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High Efficiency Silicon Solar Cells

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Abstract

Silicon remains the material of choice for photovoltaics because of its abundance, non-toxicity, high and stable cell efficiencies, the maturity of production infrastructure and the deep and widespread level of skill available in relation to silicon devices. Rapidly decreasing module prices mean that area-related balance of systems costs are an increasing proportion of photovoltaic systems price. This places a premium on efficient cells. In recent years there have been large improvements in mass production of high quality wafers, the ability to handle thin wafers, maintenance of high minority carrier lifetimes, surface passivation, minimisation of optical losses, device characterisation and in other areas. Many of these improvements are viable in mass production. The upper limit of silicon solar cell efficiency is 29%, which is substantially higher than the best laboratory (25%) [1] and large-area commercial (24%) [2, 3] cells. Cell efficiencies above 25% appear to be feasible in both a laboratory and commercial environment. Such a cell will have minimal bulk recombination due to a combination of a thin substrate with a very high minority carrier lifetime; superb surface passivation; small-area electrical contacts consistent with low contact recombination, free carrier absorption and contact resistance; excellent optical control through the use of texturing, antireflection coatings and rear surface reflectors; low edge recombination assisted by the use of thinner wafers, larger cells and edge passivation; and sufficient metal coverage to minimise resistive losses. This paper will survey current work in high-performance silicon solar cell design and fabrication, and discuss approaches to efficiency improvements.

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1. Introduction

The dominant photovoltaic material is crystalline silicon. Crystalline silicon is abundant, non-toxic, low-cost, allows the fabrication of cells with high and stable conversion efficiency, is the most mature

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photovoltaic material, and is the long-term market leader. There is very widespread and deep skill and infrastructure available in crystalline silicon technology, both within the photovoltaic and integrated circuit industries.

Thousands of researchers and companies work in the area of crystalline silicon, feeding their capabilities into the manufacture of crystalline silicon materials, cells and modules. Problems and opportunities that arise rapidly come to the attention of many skilled people and companies, leading to commercial solutions. Companies innovate rapidly, creating machines that can implement in a commercial setting improvements obtained in laboratories. Crystalline silicon photovoltaic modules that meet certification requirements are widely trusted to perform as expected for decades. Their failure modes are well understood and avoidable. Crystalline silicon modules have substantially higher efficiency than any non-concentrating modules on the market, which reduces the cost of the area-related balance of systems components. As the cost of the modules declines, the latter becomes a dominant cost of photovoltaic electricity. These attributes are not shared to the same degree by competing materials. In some cases, alternatives may have an advantage “on paper”. However, market dominance is usually difficult to change in the case where the dominant technology has many favourable attributes, as is the case with crystalline silicon. Many analysts expect the past and present domination of the photovoltaic market by crystalline silicon technology to continue into the indefinite future.

The theoretical limiting efficiency of the crystalline silicon solar cell under non-concentrating sunlight is about 29% [4]. This is not far below the theoretical limit for any single junction solar cell. The calculation of maximum efficiency assumes zero reflective losses, Lambertian light trapping, zero resistive losses, zero surface recombination, and volume recombination arising only from Auger and Radiative modes. Much higher efficiencies are possible with tandem solar cells and other theoretical concepts. The best III-V tandem cells reach 44% (Solar Junction, as reported by NREL) under concentrated sunlight. However, costs per unit area are orders of magnitude higher than for crystalline silicon cells. The best laboratory and commercial silicon solar cells currently reach 24-25% efficiency under non-concentrated sunlight, which is about 85% of the theoretical limit.

The main commercial motivation for developing higher cell efficiency is reductions in the area-related costs. These include module materials (silicon, cell fabrication, cell interconnection, glass, pottants, back sheets, frames) and systems costs (transport, fencing, land preparation, support structures, module mounting, cabling). Secondary motivations include to obtain larger power outputs from small areas such as the roofs of buildings, and to obtain the reduced temperature coefficients of efficiency that arise from high open circuit voltage cells. Given the attractive attributes of crystalline silicon summarised above, two prospective routes to higher efficiency are improved cell design and fabrication, and tandem cells based on silicon.

