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Forty Years of Photovoltaic Research at UNSW

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Abstract

The UNSW photovoltaic group started over 40 years ago in 1974, when the author was appointed as a young academic at UNSW. Within 10 years, the group had established an international reputation, achieving its first world record in the form of a silicon solar cell with independently confirmed 18% efficiency in 1983. This was a significant improvement upon efficiency levels initially established at Bell Laboratories and then further enhanced by the Communications Satellite Corporation (COMSAT, a company established specifically to develop US space communications technology). This record was the first of 18 successive internationally certified UNSW increments that took efficiency first beyond the 20% level, regarded us the "four-minute mile" of the field, eventually to 25%. The PERC (Passivated Emitter and Rear Cell) technology used to achieve the 25% result is now finding its way into commercial production as manufacturers follow the trail to higher efficiency earlier blazed in the laboratory. The PERC cell is expected to become the commercially dominant technology within the next 5 years as manufacturers inch towards 25% cell conversion efficiency in production.

Introduction

The origins of photovoltaics usually are traced back to 1839 when 19-year old Edmond Becquerel, working in his father's laboratory in Paris, measured electrical output from the electrochemical apparatus of Fig. 1a (Becquerel, 1839). It took nearly 40 years until Adams and Day demonstrated the effect in solid-state material. Working with selenium specimens originally prepared in 1873 for photoconductivity experiments by Willoughby Smith, they wondered whether it would be possible *"to start a current in the selenium merely by the action of light"* (Adams and Day, 1877). This proved to be the case although, with the required background theory still decades off, was attributed to light-induced selenium crystallisation. From their publication, the author prepared the sketch of Fig. 1b. A colleague, John Perlin, recently tracked down these specimens in London, publishing a photograph similar to the sketch (Perlin, 2013).

The first photovoltaic visionary, Charles Fritts of New York (Fritts, 1883), made a large number of thin-film solar cells with the structure sketched in Fig. 2, sufficient to install an approximately 3-m^2 rooftop system in New York. An 1884 photograph of this system has also been published by John Perlin (Perlin, 2013). Although this was still before reticulated power supply was common, Fritts foresaw the possibilities that only now are becoming a reality, noting that *"the current, if not wanted immediately, can either be "stored" where produced, in storage batteries … or transmitted … to a distance, and there used, or stored …"*. Despite this enthusiasm, subsequent progress was slow, probably due to the on-going lack of a good theoretical explanation for the observed

effects. Selenium remained a common photovoltaic material up until the 1960s, due to the good match of its response to that of the human eye.

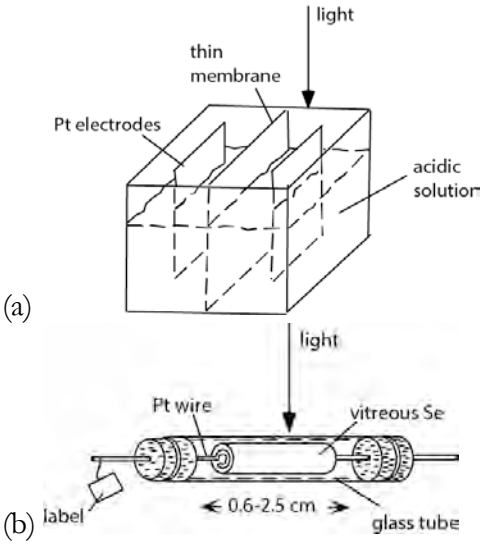


Figure 1: (a) Diagram of Becquerel's apparatus (1839); (b) Samples used by Adams and Day in 1876 for the investigation of the photoelectric effects in selenium.

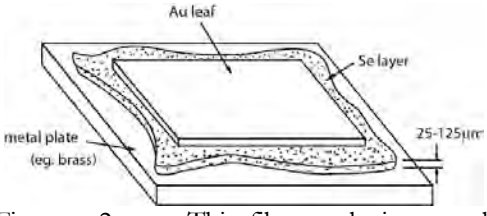


Figure 2: Thin-film selenium cell demonstrated by Fritts in 1883.

Einstein's explanation of the photoelectric effect during his "miraculous year" (Einstein, 1905) led ultimately to quantum theory and to Alan Wilson's subsequent explanation of semiconductor properties based on this theory (Wilson, 1931). Stimulated by growing interest in cuprous oxide devices (Grondahl, 1933), Walter Schottky then explained the photovoltaic effect as an interfacial effect caused by a barrier at the semiconductor surface (Schottky, 1938).

