar Energy (GSE) is one of those using stainless-steel substrates. It makes a polycrystalline thin-film CIGS PV device, aiming for lightweight, durable cells. The company can provide these cells in strings for drop-in power sets in solar glass modules, allowing use of a similar process to silicon glass module manufacture. GSE's strings come in varying power sets and can be used for glass modules in the power range 6–100W. Like Nanosolar, GSE has a roll-to-roll process. In February 2008, the plan is to expand into a new factory in Tucson, Arizona, moving from a 20,000ft^2

facility to one with 100,000ft^2. Production capacity is expected to grow from 4.2MW to 40MW.

One US company using vacuum deposition is Miasolé. The firm's management team derives much of its expertise from the thin-film hard-disk industry and from the metrology company KLA-Tencor and thin-film technologies such as PVD and plasma deposition (Novellus and Lam). The cells are wrapped in rugged, flexible encapsulants, not glass. Miasolé claims to be able to deliver products in very large quantities using its process.

Cadmium-free layers

In Japan, Honda has set up Honda Soltec, with a CIGS facility starting mass production in October 2007 (see Figure 6). Honda boasts that its next-generation solar cell achieves a reduction of 50% in the amount of energy consumed during the manufacturing process compared to conventional crystalline silicon solar cells. Honda sees this as part of its 2006 global CO_2 reduction target for its products (including automobiles) and their manufacturing. Honda also says that it is focusing on the development and sales of energy-creation products such as thin-film solar cells to reduce the threat of global warming.

The company's CIGS-based modules come with two maximum powers: 125W and 115W. The module's dimensions are 1417mm x 791mm x 37mm and the weight is 14.3kg. The highest-wattage module is priced at about $540 (¥57,500) before tax. Honda's cells are produced on glass substrates. Interestingly, the company uses an indium sulfide layer rather than a cadmium sulfide layer. One motivation for this is cadmium's highly toxic nature. Cadmium is one of six chemicals whose use is restricted in the EU by the Restriction of Hazardous Substances (ROHS) directive. On the other hand, indium is rather expensive. CIGS development is seen as one of the contributors to the current high price of indium. Moves to mass production could give a further unwelcome boost to pricing. A few other groups have tried CdS alternatives such as In(OH,S) and $Zn(Se,OH)_x$.

Honda's figure for maximum output was measured under the conditions of air mass (AM) 1.5, solar radiation intensity of 1kW/m^2, and module temperature of 25ºC. The AM1.5 standard is common for evaluating solar cell performance in northern Europe. The air mass figure (1.5) gives the relative attenuation compared with that for a straight down (zenith) light path. The AM figure is greater than 1 because the sun is only ever directly overhead at noon in the tropics. Honda's cell operating temperature range is from +40ºC to −20ºC. The maximum output will differ depending on solar radiation intensity, installation conditions (direction, angle, surrounding environment), geographical area, and temperature conditions.

Figure 6. Honda's CIGS production facility.

Shell Solar has also transferred its efforts from silicon to $CuInSe_2$ (CIS, i.e. CIGS with x = 0). It has joined with Saint-Gobain in a new company, Avancis, based in Torgau, Germany. Production is due to commence in the middle of 2008, with an annual capacity of 20MW. Among the reasons given for the change from silicon is independence from shortages of the material. The firm claims that its pilot-production 1ft x 4ft CIS modules have an average efficiency of almost 13%, compared with the best performance in small laboratory samples of more than 19%.

Putting sulfur into the CIGS mix

Based on development work over 13 years at the University of Johannesburg in South Africa, Johanna Solar Technology uses a 3μm-thick absorber layer. The firm says that, due to improved temperature coefficients — which means lower performance losses at high temperatures — its thin-film modules are especially suited to temperatures above 25ºC.

The firm is putting its devices on glass, with the first step being deposition of the molybdenum back contact. A precursor layer consisting of copper, indium and gallium is then applied. These three elements are then

Figure 7. CIGS panel on a production line at Honda.

chemically transformed in a diffusion process under a gaseous atmosphere containing sulfur and selenium, resulting in a CIGSSe ($Cu(In,Ga)(S,Se)_2$) absorber layer (Figure 8). An electrical serial connection of individual cells into a module is realized during the coating process by structuring individual layers, giving rise to a 'pinstripe' pattern for the thin-film modules.

