

## Review Article

# Silicon Thin-Film Solar Cells

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We review the field of thin-film silicon solar cells with an active layer thickness of a few micrometers. These technologies can potentially lead to low cost through lower material costs than conventional modules, but do not suffer from some critical drawbacks of other thin-film technologies, such as limited supply of basic materials or toxicity of the components. Amorphous Si technology is the oldest and best established thin-film silicon technology. Amorphous silicon is deposited at low temperature with plasma-enhanced chemical vapor deposition (PECVD). In spite of the fundamental limitation of this material due to its disorder and metastability, the technology is now gaining industrial momentum thanks to the entry of equipment manufacturers with experience with large-area PECVD. Microcrystalline Si (also called nanocrystalline Si) is a material with crystallites in the nanometer range in an amorphous matrix, and which contains less defects than amorphous silicon. Its lower bandgap makes it particularly appropriate as active material for the bottom cell in tandem and triple junction devices. The combination of an amorphous silicon top cell and a microcrystalline bottom cell has yielded promising results, but much work is needed to implement it on large-area and to limit light-induced degradation. Finally thin-film polysilicon solar cells, with grain size in the micrometer range, has recently emerged as an alternative photovoltaic technology. The layers have a grain size ranging from 1  $\mu\text{m}$  to several tens of microns, and are formed at a temperature ranging from 600 to more than 1000°C. Solid Phase Crystallization has yielded the best results so far but there has recently been fast progress with seed layer approaches, particularly those using the aluminum-induced crystallization technique.

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## 1. INTRODUCTION

Faced with the threat of global warming caused by fossil fuel consumption, humankind is looking for alternative forms of power production that lead to minimal CO<sub>2</sub> emission. Photovoltaics, the direct conversion from sunlight into electricity, promises to be a major energy technology in the future. Indeed, solar insolation is quite well distributed around the globe, and it is plentiful (although quite dilute) while photovoltaics converts solar irradiation directly into a high quality energy form with an efficiency ranging from 5 to 20%. This is much higher than most of the other energy technologies that convert (often very indirectly) solar energy into useful work.

For photovoltaic systems, to be applied on a massive scale, however, the cost of the technology has to be low, with a price per kWh, comparable to the retail price of conventional electricity. At present, the dominating photovoltaic technology is still based on the concept that led to the first practical solar cell in 1954, that is, the “bulk” or wafer-based crystalline silicon technology. Although the cost of bulk Si solar cells and modules has decreased steadily over the last decades, through better material use and improved solar cell

performance, the trend will not continue indefinitely. The process of wafering, that is, sawing slices out of a large Si ingot or brick leads to a fundamental limitation in terms of material usage. Even if wire sawing is improved drastically, it is unlikely that an Si consumption per wafer (wafer thickness + kerf loss), much less than 250  $\mu\text{m}$ , can be obtained (today, this value is typically 400  $\mu\text{m}$ ). This is a relatively large amount of a costly material prepared with a very high energy input, which is, however, not necessary for high efficiency. Indeed, the theory states that high solar cell performance can be achieved even with a very thin Si layer if optical confinement is applied [1]. As a result of the limited potential for decrease in material use, and of the expected saturation in module performance as the theoretical limit is approached, the learning curve is foreseen to slow down and the cost to eventually saturate at a given value in the order of 1 \$/Wp at module level.

Thin-film approaches aim to reach low cost by starting with a low-cost (or potentially low-cost) material system; a thin layer of semiconductor is deposited on a low-cost substrate. If high efficiency and reliability is indeed achieved, thin-film solar cell technologies could reach substantially

lower costs, 0.5 \$/Wp and even below. Although thin-film solar cells have been announced for a long time as the next best thing, they have not yet had a breakthrough. The development of these technologies has in fact been rather slow, not faster than the bulk Si technology which, however, started much earlier. Recently, because of the Si feedstock shortage, the thin-film technologies have received new momentum. Because of the limited possibility to invest in conventional Si technology due to the shortage, substantial investment capital has flown into thin-film initiatives and led to the creation of many new companies.

This article covers several thin-film technologies that use Si for the active material. Sticking to Si instead of other semiconductors presents a number of advantages. Si is nontoxic, which makes it easily accepted by the public. Moreover, Si is abundantly available in the earth crust, so that its availability (at least in its raw form) will never be an issue. Finally, Si solar cell technologies can build further upon the extensive know-how accumulated over the years in the IC industry (for crystalline Si) and the display industry (for amorphous and microcrystalline Si).

The term “thin-film crystalline Si” is in fact quite broad. It covers a wide range of technologies, from amorphous Si to monocrystalline lift-off Si solar cells. In this article, I will limit myself to the thin-film Si technologies that use only 0.1 to 5  $\mu\text{m}$  of Si. Those are amorphous Si, microcrystalline Si, and thin-film polysilicon solar cells. This article intends to give a concise overview, but excellent in-depths reviews for each of these technologies can be found in recently published books on thin-film solar cells [2, 3]. Another review paper with a similar scope to the present article but even shorter can be found in a recent issue of the MRS bulletin [4].

## 2. SINGLE JUNCTION AMORPHOUS Si SOLAR CELLS

### 2.1. Material

Amorphous Si is usually deposited using the plasma-enhanced chemical vapour deposition (PECVD) technique, and the gas silane ( $\text{SiH}_4$ ) is mostly used as precursor. As a result of decomposition, surface adsorption and surface reactions, a network of Si atoms is formed on the substrate, mostly glass or a metal foil. The deposition temperature ranges typically between 180°C and 280°C. As a result of the deposition mechanism, amorphous silicon contains a large concentration of hydrogen atoms ( $\sim 10\%$ ). Hydrogen is, in fact, crucial for the material’s electronic properties, while unhydrogenated amorphous Si is of no use for devices. Therefore, the material one usually refers to using the words “amorphous silicon” is in fact hydrogenated amorphous silicon (a-Si:H).