Schottky's work was crucial to the interpretation of a chance observation by Russell Ohl at Bell Laboratories in 1941 when he observed a photovoltage in slowly crystallised polycrystalline silicon specimens (Ohl, 1941). Pondering over this observation, the Bell Laboratory team correctly identified the effect as due to a barrier at the interface between silicon regions with different properties, *"like a Schottky barrier"*, with the material either side having properties described as positive (p-type) and negative (n-type).

Photovoltaics consequently was pivotal in the discovery of the p-n junction, the device that underpinned the subsequent microelectronics revolution. William Shockley published p-n junction theory in its full detail in 1949 (Shockley, 1949). This and associated technology development led to the reporting of the first efficient silicon solar cell in 1954 (Chapin et al., 1954). The associated press release made a big impact, with the results making it to the front page of the New York Times on April 24, 1954 (along with an update on the Petrov affair). This all seemed like ancient history to me when I made my first photovoltaic cell in 1971, but even Schottky's barrier work was closer to that date than is the present.

Silicon Cell Development

After demonstrating the first efficient silicon cell, Bell Laboratories and associated spin-off companies continued cell development, with application in space the main driver. Energy conversion efficiency improved rapidly, but stabilised at about 14% (under terrestrial sunlight) in the early 1960s. A decade later, COMSAT applied several of the substantial developments that had occurred in

microelectronics over the intervening years to improving cell technology (Lindmayer and Alison, 1973), with efficiency close to 17% by present standards established in 1974 (Haynos et al., 1974), the same year as the author joined UNSW as a young academic.

The cell structure establishing this new performance level is shown in Fig. 4. This has served as the benchmark for subsequent work, since a relatively simple way of making a lower cost version was reported at about the same time, using a screen-printing approach to form the metal contacts (Ralph, 1975). By the early 1980s, this approach had become the industry standard, with this position only now being challenged by technology incorporating subsequent UNSW improvements in the form of PERC technology.

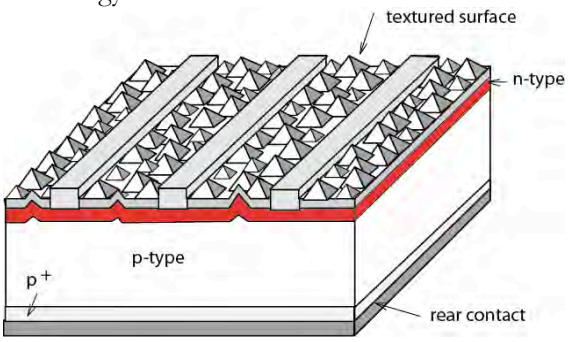


Figure 3: "Black cell" developed in COMSAT in 1974 (Haynos et al., 1974), essentially the same technology dominating the commercial production of terrestrial cells over a 30-year period from the early 1980s until recently.

The author's PhD thesis in Canada had investigated the properties of the Metal-Oxide-Semiconductor (MOS) structure when the oxide became sufficiently thin that electrons could pass through it by quantum mechanical tunnelling. One property identified was that these thin-oxide MOS devices could be designed to give properties identical to those of the ideal semiconductor p-n junctions that Shockley had earlier analysed. However, being free of some of the limitations of actual p-n junctions, they demonstrated superior properties in some applications (Green et al., 1974).

Working with my first PhD student, Bruce Godfrey, we reported our first notable result with this structure in 1976, demonstrating a 618 mV open-circuit voltage (Voc) at solar current densities (Green and Godfrey, 1976), one of the higher values for silicon at this time. Around this period, NASA-Lewis initiated a program to improve silicon space cell efficiency by improving Voc (Brandhorst, 1976). This started a competition between UNSW and several US groups being funded by NASA to achieve this outcome.

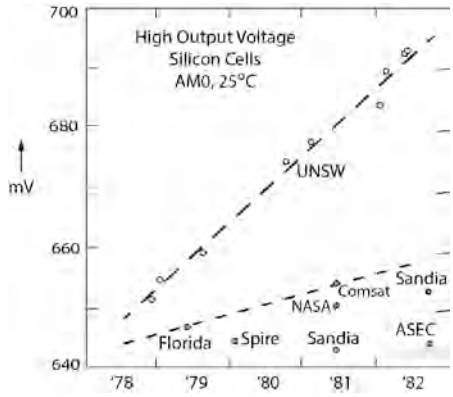


Figure 4: History of silicon cell Voc improvement showing the lead established at UNSW using surface oxide passivation.