In a silicon tandem structure, an additional cell fabricated from a material with a different bandgap would be placed either in front of or behind a high-quality silicon cell. This is a difficult structure to realise at an affordable cost. If a low band cell is placed behind the silicon cell then it contributes little to the overall efficiency but would approximately double the areal cost of the cells. Alternatively, if a high bandgap cell is placed in front of the silicon cell then it will need to convert most of the incoming sunlight into electricity with an efficiency exceeding that of the silicon cell. Unfortunately, there is no mature material that meets this requirement at an affordable cost. Additionally, it is difficult to grow different semiconductor materials on silicon.

Fortunately, there is plenty of room for improvements in silicon cell and module efficiency without resorting to exotic tandem materials and techniques. There is a long-term upward trend in average commercial cell efficiencies that is likely to continue. Some companies, notably SunPower Corporation, manufacture cells in the 23–24% efficiency range that command a premium price. Can efficiencies in the 26–27% range be reached?

2. Improving solar cell efficiencies

A high-performance silicon solar cell has excellent optics (low reflection, low parasitic absorption from free carriers and metal contacts, excellent light trapping); low levels of avoidable recombination (at surfaces, in the junction, in the bulk, and around the cell perimeter); and low resistive losses. Methods of achieving these attributes have been refined over many decades.

By the mid-1970s, Mobil, RCA, Sandia, Westinghouse, ARCO and others had achieved efficiencies in the 14–17% range. Typical cell parameters were a V_{oc} of 600–645 mV, a J_{sc} of 34–37 mA/cm² and a fill factor of 77–82%. Cells were fabricated on low resistivity p-type substrates and incorporated random pyramidal texturing. However, surface passivation was poor, and the bulk lifetime was low because of contamination during ingot growth or cell fabrication.

During the 1980s and early 1990s a sustained period of improvements to cell efficiencies took place in various laboratories, principally at the University of New South Wales (UNSW - Australia) and at Stanford University (USA). This is illustrated in the chart of best research cell efficiencies maintained by the National Renewable Energy Laboratories (Fig. 1).