Amorphous Si is a material that features short-range order but lacks long-range order. As in crystalline Si, each Si atom is mostly fourfold coordinated, but the bond lengths and angles between the bonds show a wide variation. This structure has a strong impact on the electronic structure of the material. Because the structure is no longer periodic, the strict conservation of momentum does not hold. As a result, instead of the indirect bandgap of crystalline Si, it basically has a direct bandgap. The absorption coefficient in a-Si is,

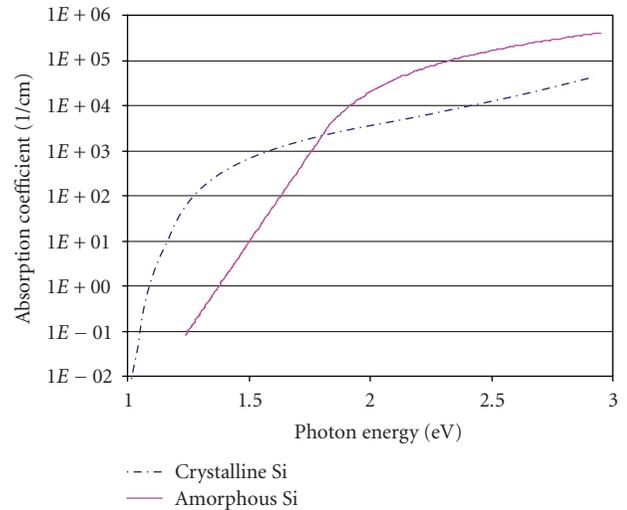


FIGURE 1: Absorption coefficient of a-Si:H versus photon energy, compared to crystalline Si.

therefore, much higher than that in crystalline Si, and, therefore, a much lower thickness is required to achieve the same absorption. However, the bandgap is also larger, 1.7 to 1.9 eV. Therefore, a large part of the infrared light cannot be absorbed in amorphous Si (Figure 1). Alloys can be deposited by adding germanium (to form a-SiGe:H) or carbon (to form a-SiC:H) precursors to the gas flow, so that the bandgap can be tuned to some extent.

In 1975, it was reported for the first time that hydrogenated amorphous Si behaved as a semiconductor, and that it was possible to vary its conductivity over many orders of magnitude by adding doping atoms [5]. Combined with the strikingly low defect concentrations that were measured (down to  $10^{15} \text{ cm}^{-3}$ ), this made the material extremely attractive for solar cells. The first amorphous Si solar cell followed soon, in 1976 [6]. Although the efficiency at the time was below 3%, it generated enormous interest and started a large research effort worldwide. Fast progress was reached in the end of the seventies and the beginning of the eighties, and, for some time, it looked like the days of crystalline Si would soon be over and that amorphous Si was going to conquer the whole PV scene. However, an important problem with amorphous Si was also identified. The new material turned out to suffer from degradation upon exposure to sunlight [7]. This phenomenon, called the Staebler-Wronski effect, causes a large increase in defect density (strong decrease in excess carrier lifetime), and is reversible upon annealing at temperatures above 150°C. From values between  $10^{15}$  and  $10^{16} \text{ cm}^{-3}$  in annealed state, defect densities increase to  $\sim 2 \times 10^{17} \text{ cm}^{-3}$  in light-soaked state. The metastable defects are believed to be dangling bonds formed by breaking weak bonds in the random network. The defect densities mentioned are valid for intrinsic amorphous Si. Doped amorphous Si, obtained by adding diborane to the gas flow for p-type material and phosphine for n-type, contains much more defect than intrinsic a-Si:H (several orders of magnitude

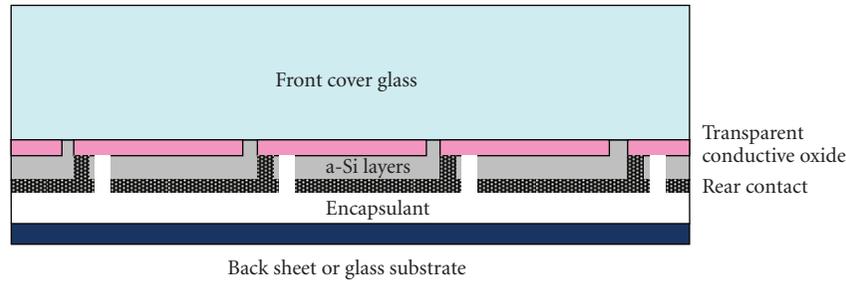


FIGURE 2: Monolithic module concept for amorphous silicon modules in superstrate configuration.

higher). Therefore, only intrinsic a-Si:H can be used as an absorber material.

Charge carrier mobility in amorphous Si is much lower than in crystalline Si. A good a-Si:H layer will show an electron mobility of around  $20 \text{ cm}^2/\text{Vs}$  at best. As a result, amorphous Si layers cannot conduct charge carriers laterally over a large distance.

The key parameters for amorphous Si are its dark conductivity, photoconductivity, and its mobility lifetime product. The conductivity of intrinsic a-Si:H in the dark is extremely low ( $< 10^{-10} \text{ S/cm}$ ) because of the low mobility, the large bandgap, and the fact that charge carriers at low concentration are trapped at defects. Under illumination, however, many of the defects get filled with photogenerated carriers and are saturated. As a result, many more charge carriers are available for charge transport, and the conductivity is many orders of magnitude higher than that in the dark. The photoresponse, defined as the ratio of the illuminated conductivity to the dark conductivity, is a good indication for the suitability of the material for devices, and should be larger than  $10^5$ . The mobility lifetime ( $\mu\tau$ ) product is the crucial parameter for the transport properties of excess charge carriers in the layer, and in device grade, amorphous Si is larger than  $10^{-7} \text{ cm}^2/\text{V}$ .

## 2.2. Solar cell and module technology

As a result of the low carrier mobility and low lifetime, collection cannot take place through diffusion. A strong drift field is an absolute requirement. This is achieved by sandwiching the intrinsic absorber layer between doped layers with opposite doping. As most of the generation takes place close to the top surface and the hole mobility is much lower than electron mobility, the device structure always features a p-doped layer on top (a side through which light enters the amorphous Si layer), while the bottom layer is n-doped. Indeed, in this way, most of the holes are generated close to the p-layer where they are majority carriers and no longer can recombine. Holes generated deeper in the layer have a higher probability of recombining and, therefore, a lower collection probability. In contrast, electrons have a high collection probability throughout the i-layer. Due to the very low lifetime in doped layers, all light absorbed in the p-layer is lost for conversion. To minimize this effect, not only the p-layer

is kept very thin ( $\sim 10 \text{ nm}$ ), but C can also be added so that the bandgap increases and the absorption decreases. The p-type layer, therefore, usually consists of a-SiC:H and is called the window layer.