We did well, as indicated in Fig. 4. Shortly after completing the original hand-drawn version of this figure and showing it to Professor Dick Collins, Chair of the technical advisory committee of the National Energy Research, Development and Demonstration Council at that time, Dick commented that I had used all the tricks of the trade for the graph, suppressing the zero on the voltage axis to magnify the advantage. In defence, I

pointed out that I had suppressed the zero on the other axis as well.

Actually, since Voc depends logarithmically on recombination caused by cell deficiencies, each 20mV gain represents a doubling of cell quality, so that graph does suggest, at least in this respect, the magnitude of the advantage UNSW was establishing. Having gained a clear lead in Voc, our focus then became to convert this into an efficiency advantage, by putting into place technology such as double layer antireflection (AR) coatings and fine linewidth, plated metallisation required to capture the full current output capability of the cell.

Figure 5: Team responsible for the world's first 18% efficient cell in 1983 (right to left): Ted Szpitalak (Professional Officer); Andrew Blakers and Stuart Wenham (author's 2nd and 3rd PhD students), Martin Green (author); Jiqun Shi (visiting Chinese scholar, one of the first to benefit from Deng Xiaoping's policy changes); and the late Erik Keller (Professional Officer).

We achieved this in 1983, when we made and had certified the world's first 18% efficiency silicon cell (Blakers et al., 1984; Green et al., 1984a). The elation of the team achieving this result is captured in Fig. 5. Within a few months, with a slight change in cell design, we increased this to an efficiency then certified as above 19% (Green et al., 1984b) (18.4% by present standards).

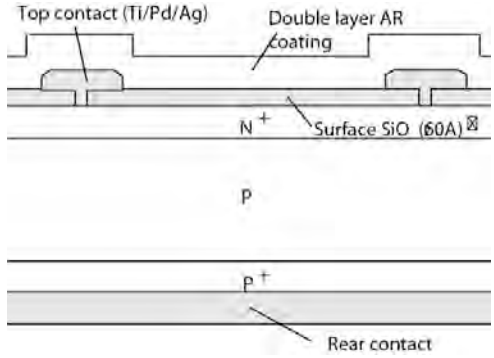


Figure 6: Passivated Emitter Solar Cell (PESC), the first silicon cell with efficiency certified as above 19%.

The new PESC cell structure (Passivated Emitter Solar Cell, with "emitter" referring to the top n^+-doped layer) is shown in Fig. 6. The reason for its high performance was the relatively high cell Voc (651 mV), as might have been expected from our previous work. Two cell features, first identified in our earlier work, were responsible for this high Voc. One was the use of a thin layer of oxide along the top surface of the cell, a vestige of our initial work on tunnelling MOS oxides. This oxide was shown crucial for our high voltages by reducing the electronic activity ("passivating") of defects normally associated with the silicon surface. The second was the way contact was made through pre-patterned holes in this oxide, giving small area contacts. This small-area contact was to reduce the impact of the poor electronic properties at the associated metal/silicon interface, an approach the author had earlier proposed in the first paper he wrote after joining UNSW (Green, 1975).

Ideas for future work were outlined in both a grant final report (Green et al., 1984c) and a grant proposal (Green, 1984d) prepared around this time (late 1983). One idea was to

texture the top surface of the cell as in Fig. 3, to reduce reflection and to couple the light obliquely into the cell, allowing it to be absorbed more strongly. The second was to apply similar ideas to those that had proved successful on the top cell surface to the rear of the cell to form the variant of the PERC cell (Passivated Emitter and Rear Cell) shown in Fig. 7.

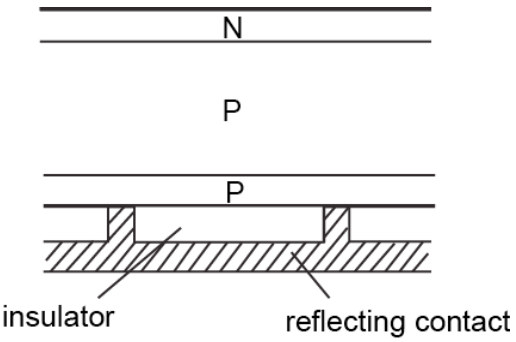


Figure 7: PERC (Passivated Emitter and Rear Cell) as originally proposed in 1983 (Green et al., 1984c; Green, 1984d).

