3. *Texturization*: NaOH etching leading to microscopic pyramids is commonly employed. Their size must be optimized, since very small pyramids lead to high reflection, while very large ones can hinder the formation of the contacts. To ensure complete texturing coverage and adequate pyramid size, the concentration, the temperature and the agitation of the solution and the duration of the bath must be controlled (in fact NaOH at a higher concentration and at a higher temperature is commonly used as an isotropic etch for saw damage removal). Alcohol is added to improve homogeneity through an enhancement of the wettability of the silicon surface. Typical parameters are 5% NaOH concentration, 80°C and 15 min [69].
Texturing alternatives for multicrystalline material are presented in Section 7.6.
4. *Phosphorus diffusion*: Phosphorus is universally used as the *n*-type dopant for silicon in solar cells. Since solid-state diffusion demands high temperature, it is very important that the surfaces are contamination-free before processing. To this end, after the texturing the wafers are subjected to acid etch to neutralize alkaline remains and eliminate adsorbed metallic impurities.

The industry uses a number of procedures to perform the phosphorus diffusion. The following classification is based on the type of furnace in which the high-temperature step takes place:

Quartz furnaces: The cells to be diffused, loaded in quartz boats, are placed in a quartz tube with resistance heating and held at the processing temperature (Figure 7.7a). The cells enter and exit the furnace through one end, while gases are fed through the opposite one. Phosphorus itself can be supplied in this way, typically by bubbling nitrogen through liquid $POCl_3$ before injection into the furnace. Solid dopant sources are also compatible with furnace processing. Five to fifteen minutes at temperatures in the range from 900 to 950°C can be considered representative. As suggested in Figure 7.6, both surfaces and the edges of the wafer will be diffused.

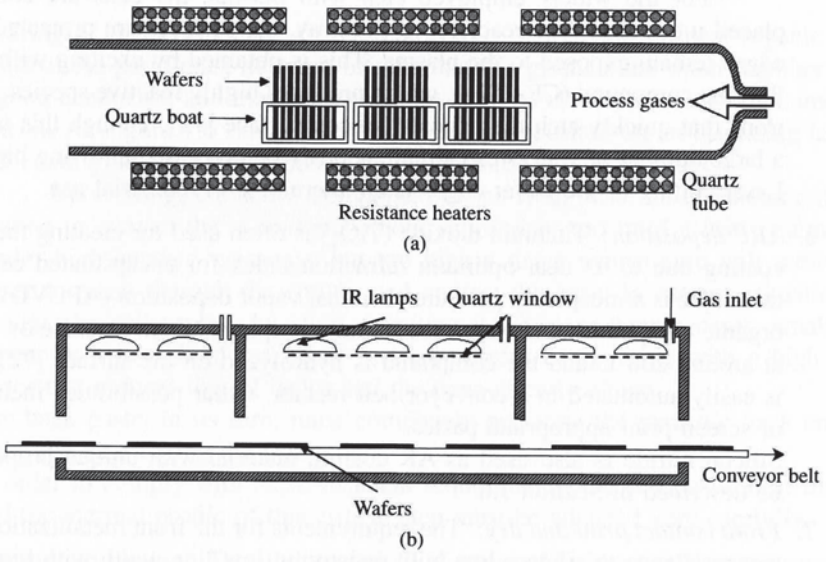


Figure 7.7 (a) A quartz furnace; and (b) a belt furnace for the diffusion of phosphorus

Belt furnaces: In this case, solid phosphorus sources are used: screen printed, spun-on or CVD pastes containing phosphorus compounds are applied on one wafer face and, after drying, placed in a conveyor belt passing through the furnace (Figure 7.7b). The temperature inside it can be adjusted in several zones and, though the furnace is open, gases can be supplied. The temperature cycle undergone by the wafer will mimic the temperature profile along the furnace with the time scale set by the advancing speed of the belt. A cycle begins with several minutes at around 600°C with clean air to burn off the organic materials of the paste, followed by the diffusion step in nitrogen at 950°C for 15 min. Only one face of the wafer is diffused, but the parasitic junction formed at the edges is also present in this technique due to diffusion from the gas phase. Resistance or infrared heating can be employed, the latter offering the possibility of faster heating–cooling rates of the wafer.

The main benefit of the quartz furnace is cleanliness, since no metallic elements are hot and no air flows into the tube. Though this is a batch step, high throughput can be achieved since many wafers can be simultaneously diffused in each tube, commercial furnaces consisting of stacks of four tubes. In a belt furnace, the ambient air can get into the furnace and the hot conveyor belt is a source of metallic impurities. The assets of belt furnaces are found in automation and in-line production, throughput and the ability to implement temperature profiles. New designs try to reconcile the advantages of both types of equipment [70].

After diffusion, an amorphous glass of phospho-silicates remains at the surface that is usually etched off in diluted HF because it can hinder subsequent processing steps.