The intrinsic layer thickness has to be chosen based on the  $\mu\tau$  product after light-soaking. If the layer is too thick, there will be large collection losses because holes generated deep in the layer recombine before being collected. If the layer is thin, the distance to be covered to be collected is shorter, and the electric field is stronger. Both effects have a very beneficial impact on carrier collection. However, a thin layer implies that a large fraction of the light does not get absorbed, but are lost through transmission or escape reflection. There is, therefore, an optimal thickness, which turns out to be around  $300 \text{ nm}$ . This low thickness is a clear advantage for manufacturing, as one of the most significant costs in amorphous silicon modules is the deposition cost. The drawback is that efficiencies are usually quite low and difficult to increase. It also explains why light trapping is an important topic in amorphous Si solar cell research, even though the material features high absorption coefficients.

Most types of amorphous silicon solar cells are in superstrate configuration, which means that the light enters the solar cell through the supporting substrate. This configuration requires a highly transparent substrate material and the presence of a transparent conductive oxide between the substrate and the active layer. These cells are also called “p-i-n” solar cells, referring to the sequence in which the different layers are deposited. The other option is to make a-Si:H cells in substrate configuration (“n-i-p” solar cells), which enables the use of a wider range of substrate materials.

After deposition of the different layers, the cells have to be isolated and interconnected with each other. Typically this is done using a combination of laser scribing and blanket deposition (transparent conductive oxide, the amorphous Si layers, and metal—combined or not with TCO—for the rear contact) in a monolithic module concept (Figure 2).

## 2.3. Industrial application

Over the years, many companies have been created to produce single junction a-Si:H modules. Generally, the modules are based on the monolithic concept shown in Figure 2, and have an efficiency ranging from 5 to 7%. Although many of

these companies stopped, a number of them have survived and grown over the years. Among those companies, the one with presently the largest production is Kaneka.

One of the problems encountered when producing amorphous silicon modules is the lack of reliable deposition equipment, with good uniformity, high up-time, and not requiring only moderate maintenance. This is because the deposition systems used are often specifically developed, sometime in-house, and have been produced only in small volumes. This situation has recently completely changed. Large companies that were so far involved in equipment manufacturing for LCD displays have entered the photovoltaic business. Their PECVD systems for amorphous Si deposition for displays are excellent platforms to develop equipment for amorphous silicon solar modules. Indeed, most of the issues concerning uniformity, cleaning, reliability, and so forth have already been solved, and they can concentrate on reaching the required material quality and production speed for solar cells. These companies are Unaxis (now Oerlikon Solar) and Applied Materials. They have hired experts in amorphous and microcrystalline deposition for solar cells, and are working to offer complete processes to the clients purchasing their systems. They are presently rapidly introducing their deposition systems into the photovoltaic market, or even complete production lines revolving around the deposition systems. In the last years, there have been many announcements of new large scale production lines based on such systems (e.g., Brilliant 234, Ersol thin-film, and Moser Baer), which should come on-line within two years.

Although all new players have plans to move to multi-junction solar cells at some point, they start with single junction amorphous modules, for which it is easier to reach the short-term cost targets. However, it is generally recognized that this technology can only be an intermediate step towards a technology with higher-efficiency potential.

#### 2.4. Outdoor performance of amorphous Si modules

The temperature coefficient of amorphous silicon solar cells is lower (in absolute value) than that of a crystalline Si. As a result, the modules do not lose so much in performance (relatively) when heated up. Moreover, amorphous Si modules have a good sensitivity to blue light, which is more present in diffuse illumination. Finally, the module efficiency under very low illumination is quite well maintained in contrast to standard crystalline Si modules, for which the performance collapses. As a result, the relative performance of single junction amorphous Si modules, expressed in kWh/kWp per year, which takes into account all the different conditions under which a PV module has to operate in a year, tends to be rather good for a-Si modules, better than that of conventional crystalline Si modules.

The long-term stability of amorphous Si modules is not necessarily granted. The producers have to pay special attention to the design of the modules, particularly to the type of transparent conductive oxide and to the encapsulation selected. Unfortunately, some poor quality products in the past gave amorphous Si a bad name, and there is a need to rectify this image.

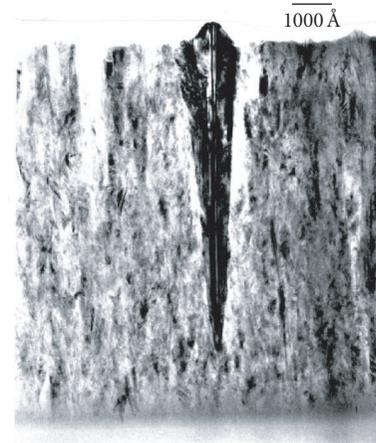


FIGURE 3: Cross-section TEM image of a microcrystalline Si layer. (Reproduced with permission from [8].)

### 3. MICROCRYSTALLINE Si SOLAR CELLS

#### 3.1. Material

Microcrystalline is a mixed phase material, containing a crystalline Si fraction and an amorphous Si fraction. The crystallites are generally only a few nanometers to a few tens of nanometers in diameters, and are present in “bunches” or “conglomerates” in the layers. These conglomerates are much larger than the crystallites themselves, up to a micron or even larger. Because the crystallites are in the nanometer range, microcrystalline Si is often referred to as “nanocrystalline Si”. The two names are nowadays used interchangeably. Like amorphous silicon, microcrystalline Si contains a lot of hydrogen (several percents), which is incorporated in situ during deposition and ensures passivation of most defects in the layers. The term “microcrystalline Si” covers, in fact, a whole range of materials, ranging from amorphous silicon with a few percents of crystalline phase to a material with only a few percents of amorphous silicon. The properties of the materials at the two extremes are quite different, and one has to pay attention not to generalize properties that are, in fact, only valid for a limited range of crystallinity. In practice, the best devices are obtained with material close to the edge between microcrystalline and amorphous Si, so most recent papers refer to this type of material, which contains a large amorphous fraction. An example of a microcrystalline layer is shown in Figure 3.