The surface texturing strategy was more quickly implemented, producing the first 20% efficient cell in 1985 (Green et al., 1985; Blakers et al., 1986). This efficiency had earlier been proposed as a practical limit on silicon cell efficiency, becoming the "4-minute mile" of the photovoltaic field. The earlier successes leading to this landmark result had allowed the team to grow by this stage, as apparent from the photograph of the successful 20% team (Fig. 8).

The work then headed off in two different directions. In one strand, we pushed on towards higher efficiency, based on the author's earlier prediction that 25% efficiency was a realistic practical target (Green, 1984e). In the other strand, we explored ways that our 20% PESC cell could be fabricated at low cost. The challenge was to find a way of implementing the cell's fine features, specifically the small area contacts and narrow metal lines, without calling upon expensive photolithographic techniques developed for microelectronics (but used in silicon space cells by this time and in our 20% device).

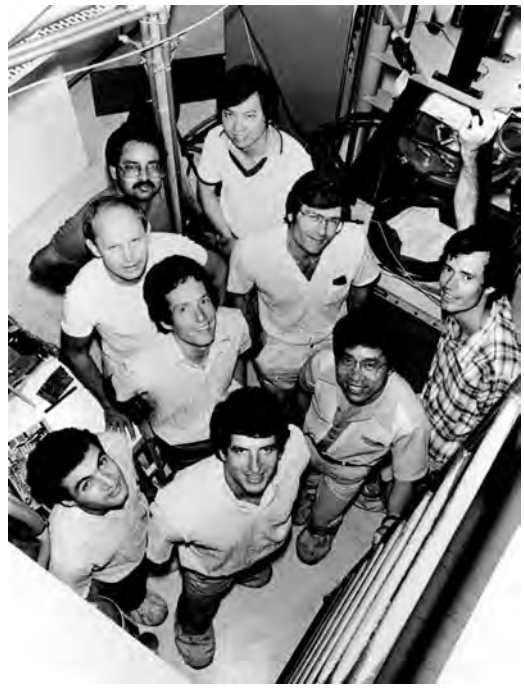


Figure 8: Photograph of the team achieving the photovoltaic "4-minute mile", the first 20% efficient silicon cell, in 1985. From right to left: Stuart Wenham (author's 3rd PhD student); Jianhua Zhao (5th PhD student); Mike Willison (Professional Officer); Chee Mun Chong at rear (7th PhD student); Martin Green at front (Team Leader); Andrew Blakers (2nd PhD student); Mohan Narayanan at rear (6th PhD student); Ted Szpitalak and Michael Taouk (Professional Officers).

The buried contact solar cell of Fig. 9 was the end result of this work. With funds from NASA-Lewis, we had purchased a second-hand laser scribing system that came with a logbook showing it had already lived a very full life dicing up microelectronic chips in the

USA throughout the 1970s. Our initial aim was to use it to cut our finished cells from the silicon wafers in which they were fabricated. Stuart Wenham converted the system to computer control, giving it the flexibility to scribe previously inaccessible patterns.

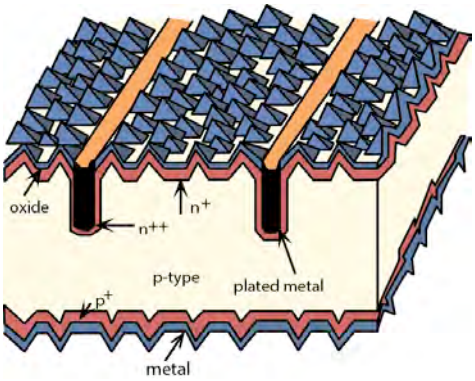


Figure 9: The buried contact solar cell, invented in 1984 (Wenham and Green, 1984).

Initially, we explored use of the laser to nucleate texturing (Wenham and Green, 1983). This stimulated the conception of the buried contact solar cell, a technology subsequently licensed to several companies. The first commercial sales under licence were by AEG Telefunken, with this company supplying buried contact cells to the "Spirit of Biel", a solar car that blitzed the field in the 1990 World Solar Challenge, the solar car race from Darwin to Adelaide. This race had been conceived by Hans Tholstrup as a way of promoting electric vehicle development.

The most successful licensee however was BP Solar, with the company marketing cells under the Saturn product name from 1991-2006 (Mason et al., 2004). Shortly after ceasing this production, BP withdrew from photovoltaic manufacturing entirely. Product valued at over $1 billion was sold under licence to UNSW over this period.