The firm's production site at Brandenburg an der Havel, Germany is due to come on-line this year with an initial output capacity of modules nominally capable of 30MW/year.

Adding sulfur extends the accessible range of bandgap energies and lattice constants (Figure 9). The bandgap determines the range of photon energies that the cell can transform to electric power (Figure 10). It gives a lower limit for photon energy absorption and hence an upper limit for wavelength. As with silicon-based solar cell technology, researchers (e.g. at NREL) are investigating multi-junction or tandem cells that can extend the range of photons that can be absorbed and converted to power, thus boosting efficiency (Figure 11). However, at this stage, tandem cell production, even in silicon, is struggling to achieve efficiencies above 10% while, as we have seen, 13% is being achieved with CIGSSe commercial production. ■

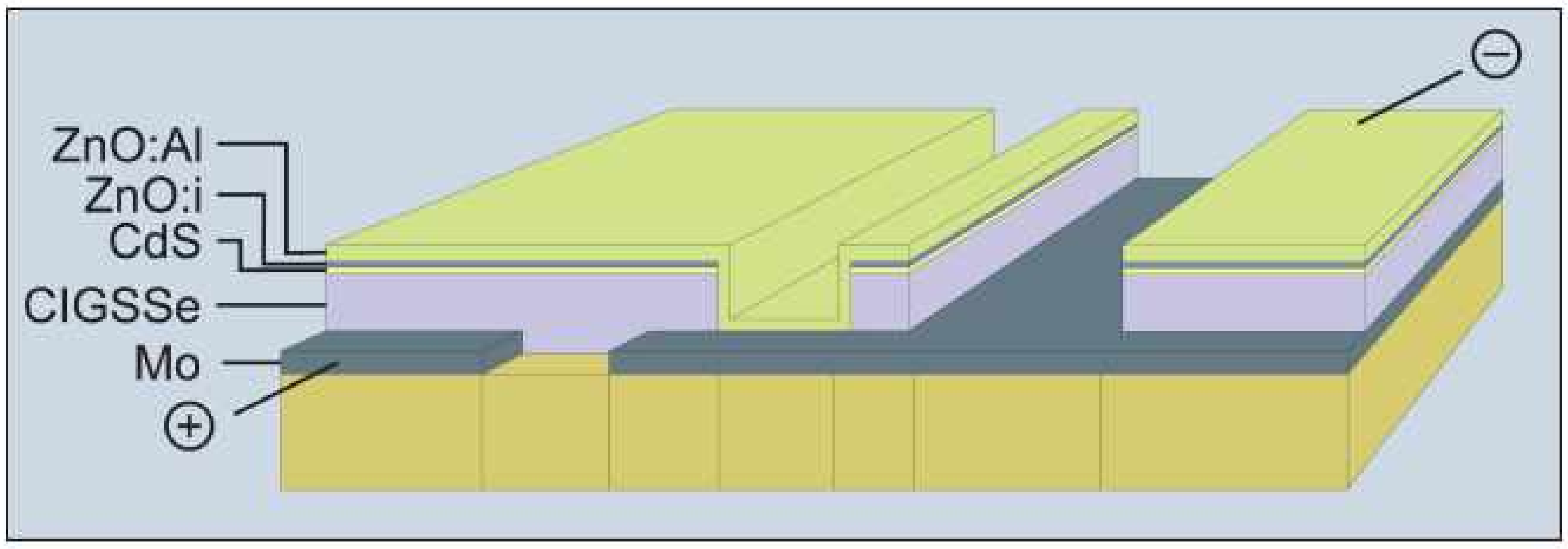

Figure 8. Schematic of Johanna Solar Technology's CIGSSe cell.

