

Current And Future Photovoltaics: Foresight

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ABSTRACT

Photovoltaics, now a billion-dollar industry, is experiencing staggering growth as increased concerns over fuel supply and carbon emissions have encouraged governments and environmentalists to become increasingly prepared to offset the extra cost of solar energy. Three 'generations' of photovoltaics have been envisaged that will take solar power into the mainstream. Photovoltaic production is currently 90% 'first-generation' or '1G' solar cells that rely on expensive bulk multi-crystalline or single-crystal semiconductors. Dominated by silicon wafers, they are reliable and durable but expensive. Half of the cost of 1G devices is the silicon wafer and efficiencies are limited to around 20%. Instead of using wafers, cheaper 'second-generation' (2G) solar cells would use cheap semiconductor thin-films deposited on low-cost substrates to produce devices of similar efficiencies. A number of thin-film device technologies account for around 5–6% of the market.

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I. INTRODUCTION

Why photovoltaics? There was a time when this was a difficult question to answer. Fossil fuel was plentiful and the supply apparently without end, and the Earth's environment appeared resilient. The photovoltaic (PV) industry was based on the niche applications of powering satellites and remote locations. However, the tide has changed dramatically with growing recognition of the environmental impact of non-renewable energy sources and the economic volatility that comes from reliance on oil. Subsidy-based market strategies, in particular in Japan and Germany in the late 1990s, have pump-primed a PV-industry that is becoming of increasing economic importance and is now a billion-dollar industry that is undergoing staggering growth (Figure 1). As well as providing an energy source that is acceptable to environmentalists, photovoltaics has the interest of a financial sector that now sees a business case for

investment. It seems possible that it will be economic arguments rather than environmental arguments that will push PV energy into the mainstream. Cost, in terms of \$/W, remains the greatest barrier to further expansion of PV-generated power, and cost reduction is the prime goal of the PV sector.

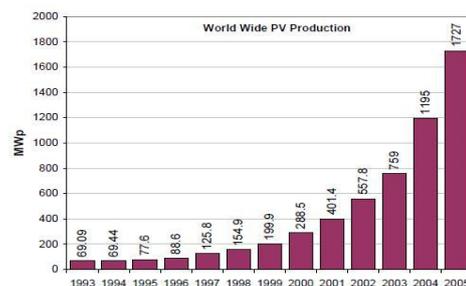


Fig 1: Yearly worldwide production of photovoltaics in MWp

II. CURRENT STATUS OF PHOTOVOLTAIC TECHNOLOGY

The current PV market consists of a range of technologies, including wafer-based silicon and a variety of thin-film technologies. The range of current technologies and possible future options have been grouped from current 1G to future 3G technologies (Green 2006).

1G PV

Current PV production is dominated by single-junction solar cells based on silicon wafers, including single-crystal (c-Si) and multi-crystalline silicon (mc-Si). This type of single-junction, silicon-wafer devices is now commonly known as 1G technology, the majority of which is based on screen-printing-based devices similar to that shown in Figure 2.

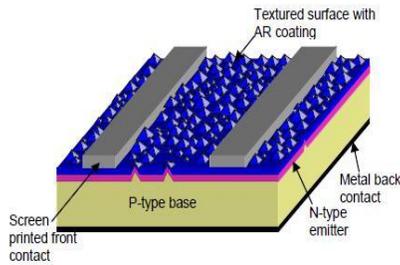


Fig 2: Schematic of a typical screen-printed single-crystal solar cell

Originally built using single-crystal wafer silicon (c-Si) and processing technology from the integrated circuit industry (IC), it is clear that 1G silicon PV benefited greatly from its symbiosis with the IC industry which provided the materials, processing know-how and manufacturing tools necessary to allow a rapid move to large-scale production. In spite of much progress, 1G PV costs around US\$4/W, and this is still around four times too expensive for truly competitive commercial production. It is likely that the cost-reduction trend will reach its limit before 1G PV reaches full cost competitiveness. Though it should be noted that relative cost reductions (for both 1G and 2G) are also resulting from spiralling energy costs.