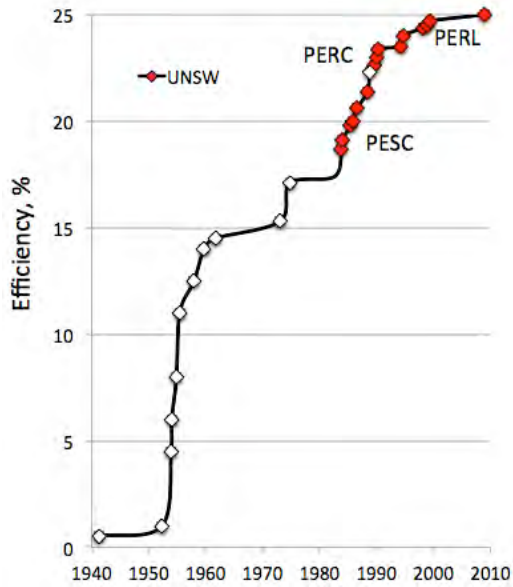


Figure 10: Evolution of silicon laboratory cell efficiency.

In parallel, development of the PERC cell continued, with 21.8% efficiency certified by Sandia National Laboratories in October 1988. The first journal publication appeared the following year (Blakers et al., 1989). Progressive refinement of the PERC structure gave incremental improvements in efficiency (Fig. 10), leading eventually to 24.7% efficiency in 1999 (Zhao et al., 1999), increasing to 25.0% efficiency after a recalibration in 2008 (Green, 2009a), using the PERC/PERL cell structure of Fig. 11.

Although the PERC nomenclature was used originally used at UNSW to denote devices with no heavily doped region under the rear contact, the designation is now being used to denote a broader range of devices, including devices that would be classified as PERL devices under the original UNSW nomenclature.

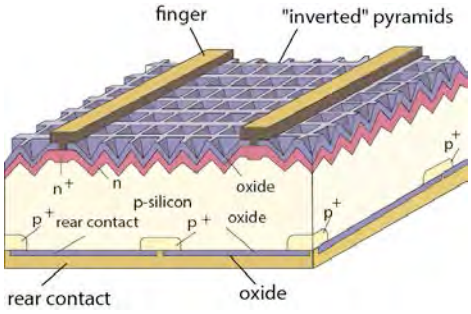


Figure 11: PERC/PERL (Passivated Emitter, Rear Locally-Diffused) solar cell, the first silicon cell to exceed 25% efficiency.

Since then, two other cell structures have shown themselves capable of comparable efficiency. One is the rear junction cell (Fig. 12), originally developed by Stanford University in the mid- to late-1980s and subsequently commercialised by SunPower. This is an unusual cell structure in that both polarity contacts are located on the cell rear. For successful operation, the approach requires high quality wafers and excellent passivation of both front and rear surfaces. Stanford's success in achieving this was instrumental in the subsequent development of PERC cells.

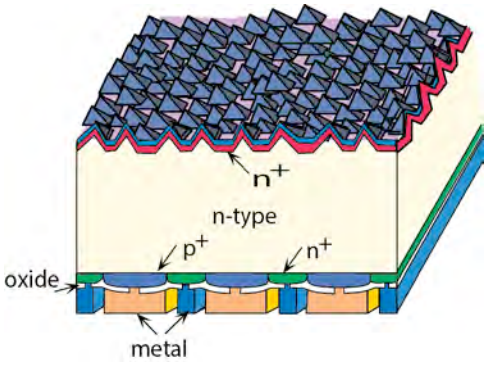


Figure 12: Rear junction solar cell first commercialised by SunPower circa 2004.

The second cell structure (Fig. 13) is the HIT cell (Heterojunction with Intrinsic Thin-layer) developed by Panasonic. The cell takes advantage of the higher energy bandgap in hydrogenated amorphous silicon (a-Si), with the heterojunction formed with crystalline silicon (c-Si) allowing even better surface passivation than the oxides developed at UNSW. However, these a-Si layers are optically more absorbing, blocking some of the incident photons from reaching the c-Si regions of the cell.