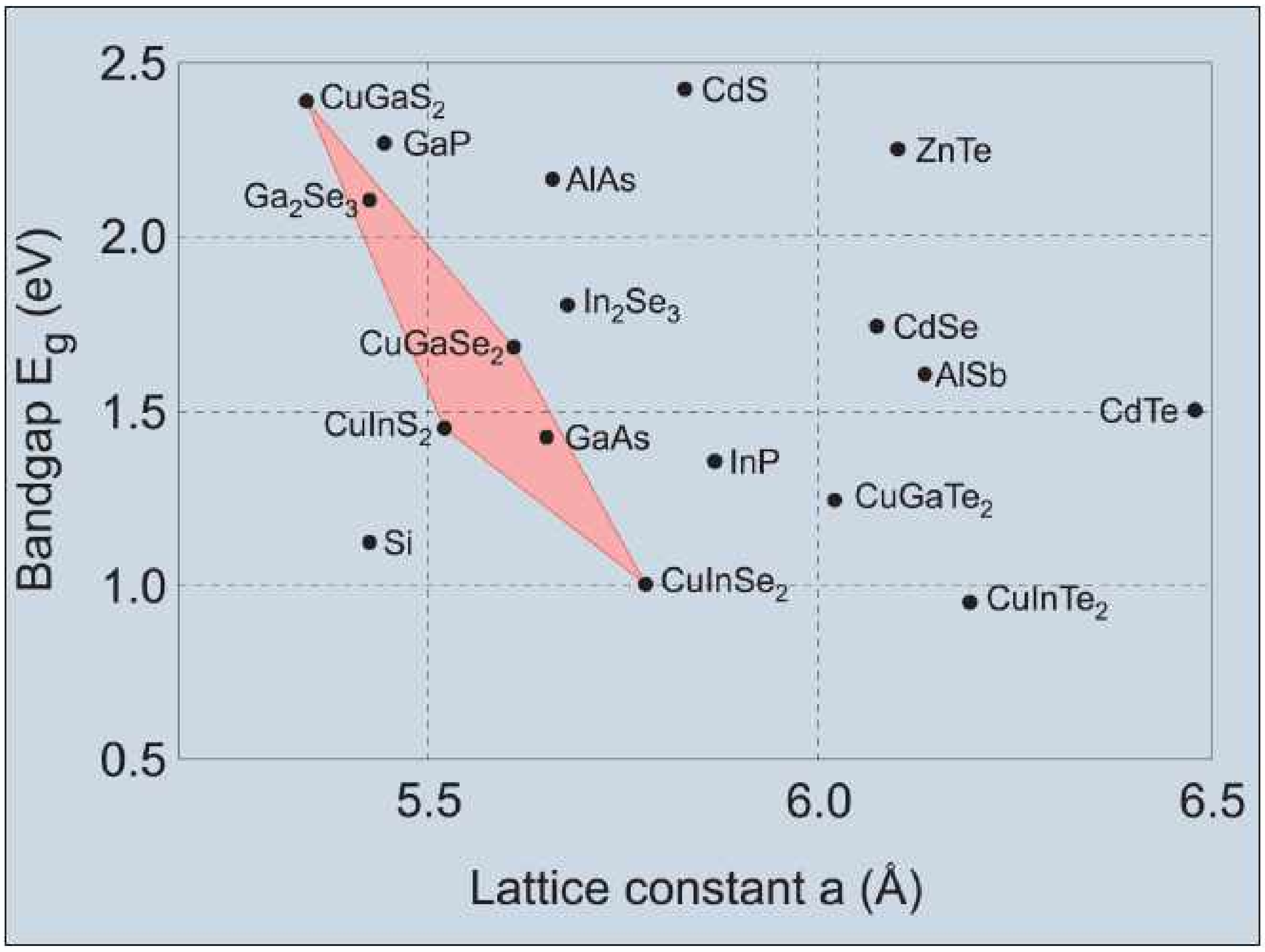

Figure 9. Bandgap energies and lattice constants of a number of semiconductor materials including $Cu(In,Ga)(S,Se)_2$, or 'CIGSSe', compounds that may be used to create single- or multijunction solar cells. The quadrilateral ($CuGaS_2$, $CuGaSe_2$, $CuInSe_2$, $CuInS_2$) shows approximate ranges (i.e. linear interpolation) for CIGSSe.