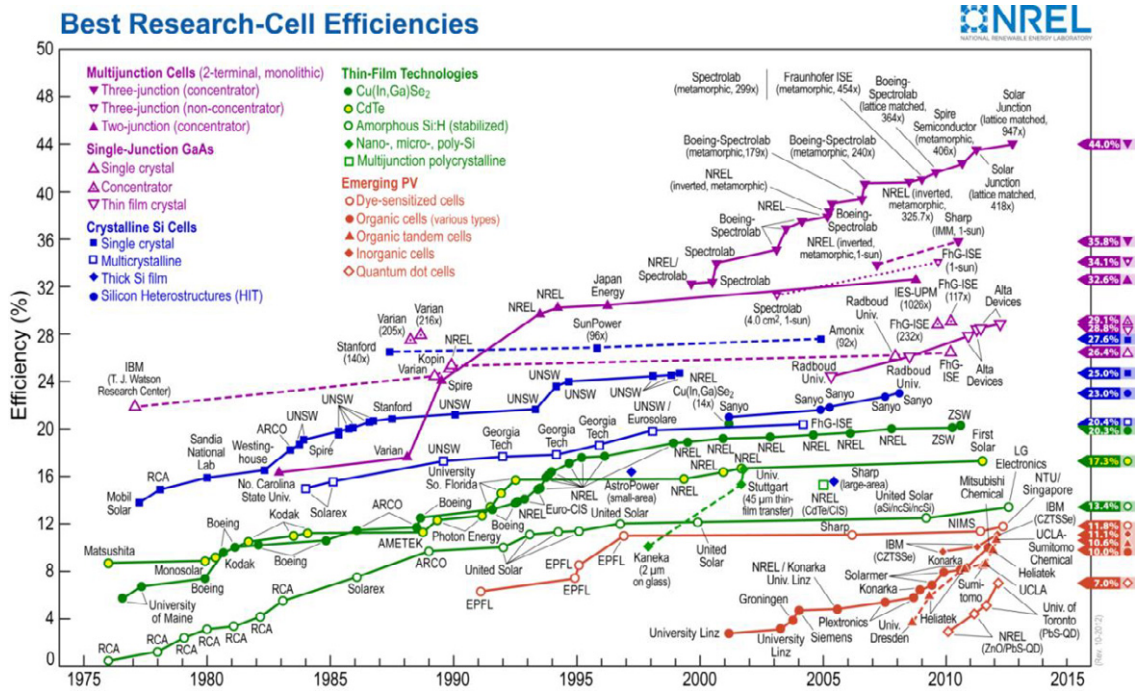


Fig. 1. Best research cell efficiencies (NREL <http://www.nrel.gov/ncpv/>, accessed November 2012)

The MIS (Metal-Insulator-Semiconductor) metal contact design from UNSW allowed the introduction of oxide passivation of the top surface of the cell. The oxide passivation was sufficiently thin that quantum mechanical tunnelling of electrons between the metal contacts and the silicon was possible. **In the regions away from the metal contacts an inversion layer was maintained through the application of a silicon monoxide antireflection coating with trapped positive charge.** This avoided the need for a phosphorus diffusion, albeit at the expense of a high effective emitter sheet resistance which necessitated closely spaced metal contacts. An additional problem was electrostatic neutralisation of the trapped positive charge over time. Incorporation of a light phosphorus emitter diffusion eliminated these problems. Efficiencies in the 18-19% range were achieved, with improved V_{oc} of 650-670 mV together with J_{sc} of 35-36 mA/cm² and fill factor of 81% [5].

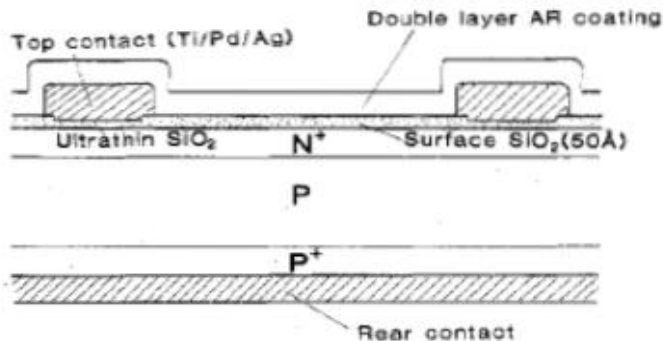


Fig. 2. MINP solar cell reproduced from [5]

The next UNSW design (“PESC”) removed the MIS metal contact in favour of a small area (~1%) aperture in a high-quality thermal oxide to allow electrical communication between the metal of the silicon while minimising contact recombination [6]. The thermal oxide minimised recombination between the metal contacts along the sunward surface. The rear surface was covered with alloyed aluminium which served the important purpose of providing excellent gettering during thermal oxidation of the sunward surface. The absence of effective furnace cleaning techniques made this essential. Light trapping and reflection control was provided by surface features including micro-grooves and micro inverted pyramids together with the introduction of a double layer antireflection coating (ZnS/MgF₂). Efficiencies in the range 20-21% were achieved, with V_{oc} of 660-670 mV, J_{sc} of 37-38 mA/cm² and fill factor of 82-83%.

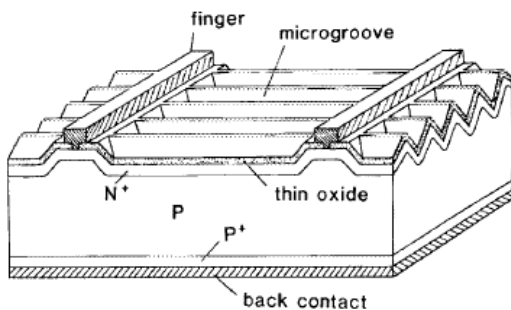


Fig. 3. PESC solar cell reproduced from [6]

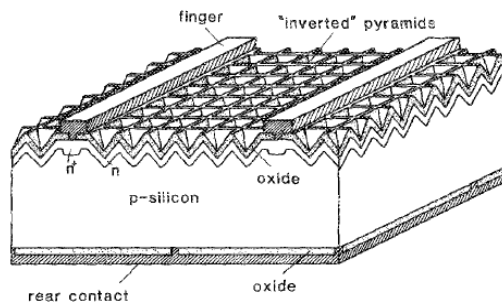


Fig. 4. PERC solar cell reproduced from [7]

The solar cells discussed above make use of float zone grown low resistivity (0.1-0.5 Ω-cm) 250-300 μm thick p-type wafers, which have high minority lifetimes, low oxygen levels and are process-tolerant.