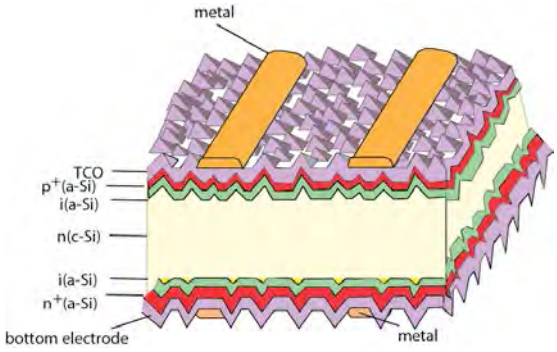


Figure 13: HIT cell commercialised by Sanyo (now Panasonic) circa 1996.

Unlike the PERC cell, both these rear junction and HIT cell structures require high quality wafers to work effectively (carriers have to diffuse from the front to the rear junctions, in one case, while good quality wafers are needed to generate the high voltage required in the HIT cell to offset the reduced coupling of photons into the c-Si substrate).

In 2014, by combining the HIT and rear junction structures, Panasonic was able to inch past the UNSW 25.0% result with a 25.6% achieved for silicon cell efficiency (Masuko et al., 2014), with this regarded as a significant achievement for Japanese science. At the triennial World Conference of Photovoltaics held in Kyoto in November 2014, there were at least 4 invited presentations on the new result solicited by the largely Japanese program committee.

Nonetheless, the commercial potential of the rear junction, HIT and the HIT rear junction approach are limited both by the high costs of the associated processing and the need for specialised wafers (ITRPV, 2015). Products based on the first two of these approaches are presently sold at a premium for the ultra-high efficiency niche market for solar modules.

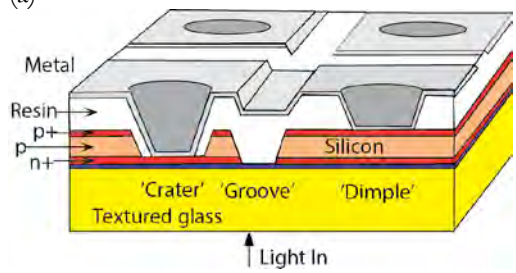
Crystalline silicon on glass (CSG) cells

Throughout the 1980s and 1990s, the prevailing view within the photovoltaic industry was that silicon wafer-based technology was too material-intensive to have the same low cost potential as a thin-film technology, where a thin active semiconductor layer is deposited on a supporting layer, usually glass.

The author's view, then as now, was that the key thin-film contenders, a-Si, CdTe and CIGS (copper-indium-gallium-selenide), had serious limitations in terms of attainable efficiency for a-Si and the use of toxic and/or scarce elements for CdTe and CIGS. Our work on trapping light into our high efficiency c-Si cells, combined with our ability to effectively passivate surfaces, convinced us that cells based on thin films of polycrystalline silicon were capable of high efficiency. This work was given a further boost when we conceived a parallel multi-junction approach (Green and Wenham, 1994) that would significantly reduce requirements on the material quality required for efficient thin-film silicon cells.

This stimulated a 5-year program starting in 1995 supported by Pacific Power, then Australia' s largest power utility company, to bring this technology to commercial readiness. A spin-off company, Pacific Solar, was formed and established a pilot-line for the new technology. By the end of the 5-year program, Pacific Power, originally scheduled to finance the following commercialisation phase, had been disbanded and new partners were required. This process resulted in a successor company, CSG Solar, being formed supported largely by Q-Cells, a German company which subsequently became the world's largest photovoltaic manufacturer.

(a)



(b)

Figure 14: (a) Crystalline silicon on glass (CSG) solar cell with a thin polycrystalline silicon layer 1-2 microns thick is deposited onto glass;
(b) 1.4-m² CSG module of 75-105W output manufactured in Germany from 2006.

CSG thin-film polysilicon modules (Green, et al., 2004; Green, 2009b) were introduced onto the market in June 2006 with annual production capacity of circa 10 MW/year. This was a period where rapid expansion of the PV industry had increased its demand for

high purity polysilicon source material beyond the ability of the microelectronics industry to supply. The subsequent shortage caused a massive escalation in prices that both provided a window of opportunity for thin-film technologies, as well as encouraging a huge number of new entrants into the polysilicon refinement industry. The long lead-time for building these polysilicon plants, however, kept the thin-film window of opportunity open for several years. During this period, about 10 MW of CSG panels were installed around Germany, often in large fractional- or multi-MW fields, such as Eurishofen and Thalheim.

