

REVIEW ARTICLE

Silicon solar cells: evolution, high-efficiency design and efficiency enhancements

Martin A Green

Centre for Photovoltaic Devices and Systems, University of New South Wales,
Kensington, Australia 2033

Received 3 July 1992, accepted for publication 20 July 1992

Abstract. With a history dating back over 50 years, silicon solar cells were amongst the first bipolar silicon devices demonstrated. Notwithstanding this long history, the last 10 years have seen rapid progress in both the efficiency of experimental devices and in the understanding of basic design constraints. The evolution of silicon cell design over the last 50 years is described and the features of current high-efficiency devices are discussed in some detail. With energy conversion efficiencies above 23 %, these devices are now approaching basic limits for conventional homojunction cells. The potential for substantially increasing cell performance above these limits, by taking advantage of concepts such as the impurity photovoltaic effect, the incorporation of alloys and superlattices, and tandem cells based on silicon, is discussed.

1. Introduction

Although the history of silicon solar cells dates back over 50 years to the very beginning of the silicon bipolar device era, the last decade has seen enormous improvements in both the performance of experimental cells and cell theory. Over the last few years, cells have reached performance levels once thought not to be physically attainable. As shown in figure 1, present laboratory cells convert over 23 % of the incident energy in sunlight into electricity, well above the value of 20 % once thought to be a basic limit.

Silicon solar cells have different design and material requirements from most other silicon electronic devices. Not only is nearly ideal passivation of silicon surfaces required, but the bulk properties must also be of uniformly high quality for high energy conversion efficiency. This is because some wavelengths of light have to pass several hundred micrometres through the silicon before absorption and produce carriers that are still collected by the cell.

This paper reviews the history of silicon solar cell development, discusses the features of modern cell design and outlines possible areas of investigation which might result in further improvements in performance in the future.

2. Cell history

The first silicon cells were produced as a result of interest in silicon for use in point-contact rectifiers. The rectifying

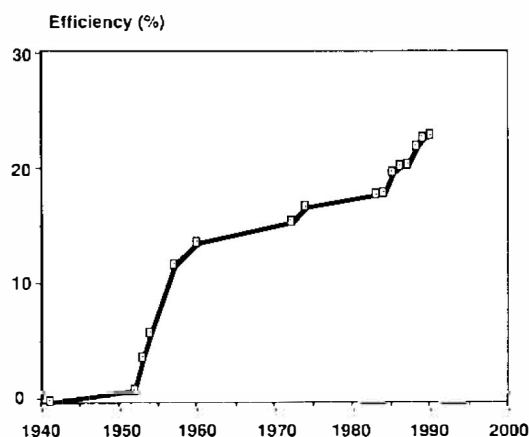


Figure 1. Evolution of the energy conversion efficiency of laboratory silicon solar cells

properties of sharp metal contacts to various crystals had been known since at least 1874 [1]. In the early days of radio, such crystal rectifiers were almost universally used as detectors in radio receivers [2]. However, with the development of thermionic tubes, these crystal rectifiers were displaced except for ultra-high-frequency work. The most suitable for this work proved to be tungsten points to silicon surfaces. This provided the incentive for improving the purity of silicon and further understanding its properties.

In studies of recrystallized melts of pure silicon prepared for this purpose, Russell Ohl of Bell Laboratories

discovered well defined barriers in polycrystalline ingots grown from some lots of commercial high-purity silicon [3]. These 'grown-in' junctions resulted from impurity segregation during the recrystallization process. Ohl found that one side of the junction reached a negative potential when samples were illuminated or heated. The same side had to be biased negatively to show low resistance to current flow across the barrier or across a point contact to this material. This led to the terminology of 'negative-' or 'n-type' silicon for the material on this side of the junction. The material of opposite type was named 'positive-' or 'p-type'. It was apparently only after this initial experimental work that the role of donor and acceptor impurities in producing these properties was shown.

In 1941, the first photovoltaic devices based on these 'grown-in' junctions were described [3]. Figure 2 shows the geometry of cells cut from the recrystallized material, in this case so that the junction was parallel to the illuminated surface. Contact was made at the periphery of the top of the device as shown, and over the entire rear surface. No energy conversion efficiency figures were reported for these cells, although an analysis of the data suggests efficiency well below 1%. The cells were obviously quite difficult to fabricate due to the lack of control over the junction location.

A more controllable method of junction formation was reported by Kingsbury and Ohl in 1952 [4]. These cells used recrystallized silicon fabricated from pure source material to prevent 'grown-in' junctions being formed. Helium ion bombardment of the surface was used to form the rectifying junction. A similar contacting scheme was used as for the earlier devices. These devices showed quite respectable spectral responsivity, although energy conversion efficiencies were again not reported. They are estimated to lie somewhere around 1%.

These early efforts were quickly overtaken by the rapid development of silicon technology, also at Bell Laboratories. Improved techniques for crystal growth producing single-crystal wafers of silicon were developed, as were techniques for doping using high-temperature diffusion of impurities. This led to the first report of a modern silicon cell in 1954 by Pearson, Fuller and Chapin of Bell Laboratories [5]. The first cells used lithium diffusion to form the junction and had an efficien-

cy of about 4.5% [6]. The lithium diffusion was soon replaced by boron diffusion with the efficiency increasing to 6% [5, 6].

These cells had the dual rear contact structure of figure 3 and opened up the first real prospects for power generation using photovoltaics [7]. Improvement in the cell structure led to demonstration of 10% efficiency within 18 months of the initial report [7]. However, given the immaturity of the silicon industry, it soon became apparent that the initial enthusiasm for widespread terrestrial use of cells was premature. An application was identified in space on satellites, and this formed the major application of the cells until the early 1970s and provided the major incentive for their continued development.

The development of cells for space resulted in further refinements such as the use of contact grids on the top surface. This pushed cell efficiency to above 14% in terrestrial sunlight by the early 1960s [8]. At about this time, the superior radiation resistance of boron-doped substrates became apparent. This led to a shift from the phosphorus-doped substrates previously preferred. Although this change reduced initial cell efficiency, it resulted in a cell more able to withstand the high-energy particles present in the space environment. Cell design then stabilized for a decade to the structure shown in figure 4. Cell size was standardized at 2 cm × 2 cm, six metal contact fingers formed by the vacuum evaporation of a Ti/Ag multilayer (subsequently Ti/Pd/Ag) were generally used to conduct carriers generated over this

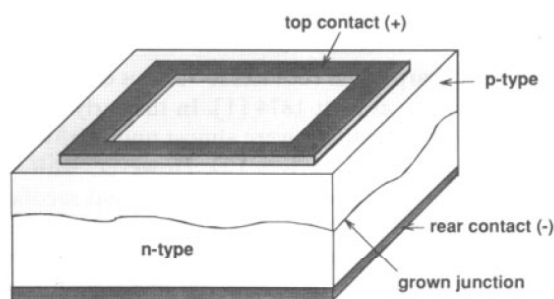


Figure 2. Silicon solar cell reported in 1941 relying on 'grown-in' junctions formed by impurity segregation in recrystallized silicon melts.