Like amorphous Si, microcrystalline Si is typically obtained by PECVD at low temperature (between 100 and 300°C). Usually, a large hydrogen flow is added, which results in microcrystalline Si instead of amorphous Si (“hydrogen dilution”). Hydrogenated microcrystalline Si was first prepared in 1968 [9], but the use of PECVD to deposit such layers was introduced in 1980 [10, 11]. The material was first used as an active layer for solar cells in 1994 by the IMT group at the University of Neuchâtel in Switzerland [12]. The deposition technique they developed was very high frequency (VHF) PECVD of microcrystalline Si. The very high

frequency (between 30 and 300 MHz) leads to a softer ion bombardment, which is more favorable to microcrystalline Si formation, and, at the same time, allows relatively high growth rates. It is, however, possible to obtain excellent results using the standard RF PECVD technique at 13.56 MHz, provided the right parameters in terms of pressure and gas flow are selected. The conditions used are the so-called “high pressure depletion” (HPD) conditions, where the relatively high pressure ( $\sim 10$  Torr) ensures that ions lose a lot of their energy before reaching the surface. It is important to ensure a high hydrogen content in the plasma in HPD regime, which is usually obtained by a high hydrogen flow, but can also be achieved with pure  $\text{SiH}_4$  by preconditioning the chamber [13]. The combination of Very High Frequency and HPD conditions has led to excellent solar cells [14], sometimes at relatively high-growth rates [15]. As the growth rate (as will be discussed later) is a crucial topic for industrial implementation, a lot of effort is put into developing deposition conditions that yield high growth rates (over 2.3 nm/min, to be compared to values below 0.5 nm/min for conventional conditions) with only slightly lower efficiency [16, 17]. Other alternatives to deposit microcrystalline silicon are hot wire deposition and microwave plasma depositions though the results obtained so far are well below the more standard techniques for microcrystalline deposition.

An important aspect for all deposition techniques is the need to control the crystallinity profile of the microcrystalline layer throughout the active layer. As the material is formed through nucleation from an initial amorphous Si layer after which the crystallites grow, the crystallinity is not constant throughout the layer if no attempt is made to control it, which may result in far from optimal layers. Therefore, research in microcrystalline Si deposition puts a lot of effort into crystallinity control during deposition through varying the deposition parameters.

The bandgap of microcrystalline Si depends on the fraction of amorphous Si in the material. Layers with a substantial crystalline fraction have a bandgap close to that of crystalline Si (1.1 eV). The apparent higher absorption for such microcrystalline layers compared to single crystalline Si has been demonstrated to be caused by light scattering at the layer surfaces [18]. The absorption below the bandgap is much higher than that for crystalline Si, and is caused by defects within the bandgap. The absorption coefficient at those long wavelengths, therefore, gives a measure for the layer quality. It can be measured in different ways, but a powerful measurement technique that is increasingly being used is the Fourier transform photocurrent spectroscopy (FTPS) [19]. In Figure 5, the absorption coefficients at 0.8 eV of different layers are plotted as a function of the measured crystallinity [20]. The lowest  $\alpha$  (corresponding to the lowest defect density) is found in the transition region.

Figure 4 also gives important insight in layer quality degradation in microcrystalline silicon. When the first microcrystalline silicon solar cells were demonstrated, tests on devices with relatively high crystallinity led to the conclusion that microcrystalline Si did not suffer from light-induced degradation. As better devices closer to the transition were made and more detailed degradation studies were carried

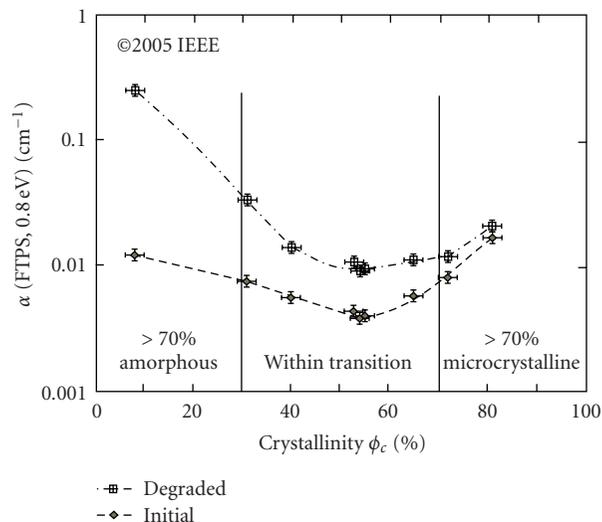


FIGURE 4: Defect-related absorption in initial and degraded state for a series of p-i-n type single-junction microcrystalline silicon solar cells with varying Raman crystallinity of the i-layer. (Reproduced with permission from [20].)

out, a more subtle picture has emerged: microcrystalline silicon suffers from a mild form of the photo-induced degradation [20, 21]. The degraded values (after 1000 hours under standard illumination) in Figure 4 show that, as expected, the degradation is worst for fully amorphous silicon, while it is negligible for almost fully crystalline layers. For microcrystalline layers in the transition region, there is a small yet significant degradation. There is, however, no degradation at all if the high energy photons are filtered out [22], as is the case in tandem solar cells.

### 3.2. Solar cell technology

The device structure of microcrystalline Si solar cells is very similar to that of amorphous Si solar cells. As with amorphous silicon, both superstrate (pin) and substrate (nip) configurations are possible. Most cells are pin cells, which requires a transparent substrate, usually soda-lime glass. To provide the top electrode, a conductive oxide is deposited, either indium tin oxide (ITO), tin oxide ( $\text{SnO}_2$ ), or zinc oxide ( $\text{ZnO}$ ). ITO is highly transparent and conductive but it is not very stable in the presence of a silane plasma, and it is relatively expensive. Therefore, solutions based on  $\text{SnO}_2$  or  $\text{ZnO}$  are preferred.