5. *Junction isolation*: The *n*-type region at the wafer edges would interconnect the front and back contacts: the junction would be shunted by this path translating into a very low shunt resistance. To remove this region, dry etching, low temperature procedures are used.

   For the widely employed etch with plasma, the cells are coin-stacked and placed into barrel-type reactors. In this way, the surfaces are protected and only the edges remain exposed to the plasma. This is obtained by exciting with an RF field a fluorine compound (CF_4, SF_6), which produces highly reactive species, ions and electrons that quickly etch the exposed silicon surface [71]. Though this is a batch step, a large number of wafers can simultaneously be processed allowing high throughput. Laser cutting of the wafer edges is an alternative in industrial use.

6. *ARC deposition*: Titanium dioxide (TiO_2) is often used for creating the antireflecting coating due to its near-optimum refraction index for encapsulated cells. A popular technique is atmospheric pressure chemical vapor deposition (APCVD) from titanium organic compounds and water: the mixture is sprayed from a nozzle on the wafer held at around 200°C and the compound is hydrolyzed on the surface [72]. This process is easily automated in a conveyor-belt reactor. Other possibilities include to spin-on or screen print appropriate pastes.

   Silicon nitride is also used as AR coating material with unique properties that will be described in Section 7.6.

7. *Front contact print and dry*: The requirements for the front metallization are low contact resistance to silicon, low bulk resistivity, low line width with high aspect ratio, good mechanical adhesion, solderability and compatibility with the encapsulating

materials. Resistivity, price and availability considerations make silver the ideal choice as the contact metal. Copper offers similar advantages, but it does not qualify for screen printing because subsequent heat treatments are needed during which its high diffusivity will produce contamination of the silicon wafer.

Screen printing compares very unfavorably with vacuum evaporation in the first three requirements. It has been already commented how this affects the cell design and leads to a significant efficiency gap between laboratory and commercial cells. But throughput and cost compensate for it.

Screen printing will be described in more depth in the following section. It is used to stick a paste containing silver powder to the front face of the wafer in the comblike (fingers plus bus bars) pattern. Automatic screen printers are available that are capable of in-line, continuous operation with high throughput. These machines accept wafers from packs, cassettes or a belt line, place them with sufficient accuracy under the screen and deliver the printed wafers to the belt line. The paste is a viscous liquid due to the solvents it contains; these are evaporated in an in-line furnace at 100 to 200°C. The dried paste is apt for subsequent processing.

8. *Back contact print and dry*: The same operations are performed on the backside of the cell, except that the paste contains both silver and aluminum and the printed pattern is different.

   Aluminum is required because silver does not form ohmic contacts to p-Si, but cannot be used alone because it cannot be soldered. The low eutectic temperature of the Al-Si system means that some silicon will be dissolved and then recrystallize upon cooling in a p-type layer.

   Though in principle a continuous contact will give better electrical performance (lower resistance), most commercial wafers feature a back contact with a mesh structure: apart from paste-saving considerations, this is preferred to a continuous layer because the different expansion coefficients would produce warp of the cell during the subsequent thermal step.

9. *Cofiring of metal contacts*: A high-temperature step is still needed: organic components of the paste must be burnt off, the metallic grains must sinter together to form a good conductor, and they must form an intimate electric contact to the underlying silicon. As Figure 7.6 shows, the front paste is deposited on an insulating layer (the AR coating) and the back contact on the parasitic n-type rear layer.

   Upon firing, the active component of the front paste must penetrate the ARC coating to contact the n-emitter without shorting it: too mild a heat treatment will render high contact resistance, but too high a firing temperature will motivate the silver to reach through the emitter and contact the base. In extreme situations, this renders the cell useless by short-circuiting it. In more benign cases, small shunts appear as a low shunt resistance or dark current components with a high ideality factor that reduces the fill factor and the open-circuit voltage.

   The back paste, in its turn, must completely perforate the parasitic back emitter to reach the base during the firing.

   In order to comply with these stringent requirements, the composition of the pastes and the thermal profile of this critical step must be adjusted very carefully.

10. *Testing and sorting*: The illuminated $I-V$ curve of finished cells is measured under an artificial light source with a spectral content similar to sunlight (a sun simulator)

at a controlled temperature of 25°C. Defective devices are then rejected, and the rest are classified according to their output. The manufacturer establishes a number of classes attending, typically, to the cell current at a fixed voltage near the maximum power point. Modules will subsequently be built with cells of the same class, thus guaranteeing minimal mismatch losses. If, for instance, cell currents within a class must be equal within 5%, the accuracy and stability of the system must be better than that. Automatic testing systems that meet the very demanding requirements of high throughput processing are available.

7.4.2 Screen-printing Technology

Screen printing is a thick-film technology, a terminology that opposes it to the usual microelectronic procedures of evaporation of thin films. It consists in translating a layer of a material in a desired pattern to the surface of the wafer. Though it can be employed for virtually any step in solar cell manufacturing, contact formation constitutes the most demanding, frequent and conspicuous application of screen printing. Screens and pastes are the essential elements of this technology [68].