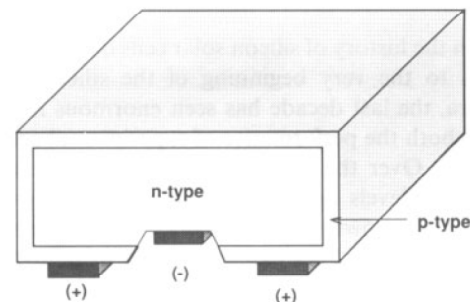


Figure 3. First modern silicon cell, reported in 1954, fabricated on single-crystalline silicon wafers with the p-n junction formed by dopant diffusion.

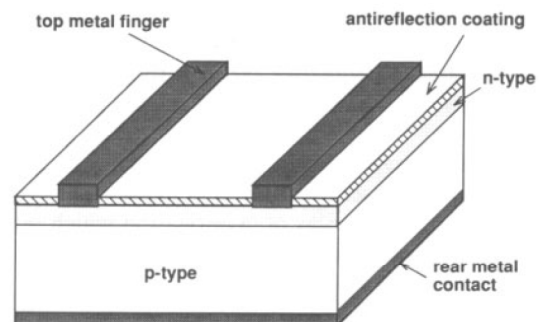


Figure 4. Space silicon cell design developed in the early 1960s which became a standard design for over a decade.

area to a 1 mm wide busbar (not shown), and a silicon monoxide quarter-wavelength antireflection coating was used to reduce reflection from the top surface of the cell.

The first half of the 1970s saw several innovations introduced into cell design. The first resulted from the observation that alloying aluminium into the rear of the cell produced improved current and voltage output. The effect was initially attributed to gettering of impurities in the cell bulk by the aluminium [9, 10]. It was subsequently explained in terms of the heavily doped p-type layer produced at the rear surface by the alloyed aluminium [11, 12]. Today, this is commonly described as a 'back surface field' effect, although the effect can more usefully be described in terms of a reduction in the effective minority carrier recombination velocity at the rear of the cell. The region with heavily doped aluminium suppresses minority carrier concentrations near the rear of the cell, restricting their flow to the rear contact. The gettering effect of rear aluminium treatments has also since been well established [13, 14].

A further improvement was obtained at Comsat Laboratories [15] by applying the photolithographic techniques developed for microelectronics to the definition of the top metal contact. This produced much finer metallization fingers than possible with the previous technique of evaporation through a metal shadow mask. Finer metal fingers meant that fingers could be more closely spaced without excessive shadowing of the top surface of the cell. This allowed much shallower diffusions to be used to form the top junction, eliminating dead layers which resulted from excessive dopant concentrations near the surface in earlier cells [15]. By this approach, the response of the cells to light of wavelengths at the blue end of the spectrum was greatly improved, since this light is strongly absorbed near the surface of silicon. New antireflection coatings which did not absorb such light were developed to take advantage of this new capability [15].

At about the same time, the use of anisotropic etching to expose crystal planes in silicon was being explored in microelectronics. This technique was extended, also by Comsat Laboratories [16], to produce pyramids randomly located on the top surface of (100)-orientated silicon. In this approach, the square-based pyramids are formed by intersecting (111) crystallographic planes. This approach reduces reflection from the top surface of the cell as well as coupling the light obliquely into the cell, allowing it to be absorbed closer to the most active region of the cell near the top junction. Figure 5 shows a cell incorporating all the previous advanced features, which resulted in cells of approximately 17% efficiency under terrestrial sunlight [17]. This performance figure was unsurpassed for nearly a decade.

The next improvements in cell performance came primarily as a result of increased output voltage due to improved passivation of the electronic activity at the top surface of the cell. This improved passivation resulted from the use of thermally grown oxide to passify non-contacted areas of the cell and the use of a variety of techniques to reduce the activity at the interface with the

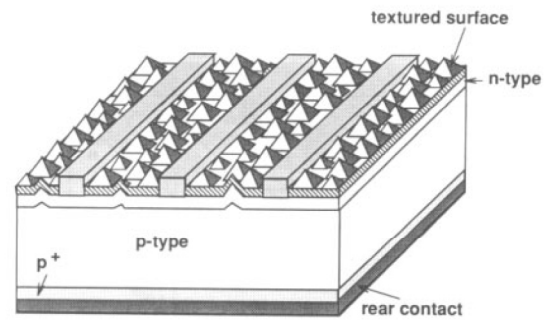


Figure 5. Textured 'black' cell of the mid-1970s which used crystallographic texturing of the top surface to reduce reflection loss, photolithographically defined top contact fingers, a shallow top junction diffusion and an improved antireflection coating (not shown). Also shown is a heavily doped region near the rear contact resulting from aluminium alloying.

top metal contact. The passivated emitter solar cell (PESC) of figure 6 used a reduced area of contact at the top surface to minimize the effects of such activity. Due to the improved top-surface properties of this cell, it was able to take fuller advantage of high-quality starting wafers than earlier designs. By using high-quality float-zone wafers relatively highly doped with boron, 20% efficiency was surpassed with this structure in 1985 [18]. This efficiency figure had long been thought to be a fundamental limit for silicon—the 'four minute mile' of silicon photovoltaics.

The next major advance in cell design resulted from extending oxide passivation to both front and rear surfaces of the cell. The first successful design of this type was the point contact solar cell of figure 7 [19]. In this design, the effects of contact recombination were further reduced by localizing contacts to small points on the non-illuminated surface of the cell (the uppermost surface in figure 7). These cells depend on having both extremely good passivation of cell surfaces and extremely high-quality bulk properties. Not only do most of the light-generated carriers have to travel long distances from the point of generation near the illuminated surfaces, but also this passage is hampered by the carriers having to squeeze into the small rear contact areas. This

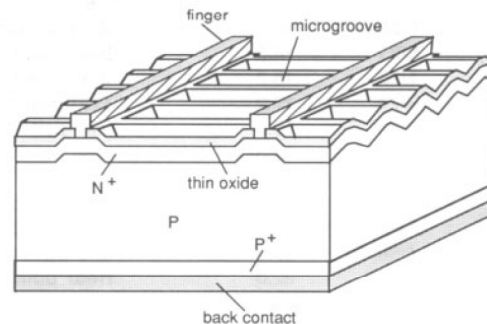


Figure 6. The passivated emitter solar cell (PESC), the first silicon cell to surpass 20% energy conversion efficiency—the 'four minute mile' of silicon photovoltaics.

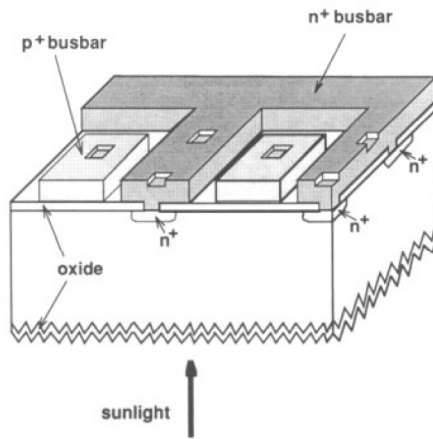


Figure 7. Innovative point contact solar cell relying on high-quality bulk material and oxide passivation of both top and rear surfaces. Dopant diffusions are limited to small islands ($10\ \mu\text{m} \times 10\ \mu\text{m}$) spread over the non-illuminated surface of the cell with contact made via smaller contact holes through the oxide. Carriers, mostly generated close to the illuminated surface, find their way across the substrate, typically $100\ \mu\text{m}$ thick, to the contact regions.

compression causes larger carrier gradients than in other designs, increasing carrier concentrations near the illuminated surface and putting even more pressure on bulk and top-surface quality. Such high bulk quality can only be obtained by using very lightly doped substrate material which causes the cells to operate in high injection. Processing the cells presents challenges. Not only does bulk and surface quality have to be maintained during processing, but excellent rear oxide integrity is also

essential. Defects in this oxide can cause shunting between the rear contacts and the substrate [20]. These highly innovative cells were the first to exceed 22% efficiency under normal terrestrial testing, although 27% efficiency has been demonstrated under highly concentrated sunlight [21].