The optimal thickness of the i-layer is much larger than that for amorphous Si cells, from 1 to  $2\ \mu\text{m}$ . This is related with the weaker absorption by the amorphous Si and the higher  $\mu\tau$  product. In order to reach high efficiencies, the TCO is usually textured. This is either obtained as the natural morphology induced by the TCO deposition, or by subsequent etching.

It is difficult to say which group holds the record for single junction microcrystalline cells because of the issue of degradation and the fact that laboratory cells are very small, limiting the accuracy of the short-circuit values, particularly

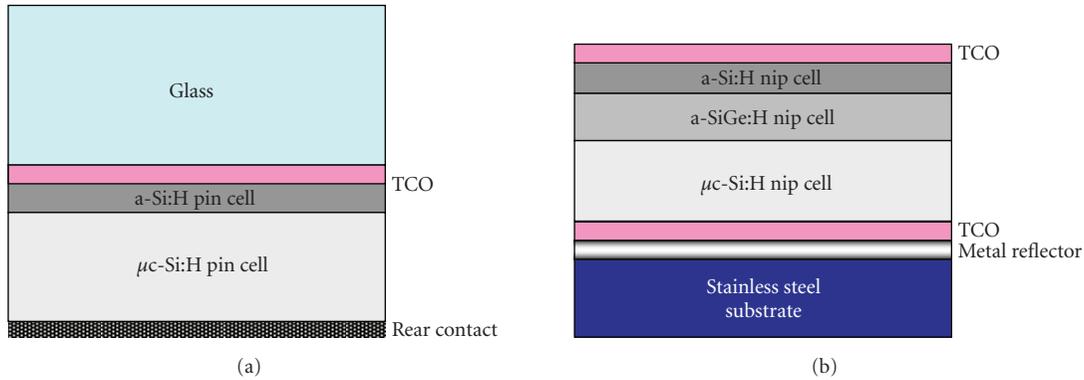


FIGURE 5: Schematic drawing of two types of tandem thin-film Si solar cells: (a) a “micromorph” or “hybrid” a-Si:H/ $\mu$ m-Si:H tandem cell, (b) a triple junction a-Si/a-SiGe:H/ $\mu$ c-Si:H solar cell.

for cells in superstrate configuration. It is, however, generally valid to say that the best solar cells have an efficiency value around 10% [14, 23, 24].

### 3.3. Issues with industrial application

The main issue for industrial application of microcrystalline silicon cells is the relatively low growth rate when a high hydrogen dilution condition is used, combined with the relatively large thickness of the layer. If the deposition time is too long, the throughput of the deposition system will be low, and the investment cost per module produced will be accordingly too high. That is why there are intense efforts to increase the deposition rate of microcrystalline Si deposition. The high pressure depletion regime combined with VHF excitation gives a good hope to reach a sufficient deposition rate while maintaining material quality, but it is a challenge to achieve sufficient uniformity on large areas in such conditions.

## 4. MULTIJUNCTION THIN-FILM Si SOLAR CELLS

Multijunction thin-film silicon solar cells consist in stacking two (tandem) or even three (triple) junction structures on top of each other, the different subcells being connected in series. This concept has the potential to increase device performance well beyond that of single junction devices, particularly when the materials are selected so as to better exploit the solar spectrum. Indeed, if a high bandgap material is used for the top cell, less thermalization losses will occur as a result of absorption of high energy photons. The longer wavelength photons, which are not absorbed in the top cell, get absorbed in the bottom cell which consists of a lower bandgap material. The fraction of unused photons from the spectrum is lower for tandem cells as the cut-off wavelength is given by the optical bandgap of the lowest bandgap material.

There are different types of multijunction thin-film Si solar cells, depending on the chosen configuration and layer type. In Figure 5, we show two structures of a particular interest.

The structure in Figure 5(a) is that of a “micromorph” solar cell, also called “hybrid” solar cell. It is a device in superstrate configuration, with an amorphous silicon top cell and a microcrystalline Si bottom cell. The substrate is a TCO covered glass substrate. This combination was first proposed by IMT [25] and is now regarded as one of the most promising concepts for thin-film solar modules.

In Figure 5(b), a triple junction solar cell in substrate configuration is depicted with an amorphous Si top cell, an amorphous SiGe middle cell, and a microcrystalline Si bottom cell. Because the p-layer always has to be on the side where light enters the cell, the subcells are all of the nip type. There is a large freedom concerning the substrate because it needs neither to be transparent nor to act as a front cover. A popular choice is a stainless steel foil, which is inexpensive and flexible, and which withstands, relatively, high temperatures. A drawback is that it is conductive and is, therefore, ill-suited for a monolithic module concept. The substrate is usually covered by a metal layer with high reflection, such as a silver layer. The United Solar Company, one of the major thin-film solar cells companies, is well known for its triple junction cells. Until recently, the middle and bottom cells were based on a-SiGe:H with two different Ge concentrations, but they have introduced new structures like the one in Figure 5(b), and even with microcrystalline Si in both the middle and bottom cells [26].

To connect the cells in series, good tunnel junctions are required, which demands a good control of the doping level of the doped layers. Another crucial aspect is current matching. One has to ensure that all subcells have about the same short-circuit current density; otherwise, the subcells will operate far from their maximum power points, leading to large losses. In the subcell optimization, one has to take light-induced degradation of the top cell into account. Indeed, the currents have to match after light-soaking, unless one only aims at a top initial efficiency. Figure 6 shows the internal quantum efficiency curves of the different subcells of a triple junction a-Si:H/a-SiGe:H/ $\mu$ c-Si:H cell.

In order to reduce losses in dual junction cells, caused by the degradation of the top cell, it has been proposed to

introduce an intermediate reflector, typically a TCO layer, and to further reduce the thickness of the top cell. Very thin amorphous Si cells show extremely limited degradation, but their current is very low due to limited absorption. By introducing an intermediate reflector, the current can be maintained at a high value, enabling high efficiencies with minimal degradation. The process complexity is increased, but promising efficiencies have been achieved with this concept [27, 28].