1. *Screens*: Screens are tight fabrics of synthetic or stainless steel wires stretched on an aluminum frame, as sketched in Figure 7.8. The screen is covered with a photosensitive emulsion, which is treated with photographic techniques in such a way that it is removed from the regions where printing is desired.

   For printing fine and thick layers, as is needed for the front contact of a solar cell, the wires must be very thin and closely spaced [73]. On the other hand, the opening of the reticule must be several times larger than the largest particle contained in the paste to be printed. Screens for solar cell production typically feature 200 wires per inch, wire diameter around 10 μm, mesh opening around 30 μm, corresponding to

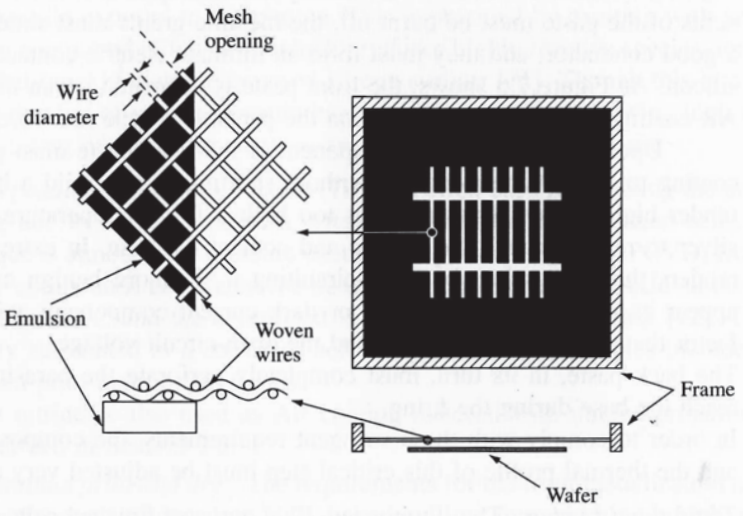


Figure 7.8 A screen for transferring the top contact pattern to a solar cell

nearly 50% open surface, that is, not intercepted by wires and a total thickness (woven wires plus emulsion) of around 100 μm.

2. *Pastes*: The pastes are the vehicles that carry the active material to the wafer surface. Their composition is formulated to optimize the behavior during printing. A paste for the metallic contacts of the solar cell is composed of the following:

   Organic solvents that provide the paste with the fluidity required for printing
   Organic binders that hold together the active powder before its thermal activation
   Conducting material, which is a powder of silver composed of crystallites of a size of tenths of microns; for the *p*-contact, aluminum is also present. This amounts to 60 to 80% in weight of the paste
   Glass frit, 5 to 10% in weight, a powder of different oxides (lead, bismuth, silicon etc.) with a low melting point and high reactivity at the process temperature, that enables movement of the silver grains and etches the silicon surface to allow intimate contact.

   The paste composition is extremely important for the success of the metallization and is critically linked to the heat treatment.

3. *Printing*: Figure 7.9 illustrates the process of printing a paste through the patterned emulsion on a screen. The screen and the wafer are not in contact, but a distance apart called the *snap-off*. After dispensing the paste, pressure is applied to the squeegee, which can be made of metal or rubber: this puts the screen in contact with the wafer. The squeegee is then moved from one side of the screen to the opposite one, dragging and pressing the paste in front of it. When an opening is reached, the paste fills it and sticks to the wafer, remaining there after the squeegee has passed and the screen has elastically retired.

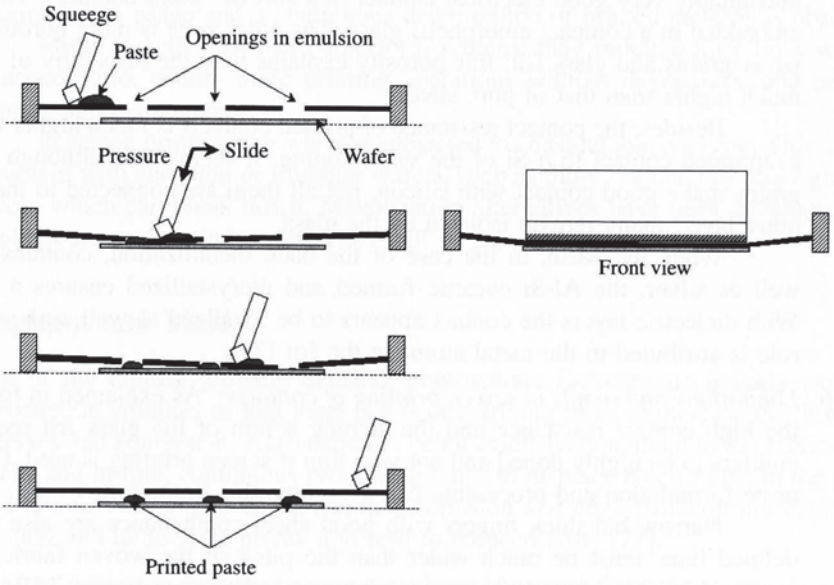


Figure 7.9 Illustration of a printing sequence

The amount of printed paste depends on the thickness of the screen material and the emulsion and the open area of the fabric. It also depends on the printed line width.