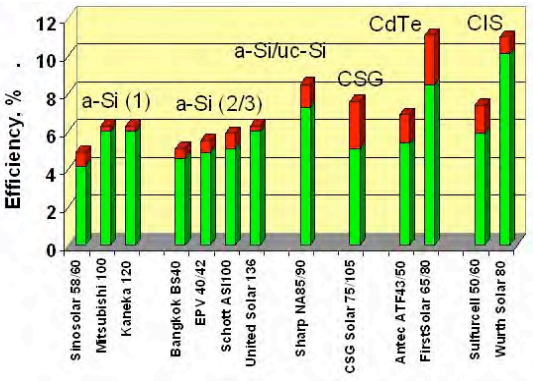


Figure 15: Aspiring thin-film companies listed by Photon International as having product on the market in February 2008. Bars show nominal module efficiency, including range meeting specifications.

However, as new polysilicon refining capacity came on line, the polysilicon shortage quickly turned into a glut and the price of silicon cells dropped precipitously. Of the dozen or so aspiring thin-film companies marketing product in 2008 (Fig. 15), only one (First Solar) was sufficiently well established to survive the onslaught. All others, including CSG Solar, eventually disappeared, although Solar Frontier, with its Cd-free CIGS technology and parents with deep pockets (Shell and Aramco) has since established a viable market position (helped somewhat by the fortuitous timing of the rapid recent growth of a somewhat parochial Japanese photovoltaic market).

The subsequent ongoing reduction in silicon wafer-based manufacturing costs has increased the difficulty of market entry for aspiring thin-film market entrants. The author's present perspective on this is that it is now difficult for any thin-film technology to match silicon's costs, unless the thin-film technology can produce comparable or better energy conversion efficiency. This would be possible with tandem cell stacks, although implementation with CdTe or CIGS technology does not seem imminent.

Market Transition to PERC Cells

As previously mentioned, the cell structure of Fig. 3, first fabricated in 1974 prior to the impact of UNSW research, has been the prototype for most past solar cell production (referred to as the "Al-BSF" approach). The UNSW "buried contact" cell of Fig. 9, the Panasonic HIT cell of Fig. 13 and the Stanford/SunPower Rear Junction cell of Fig. 12 have been higher efficiency variants that have gained restricted market share, championed by a single manufacturer in each case. Similarly, thin-film technologies have also been restricted to a small and diminishing market share, with only First Solar (CdTe) and Solar Frontier (CIGS) manufacturing in any volume in 2015.

Due largely to improvements in the pastes used to form the contacts and the ability to print increasingly narrow contact fingers, combined with the use of hydrogenated silicon nitride AR layers on top of thin interfacial oxides for top surface passivation, the performance of the standard Al-BSF cells have steadily improved to the stage where 19% efficiency on monocrystalline wafers was

quite common in manufacturing in 2014. To break through the 20% barrier in production, more innovative technology was required.

This has focussed mainstream interest on bringing the UNSW PERC cell into production. PERC production capacity has increased rapidly over the past 3 years as indicated by Fig. 16, accounting the largest share of new production capacity added over this period (Fig. 17).

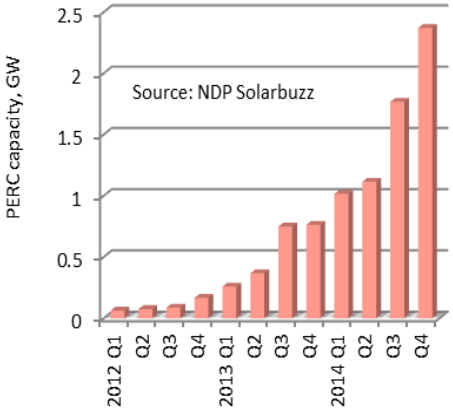


Figure 16: New PERC cell production capability added over recent years (total worldwide capacity for all cell types estimated as 50 GW at end 2014; 1 GW is the output of a large nuclear or coal fired power station) (Data Source: NDP Solarbuzz, Oct. 2014).

Although the PERC cell involves more processing steps than the Al-BSF approach and it is therefore more expensive to make each cell, this extra cost is largely negated by the time the cells are encapsulated into modules, since each module gives extra power output. When installed into system, the same leveraging results in lower costs than with Al-BSF product, since fewer modules need to be installed for the same rating. Moreover, as the technology is scaled and streamlined, the difference in processing costs between PERC and the former standard Al-BSF approach will decrease.