Efficiencies of tandem thin-film solar cells on small area devices reach impressive values of around 15% initial [26, 28] and around 13% stabilized. However, research and development is now focusing on upscaling the processes to large areas, producing minimodules and modules, and solving issues for industrial application, notably large-area TCO deposition. In Table 1, we list the best results of large-area tandem devices reported so far.

A specific issue with tandem cells is the risk of increased spectral sensitivity and its impact on the module energy yield. Indeed, losses related to current mismatch can be exacerbated by natural changes in spectrum (related to different times of the day or different seasons) because the relative absorption in the subcells may change. It has been found that, indeed, multijunction cells are more spectrally sensitive than classical modules [33]. If the module is well designed, however, it reaches its optimal energy yield for the most relevant spectra. High relative performance in kWh/kWp/year has been reported for double and even triple junction modules [34, 35].

## 5. THIN-FILM POLYCRYSTALLINE SI SOLAR CELLS

As we have seen, microcrystalline Si was introduced to improve solar cell performance and enhance stability of thin-film silicon solar cells. The development of thin-film polycrystalline silicon (polysilicon) for solar cells can be seen as the continuation of this trend towards higher crystallinity. Thin-film polysilicon is a material with grain size in the range  $1\ \mu\text{m}$  to  $1\ \text{mm}$ . In contrast to microcrystalline silicon, this material does not contain any amorphous tissue, or only a very small amount (well below 1%). One could think that the border between microcrystalline and polycrystalline silicon is not very sharp. In practice, there is a very clear distinction between the two materials because polysilicon is very far from the amorphous-to-crystalline transition, and always involves much higher temperatures than those used for microcrystalline silicon. Thin-film polysilicon solar cells have active layers that are usually thinner than  $5\ \mu\text{m}$ , often about only  $2\ \mu\text{m}$ . The technology is more recent and less mature than amorphous and microcrystalline Si, but progress in the last few years has been very fast.

### 5.1. Material

Thin-film polysilicon layers can be formed in various ways, which, however, all have in common that relatively high temperatures (between  $400$  and  $1200^\circ\text{C}$ ) are used. The films formed at moderate temperature usually undergo a short treatment at high temperature (between  $900$  and  $1000^\circ\text{C}$ )

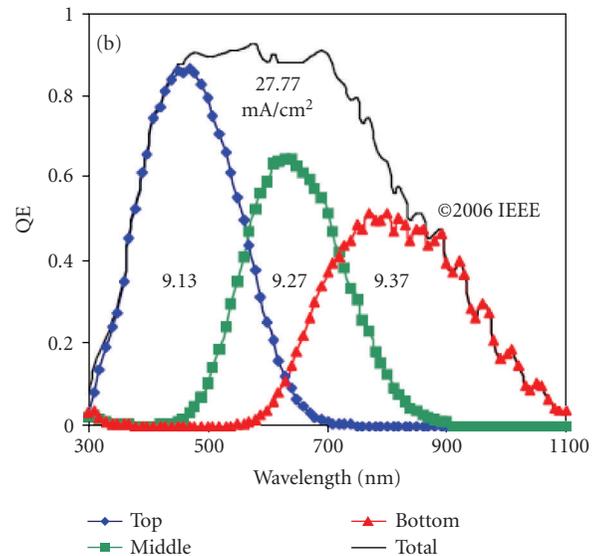


FIGURE 6: Quantum efficiency of an a-Si:H/a-SiGe:H/ $\mu\text{c}$ -Si:H triple-junction solar cell. (Reproduced with permission from [26].)

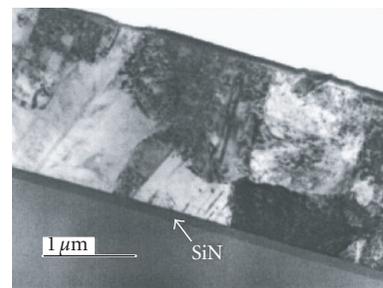


FIGURE 7: Cross-sectional transmission electron image of an SPC polysilicon film made on planar SiN-coated glass. (Figure reproduced with permission from [36].)

[36] to remove crystallographic defects, ensure full crystallinity, and enhance dopant activation. As a result, the very low-cost substrates used for microcrystalline and amorphous Si, such as soda-lime glass and polymer foils, cannot be used. Instead, borosilicate or aluminosilicate glass is used, or, if longer treatments at high temperature are needed, ceramic or glass-ceramic substrates.

The most successful film formation technique so far is solid phase crystallization (SPC) of amorphous silicon [37–39]. After deposition (by PECVD or evaporation), the a-Si films, typically  $1$  to  $3\ \mu\text{m}$  thick, are annealed at temperatures between  $550$  and  $700^\circ\text{C}$ , for a period of time ranging from a few hours to several tens of hours. The higher the temperature, the faster full crystallization will be reached, but the smaller the grains will be. If the temperature is too low, full crystallization is not reached within a reasonable time. The compromise temperature is usually  $600^\circ\text{C}$ . The doping profile is created during amorphous Si deposition, and is maintained during the crystallization process. The average

TABLE 1: Overview of the best results of tandem thin-film Si modules or minimodules.

Device structure	Company/institute	Area (cm <sup>2</sup> )	Initial efficiency (%)	Stabilized efficiency (%)	Reference
Double junction in superstrate configuration: a-Si:H/intermediate reflector/ $\mu$ c-Si:H (“Hybrid Plus”)	Kaneka	4140	13.5	?	[28]
Double junction in superstrate configuration: a-Si:H/ $\mu$ c-Si:H	IPV Jülich	64	10.8	10.1	[29]
Double junction in substrate configuration: a-Si:H/ $\mu$ c-Si:H (one single laminated cell)	United Solar	420	11.8	9.5	[30]
Double junction in superstrate configuration: a-Si:H/ $\mu$ c-Si:H	Applied Materials	676	10.1	?	[31]
Double junction in superstrate configuration: a-Si:H/ $\mu$ c-Si:H	Oerlikon Solar	64	10.0	?	[32]