The highest terrestrial silicon cell efficiency confirmed to date has been obtained by the passivated emitter, rear locally diffused (PERL) cell of figure 8. This cell essentially combines the best features of the two previous designs of figures 6 and 7 to give cell efficiencies above 23% [22]. The design and operating features of this cell will be discussed in more detail in the following section. Table 1 summarizes the key results in the evolution of silicon cell efficiency.

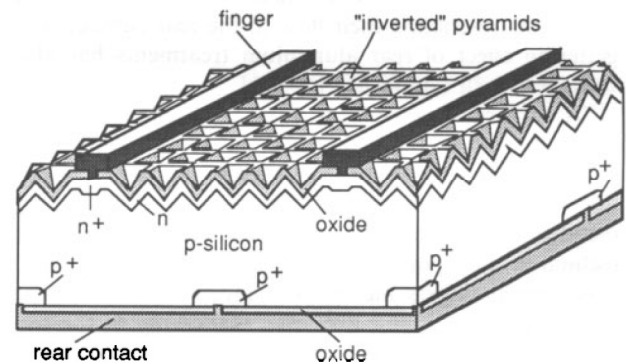


Figure 8. Passivated emitter, rear locally-diffused cell (PERL cell) which has demonstrated independently confirmed energy conversion efficiency above 23%.

Table 1. Evolution of silicon solar cell efficiency ($> 1\ \text{cm}^2$ area) nominally under the IEC 904 global or ASTM E892-87 global AM1.5 spectrum at $25\ ^\circ\text{C}$ and $1000\ \text{W m}^{-2}$ illumination intensity.

Date†	Efficiency(%)	Cell structure	Organization	Reference
3/41	< 1	Melt-grown junction	Bell Laboratories	3
3/52	~ 1	He bombardment	Bell Laboratories	4
~ 12/53	~ 4.5	Li-diffused wraparound	Bell Laboratories	6
1/54	~ 6	B-diffused wraparound	Bell Laboratories	5
11/54	~ 8	B-diffused wraparound	Bell Laboratories	7
5/55	~ 11	B-diffused wraparound	Bell Laboratories	7
~ 12/57	12.5	$0.5 \times 2\ \text{cm}$, B-diffused	Hoffman Electronics	34
8/59	14	Grid-contact, B-diffused	Hoffman Electronics	34
8/61	14.5	B-diff. AR coat, gridded	Commercial, USASRD	8
1/73	15.2	Violet cell	Comsat Laboratories	15
9/74	17.2	Textured non-reflecting	Comsat Laboratories	16
9/83	18.0	MINP cell	University of NSW	22
12/83	18.3	PESC	University of NSW	22
5/85	19.0	PESC	University of NSW	22
10/85	20.0	Microgrooved PESC	University of NSW	22
7/86	20.6	Microgrooved PESC	University of NSW	22
4/88	20.8	Microgrooved PESC	University of NSW	22
9/88	22.3	Rear point contact cell	Stanford University	22
12/89	23.0	PERL cell	University of NSW	22
2/90	23.3	PERL cell	University of NSW	22

† Date of submission or presentation of paper reporting result or date of independent efficiency confirmation (month/year).

3. PERL cell design

3.1. Optical features

It is obvious that, to maximize cell performance, as much light as possible of useful wavelengths should be coupled into and absorbed by the cell. Modern cell designs such as the PERL cell of figure 8 incorporate several features of a primarily optical nature to achieve this result.

The inverted pyramids along the top surface serve primarily such an optical role. Most light incident on this structure will hit one of the side walls of the pyramids at the first point of incidence. The majority of this light will be coupled into the cell. That reflected will be reflected downwards, ensuring that it has at least a second chance of entering into the cell. Some of the light incident near the bottom of the pyramids has three such chances. The pyramids are covered by an oxide layer of appropriate thickness to act as a quarter-wavelength antireflection coating [23].

Light coupled into the cell moves obliquely across the cell towards the rear surface with most absorbed on the way. Weakly absorbed light reaching the rear surface is reflected by the very efficient reflector formed by the combination of the rear oxide layer covered by an aluminium layer. The reflectance from this combination depends upon the angle of incidence of the light and the thickness of the oxide layer, but is typically above 95% for angles of incidence close to the normal, decreasing to below 90% as the incidence angle approaches that for total internal reflection at the silicon/oxide interface (24.7°), and increasing to close to 100% once this angle is exceeded [24].

Light reflected from the rear then moves towards the top surface. Some reaching this surface strikes a face of a pyramid of opposite orientation to that which coupled it into the cell. Most of this immediately escapes from the cell. Light striking other faces of the pyramid is totally internally reflected. This results in about half the light striking the top surface internally at this stage being reflected back across the cell towards the rear contact [25]. The amount of light escaping after the first double pass depends on the precise geometry involved. It can be reduced by destroying some of the symmetries involved, for example by using tilted inverted pyramids [26] or by using the 'tiler's pattern' approach of figure 9 [25]. The latter approach is currently used in PERL cell designs.

The combination of the inverted pyramids and the rear reflector therefore forms a very efficient light-trapping scheme, increasing the pathlength of weakly absorbed light within the cell. Effective absorption thicknesses of the cells are measured to be about 30 times the physical thickness. The light trapping boosts the infrared response of the cell. The external responsivity (amps per watt of incident light) of PERL cells peaks at longer wavelengths at higher values than previous silicon cells, with values of 0.75 A W^{-1} measured at $1.02 \mu\text{m}$ wavelength. Energy conversion efficiency under monochromatic light peaks at the same wavelength with values above 45% measured [27]. Further improvement in light trapping could push this figure to above 50% at $1.06 \mu\text{m}$.

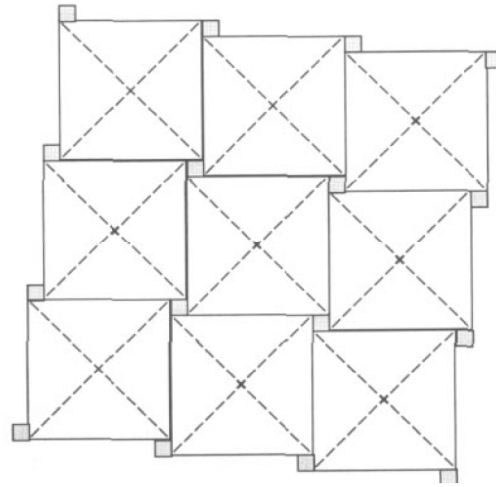


Figure 9. Staggered inverted pyramid layout ('tiler's pattern') used to improve the trapping of weakly absorbed light into PERL cells.

Other optical losses are due to reflection from, and absorption in, the top metal fingers of the cell. This can be minimized by making these lines as fine as possible with, ideally, as large an aspect ratio (height to width ratio) as possible. Alternatively, optical approaches can be used to steer incoming light away from these lines or to ensure that light reflected from them eventually finds its way to the cell surface [28].