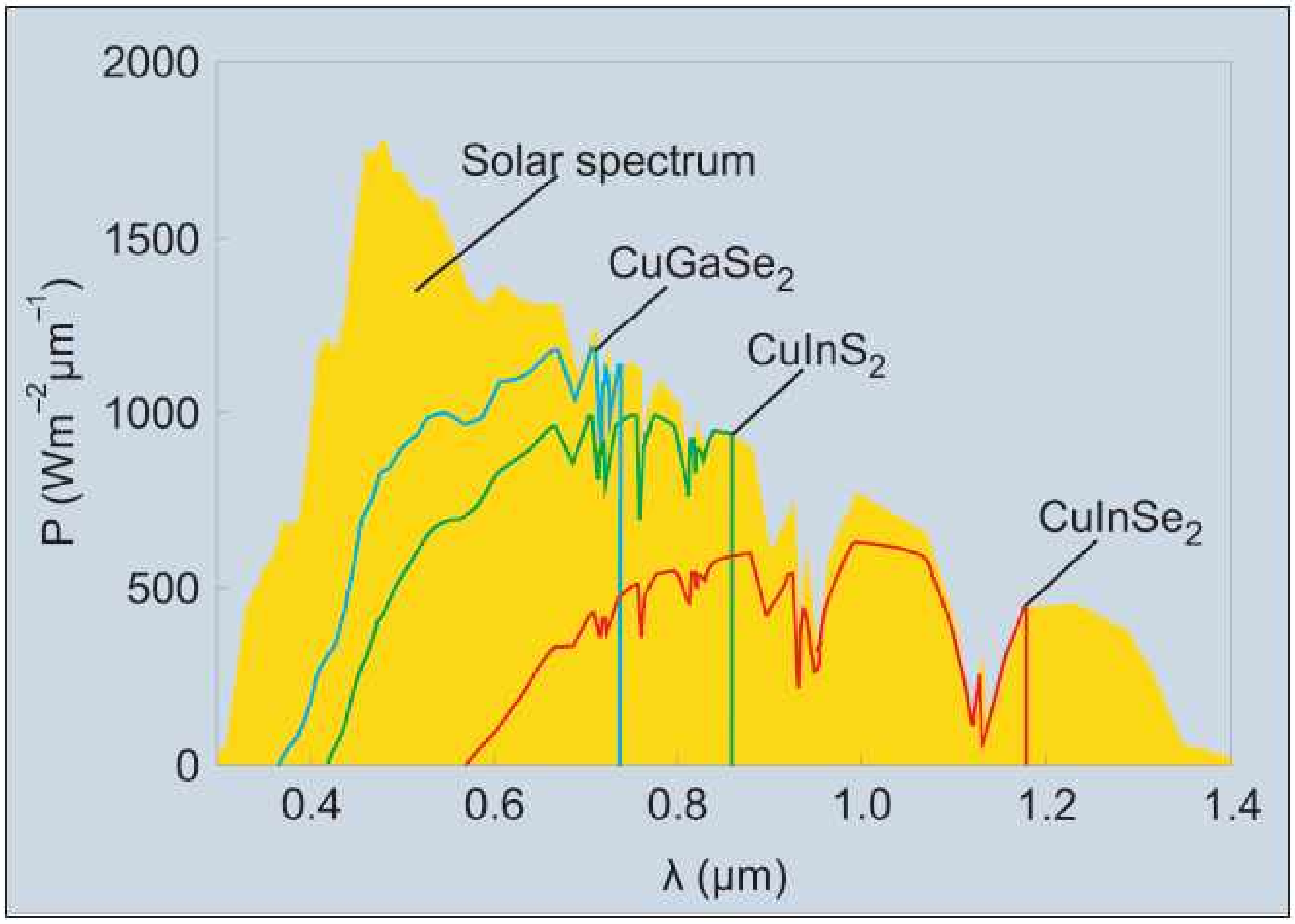

Figure 10. Solar spectrum and response of CIGS materials, showing possibilities for multi-junction solar cells.