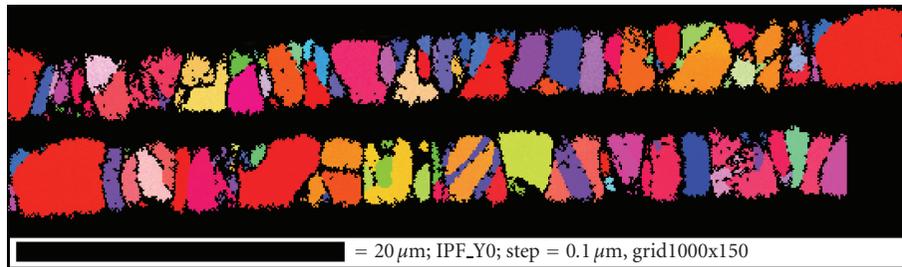


FIGURE 8: Cross-section electron backscatter diffraction image of an epitaxially thickened poly-Si AIC layer on a glass-ceramic substrate. The AIC layer is situated at the bottom but cannot be distinguished from the epitaxial layer. The scan of 100  $\mu$ m length is cut in two. The top right grain is the same as the bottom left one. (Reprinted with permission from [49].)

grain size of device grade SPC polysilicon is 1 to 2  $\mu$ m (see Figure 7). The material contains a large density of intragrain defects and many horizontal grain boundaries. Devices made in as-deposited material show extremely poor performance. However, SPC polysilicon responds particularly well to a defect anneal by rapid thermal treatment after crystallization [36].

Although SPC is a slow process, suitable throughput can be achieved in industrial conditions by using large batches. The cycle time, however, remains rather long. Polysilicon films can be formed faster by direct silicon deposition on foreign substrates [40–42], but coarse-grained continuous layers deposited in this way are never very thin.

In an effort to create thin layers with high crystallographic quality, the research focus has shifted in recent years to seed layer approaches. In a seed layer approach, a thin continuous layer with large grains is first formed. This seed layer shows good crystallographic quality but is either too thin or too highly doped, or both, to be used as an active layer in a solar cell. In the second phase, an epitaxial deposition process is applied. The main techniques to form seed layers are laser crystallization and aluminium-induced crystallization (AIC). Laser crystallization makes use of laser-light pulses to melt the silicon locally, inducing crystallization. Aluminium-

induced crystallization involves the transformation of amorphous to polycrystalline Si during thermal annealing of an a-Si/Al layer stack [43]. For the epitaxy, conventional thermal chemical vapor deposition (CVD) taking place at typically 1100°C can be used [44], but several low-temperature epitaxy techniques are also investigated, such as ion-assisted deposition (IAD) [45] and ECR-CVD [46, 47]. An example of an active layer grown by a combination of AIC and CVD on glass-ceramic is shown in Figure 8. In spite of the larger grain sizes achieved, the seed layer approach has not yet matched the SPC results (see cell results later in the text). The reason for the much more modest increase in performance than expected, based on the grain size, appears to be a very large density of electrically active intragrain defects [48]. It is, therefore, crucial to improve the intragrain quality to achieve the efficiency potential of the seed layer approach.

Thin-film polysilicon contains many defects compared to multicrystalline Si. In contrast to microcrystalline Si, in situ defect passivation by hydrogen atoms cannot take place because of the high temperatures during film formation, which causes hydrogen to diffuse out of the film. A separate, subsequent defect passivation step by hydrogenation is, therefore, carried out to obtain device quality layers [45, 50, 51]. This is typically done in a hydrogen plasma at a temperature of

TABLE 2: Best thin-film polysilicon solar cell results (unless mentioned, the cell size is 1 cm<sup>2</sup> or less). LLC stands for layer-by-layer crystallization, RTA for rapid thermal anneal, ECRCVD for electron cyclotron resonance chemical vapor deposition.

Institute/company	Substrate	Technique	V <sub>oc,max</sub> (mV)	Eff. <sub>max</sub> (%)
CSG Solar	Borosilicate glass	SPC + RTA	497 [51]	9.8 [57] (96 cm <sup>2</sup> )
Sanyo 1995 [37]	Metal	SPC	553	9.2
IMEC [58]	Ceramic	AIC + CVD	534	8.0
UNSW	Borosilicate glass	SPC + RTA	517 [59]	7.0 [55] (4.4 cm <sup>2</sup> )
IMEC [60]	High-T glass	AIC + CVD	539	5.4
IPHT [61]	Borosilicate glass	Laser + LLC	510	4.8
InESS [41]	Ceramic	CVD	500	3.3
UNSW [62]	Borosilicate glass	AIC+ IAD (“ALICIA”)	480	3.0
NAIST [42]	Ceramic	CVD	410	2-3
HMI [63]	Borosilicate glass	AIC + ECRCVD or e-beam evaporation	386	1.3

400°C although studies indicate that more effective passivation can be obtained at higher temperatures [45]. In general, the effect of hydrogenation is spectacular for thin-film polycrystalline cells. It is not uncommon to observe an increase of 200 mV or more in V<sub>oc</sub> as a result of hydrogenation.

## 5.2. Solar cell and technology

Thin-film polycrystalline cells do not have a p-i-n structure, but rather than p-n structure of conventional Si solar cells. Both p-type and n-type base devices have been demonstrated with no obvious advantage for one of the two. The base doping level ranges from 10<sup>15</sup> to 10<sup>17</sup> cm<sup>-3</sup>. A highly doped region is created at the back to act as a back-surface field (BSF) to provide a high conductivity path for a majority of carriers in the base. The total layer thickness is usually in the range of 1.5 to 3 μm. At the present stage of material development, the diffusion length is very short (a few micrometers at best). Increasing the device thickness beyond the diffusion length brings no benefit. On the contrary, it results in a lower V<sub>oc</sub> (solely determined by the diffusion length) and lower current (a lot of useless absorption in the area of the base which is further away than a diffusion length from the junction).

Both substrate and superstrate configurations have been implemented, the latter giving advantages in terms of lower shadow and resistive losses but making the device processing more challenging. Both homojunction and heterojunction designs are possible. Heterojunction devices consisting of a polycrystalline Si base with a very thin (~5–10 nm) amorphous Si emitter give rise to higher V<sub>oc</sub>s than homojunctions [37, 52]. There is evidence that this is related to the reduction of dopant smearing effects due to the lower thermal budget. Indeed, during high temperature steps, dopant atoms tend to diffuse along grain boundaries and dislocations, modifying the initial profile and increasing the junction area.