2G PV

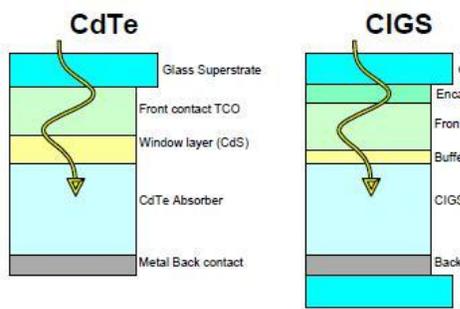


Fig 3: Schematic diagrams of thin-film CdTe, CIGS, and a-Si thin-film PV devices

The obvious next step in the evolution of PV and reduced \$/W is to remove the unnecessary material from the cost equation by using thin-film devices. 2G technologies are single-junction devices that aim to use less material while maintaining the efficiencies of 1G PV. 2G solar cells use amorphous-Si (a-Si), CuIn(Ga)Se₂ (CIS), CdTe/CdS or polycrystalline-Si (p-Si) deposited on low-cost substrates such as glass (Figure 3). These technologies work because CdTe, CIS and a-Si absorb the solar spectrum much more efficiently than c-Si or mc-Si and use only 1-10µm of active material. Meanwhile, in very promising work in the last few years, p-Si has been demonstrated to produce ~10% efficient devices using *light-trapping* schemes to increase the *effective thickness* of the silicon layer (Figure 4).

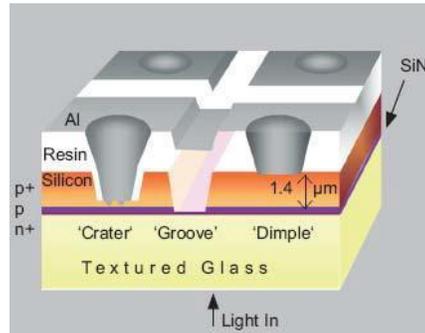


Fig 4: Key features of the crystalline silicon on glass (CSG) technology

3G PV

As 2G technology progressively reduces the active material cost with thinner films, eventually even the low-cost substrate will become the cost limit and higher efficiency will be needed to maintain the \$/W cost reduction trend. The possible future is for 3G devices, which exceed the limits of single-junction devices and lead to ultra-high efficiency for the same production costs of 1G/2G PV, driving down the \$/W (Green 2006). 3G concepts can be applied to thin-films on low-cost substrates to retain material cost savings, but there is also benefit in applying 3G concepts using thin-films on c-Si as *active substrates*. Such an attractive proposition as this may allow current 1G PV manufacturing plants to access the step-change efficiencies of 3G without necessarily undertaking a step-change in retooling and thereby minimising the type of uptake barrier to investment that is seen for 2G PV.

The emergence of 3G approaches are already

showing up commercially in 32% efficient, thin-film GaInP/GaAs/Ge triple-junction space-PV for satellites (Karam et al. 1999). These space-cells are too expensive for terrestrial application, but nevertheless demonstrate the viability of the 3G approach. Lower-cost 3G-PV is also appearing, such as Kaneka's 11.7% *micromorph* a-Si/ μ c-Si heterostructures (Yoshimi et al. 2003), and 10.4% triple-junction a-Si/a-SiGe devices (Yang et al. 1994).

III. FUTURE ADVANCES TO 2050 AND BEYOND

As we have discussed, progress in PV technology should be measured in \$/W, and many scientific advances, fascinating as they are, will only be relevant to the industry if they can be implemented at affordable costs. In this sense, we can envisage two routes to cheaper photovoltaic energy that will be brought about by new science and 3G concepts. The first is based on the pragmatic use of new technology to improve the performance or decrease the cost of current devices capitalising on existing manufacturing plant and proven mass-production capacity. The second, more revolutionary, possibility might involve new whole-device concepts. Indeed, in recent years, we have seen the emergence of *dye-sensitised* (Gratzel 2001) and polymer-based solar cells (including organic/inorganic hybrids) (Kanicki 1986; Brabec and Sariciftci 2001) as fundamentally new types of device, and although none of these have come close to outperforming wafer-based silicon devices in cost or efficiency, there is every chance that these devices might still demonstrate step-change improvements or that new types of device may yet emerge. Some of the most interesting 3G concepts discussed in the last 30 years include multi-junction systems such as tandem cells (Henry 1980), the use of quantum wells and quantum dots to enhance absorption (Barnham and Duggan 1990), the use of fluorescent collectors (Weber and Lambe 1976; Goetzberger and Greubel 1977), impact-ionisation to utilise the kinetic energy of carriers (Landsberg et al. 1993; Kolodinski et al. 1993), the use of impurity levels (Corkish and Green 1993) and hot-electron effects (Ross and Nozik 1982). While many of these exciting ideas have fired the imagination and provided interesting debate, most have proven very difficult to demonstrate in principle and have often only ever served to manage to decrease the overall efficiencies of devices they hoped to improve. In a similar way, dye-sensitised cells (Gratzel 2001) still face difficult issues related to poor charge mobility and device stability and we can't confidently predict that these devices will have a commercial

impact. In the remainder of this paper, we focus on new concepts that we believe can have significant practical impact.