Present PERL cells lose about 5% of incoming light due to absorption or reflection loss associated with these metal fingers, when combined with reflection from the unmetallized top surface of the cell. They also lose one or two per cent in performance from the use of a less than optimum light-trapping scheme and from less than 100% reflection of light from the rear surface of the cell. There is therefore some scope for small to moderate gains in performance by further improving the optical properties of these cells.

3.2. Electronic features

3.2.1. Bulk recombination. To obtain good cell performance, recombination throughout the cell has to be kept to a minimum. The advantages in producing increased current output are obvious. It makes no sense to waste photogenerated carriers by allowing them to recombine before being collected by the cell. Decreased recombination also increases the voltage output of the cell. Any voltage appearing across the cell produces increased internal carrier concentrations, increasing recombination rates within the cell. On open circuit, the nett generation rate of carriers throughout the cell is balanced by the recombination rate due to this voltage bias effect. The cell open-circuit voltage is often a more sensitive indicator of recombination rates in the cell than the short-circuit current.

As apparent in figure 8, most of the PERL cell volume consists of uniformly doped bulk material, with surface

regions divided into contacted and non-contacted areas. Recombination in bulk regions can be minimized by choosing as high a quality starting material as possible. Material quality is generally characterized by a minority carrier lifetime, τ . The lower the dopant concentration in the substrate, generally the higher this lifetime will be. This is offset by a compensating effect of doping upon recombination rates. This compensation is due to the fact that the higher the dopant density, the lower the minority carrier concentration for any given voltage across the cell. The recombination rate is determined by the product of this concentration and the inverse of the carrier lifetime. For ideal silicon material, low dopant density is undoubtedly the best choice to minimize this product [29]. For actual material, several other issues are involved and the optimum dopant density depends upon the particulars of cell design. Obviously, the thinner the bulk region, the lower the bulk recombination will be. The trade-off here is a reduction in the mechanical strength and the light-absorbing capability of the cell. The light-trapping schemes previously mentioned push the optimum thickness to lower values than would otherwise prevail.

3.2.2. Surface recombination. Recombination in non-contacted areas of the surface can be minimized by the growth of a high-quality thermal oxide. Conditions for producing low interface state densities have been well documented for microelectronics [30]. (Interface states are referred to, in that area, as 'interface traps'.) However, other properties simultaneously required for microelectronics, such as high oxide breakdown strength, would not appear as important for photovoltaics, giving scope for 'customizing' growth conditions. Particularly interesting is the effect of surface doping type and doping level upon the recombination rate at the oxide interface.

The present consensus is that, for the highest-quality oxides, the capture cross section of interface states for electrons is very much higher than the capture cross section for holes [31]. This may be a fundamental physical property of these states. The large asymmetry implies that the states may be electrostatically attractive to electrons but electrostatically unattractive to holes, e.g. have donor-like properties with a positive charge state when unoccupied. Due to the known correlations between interface state densities and oxide fixed charge (usually positive charge), it has been argued elsewhere that these fixed positive charges may be the physical source of interface states [32].

Regardless of the physical origin of the asymmetry, it produces different recombination properties for n-type and p-type surfaces. For n-type surfaces, there will usually be a small hole concentration at the surface. The capture of holes will therefore be the rate-limiting process determining surface recombination. The recombination rate will be very small due to the combination of small hole concentration and small hole capture cross sections, as shown schematically in figure 10(a).

The situation for p-type surfaces is more complex.

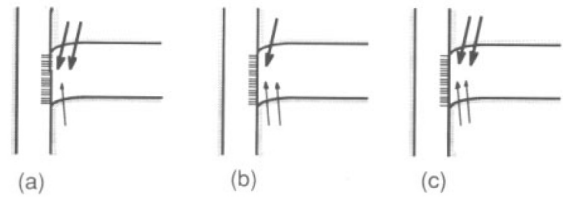


Figure 10. Surface recombination resulting from asymmetrical capture cross sections for electrons and holes. The probability of capture depends on both the capture cross section of the interface states and the interface concentrations of the respective carriers. The widths of the arrows represent the probability contribution from the former, while the number of arrows indicates that from the latter. The overall surface recombination rate is determined by the weakest link in terms of the weight of arrows: (a) n-type silicon at low cell voltages, where hole capture is the rate-limiting process; (b) p-type silicon at low cell voltages, where electron capture can be rate limiting; (c) n-type and p-type silicon at high cell voltages, where hole capture is rate limiting.

Here, hole concentrations will tend to be large, although electron concentrations can be small. The latter will increase as the voltage output of the cell increases. At low voltages, the capture of electrons will be the rate-limiting process as suggested by figure 10(b). Recombination processes will be much more effective than in n-type material at these voltages due to the larger electron capture cross section. However, as the voltage across the cell builds up, a transition will eventually occur where hole capture becomes the rate-limiting process. Since the hole concentration at the surface will not increase as rapidly as that of electrons in the bulk of the cell, the result is a rapid reduction in the effective surface recombination velocity with increasing cell voltage. Eventually, recombination rates will become similar to those of n-type material at any given large voltage.

This effect was first analysed by Eades and Swanson [33], assuming 'flat-band' (zero-field) conditions at the cell surfaces. The tendency for p-type surfaces to be depleted, either by the nett positive charge in the oxide or by work function differences between p-type silicon and metals such as aluminium and titanium which may overlie oxides, will help make this effect apparent at lower cell voltage than predicted by such a flat-band treatment.

For the present PERL cells, this effect is particularly important for the non-contacted regions of the rear surface. The effective recombination velocity in these regions decreases from very large values of the order of 10^4 cm s^{-1} to low values below 30 cm s^{-1} as the voltage across the cell increases from the short-circuit to the open-circuit voltage point. The major effect is a lower cell fill factor than would otherwise be the case [34]. Examination of the dark current-voltage characteristics of PERL cells has allowed the change in this recombination velocity to be determined as a function of voltage across the cell [34]. Similar measurements confirming a steadily reducing surface recombination velocity with injection level have also been reported upon unmetallized p-type silicon surfaces [31].

The full implications of such asymmetrical capture cross sections for cell design have not yet been determined. Further work is required to gain confidence that the effects described will not be overridden by additional effects not identified in the work mentioned above. For example, earlier results by Yablonovitch *et al* [35], investigating the effect of surface electrostatic conditions on surface recombination, also confirmed the existence of a set of states with large electron to hole capture cross section ratios. However, in this case, a second set of states was found with much larger hole capture cross sections than electron capture cross sections. This would be the property expected from acceptor-type states (negatively charged when occupied). A mitigating factor may be that the substrate doping was higher than in the other work mentioned. Also, fabrication details may be important in determining the situation prevailing at any given interface (for example, there was no 'annealing' step in the cited work [35]).

Assuming larger electron capture cross sections than those for holes, the design rule for non-diffused surfaces is to keep hole concentrations at the surface to a minimum. This can be effected by using n-type surfaces or by depleting hole concentrations at p-type surfaces, either electrostatically, by positive oxide charge or low work function metallic capping layers as at the rear of PERL cells, or by dopant depletion as occurs during silicon oxidation [30].