The viscous properties are of utmost relevance: when printing, the paste must be fluid enough to fill without voids all the volume allowed by the fabric and the emulsion, but after being printed it must not spread over the surface.

Critical parameters of this process are the pressure applied on the screen, the snap-off distance and the velocity of the squeegee.

4. *Drying*: Solvents are evaporated at 100 to 200°C right after printing so that the wafer can be manipulated without the printed pattern being damaged.

5. *Firing*: Firing of the pastes is usually done as a three-step process in an IR belt furnace. In the first step, when heating up, the organic compounds that bind the powder together are burnt in air. In the next step, the highest temperature between 600 and 800°C is reached and maintained for a few minutes. Higher temperatures are needed if an AR coating must be penetrated; crystal orientation and paste composition must be considered too. In the last step, the wafer is cooled down.

   The phenomena that take place during firing are very complex and not completely understood. The oxides forming the glass frit melt, enabling silver grains to sinter and form a continuous conductor so that the layer can present low sheet resistance. Neither the silver melting point nor the silicon–silver eutectic temperature is reached, sintering consisting of the intimate contact of solid silver crystallites. At the same time, the reactive molten glass etches some silicon and silver grains are allowed to form intimate contact with the substrate. The amount of etched silicon is on the order of 100 nm. When a layer of TiO_2 or SiN is present, the glass frit is able to etch through it. In fact, the quality of the contact improves because of a better homogeneity.

   The picture of the contact after cooling down shows two zones [74]. In the inner one, crystallites of silver are plugged into silicon forming crystalline interfaces and presumably very good electrical contact in a sort of "point contact". These grains are embedded in a compact amorphous glass. The outer zone is more porous and contains silver grains and glass frit: this porosity explains why the resistivity of silver paste is much higher than that of pure silver.

   Besides, the contact resistance of printed contacts is much higher than that of an evaporated contact to *n*-Si of the same doping. It seems that, although enough silver grains make good contact with silicon, not all them are connected to the grains in the outer layer; many remain isolated by the glass.

   When the paste, in the case of the back metallization, contains aluminum as well as silver, the Al-Si eutectic formed and recrystallized ensures a good contact. With dielectric layers the contact appears to be localized as well, and some beneficial role is attributed to the metal atoms in the frit [75].

6. *Limitations and trends in screen printing of contacts*: As explained in former sections, the high contact resistance and the etching action of the glass frit require the front emitters to be highly doped and not very thin if screen printing is used. Only improved paste formulation and processing can overcome this limitation.

   Narrow but thick fingers with good sheet conductance are also needed. Well-defined lines must be much wider than the pitch of the woven fabric; 60-μm lines seem achievable, with 100-μm ones being standard (see Figure 7.10). Incrementing the amount of transferred paste implies increasing the thickness of the emulsion or the

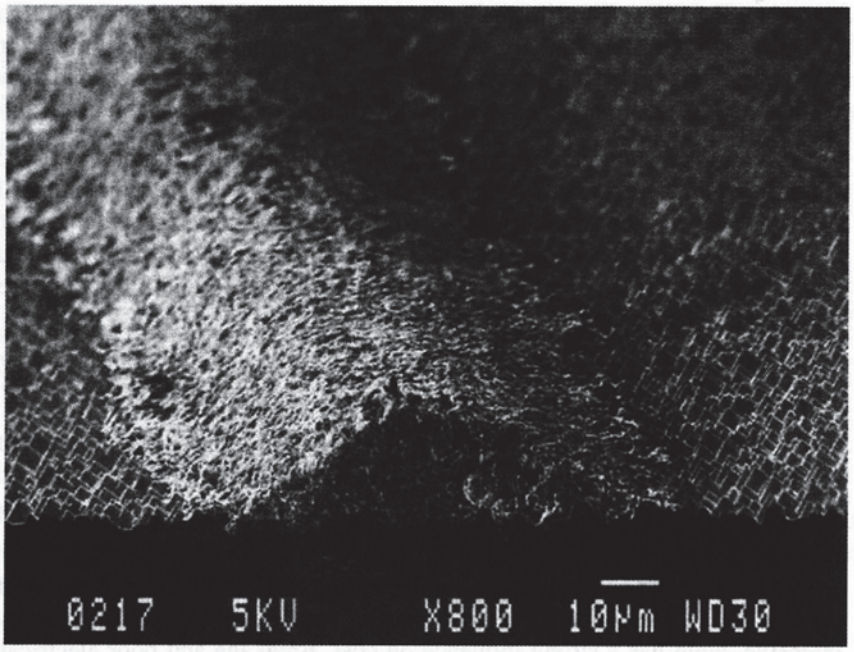


Figure 7.10 Screen-printed contact finger; texture pyramids are also visible. (Reprinted from *Solar Energy Materials and Solar Cells*, **41/42**, Nijs J, Demesmaeker E, Szulfcik J, Poortmans J, Frisson L, De Clerq K, Ghannam M, Mertens R, Van Overstraeten R, "Recent improvements in the screen-printing technology and comparison with the buried contact technology by 2D-simulation", 101–107, (1997), with permission from Elsevier Science)

pitch-to-diameter ratio of the wires, which are both limited. Besides, screens become deformed with usage and a continuous deterioration of printed patterns is observed.