IV. MATERIALS DEVELOPMENTS

Photovoltaic performance is heavily dependent on the properties of materials. In particular, the active layers of solar cells require long carrier diffusion lengths and bulk material must be defect-free, and surfaces and *grain-boundaries* must be passivated. Fundamental materials research, of materials, grain boundaries, surfaces and passivating materials, can always be justified in this context. Although it seems unlikely that any future developments of known materials can produce a step-change in headline efficiencies, improvements in production yield or stability can be expected and research emphasis needs to be on materials produced by large-volume tools. An exceptional case for materials developments can be made for semiconducting polymers, where the vast parameter space and inherent simplicity of device fabrication allows for considerable optimisation and optimism

III. OPTICAL METAMATERIALS

Photovoltaic arrays can either track the sun as it moves across the sky (at some expense) or remain fixed and have to accept a loss of efficiency as increasingly acute angles of incidence reduce the area of the device and significantly increase reflection. For fixed systems, around 20% of available photons are lost over a day as a result of reflection (Boden and Bagnall 2006), but now the emergence of nanotechnologies and optical-metamaterials is beginning to offer solutions to this issue. Currently, some commercial manufacturers use self-organised nanostructured glass surfaces to improve system efficiencies by around 10% (Wohlgemuth et al.). More carefully constructed nanostructures that mimic the eyes of species of moth (Figure 5) (Vukusic and Sambles 2003) promise further improvements but are currently too expensive to implement.

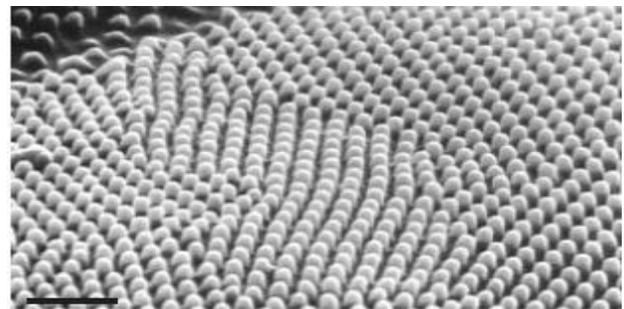
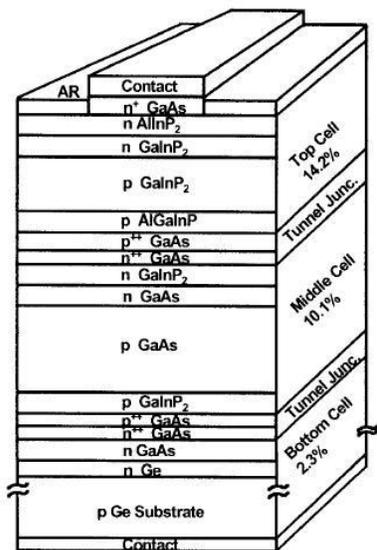


Fig 5: SEM micrograph of surface of the cornea of a night-flying moth (scale bar is 1 μm)

In the next 10 years, similar optical technologies might also allow for improved light-trapping in thin-film solar cells and concentrator cells (see below). As we have seen, thin-film silicon devices, in particular, require multiple reflections within the silicon layer to ensure the absorption of photons. Optical constructs are required to ensure that light is coupled into a waveguiding mode of the thin-film (Heine et al. 1996). At present, thin-film silicon devices rely on diffuse reflectors produced by relatively simple etching regimes that are cheap to realise over large areas (for example, Yamamoto 1999; Chuangsuwanich et al. 2004), designed nanostructured surfaces are likely to offer routes that are optically more efficient that might also be applicable to *ultra-thin* CdTe- and CIGS-based thin-film devices. Increases in efficiency here are less important than the reduction in the thickness of absorbing material that is required and the commensurate reduction in cost. Tandem devices are naturally the most advanced multi-junction technology and there are many examples of combinations of 1G and 2G devices to produce 3G devices. The highest-performing devices are, however, expensive devices that can only be reasonably contemplated for concentrator or space applications (Karam et al. 1999). More cost-effective terrestrial multi-junction devices combine the polysilicon and amorphous thin-film silicon technologies (Yoshimi et al. 2003; Yang et al. 1994). These devices are relatively inexpensive for their efficiency but do not realise the full potential of multi-junction efficiency improvements.