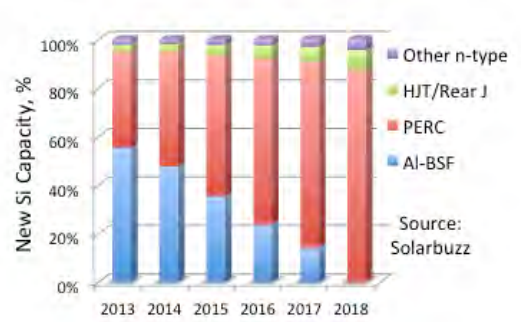


Figure 17: Share of new silicon-based production capacity for different cell approaches (Data Source: NDP Solarbuzz, October 2014).

Consequently, the industry expects that by 2019, UNSW PERC technology will have the largest share of the photovoltaic market and hence leverage the largest share of clean energy investments in solar, estimated as totalling US$149 billion in 2014 (Liebreich, 2015). Figure 18 shows the International Technology Roadmap for Photovoltaics (ITRPV, 2015) estimates for market share of different cell technologies over the coming decade.

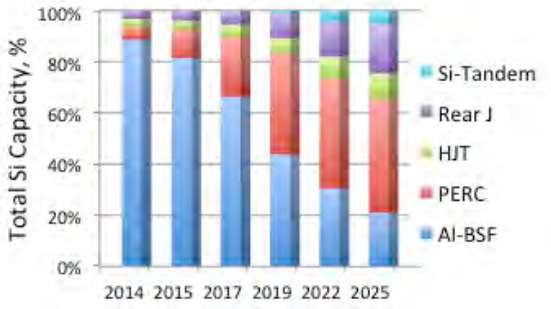


Figure 18: Industry consensus on expected market share of different silicon cell technologies (ITRPV, 2015).

Landmark Achievements

As well as producing the first 20% silicon cell in 1985, several other landmark results have been achieved at UNSW over its 40-year history. In 1989, the group supplied cells to Sandia Laboratories that were used to construct the first photovoltaic system to convert more than 20% of the incident sunlight into electricity, in this case, by focussing the sunlight onto the UNSW cells. In 1993, UNSW repeated this feat for the more challenging case of unconcentrated sunlight. The group also produced the first silicon cell to convert over 20% of space sunlight into electricity, as confirmed by NASA in high-altitude aircraft testing (resulting in a Space Aviation Award to the group). Another 20% first was the first 20% cell on the lower quality multicrystalline silicon that forms the bulk of present commercial production, achieved in 1998 (Green, 2009).

More recent results include the first 25% efficient silicon cell in 2008 (Green, 2009) and, in November 2014, the first photovoltaic system to convert over 40% of incident sunlight into electricity, again by focussing the sunlight (Green et al., 2015). We again hope to duplicate this result in the not too distant future for the more challenging case of unconcentrated sunlight.

Conclusions

The first 40 years of UNSW photovoltaic research has produced some notable research achievements and greatly increased expectations of the efficiency levels that can be attained in commercial production.

Another notable output from the laboratory, only briefly alluded to (Figs. 5 and 8) in the above condensed history, has been the highly trained researchers produced. Many of these have provided the expertise for the transition of the manufacturing industry from high cost regions of the world to the Asian-Pacific region. This, in turn, has being responsible for the dramatic reduction in manufacturing costs over recent years that has positioned photovoltaics as one of the lowest cost options for future electricity production.

To mention only a few of these researchers and their achievements, Stuart Wenham (Figs. 5 and 8), as part-time Chief Technical Officer (CTO) supporting another of my students, Zhengrong Shi (12th PhD student), established the first successful photovoltaic manufacturing venture in China. This was in the form of Suntech Power, which became the world's largest manufacturer, after being the subject of the largest technology float worldwide when the company listed on the New York Stock Exchange in 2005.

Ted Szpitalak (Figs. 5 and 8) headed teams that established the production lines not only at Suntech, but also at JA Solar, China Sunergy and Global Sunrise (Taiwan). Jianhua Zhao (Fig. 8) has been CTO of China Sunergy since 2004, including when the company listed on NASDAQ. Mohan Narayanan (Fig. 5) has had a diverse career in the industry, which included being CTO of Trina Solar, the world's largest manufacturer in 2014, at the time of its initial public offering (IPO). In fact, of the top-5 photovoltaic manufacturers in 2014, all either have former UNSW researchers at CTO or had them at critical stages of the company's development, such as at IPO.

With photovoltaics poised to become one of the largest energy industries of the future, it is hoped that, over the next 40 years, the laboratory will continue its combined roll of blazing the path to future generations of technology while producing researchers able

to spearhead the ongoing growth of the industry.

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