Metal stencils [76] can outperform screens: they produce finer lines with better aspect ratio, endure more printing operations without degradation and need less cleaning and maintenance.

In screen printing, the wafer is subjected to considerable pressure. This can pose a problem with very thin or irregular wafers, such as those obtained by sheet growth of silicon, which can break down. Metallization alternatives have been developed, some of which are used in industries. They will be presented in Section 7.7.

7.4.3 Throughput and Yield

Because of the rapidly growing demand, photovoltaic factories are quickly expanding their production volumes so that there is a strong driving force to increase the throughput of processes and equipment. Automation is being extensively applied to the fabrication of solar cells and in-line, continuous processing tends to displace batch steps: in the process outlined above, only chemical etches, tube diffusion and edge isolation are batch steps. Automation and large-scale production lead to reduced costs [77].

Most processes described above have been borrowed from the electronic industry: diffusion, plasma etching, and so on are standard in microelectronics, while screen printing

was extensively used by thick-film technology in hybrid circuits. The character of the industries being different, their requirements for equipment differ, and it is to be expected that substantial improvements of photovoltaics will take place, now that the business volume makes it attractive for equipment manufacturers to get involved in.

A modern fabrication line is capable of processing around 1000 wafers h^{-1}, that is, an operation in a cell takes 2 to 3 s. Of course, the slowest operation along the flow line will limit the overall throughput. In order to get an estimate of how this translates into yearly production, let us consider 10×10 cm^2 cells with 15% efficiency (1.5 Wp power per cell). If the line operates without interruption and all wafers are successfully processed, during one year it will produce

$$1.5 \text{ Wp/cell} \times 1000 \text{ cells/h} \times 24 \text{ h/day} \times 365 \text{ days/year} \cong 13 \text{ MWp/year}$$

This number has to be decreased by (1) the downtime of the equipment due to maintenance, repair, and so on and (2) the yield, that is, the percentage of defective or broken wafers. Allowing for both would give a throughput in the range of 5 to 10 MWp/year per production line with available, commercial equipment.

Yield is a most important parameter for cell production: it can be defined as the ratio of successful finished cells to starting wafers. Since PV technology is material-intensive, yield has a strong influence on cost. Breakage and poor electrical performance are the causes of low yield, which is, generally speaking, benefited by automation. In this respect, in-line quality control acquires a great relevance to quickly detect and amend problems affecting yield.

For a given time per operation per cell, the throughput increases if the power of the cell increases. This is achieved by increasing the cell's area and the efficiency, which also helps in decreasing the cost. The standard wafer size is shifting from 10×10 cm^2 to 12.5×12.5 cm^2 and 15×15 cm^2. Series resistance and the uniformity of the obtained layers (emitter, AR coating), that may compromise the electrical performance, become important issues. Besides, larger cells are more difficult to handle without breaking and the yield may be affected.

There is a lot of room for efficiency improvement of industrial solar cells and the processes to realize it are proved in the laboratory. The question is how to implement them in an industrial environment so that they are cost-effective.

7.5 VARIATIONS TO THE BASIC PROCESS

This section introduces some variations to the basic process described above that aims at improving the efficiency, the throughput or the cost. While some modifications are already in production, most of these improvements are still being developed at the laboratory.

7.5.1 Thin Wafers

Wafering and sheet-growth techniques improve and produce thinner substrates, with wafer thickness below 200 μm being envisaged for the near term [78]. When processing these thin cells, several relevant issues appear.

The probability of fracture of the wafer during handling increases, especially in conjunction with a larger size. Adequate handling tools must be designed. Some steps appear to be critical: for instance, in chemical baths convection can exert significant torque on the wafers. This issue is fostering the study of the mechanical properties of silicon [79, 80] and even the development of new crystallization procedures.

The behavior during heat treatments is modified due to a decreased thermal mass. On the other hand, wafers can more easily become bent. Processes need to be specifically optimized for thin cells [81].

Thin cells largely depend on surface passivation and optical confinement. If attained to reasonable degrees, efficiency improvement comes as a bonus for thin cells, but otherwise the performance is degraded. New optimal structures must be developed.