Fig 6: Schematic cross-section of the Spectrolab triple-junction cell

Multi-junction cells no longer require proof of principle, but they do require technological advances aimed at cost reduction. These cost reductions can come about by being able to produce much cheaper devices or by using high-concentration systems. A key issue with concentrator systems is the need for mechanical tracking, with associated higher production and maintenance costs that offset the efficiency gains. At the device level, key requirements are in material growth, contacting, bonding and insulation and nanotechnology, and the principles of self-alignment and self-organisation may well help solve some of these key difficulties over the next 20 years. We are confident that some large-volume high-efficiency multi-junction devices will be well positioned in the terrestrial market place within 20 years. Perhaps the most promising futuristic prospect for multi-junction approaches will be based on polymer semiconductors, or combinations of polymer semiconductors with crystalline semiconductors. The intrinsic ability to tune polymer bandgaps and the forgiving low-cost, low-temperature, versatile deposition capability make polymers a natural choice, although the contacting issues generic to multi-junction cells and the long-term stability problems that affect polymer solar cells will remain problematic. By 2050, it is possible to imagine that self-organised semiconducting polymer structures, in multi-junction arrangements could be the mainstream 50%-efficient PV technology.



VI. SPECTRAL CONVERSION

A number of 3G concepts would make use of surface layers and structures to convert the solar spectrum to a spectral distribution that is more useful to the underlying device. Classically, one would like to use the non-linear optics (NLO) concepts to produce bandgap energy photons from low-energy photons (up-conversion). The reverse of this type of process could produce bandgap photons of short wavelength, high-energy photons (down-conversion). These schemes have been explored theoretically and predicted to produce device efficiencies of 63 % for up-conversion and 40% for down-conversion (Trupke et al. 2002). NLO crystals are routinely used to efficiently perform these types of conversion. However, even the most efficient NLO materials can only operate at specific wavelengths and angles of

incidence, and with relatively high and often coherent optical densities. At the moment, NLO materials seem unlikely to be able to help mainstream photovoltaics. More likely systems for spectral conversion are based around quantum dots (van Sark et al. 2004), rare-earth doping and (Matsura 2002) luminescent dyes (Richards and McIntosh 2006). In each case, an 'optical' layer above a device is designed to absorb one set of photons and then emit a set of more appropriate photons. The generic difficulties associated with these processes are connected with the need for broad-band absorption across the wavelength ranges of interest (most of these systems have very sharp spectral features) and the need for 100% efficiency (or transparency) in spectral regions close to the band edge. Broad-band absorption can be achieved by the use of inhomogeneous broadening mechanisms. In the case of quantum dots, this would be readily achieved by changing the size distribution of the dots, but for rare-earth doping systems, broadening requires variation in the material supporting the atoms and this is more problematic. Meanwhile, mixtures of dyes are needed to broaden absorption. In each case, broadening the absorption leads to broadening of the emission and this will normally decrease the optical conversion efficiency. It is therefore likely that spectral conversion will always be a difficult issue, and it seems unlikely that very high-efficiency devices could be created. We can, however, anticipate two promising avenues for exploitation that might impact on commercial production. First, it seems highly likely that quantum dots embedded in dielectric layers directly above traditional devices might readily add 3–5% to device efficiency with little extra cost (van Sark et al. 2004). Second, spectral conversion could be applied within fluorescent collectors (Weber and Lambe 1976; Goetzberger and Greubel 1977) where large-area waveguiding layers containing dye molecules, quantum dots or nanocrystals could be used to concentrate light into the sides of small-area pn-junctions. Here, the benefit is not high-efficiency devices. Instead, the benefit is in semiconductor volume reduction; two orders of magnitude less silicon might be needed to produce 20% devices (Markvart 2006).

VII. SELF-ORGANISED QUANTUM DEVICES AND NANOSTRUCTURES

In addition to the possible use of quantum dots as spectral converters, the use of quantum wells and quantum dots has also been proposed to extend the bandgap (Barnham and Duggan 1990) and as a

means to provide multiple electrons from a single photon through impact ionisation (Kolodinski et al. 1993; Ross and Nozik 1982).