3.2.3. Contact area recombination. The regions where metal contact to the cell is made are regions of potentially very high recombination. Two strategies are used in the PERL cell of figure 8 to minimize such recombination. One is simply to keep the contact area small. For example, the top metal contact to the PERL cell is made at narrow stripes through the top surface oxide of only 3 μm width, while the rear metal contact is made through 10 $\mu\text{m} \times 10 \mu\text{m}$ contact holes normally spaced 250 μm apart. This means that metal contact is made to only 0.4% of the top surface area of the cell and 0.2% of the rear surface of the cell. The second strategy is to heavily diffuse these contact areas. Such heavy diffusion suppresses the minority carrier concentration in the contact areas, reducing contact recombination rates. This is the same effect as the 'back surface field effect' discussed in connection with figure 5.

Other techniques have also proved effective in reducing contact recombination, although not frequently used in present cell design. One is based on the use of tunnelling metal-insulator-semiconductor contacts [36]. The others are somewhat related in that tunnelling processes may also be involved in transport across the contact. These are based on the use of semi-insulating polysilicon (SIPOS) contacts [37] or doped polycrystalline or amorphous silicon contacts to the silicon substrate [38].

3.2.4. Present recombination relativities. The author's assessment of the recombination balance in present PERL

cells is along the following lines. Bulk recombination can be made negligible in present designs with appropriate choice of substrate and processing conditions. Rear surface recombination in non-contacted areas is not important at open circuit but is important at the maximum power point voltage, due to the dependences on cell voltage previously mentioned. This recombination becomes apparent in the cell characteristics as reduced cell fill factor. At the open-circuit voltage, recombination in the top diffused layer and its contact region is the most important.

On-going improvement in cell design and fabrication technologies should see bulk recombination eventually become the dominant recombination component.

4. Future improvements

4.1. General

In previous sections, design features of present high-efficiency silicon cells were outlined. Modifications likely to lead to incremental improvements in performance were also mentioned, such as the incorporation of improved light-trapping schemes, the elimination of losses due to reflection from both metallized and non-metallized regions of the top surface of the cell, the reduction of top diffused region and contact recombination, and so on. Incorporating such improvements may lead to cell energy conversion efficiencies above 25% in the relatively near future. In the present section, broader issues will be discussed. Concepts will be described which change the ground rules determining the framework on which conventional efficiency calculations are based, and hence provide the potential for 'supercharging' cell performance.

These concepts will be discussed under three headings. Concepts are discussed that are likely to lead to an improvement in current output, an improvement in voltage output or to innovative device structures that do not fit readily into a current or voltage framework.

4.2. Current improvement

As pointed out elsewhere, the normal 'threshold' approach to calculating limits upon current output for photovoltaics is not particularly appropriate for silicon [39]. This is because most of the absorption in silicon cells occurs with the involvement of phonons. Hence, there is no single threshold energy for band-to-band excitations in silicon. Rather, there is a threshold for processes involving one phonon, two phonons, three phonons and so on. These processes, however, become progressively weaker as an increasing number of phonons are involved in the transition. A more appropriate approach is to look at the balance between processes that absorb photons with electron-hole pair creation and those which absorb photons without creating these pairs. Examples of the latter are free carrier absorption and absorption in the rear metal reflector of the PERL cell of

figure 8. The latter rear reflection losses can, in principle, be kept very small, for example by relying on total internal reflection. Free carrier absorption can be minimized by keeping carrier concentrations small.

One model often used in calculating fundamental efficiency limits upon cell performance could be described as an 'infinite mobility' model. Assuming infinite carrier mobilities allows ohmic losses in the cell to be neglected and also removes the need for consideration of losses due to imperfect carrier collection. In this model, when the cell is short circuited, free carrier concentrations in undoped regions of the cell would be equal to the intrinsic carrier concentration. This gives very low free carrier absorption, allowing most of the photons in incident sunlight to create electron-hole pairs, in principle, in very weak processes involving large numbers of phonons. As the voltage across the cell increases, so do the carrier densities and the corresponding free carrier absorption. Figure 11 shows the limit on the light-generated current in a silicon cell as a function of voltage across it resulting from these considerations [39]. These 'infinite mobility' calculations suggest that, around the likely operating voltages of silicon cells, light-generated current limits corresponding to a one- or two-phonon assisted threshold may be the most appropriate. Present PERL cells of highest efficiency operate in low injection. Free carrier absorption is therefore higher than that involved in the calculations of figure 11. The diffused regions along the top and rear surface of the cell account for about half the free carrier absorption with the dopant concentration in the bulk accounting for the other half.

The above arguments suggest that even though substantial increases in short-circuit current may be obtained in silicon cells by carefully addressing the issue of free carrier absorption, these improvements will not be available at the maximum power point. The light-gener-

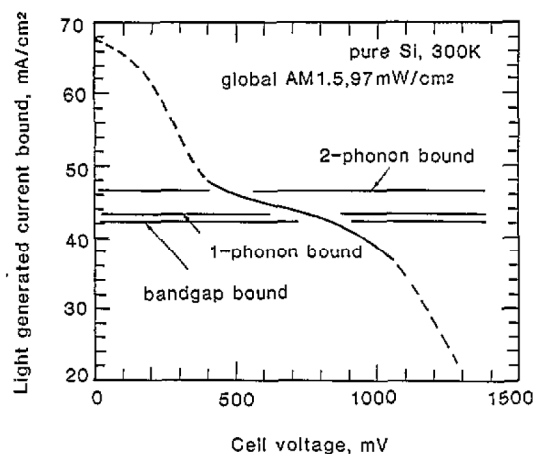


Figure 11. Calculated upper limit on the light-generated current within a silicon cell as a function of the voltage across the cell. The illumination is the global AM1.5 spectrum with an intensity of 97 mW cm^{-2} . Also shown are the limits obtained by assuming thresholds for electron-hole pair creation determined by the silicon bandgap and the energetics of one- and two-phonon assisted absorption processes.

ated current within the cell would become voltage dependent, resulting in reduced cell fill factor. The bound on the light-generated current near the maximum power point remains close to values calculated by the more standard approaches.

One way of increasing the current output beyond such bounds is to design regions of the cell to have a lower bandgap than that of pure silicon. Doping, alloying and electric fields provide ways of reducing the bandgap (or effective bandgap) of silicon [39]. The latter effect, the Franz-Keldysh effect, is quite weak and it does not appear likely that sufficiently large fields can be generated in a homojunction cell to allow any significant improvement to be obtained by this approach [39]. Quite high dopant concentrations are required to get appreciable bandgap narrowing. The difficulty is that doped regions generally are regions of high carrier concentration, which means that they are regions of increased free carrier absorption. Alloying appears to be the most promising of the three approaches mentioned above. Germanium is the only material which appears suitable for appreciable bandgap reduction in this way. Calculations show this approach will be most effective when the alloyed region is away from the cell surface, but extends across the depletion region associated with the cell junction [40, 41]. Efficiency improvements can be achieved, in this case, when the cell performance is limited by surface effects (as in present PERL cells).

Another approach to increasing current output, suggested some time ago [42], is to use multiple-step optical excitations through defect levels within the forbidden bandgap of silicon. As pointed out by Shockley and Queisser [43], this improved carrier generation will be at the expense of increased recombination in the cell, limiting the scope for performance improvement. A subsequent analysis confirmed that mid-gap states were not promising in this role [44]. However, reformulation of the Shockley-Read-Hall theory of recombination through defect levels to take into account optical excitation through the defect level [39], combined with the development of light-trapping theory, has allowed the issue to be re-addressed [45]. The conclusion is that impurity levels lying closer to the band edge than to mid-gap can improve current output, without excessive loss in cell voltage [45].