The minority carrier diffusion length was similar to the wafer thickness. The gettering advantage of an alloyed aluminium rear surface outweighed the relatively high recombination and optical absorption rates within the alloyed region. The oxide passivation and light emitter phosphorus doping led to good blue response and creditable open circuit voltage. The metal fingers comprised evaporated Ti/Pd contacts followed by silver electroplating. The cells were generally 4 cm² in area, which avoided the elevated series resistance losses associated with large cells. They were not cut out of the host wafer prior to measurement - an aperture mask was used to measure the current instead. This avoided the high recombination associated with cut edges. Larger cells have smaller perimeter to area ratios and are less affected by detachment from host wafers, but at the expense of increased series resistance.

The next innovation from UNSW was the PERC (Passivated Emitter and Rear (local) Contact) cell [8]. The alloyed aluminium rear contact was removed and replaced by a thermal oxide. Direct rear metal contact was made between the silicon and an overlying non-alloyed aluminium layer via thousands of small apertures occupying about 1% of the cell surface, and spaced about a millimetre apart. This small contact fraction suppressed recombination at the rear metal contacts, while **the rear surface oxide suppressed recombination between the contacts**. The cell took advantage of the fact that **aluminium can make good electrical contact to relatively lightly doped p-type silicon surfaces**. An additional feature was a heavily phosphorus doped region directly under the front metal contact. Crucial to the design of these cells was the use of trichloroethane (TCA) to clean furnaces and thus preserve the high starting minority carrier lifetime of the wafers - there was no alloyed aluminium to getter impurities. Efficiencies of around 22% were obtained, with V_{oc} of 670-705 mV, J_{sc} of 38-40 mA/cm² and fill factor of 81-82%.

Finally, the UNSW PERL [8] cell added boron to the rear point contacts to suppress contact recombination and improve contact resistance. After refinement of all of the features of the cells, and shifting to 1-3 Ω-cm p-type substrates, efficiency in the range 24-25% was reached, with V_{oc} of 700-715 mV, J_{sc} of 41-42 mA/cm² and fill factor of 82-83%.

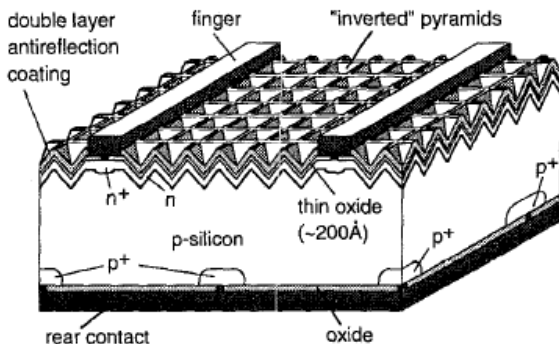


Fig. 5. PERL cell [8]

In parallel to the work at UNSW, Stanford University was working on back contact solar cells. In these solar cells both the N and P contacts are removed to the rear surface to eliminate shading of the front surface by metal gridlines. Substantial reductions in resistive losses are also possible because the N and P contact metallisation can cover much or all of the rear surface - even overlapping provided that an interposed pinhole-free insulating layer is used. Excellent front surface passivation is required because both the holes and electrons must be transported to the rear surface for collection without excessive front surface recombination. The minority carrier diffusion length must be at least several times larger than the wafer thickness in order to achieve high collection probability at the rear surface for electrons and holes that are mostly created at the front surface. The Stanford team introduced TCA processing to

photovoltaics in order to obtain high minority carrier lifetimes. Additionally, high resistivity n-type wafers were utilised. Efficiencies at one sun of 22% were obtained, with V_{oc} of 700 mV, J_{sc} of 41 mA/cm² and fill factor of 78% [9].