Impact ionisation is a process in which absorbed photons in semiconductors of at least twice the bandgap can produce multiple electron-hole pairs. Kolodinski proposed the use of Ge superlattices for this purpose (Kolodinski et al. 1995). Alternatively, Si/Ge or Si/SiO₂ superlattices could be used (Green 2006), or certain quantum dots (Ellinson et al. 2005) that can generate two or three excitons (electron-hole pairs) per photon, which could tunnel or transfer (via polariton modes) from surface layers into the conduction band of 1G or 2G devices and thereby increase the efficiency. The prospects for impact ionisation will be limited by the finite flux of high-energy photons and the need for effects over a broad spectral range. As with some of the other concepts already discussed, the most likely practical implementation would be in the simple addition of a cheap layer of self-organised structures that might add 2% or 3% to device efficiency. A truly futuristic and nanotechnological approach to photovoltaics might involve the use of self-organised structures. Most of mainstream PV to date has been based on layered, large-area devices, as alternative would be the use of arrays of high densities of self-forming nanodevices, many semiconductors have been grown in nanowires or nanorods (Kayes et al. 2005) via vapour-liquid-solid (VLS) techniques. It is also possible to imagine other seeded or selective growth techniques to provide small high-quality crystallites that could also form the basis of nanodevices. Advantages of such approaches would include the reduction of material volume, uniformity of device behaviour, good crystalline growth on amorphous substrates and prospects for multi-junctions.

VIII. CONCLUSIONS

In the next 20 years, we can foresee only small improvements in the production efficiencies of 1G silicon technologies. However, we can expect fabrication, installation and operational cost reductions (up to 30%) that will continue to provide reduced \$/W and increasing competitiveness. During the next 20 years, we will witness a change from predominantly 1G production to an era including a significant market share of 2G devices, probably based on thin-film silicon (up to 30% cost reduction). While these two mainstreams will dominate the commercial PV sector, we expect that, over the 20 years, we will see increasing use of new and 3G technologies that will enhance the performance (or reduce the cost) of 1G and 2G solar cells. These technologies are very likely to include some multi-

junction concepts and constructs based on the emerging fields of optical metamaterials, plasmonics, quantum technology, nanotechnology and polymer semiconductor science.

By 2025, we fully expect photovoltaics to have become a truly cost-competitive energy supply, though the timing of this will depend on levels of research investment, market stimulation, the levels of national, international and multinational co-operation and the rate of increase in the cost of non-renewable energy supplies.

REFERENCES

1. Barnham, K.W.J. and Duggan, G. 1990. A New Approach to High-Efficiency Multi-Band-Gap Solar Cells. *Journal of Applied Physics*, 67:3490–3493.
2. Brabec, C.J. and Sariciftci, S.N. 2001. Recent Developments in Conjugated Polymer-Based Plastic Solar Cells. *Chemical Monthly*, 132:421.
3. Boden, S.A. and Bagnall, D.M. 2006. Proceedings of the 4th WPSEC, Hawaii.
4. Bohren, C.F. and Huffman, D.R. 1983. *Absorption and Scattering of Light by Small Particles*. New York: John Wiley & Sons.
5. Bruton, T. et al. 2003. Proceedings of the 3rd World Conference on Photovoltaic Energy Conversion. Osaka.
6. Chuangsuwanich, N., Widenborg, P.I., Campbell, P. and Aberle, A.G. 2004. Technical Digest, 14th IPSEC, Bangkok. 325.
7. Compaan, A.D., Sites, J.R., Birkmire, R.W., et al. 2003. Electrochemical Society Symposium Proceedings, ECS99-11.
8. Corkish, R. and Green, M.A. 1993. 23rd IEEE Photovoltaic Specialists' Conference. Louisville, 675.
9. Ellinson, R., Beard, M. and Johnson, J. 2005. Highly Efficient Multiple Exciton Generation in Colloidal PbSe and PbS Quantum Dots. *Nano Letters*, 5(5) 865– 871, American Chemical Society 2005.
10. EurObserv'ER 2006. Photovoltaic Energy Barometer.
11. Goetzberger, A. and Greubel, W. 1977. Solar-Energy Conversion with Fluorescent Collectors. *Applied Physics*, 14:123–139.
12. Green, M. 2006. *Third-Generation Photovoltaics: Advanced Solar Energy Conversion*. Berlin: Springer.
13. Green, M.A., Basore, P.A., Chang, N., et al. 2004. Crystalline Silicon on Glass (CSG) Thin-Film Solar Cell Modules. *Solar Energy Materials and Solar Cells*, 77:857.