Recently, a silicon cell of a reported, but not independently confirmed, efficiency of 35% has been described [46]. The change in cell design responsible for this apparent improvement is the implantation of hydrogen followed by annealing to form cavities submerged within the silicon close to the cell junction. The improved parameter producing this apparently high efficiency is a reported short-circuit current density of 69.1 mA cm^{-2} , approximately twice that expected from cells with a planar surface and a single-layer antireflection coating, as in the reported cells. The improved current output was attributed to impurity-assisted photoabsorption, as discussed above. However, this effect cannot account for the extraordinarily high current density reported, although it can account for the extended response at wavelengths

past the bandgap edge of silicon reported for these cells. The most likely explanation for the reported high current densities is the very small size of the cells tested (2.3 mm × 2.3 mm). As described elsewhere [47], peripheral collection effects can produce errors of up to 100% in measuring short-circuit current densities in cells of this extremely small size. Alternatively, new physical principles would have to be introduced into photovoltaic theory, since there are not enough photons in sunlight to produce such high current density, even ignoring the not insignificant reflection and collection losses expected for a cell of the reported design. Each photon would have to produce multiple electron-hole pairs, even if it did not have the required energy.

4.3. Voltage improvement

The open-circuit voltage of present PERL cells is limited by recombination along the top surfaces of the cell. By careful design and improvements in processing technology, it should be possible to increase these voltages to reach intrinsic voltage limits, determined by Auger recombination processes within the bulk of the cell [29]. The highest voltages will be reached in lightly doped material with the voltage being given by

$$V_{oc} = \frac{2}{3}(kT/q) \ln[J_L/(qn_i^2(C_n + C_p)W)] \quad (1)$$

where kT/q is the thermal voltage (25.85 mV at 300 K), J_L is the light-generated current (at the open-circuit voltage point), n_i is the intrinsic carrier concentration, W is the cell thickness and C_n and C_p are the electron and hole Auger recombination coefficients in silicon [39].

Since this expression was originally derived [29], there have been compensating changes in the accepted values of the Auger coefficients and the intrinsic carrier concentration of silicon. Using the values of $1.66 \times 10^{-30} \text{ cm}^6 \text{ s}^{-1}$ and $1.00 \times 10^{10} \text{ cm}^{-3}$ at 300 K, respectively, gives a value of the open-circuit voltage limits of 748 mV for a 280 μm thick cell and 770 mV for an 80 μm thick cell, both at 25 °C. Current experimental high-performance PERL cells give experimental values of just over 700 mV with test structures giving values up to 717 mV [48].

Cells which approach the limiting voltages previously mentioned will have ideality factors approaching 2/3 [29]. This will make possible higher fill factors than in present cells.

The minority carrier lifetimes required to reach the limiting voltages are values significantly above 2 ms and 0.8 ms for the two different thicknesses mentioned. Experimentally, lifetimes as high as 30 ms have already been reported in unprocessed silicon wafers [49]. More challenging is the value of the surface recombination velocity required to reach the limiting voltage, with values well below 8 cm s^{-1} and 5 cm s^{-1} required respectively over both front and rear surfaces. Such values can be reached in oxidized surfaces or at least temporarily in surfaces subjected to hydrofluoric acid treatments [49]. The total contribution from diffused regions has to be less than 10 fA cm^{-2} and 4 fA cm^{-2} of cell surface area respective-

ly. Values as low as 25 fA cm^{-2} of diffused surface have been demonstrated in experimental cells [48].

4.4. Innovative structures

4.4.1. Tandem cells. An example of a structure which can substantially increase cell efficiency above the limits for a homojunction cell, and so falls into the present category, is a tandem cell structure [50]. Silicon has an appropriate bandgap to be used as the lower cell in a two- or three-cell tandem. One difficulty is that there are not many materials with a suitable lattice constant and bandgap to form an epitaxially grown top cell on silicon [51]. One approach is to have an intervening buffer layer, of higher bandgap than silicon, to take up the lattice mismatch. This layer could also be used to provide electrical connection between the overlying cell and silicon. High-efficiency cells by this approach are extremely likely over coming years. At present, the efficiency of such a tandem cell on a silicon substrate is limited to about 20% [52]. Since GaP is lattice matched to silicon and good results have recently been reported for cells made with alloys of this material and InP [53], these might be promising materials for further investigation of this approach.

Hydrogenated amorphous silicon cells on silicon substrates have also been extensively investigated, primarily in Japan [54]. Although amorphous silicon has an appropriate bandgap for the top cell in such a tandem, it does not form the basis of a good design due to the relatively low open-circuit voltage and poor blue response of cells made from this material. Ideally, the top cell in a two-cell tandem should contribute about two-thirds to the total power output [50] and so should be the better cell in the combination. Although efficiencies above 19% have been reported for such tandem cell structures [55], these are small-area devices which present the same measurement difficulties as previously mentioned. There are simply not enough photons in sunlight to produce the current densities reported for such devices (totalling 40.4 mA cm^{-2}), given the high optical losses in the experimental cells [55]. There would appear to be about a 10% over-estimation of the current output for these devices, suggesting actual efficiencies around 17%. Having an amorphous silicon layer on top of crystalline silicon substrate is actually likely to degrade the performance of the substrate, since a crystalline silicon cell can efficiently convert many of the ultraviolet photons which would be wasted in a tandem cell of this type. In other words, the optimum thickness of the amorphous material in the tandem is probably zero.

The possible advantages of a crystalline silicon on crystalline silicon cell tandem have also been explored [56]. Since blue light is very strongly absorbed in silicon, only a thin layer of silicon is required for the uppermost cell in a two-cell, current-matched tandem combination. From equation (1), this greatly increases the voltage capability of the uppermost cell. However, calculated performance improvements by this approach are quite small even if quite challenging technological problems

are overcome. The highest potential of this approach seems to be as a way of up-grading the performance of low-quality starting substrates [56].

4.4.2. Superlattices. Semiconductor/semiconductor and semiconductor/insulator superlattices provide a new, still largely unexplored field for semiconductor electronics. The full potential of this field for photovoltaics has not yet been evaluated. It has recently been suggested that superlattice cells can provide similar efficiencies to those predicted for tandem cells [57, 58]. However, this conclusion is based on what is, essentially, an assertion that the bandgap for absorption of light and that for recombination can be decoupled. Such a property would seem to violate detailed balance arguments which inextricably relate absorption and recombination processes [43]. However, thorough analysis of particular material systems is undoubtedly warranted to see how much can be gained in this regard.

In the case of silicon, most interest has been shown in silicon/germanium superlattices. The presence of strain in such superlattices, due to the lattice mismatch between the components, produces additional interesting effects beyond those in an unstrained structure. The advantages of including some alloyed material within a conventional silicon cell in some circumstances have already been mentioned [40, 41]. Not only do superlattices open up the prospects for additional advantages along the lines claimed in recent work [57, 58], they also open up the possibility of increased absorption by imparting quasi direct-bandgap properties to this indirect-bandgap system by band-folding effects [59]. Evidence for increased absorption in such short-period superlattices has already been reported [60]. However, the increased absorption occurs at a threshold energy below 0.8 eV, and the effective absorption coefficients are only of the order of 1000 cm^{-1} ; neither of which makes these quasi direct-gap properties look particularly promising for silicon-based photovoltaics at first sight.