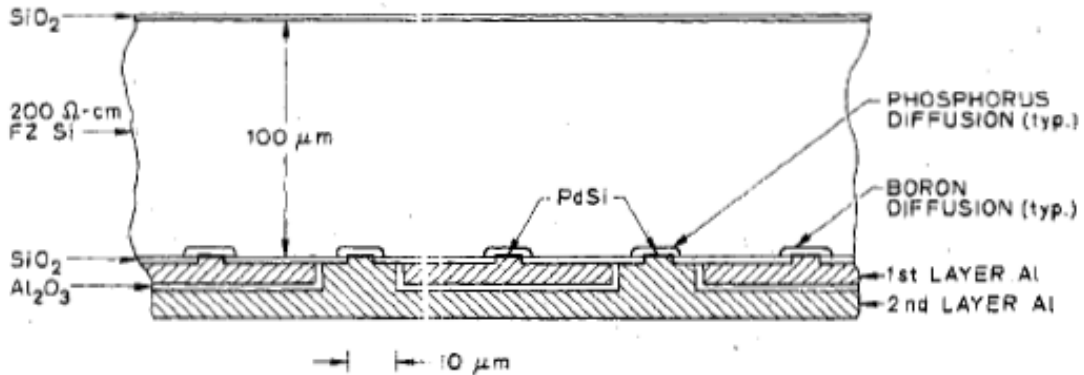


Fig. 6. Back contact solar cell reproduced from [10]

The original reason for the development of back contact solar cells by the Stanford group was to obtain high-performance silicon concentrator cells. However, the development of III-V tandem solar cells with much higher efficiency potential than single junction silicon cells eliminated the concentrator market for silicon. SunPower Corporation grew out of the work of the Stanford group, and set out to simplify and improve back contact cells for large-scale one sun commercial applications. SunPower makes the best silicon solar cells presently on the market, with efficiencies of over 24% for the best large area (155 cm²) cells, and V_{oc} of 720 mV, J_{sc} of 41 mA/cm² and fill factor of 83% [2, 3].

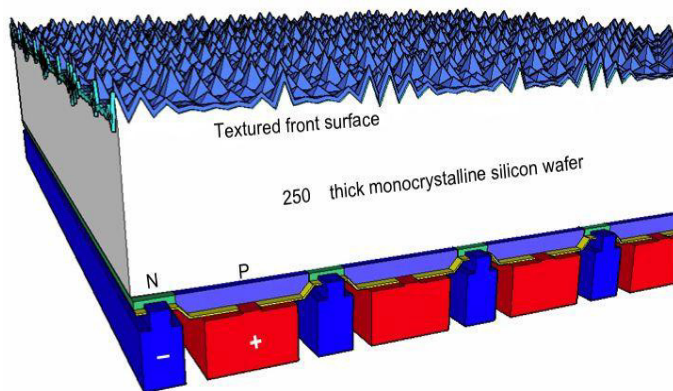


Fig. 7. SunPower back contact cell [2, 3]

Silicon Heterojunction (SHJ) Solar Cells have attracted much attention due to the fact that the SHJ design enables low processing temperature and thinner substrate, and conversion efficiency of 23-24% in an industrial environment [11]. Record open-circuit voltages approaching 750 mV have been obtained in test structures. The key innovation of SHJ is the use of heterostructures to provide superb surface passivation across the cell surface, including at the contact regions.

The schematic design of SHJ solar cells developed by Sanyo is illustrated in Fig. 1. The SHJ device (Fig. 1) is made from n-type silicon. The sunward surface has an intrinsic a-Si:H passivation layer and a

boron-doped amorphous silicon (p a-Si:H) emitter, which are deposited successively by plasma enhanced chemical vapour deposition (PECVD). A transparent conducting oxide (TCO) overlies the p a-Si:H. Metallisation is by screen-printing. The rear surface has a stack of intrinsic a-Si:H, n a-Si:H, a TCO film and metallisation.