7.5.2 Back Surface Passivation

The enhancement of material quality and the decrease of wafer thickness will make it necessary to passivate the back surface. Several approaches are feasible to be incorporated to the basic screen-printing process [55, 82]:

- *Aluminum back surface field*: With the benefit of gettering action, a highly doped *p*-type region at the back can easily be formed by screen-printing aluminum paste on the entire surface followed by high-temperature alloying. Several manufacturers implement aluminum BSF in their production lines. It can be integrated in the process flow (1) before metallization, possibly at the same time as phosphorus diffusion, and (2) by printing the aluminum paste after the front contact print so that the alloy forms during paste firing, though in this case lower temperatures are possible leading to worse properties.

  In either case, a back, silver-based contact is still needed for solderability. Bending of the wafers is an issue for thin cells.
- *Boron back surface field*: Like phosphorus, boron can be diffused from solid sources, so that it can easily be integrated into the basic process. Though it would be very attractive to diffuse both phosphorus and boron during the same thermal step, it appears that the obtained profiles are far from optimum and that a two-step diffusion seems necessary.
- *Silicon nitride passivation*: The surface and bulk passivation properties of silicon nitride are explained below. This replaces AR coating deposition and does not alter the basic process, though the parasitic junction must not be allowed to form in this case. This structure, as well as boron BSF, is compatible with the bifacial operation of the solar cell.

7.5.3 Improvements to the Front Emitter

Quantitative improvements in both recombination currents and spectral response will be derived from front surface passivation only when better paste formulations and finer line prints allow more resistive emitters – thinner and/or less doped – to be used [83]. In that case, tube oxidation and silicon nitride deposition appear as good candidates for industrial use.

Selective emitters are being developed at the laboratory level for screen-printed solar cells. A number of techniques have been proposed [84] that are compatible with the screen-printing process; none of them is at present implemented in production lines:

- Two separate diffusions for metallized and unmetallized regions, the heavy diffusion being restricted to the regions to be metallized by a screen-printed mask.
- A homogeneous and thick emitter is diffused by conventional means; a screen-printed mask is applied to protect the regions to be metallized from the plasma etch that follows. In this way, in the unprotected regions the emitter is thinner and less doped.
- Self-aligned selective emitter by diffusion from a patterned solid dopant source: under the dopant source a highly doped emitter is formed, while a much lighter diffusion from the gas phase takes place at the uncovered regions.
- First a high sheet resistance emitter is formed to which self-doping pastes containing phosphorus as well as silver are applied. Firing is performed above the silver–silicon eutectic temperature, thus leading to the formation of an alloyed layer heavily doped with phosphorus [85].

Except the last one, all the techniques require some kind of pattern aligning to print the front contact fingers on the heavily doped regions. Automatic screen printers feature enough accuracy to perform this task.

Obviously, the unmetallized part of these emitters is sensitive to surface passivation, which must thus be implemented by oxidation or nitride deposition.

7.5.4 Rapid Thermal Processes

In conventional furnaces of the closed-tube or conveyor-belt types, not only are the wafers heated to the process temperature but also the equipment itself: chambers, substrates or boats and so on. This brings about (1) long heating–cooling times, due to the large thermal masses involved, (2) a high potential for contamination, since a lot of parts, some of them metallic, are held at a high temperature and (3) high-energy consumption.

On the other hand, the microelectronic industry has developed in the last years, so-called *rapid thermal processes* (RTP), whereby only the wafers, and not their environment, are heated up to high temperature. Selective heating is accomplished by intense UV illumination of the semiconductor. The interest of RTP for solar cell fabrication comes from very short thermal cycles down to a few minutes including heating and cooling, so that throughput can be boosted. Besides, the absence of hot parts in the equipment diminishes potential contamination and energy consumption.

At the laboratory scale rapid thermal diffusion of very thin emitters (which is beneficial from the electrical point of view) has been demonstrated. Rapid thermal firing of screen-printed contacts and aluminum alloying have also been successfully implemented, along with other promising techniques such as rapid thermal nitridation and oxidation of the surfaces for passivation purposes [86, 87]. It can be said that every thermal step in the solar cell process can be made by RTP.

A possible drawback of the technique is a degradation of substrate lifetime as compared to conventional processing of some materials, due to the formation and quenching-in

of defects because of the very fast heating and cooling cycles and possibly also due to precluded gettering action [88].

A hurdle to industrial deployment of RTP is the lack of suitable equipment, since Microelectronics uses one-wafer reactors while Photovoltaics would need large capacity batch reactors or, better, in-line continuous equipment. It seems possible to furnish conveyor-belt furnaces with UV lamps to obtain these industrial RTP reactors, but some problems such as temperature uniformity must be solved [89].

7.6 MULTICRYSTALLINE CELLS

It has already been pointed out that the peculiarities of mc cells may prevent, in some cases, the use of standard processing technologies. Some of the proposed alternatives are not yet so cost-effective as to be incorporated in an industrial production line, but others are finding their way. Two main differences with single-crystalline silicon can be highlighted:

- Mc-material quality is poorer because of crystalline defects (such as grain boundaries, dislocations, etc) and metallic impurities (dissolved or precipitated), giving lower bulk lifetimes and hence lower cell efficiencies. To address this problem, two main strategies are followed: implementation of gettering steps and defect passivation with hydrogen.
- Texturing is more difficult because of different exposed crystallographic planes, so that standard alkaline solutions are not appropriate. To improve light-trapping and absorption, other techniques have to be implemented.