Clearly, much more work is required before the full potential of superlattices for silicon photovoltaics can be clarified.

5. Conclusion

Although the history of silicon cells dates back over 50 years, the last 10 years have seen enormous developments both in the efficiencies of experimental cells and cell theory. Design approaches capable of producing cells of limiting performance within the homojunction context are now well understood. Present efficiencies of 23% are reasonably close to practical limiting efficiencies of 26% expected with further improvement of the cell voltage and a reduction of optical losses in present cells.

Present high-performance silicon cells incorporate several optical design features to reduce reflection loss

from the top surface of the cell and to ensure multiple passes of weakly absorbed light across the cell. Recombination throughout the cell has to be minimized, not only to ensure the full collection of photogenerated carriers, but also to obtain the highest possible open-circuit voltage of the cell. An interesting recent development in this area has been the demonstration of effects in experimental devices attributed to an asymmetry between the electron and hole capture cross sections at interface states at oxide-silicon interfaces. This asymmetry may form the basis of new design criteria for further reducing the corresponding surface recombination rates. Ultimately, the performance of a homojunction silicon cell will be limited by intrinsic Auger recombination in bulk regions.

Further improvements beyond the figure of 26% efficiency previously mentioned will depend upon innovative concepts, which produce device structures which cannot be treated within the homojunction formalism. Increasing the absorption of sub-bandgap light by alloying or by incorporating multistep excitation through defect levels has some potential in this regard. Tandem cells on silicon offer prospects for substantially improved performance. The merits of this approach when bulk, self-supporting silicon substrates are used are obvious. It may be possible to significantly improve performance, in this case, by applying thin surface layers in additional steps, similar to applying chemically deposited antireflection coatings onto a cell. The merits of using silicon in such a tandem in an all-thin-film cell are less apparent. An all-silicon thin-film tandem based on a hydrogenated amorphous silicon cell as the upper layer and crystalline or polycrystalline silicon as the lower layer is not regarded as a particularly promising approach, due to the low performance potential of the amorphous material.

Superlattices offer additional scope for innovative concepts. Although the limited amount of work to date has not demonstrated any overwhelming advantages likely to accrue from the use of superlattices, the promise of this approach lies in the vast amount of territory still to be explored.

Acknowledgments

The author would like to thank the other members of the Centre for Photovoltaic Devices and Systems who have contributed to this work, particularly Armin Aberle, Patrick Campbell, Richard Corkish, Stephen Healy, Mark Keevers, Aihua Wang, Stuart Wenham and Jianhua Zhao. Portions of the work at the University of New South Wales mentioned in the text were supported by the Australian Research Council, the Energy Research and Development Corporation and Sandia National Laboratories. The Centre for Photovoltaic Devices and Systems is supported by the Australian Research Council and Pacific Power.

References

- [1] Braun F 1874 On conductance in metal sulphides *Ann. Phys., Lpz.* **153** 556
- [2] Torrey H C and Whitmer C A 1948 *Crystal Rectifiers* (New York: McGraw-Hill) pp 5-11
- [3] Ohl R S 1941 Light-sensitive electric device *US Patent* 2402622, filed 27 March 1941; 1941 Light-sensitive device including silicon *US Patent* 2443542, filed 27 May 1941
- [4] Kingsbury E F and Ohl R S 1952 Photoelectric properties of ionically bombarded silicon *Bell Syst. Tech. J.* **31** 802
- [5] Chapin D M, Fuller C S and Pearson G L 1954 A new silicon p-n junction photocell for converting solar radiation into electrical power *J. Appl. Phys.* **25** 676
- [6] Pearson G L 1985 P V founders award luncheon *Conf. Record, 18th IEEE Photovoltaic Specialists Conf., Las Vegas, 1985* (New York: IEEE)
- [7] 1954 *Bell Labs. Record* November p 436; 1955 *Bell Labs. Record* May p 166
- [8] Mandelkorn J, McAfee C, Kesperis J, Schwartz L and Pharo W 1962 Fabrication and characteristics of phosphorus-diffused silicon solar cells *J. Electrochem. Soc.* **109** 313
- [9] Iles P A 1970 Increased output from silicon solar cells *Conf. Record, 8th IEEE Photovoltaic Specialists Conf., Seattle, 1970* (New York: IEEE) pp 345-52
- [10] Gereth R, Fischer H, Link E, Mattes S and Pschunder W 1970 Silicon solar technology of the seventies *Conf. Record, 8th IEEE Photovoltaic Specialists Conf., Seattle, 1970* (New York: IEEE) pp 353-9
- [11] Mandelkorn J and Lamneck J H 1973 A new electric field effect in silicon solar cells *J. Appl. Phys.* **44** 4785
- [12] Godlewski M P, Baraona C R and Brandhorst H W 1973 Low-high junction theory applied to solar cells *Conf. Record, 10th IEEE Photovoltaic Specialists Conf., Palo Alto, 1973* (New York: IEEE) pp 40-9
- [13] Narayanan S and Green M A 1989 Improvement in the open circuit voltage and efficiency of silicon solar cells by rear aluminium treatment *Solar Cells* **26** 329
- [14] Pasquinelli M, Martinuzzi S, Natoli J Y and Floret F 1991 Improvement of phosphorus gettered multicrystalline silicon wafers by aluminium treatment *Conf. Record, 22nd IEEE Photovoltaic Specialists Conf., Las Vegas, 1991* (New York: IEEE) pp 1035-9
- [15] Lindmayer J and Allison J 1973 The violet cell: an improved silicon solar cell *COMSAT Tech. Rev.* **3** 1
- [16] Haynos J, Allison J, Arndt R and Meulenberg A 1974 The Comsat non-reflective silicon solar cell: a second generation improved cell *Int. Conf. on Photovoltaic Power Generation, Hamburg, September 1974* p 487
- [17] Rittner E S and Arndt R A 1976 Comparison of silicon solar cell efficiency for space and terrestrial use *J. Appl. Phys.* **47** 2999
- [18] Green M A, Blakers A W, Wenham S R, Narayanan S, Willison M R, Taouk M and Szpitalak T 1985 Improvements in silicon solar cell efficiency *Conf. Record, 18th IEEE Photovoltaic Specialists Conf., Las Vegas, 1985* (New York: IEEE) pp 39-42
- [19] Sinton R A, Kwark Y, Gruenbaum P and Swanson R M 1985 Silicon point contact concentrator solar cells *Conf. Record, 18th IEEE Photovoltaic Specialists Conf., Las Vegas, 1985* (New York: IEEE) pp 61-5
- [20] Sinton R A, Crane R A, Beckwith S, Cuevas A, Gruenbaum P E, Kane D E, Gan J Y, King R R, Midkiff N and Swanson R M 1990 Developments in module ready Si backside-contact solar cells *Conf. Record, 21st IEEE Photovoltaic Specialists Conf., Kissimmee, 1990* (New York: IEEE) pp 302-6
- [21] Sinton R A, Kwark Y, Gan J Y and Swanson R M 1986 27.5% Si concentrator solar cells *IEEE Electron Device Lett.* **7** 567
- [22] Green M A 1991 Recent advances in silicon solar cell performance *Proc. 10th European Communities Photovoltaic Solar Energy Conf. Lisbon, April 1991* (Dordrecht: Kluwer) pp 250-3
- [23] Zhao J and Green M A 1991 Optimized antireflection coatings for high efficiency silicon solar cells *IEEE Trans. Electron Devices* **38** 1925
- [24] Campbell P R 1989 Light trapping and reflection control in a crystalline silicon solar cell *PhD Thesis* University of New South Wales
- [25] Campbell P and Green M A 1987 Light trapping properties of pyramidally textured surfaces *J. Appl. Phys.* **62** 243-9
- [26] Campbell P, Wenham S R and Green M A 1989 Improved reflection and light trapping using tilted pyramids and grooves *Proc. 4th Int. Photovoltaic Science and Engineering Conf., Sydney, February 1989* pp 615-20
- [27] Green M A, Zhao J, Wang A and Wenham S R 1992 45% efficient silicon photovoltaic cell under monochromatic light *IEEE Electron Device Lett.* **13** 317-18
- [28] Sinton R A and Swanson R M 1987 Increased photogeneration in thin silicon concentrator solar cells *IEEE Electron Device Lett.* **8** 547
- [29] Green M A 1984 Limits on the open circuit voltage and efficiency of silicon solar cells imposed by intrinsic Auger processes *IEEE Trans. Electron Devices* **31** 671-8
- [30] Balk P (ed) 1988 *The Si-SiO₂ System* (Amsterdam: Elsevier)
- [31] Aberle A, Glunz S and Warta W 1992 Impact of illumination level and oxide parameters of Shockley-Read-Hall recombination at the Si-SiO₂ interface *J. Appl. Phys.* **71** 4422
- [32] Goetzberger A, Heine V and Nicollian E H 1968 Surface states in silicon from charges in the oxide coating *Appl. Phys. Lett.* **12** 95
- [33] Eades W and Swanson R 1985 Calculation of the surface generation and recombination velocities at the Si-SiO₂ interface *J. Appl. Phys.* **58** 4267
- [34] Green M A, Wenham S R, Zhao J, Wang A, Dai X, Milne A, Taouk M, Shi J, Yun F, Chan B, Sproul A B and Stevens A 1992 One-sun silicon solar cell research *Final Report, Sandia Contract 66-5863*
- [35] Yablonovitch E, Swanson R M, Eades W D and Weinberger B R 1986 Electron-hole recombination at the Si-SiO₂ interface *Appl. Phys. Lett.* **48** 245
- [36] Green M A and Blakers A W 1983 Advantages of MIS structures for silicon solar cells *Solar Cells* **8** 3-16
- [37] Yablonovitch E, Gmitter T, Swanson R W and Kwark Y K 1985 A 720 mV open circuit voltage SiO₂:c-Si:SiO₂ double heterostructure solar cell *Appl. Phys. Lett.* **47** 1211
- [38] Lindholm F A, Neugroschel A, Arienzo M and Iles P A 1985 Heavily doped polysilicon contact solar cells *IEEE Electron Device Lett.* **6** 363
- [39] Green M A 1987 *High Efficiency Silicon Solar Cells* (Aedermannsdorf: Trans. Tech. Publications)
- [40] Healy S A 1992 The low temperature solution growth of thin-film silicon and silicon germanium alloys and their use for photovoltaic applications *PhD Thesis* University of New South Wales
- [41] Healy S A and Green M A 1992 Efficiency enhancements in c-Si solar cells by the incorporation of a region alloyed with germanium *Solar Energy Mater.* at press