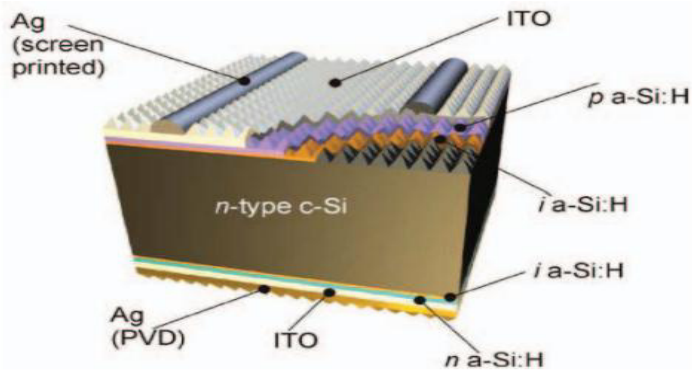


Fig. 8. Silicon Heterojunction Solar Cell Structure. Picture taken from [12].

The SHJ cell structure makes use of a few nanometre thick, wide bandgap, amorphous silicon buffer layer, that passivates the crystalline silicon surface, both in the contacted and non-contacted regions [13]. Research on a-Si:H and c-Si heterostructures took place as early as 1974 [14]. In 1983 Hamakawa and co-workers investigated tandem junction solar cells using a-Si:H and poly-Si heterostructure as a bottom cell [15, 16]. In the late 1980s Sanyo started incorporating heterojunction structures into c-Si solar cells and presented cells with efficiencies of 12%, 14.5% [17], 18% [18], 20% [19], and most recently 23.7% [11] for a large-area (>100 cm²) wafer-based solar cells. Despite the advantages discussed above, SHJ solar cells have drawbacks including reduced current density due to parasitic absorption in the TCO and the a-Si:H emitter, trade-off between series resistance and anti-reflection layer of the front TCO, and shading by the metal grid. To overcome these limitations, combining the SHJ cell structure with an interdigitated back-contact (IBC) cell structure is a natural way forward.

3. 26-27% Efficient silicon solar cells

Improvement in solar cell efficiencies above 26% requires attention to every detail of the cell design. Back contact designs have advantages outlined previously, and are considered here as an illustration of a route to 26% efficiency.

Detailed modelling of the AM1.5G standard spectrum shows that the current density available from a 500 μm thick silicon cell is limited to 45 mA/cm². This assumes that there are no unavoidable losses. Taking a 25% efficient PERL cell as a model, the avoidable losses in a real cell are illustrated in Fig. 9. Features of this cell design include excellent light trapping, a double layer antireflection coating, low free carrier absorption due to localisation of heavy diffusions, low metal reflection due to narrow, rounded fingers, no busbars (they are located outside the 4 cm² aperture area) and no cutting of the cell from the host wafer (thus minimising edge losses).

An obvious improvement could be made by eliminating the reflection loss from the metal grid on the front surface (0.8 mA/cm²) by utilising a back contact design. Imperfect light trapping, free carrier absorption, non-metal reflection and absorption in the antireflection coating remain. However, a back contact cell must be thin in order to achieve low-loss transport of electrons and holes to the rear surface.