7.6.1 Gettering in mc Solar Cells

As already explained, gettering processes are also used in monocrystalline Si processing, but in the case of mc-Si they are even more important to improve material quality. P and Al gettering steps are routinely integrated in mc solar cell processing. Gettering conditions (temperature, process duration etc) differ from those of single crystal, because of the interaction among metal impurities, crystalline defects and other impurities present in mc-materials (mainly O and C).

It has been realized that gettering efficiency is strongly material dependent [90, 91]. This is explained by the fact that different techniques to grow mc-Si ingots produce wafers with different number and distribution of defects. Differences are even found in regions of the same ingot [92].

Additionally, a single mc wafer may exhibit nonuniform properties, both areal and in-depth, so that response to a gettering process can be inhomogeneous, affecting the final electrical performance of the solar cell [93, 94].

7.6.2 Passivation with Hydrogen

Silicon nitride is widely used as masking film in microelectronics [95]. For solar cells, it presents the advantage of performing as an effective antireflection coating. Films can

be deposited by several techniques, but the most commonly used process is chemical vapor deposition (CVD), involving the reaction of silane gas and ammonia. Plasma-Enhanced Chemical Vapor Deposition (PECVD) is preferred to other CVD technologies (atmospheric pressure CVD or low pressure CVD) because it is a low temperature process ($T < 500°C$), and this means reducing complexity and preventing lifetime degradation.

But the most outstanding property of PECVD for mc-material is that it produces hydrogenation, and its benefits for silicon are well known [96, 97]. Atomic H interacts with impurities and defects in the bulk of Si, neutralizing their recombination properties to a certain extent, a phenomenon that is usually expressed as "bulk passivation". In the case of PECVD, amorphous silicon nitride films are produced with up to 40 atomic % of hydrogen (i.e. although these films are usually referred to as SiN_x they are really a-SiN_x:H). A subsequent thermal step is needed to activate hydrogenation, and in an industrial process the metal firing step fulfills this objective [98].

Additionally, surface passivation due to SiN_x deposition by PECVD has also been reported [99]. Achievable surface recombination velocity on a phosphorus-doped emitter is similar to that of a high-quality oxide passivated one, and a value as low as 4 $cm\,s^{-1}$ has been obtained on a polished 1.5 Ω·cm FZ p-type silicon wafer [100].

These three different properties (AR coating, bulk passivation and surface passivation) cannot be varied independently, an optimization of processing parameters (temperature, plasma excitation power and frequency, gas flow rate) is necessary, and a compromise should be reached [101, 102]. Furthermore, there are different PECVD techniques giving different results.

The state of the art of the industrial PECVD equipments today is the "direct" PECVD, schematized in Figure 7.11(a). The processing gasses are excited by means of an electromagnetic field, and the wafers are located within the plasma. Bulk is effectively passivated, but surface damage is sustained due to direct exposure of wafers to plasma, precluding the achievement of good surface passivation. Furthermore, surface passivation degrades with exposition to UV light.

There is a high frequency direct PECVD (13.56 MHz) and a low frequency one (in the range of 10–500 kHz), the former being better in terms of surface passivation and UV stability. On the other hand, it is more difficult to obtain uniform layers.

A different approach is the "remote" PECVD, where wafers are located outside the region in which the plasma is formed. Surface damage is avoided in this way, so that

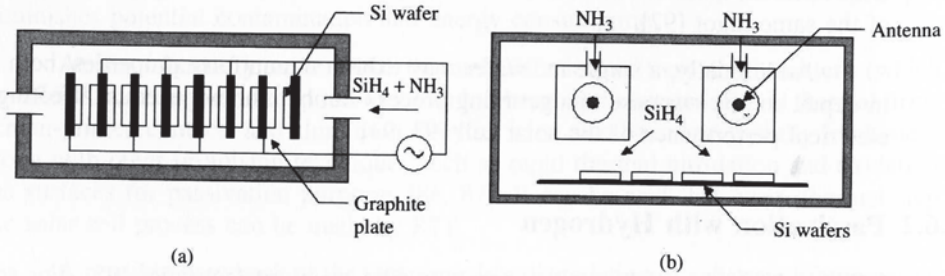


Figure 7.11 Industrial PECVD reactors: (a) direct-plasma reactor; and (b) remote-plasma system

better surface passivation is achieved. On the other hand, bulk passivation is reduced. This technique has been developed at the laboratory level in the last decade, and is currently being introduced into the industry. Figure 7.11(b) shows a sketch of an industrial remote PECVD. It implements a continuous feed of wafers, an advantage that should be compared to the batch-type direct PECVD.