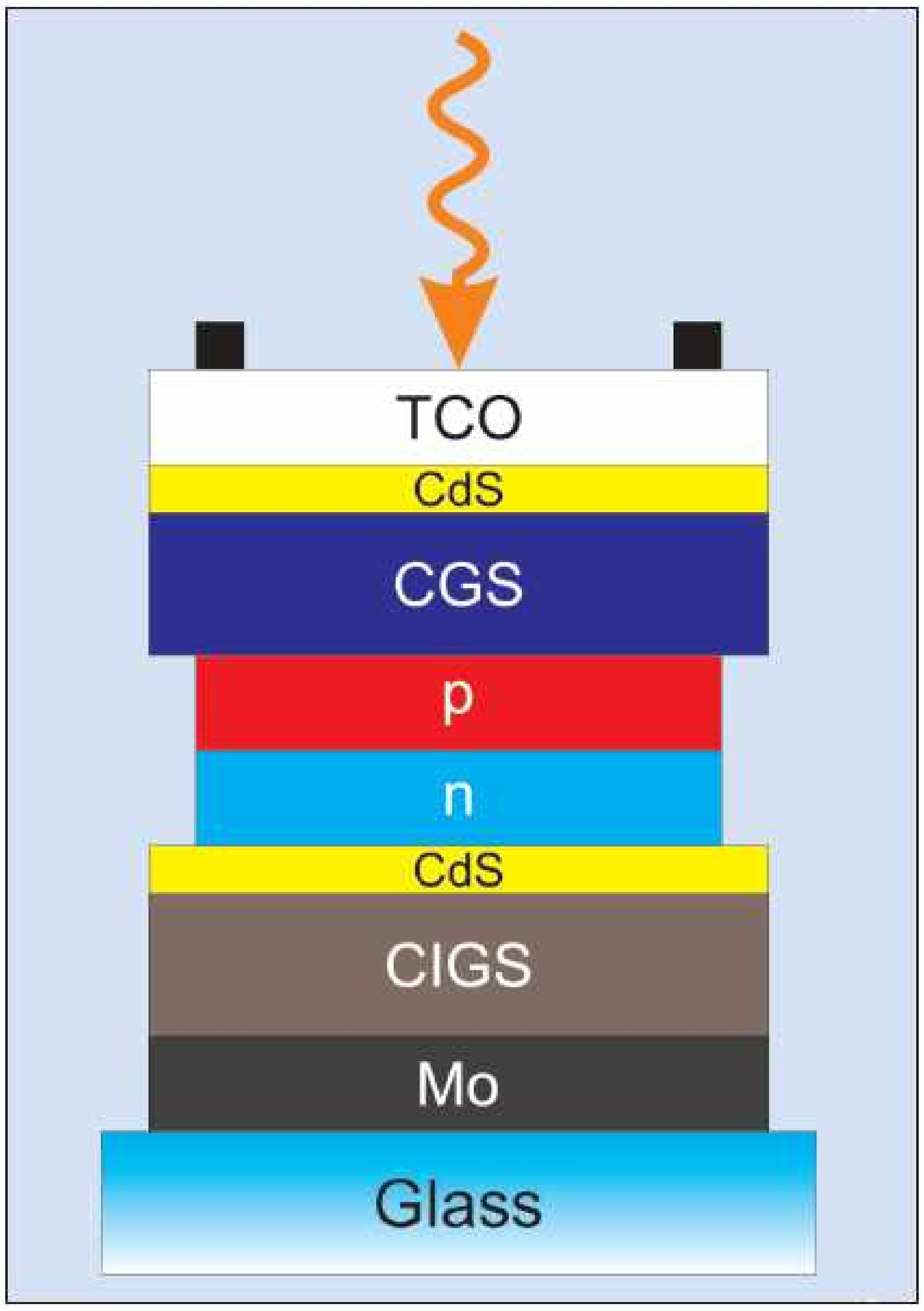

Figure 11. Structure for multi-junction CIGS solar cell being investigated by NREL.