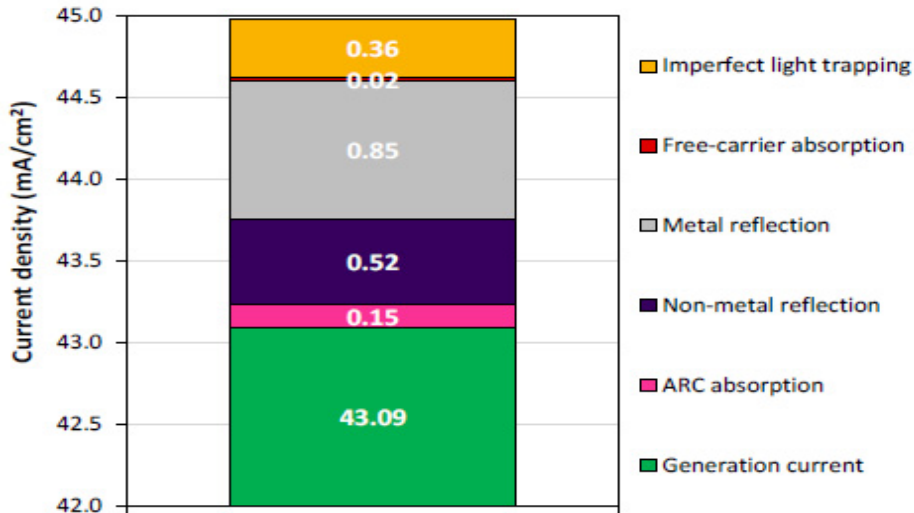


Fig. 9. Optical losses in a high performance PERL cell

Figure 10 shows the effective available current density as a function of cell width assuming that all losses are suppressed. The typical thickness of a back contact solar cell is 120 μm , which entails a loss of potential current equal to the gain achieved by removing the front metal contacts (0.8 mA/cm^2). Small gains in the quality of the antireflection coating could be achieved, but avoidable losses from free carrier absorption and insufficient light trapping are very small. The conclusion is that a current density of a little more than 43 mA/cm^2 is practically achievable with current technology in either an optimised back contact or bifacially contacted solar cell.

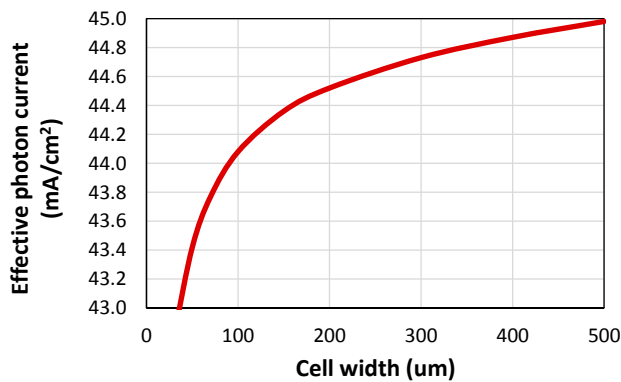


Fig. 10. Maximum effective current density as a function of cell thickness (width)

Upper bounds on fill factor and open circuit voltage can be calculated for a rear contact cells under the assumptions of Auger dominated recombination, the Kerr-Cuevas Auger model, constant mobility, negligible lateral carrier flow, moderate injection, optimum doping (1-5 $\Omega\text{-cm}$) and no resistance losses. The results are presented in Fig. 11.

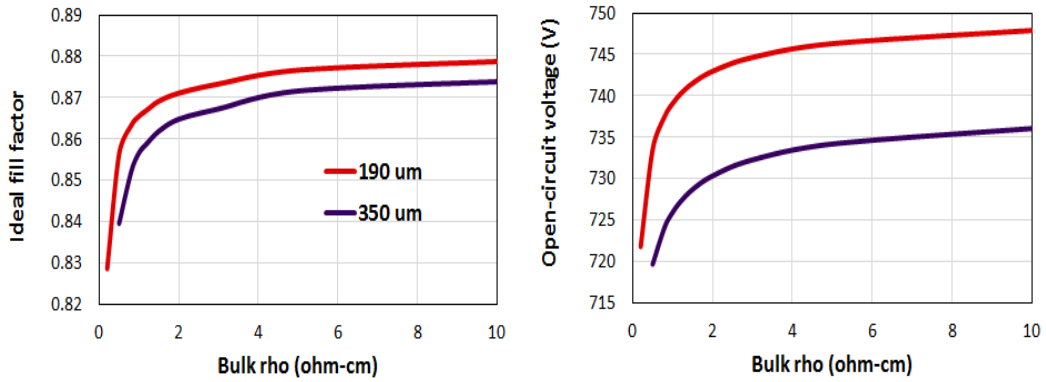


Fig. 11. Upper bounds on fill factor and open circuit voltage (see text for details)

Technologically achievable recombination losses must be taken into account. Taking front surface recombination of 5 fA/cm^2 measured on textured Al_2O_3 coated surfaces; rear surface recombination of 15 fA/cm^2 (including both diffused & non-diffused regions); negligible metal contact recombination (due to the small areas involved), a bulk lifetime of 10 msec and negligible edge recombination (the cell is not cut from the host wafer), the possible fill factor and open circuit voltage is illustrated in Fig. 12. Both are dependent upon the cell thickness.