- [42] Wolf M 1960 Limitations and possibilities for improvement of photovoltaic solar energy converters *Proc. IRE* **48** 1246
- [43] Shockley W and Queisser H J 1961 Detailed balance limits of efficiency of p-n junction solar cells *J. Appl. Phys.* **32** 510
- [44] Guttler G and Queisser H J 1970 Impurity photovoltaic effect in silicon *Energy Conversion* **10** 51
- [45] Keevers M and Green M A Impurity photovoltaic effect in silicon *J. Appl. Phys.* to be submitted
- [46] Jianming Li, Ming Chong, Jiancheng Zhu, Yuanjing Li, Jiadong Xu, Peida Wang, Zuoqi Shang, Zhankun Yang, Ronghua Zhu and Xiolan Cao 1992 35% efficient non-concentrating novel silicon solar cell *Appl. Phys. Lett.* **60** 2240
- [47] Godfrey R B and Green M A 1977 Enhancement of MIS solar cell 'efficiency' by peripheral collection *Appl. Phys. Lett.* **31** 705-7
- [48] Wang A, Zhao J, Wenham S R and Green M A 717 mV open-circuit voltage silicon solar cells using hole-capture limited surface passivation, submitted
- [49] Yablonovitch E, Allara D L, Chang C C, Gmitter T and Bright T B 1986 Unusually low surface-recombination velocity on silicon and germanium surfaces *Phys. Rev. Lett.* **57** 249
- [50] Fan J C C 1984 III-V compounds for single-junction and tandem applications, *1st Int. Photovoltaic Science and Engineering Conf. Kobe, November 1984* (Tokyo: Japan Convention Services) pp 343-50
- [51] Corkish R 1991 Some candidate materials for lattice-matched liquid-phase epitaxial growth on silicon *Solar Cells* **31** 537
- [52] Yamaguchi M 1992 Compound solar cells for space use *Proc. 6th Int. Photovoltaic Science and Engineering Conf., New Delhi, February 1992* (New Delhi: Oxford/IBM) pp 503-10
- [53] Olson J M, Kurtz S R, Kibbler A E and Faine P 1990 Recent advances in high efficiency GaInP₂/GaAs tandem solar cells *Proc. 21st IEEE Photovoltaic Specialists Conf., Kissimmee, May 1990* (New York: IEEE) pp 24-9
- [54] Hamakawa Y 1992 Recent progress of amorphous silicon solar cell technology *Proc. 6th Int. Photovoltaic Science and Engineering Conf., New Delhi, February 1992* (New Delhi: Oxford/IBM) pp 3-10
- [55] Ma W, Horiuchi T, Yoshimi M, Hattori K, Okamoto H and Hamakawa Y 1992 a-Si/poly-Si four terminal stacked solar cell having an efficiency more than 19% *6th Int. Photovoltaic Science and Engineering Conf., New Delhi, February 1992* (New Delhi: Oxford/IBM) pp 463-8
- [56] Green M A 1986 Crystalline and Polycrystalline silicon tandem junction solar cells: theoretical advantages *Solar Cells* **18** 31-40
- [57] Barnham K W J and Duggan G 1990 A new approach to high-efficiency multi-band-gap solar cells *J. Appl. Phys.* **67** 3490
- [58] Barnham K W J, Braun B, Nelson J and Paxman M 1991 Short-circuit and energy efficiency enhancement in a low-dimensional structure photovoltaic device *Appl. Phys. Lett.* **59** 135
- [59] Pearsall T P (ed) 1990 Strained-layer superlattices: physics *Semiconductors and Semimetals* vol 32 (Boston: Academic)
- [60] Okumura H, Miki K, Misawa S, Sakamoto K, Sakamoto T and Yoshida S 1989 Observation of direct band gap properties in Ge_nSi_m strained-layer superlattices *Japan. J. Appl. Phys.* **28** L1893