An important issue to obtain high efficiency devices is light confinement because the layers are thin and the material is not an efficient light absorber. A major component of any light trapping scheme is to ensure oblique coupling of the light into the active layer. The traditional methods used for crystalline silicon, namely, etching in dedicated alkaline

or acidic solutions to texture the surface, cannot be used because they are not adapted to polysilicon materials and consume too much Si. Texturing of the glass prior to active layer formation has been successfully applied for thin-film poly cells, either by coating with an oxide film containing small beads [53] (process used at CSG Solar) or by a chemical reaction with Al [54, 55]. Another possibility is to apply a plasma texturing process after active layer formation that consumes very little silicon while causing minimal damage to the active layer. A strong increase in performance of AIC-based cells has recently been achieved with this process [56].

The best results reported for thin-film polysilicon solar cells are given in Table 2. As can be seen in the table, the best thin-film polysilicon results, so far, have been achieved by CSG Solar, with an efficiency of 9.8%, using SPC of PECVD deposited amorphous silicon. This result is remarkable in many respects, not least because it is the efficiency of a 10 × 10 cm<sup>2</sup> minimodule, and not of a small single cell. This exceeds the efficiencies of the best single junction amorphous or microcrystalline Si minimodules, and is in fact comparable to the stabilized efficiency of state-of-the-art tandem amorphous-microcrystalline minimodules (see Table 1).

Module fabrication involves the separation of the film into long and narrow segments, usually by laser scribing: cell isolation using an insulating material, formation of openings to access the base and/or the emitter, and finally the cell metallization and interconnection using a metal grid usually carried out in a single metallization step. The positive contacts of each cell are connected, over the isolation grooves, to the negative contacts of the next cell. Note that, in contrast with amorphous and microcrystalline Si, the conductivity of the doped layers in polysilicon is high enough to ensure lateral transport of the collected carriers over hundreds of micrometers. Figure 9 shows the elegant interconnection scheme used at CSG Solar. Here, the whole rear surface is covered with the isolating material (a polymer-based resin), not only the groove. The contacts are made through holes in the resin. For the negative contacts, the silicon is etched locally to access the emitter. A blanket aluminium layer is then deposited and patterned with laser into an interdigitated pattern.

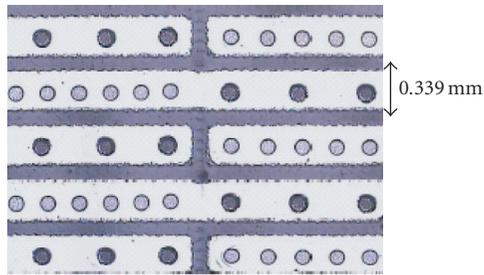


FIGURE 9: Metallization and interconnection scheme of a CSG Solar module. The positive contacts (lighter dots) are connected with the negative contacts (darker dots) of the next cell. The isolation groove runs vertically in the middle of the picture and is filled by an insulating resin. (Figure reprinted with permission from [38].)

There is very limited data on reliability and durability of thin-film polysilicon modules because the technology is so new. The expectation is that, based on the fully crystalline nature of the active layer and the absence of a degradation-prone TCO, very little degradation will occur. The scarce experimental data [64, 65] available, indeed, give very positive indications.

The first commercial thin-film polysilicon modules were delivered by CSG Solar in December 2006.

## 6. CONCLUSION

In this paper, I reviewed the field of thin-film silicon solar cells with active layer thickness of only a few microns. These solar cells are appealing because they can potentially deliver very low cost while using an abundant, non-toxic element, namely, silicon. There is a large R&D effort world-wide to reach sufficient conversion efficiency and to implement the different technologies industrially.

The oldest thin-film silicon solar cell technology is single junction hydrogenated amorphous silicon. Although this is a disordered material suffering from light-induced degradation and the thickness of the active layer is only a few hundreds of nanometers, efficiencies close above 9% have been reached on small areas. Commercial modules, however, have a stable efficiency of only 5–7%, which is not sufficient for long-term success. Nevertheless, large investments are now being made, notably by the equipment manufacturers with experience in deposition systems for the LCD display business. Everyone is well aware of the limitation of the single junction amorphous technology but is banking on the next generation of thin-film technology based on microcrystalline silicon, for which the same or similar equipment can be used.

Microcrystalline silicon, which contains nm-sized crystallites embedded in an amorphous matrix, was developed to reach higher and more stable efficiencies. This is a more complex material, and intense material research is being carried out to understand it better and improve device performance. If deposited in the right conditions, microcrystalline Si contains substantially less defects than light-soaked amorphous silicon. Efficiencies of around 10% on small areas have been reached. An important topic of research is the development

of deposition conditions which yield high growth rate while maintaining layer uniformity and electronic quality.

Multijunction thin-film solar cells, where two or three cells made of different thin-film materials are deposited on top of each other, are seen as the way forward to bring amorphous and microcrystalline technology to high module performance. Impressive efficiencies of up to 15% have been reached for devices with a-Si:H top cell and  $\mu$ c-Si:H bottom cells, but these values are before degradation and for small area devices. Stabilized efficiencies on large area devices are at present in the range of 10%, but strong R&D efforts are going on aiming at high stabilized efficiencies on large areas.

Finally, the field of thin-film polysilicon solar cells was reviewed. This material is investigated because of its high efficiency potential even for only one junction. These technologies depart quite a lot from amorphous and microcrystalline technologies because they involve relatively high temperatures and more costly substrates (although still compatible with low-cost modules). The most successful approach, so far, involves solid phase crystallization of PECVD amorphous silicon, yielding efficiencies up to 9.8% at minimodule level. A lot of research is going into developing a material with higher-crystallographic quality through a seed layer approach. In general, the field of thin-film polysilicon solar cells is not yet as mature as amorphous and microcrystalline Si technologies but there has been very rapid progress over the last few years.

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