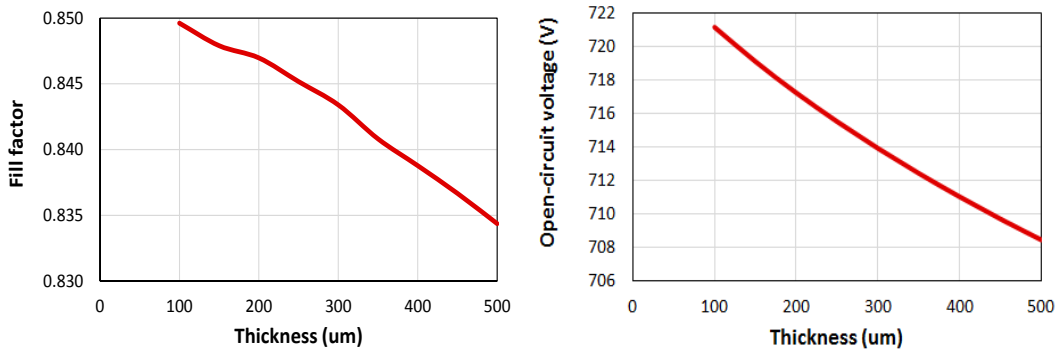


Fig. 12. Practical limits to fill factor (left) and V_{oc} (right)

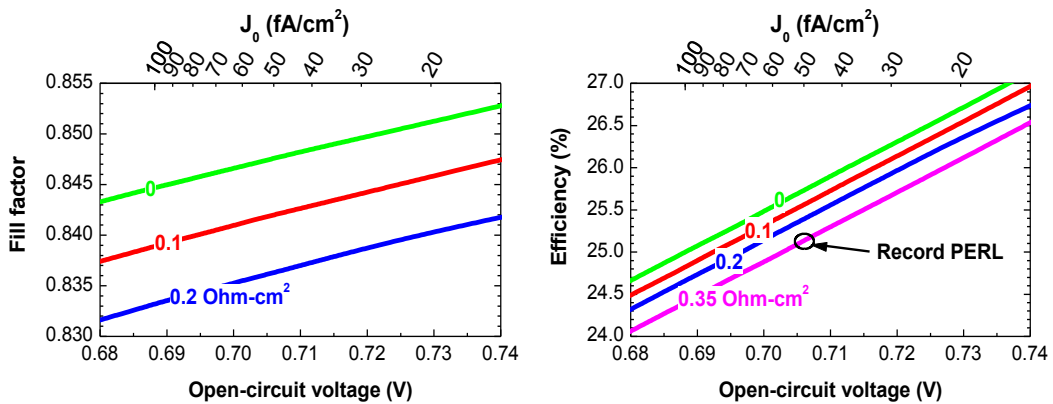


Fig. 13. Practical (a) fill factor (left) and (b) efficiency (right) as a function of V_{oc}

The fill factor in the presence of nonzero resistance losses is graphed in Fig. 13(a) as a function of open circuit voltage. A back contact cell can have very low series resistance of around $0.1 \Omega\text{cm}^2$. The dependence of efficiency upon open circuit voltage is graphed in Fig. 13(b).

4. Conclusion

The parameters discussed in the paper (above) are realistically achievable using current process techniques in a back contact solar cell. The main advantage of the back contact design is reduced resistance losses. An open circuit voltage above 720 mV (35 fA/cm^2) is compatible with 26% efficiency. Taking account of the progress of SunPower, Sanyo and other companies, the process requirements to achieve such an efficiency are likely to be achievable in a commercial setting, albeit at a cost premium. In summary, laboratory and commercial efficiencies are likely to progress to the 26-27% range over the next few years.

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