7.6.3 Optical Confinement

Anisotropic texture with alkaline solutions (NaOH or KOH), standard in single crystal solar cells, is also applied to multicrystalline wafers, but with much poorer results, which is one of the reasons for their reduced performance. Reflectance of the textured wafers is relatively high because for randomly oriented grains the etch rate is not the same as that of (100) crystals. Another drawback is the existence of steps between grains, which may cause interruption in the screen-printed metal contacts.

That is why new alternatives are being considered. Their evaluation should take into account not only gains in reflectivity, but also surface damage and compatibility with metallization. In any case, the potential of some of these have been proved, and they are now being developed for industrial applications. Others need more research. The surface features produced by some of these are comparable in size or smaller than the wavelength, and geometrical optics is no longer applicable. They act as diffraction gratings, as scattering media or, in the limit of very small feature size, as graded index layers.

7.6.3.1 Chemical texturing

Several chemical techniques have been proposed. Some of them result in an inverted pyramid structure, but need photolithography patterning, which is a serious drawback for compatibility with the industry [103]. The result of nearly 20% for a mc-Si solar cell relies on an oxide-forced acidic texturing scheme [104]. A simpler approach is based on isotropic etching with an acidic solution containing nitric acid, hydrofluoric acid and some additives. The resulting etch pits of 1–10 μm in diameter are uniformly distributed, giving a homogeneous reflectance over the surface of the wafer and the absence of steps between grains (see Figure 7.12). An increase of short-circuit current of about 1 $mA \cdot cm^{-2}$ is reported for solar cells processed on isotropic textured wafers when compared to cells processed on anisotropic textured wafers [105]. Some technical difficulties, such as depletion of the solution and exothermic effects, can be encountered to come to an industrially compatible processing step. An automatic wet-bench, with temperature control of the etching solution and automatic replenishment of chemicals, has been designed recently.

Reduction in reflection, by forming porous silicon, is also being developed [106]. A detailed analysis taking into account the sum of reflectance and absorption within the porous Si layer shows an optimum of about 5 to 6% total optical loss. Besides its potential, the compatibility of the porous Si formation with screen-printed contacts still needs to be addressed.

7.6.3.2 Mechanical texturing

V-grooves about 50-μm deep can be formed in Si wafers by mechanical abrasion using conventional dicing saws and beveled blades, followed by an alkaline etching to reduce

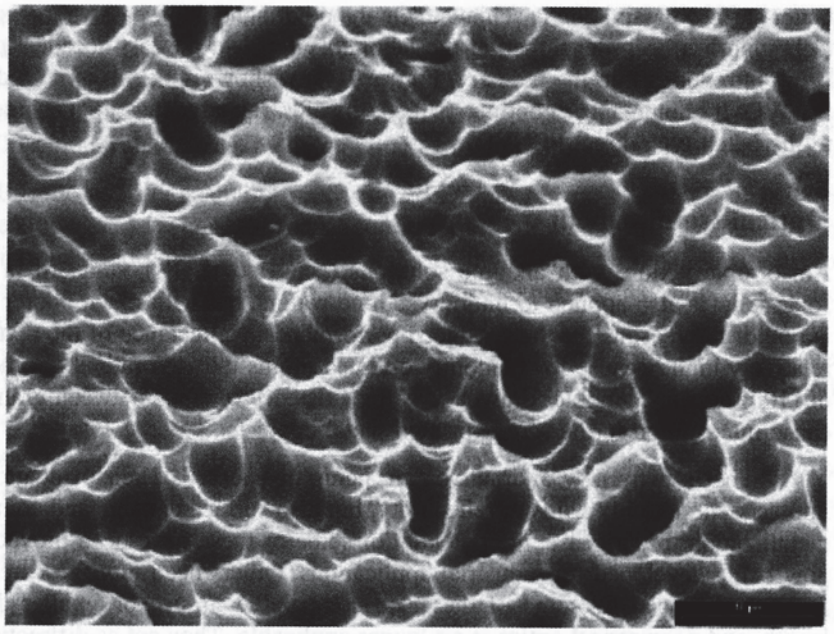


Figure 7.12 Mc-Si surface after acid etching. (Reprinted from *Solar Energy Materials and Solar Cells*, **74**, Szulfcik J, Duerinckx F, Horzel J, Van Kerschaver E, Dekkers H, De Wolf S, Choulat P, Allebe C and Nijs J, "High-efficiency low-cost integral screen-printing multicrystalline silicon solar cells", 155–164, (2002), with permission from Elsevier Science)

surface damage. With this technique, efficiency gains of 5% (relative) after encapsulation have been reached [107]. Contact fingers should be screen printed parallel to the grooves, on plateaus left untextured to ensure easy printing, so that some kind of alignment is maintained. Other contacting alternatives can be implemented, such as roller printing [108] or buried contact [109]. Currently, automated systems are being developed to check industrial feasibility.

Another approach is scribing grooves by laser [110]. Upright pyramids of 7-μm height can be created by two orthogonal sets of parallel grooves, followed by a chemical etch to remove the silicon residues. Combined with a single layer ARC, laser texturing can reduce weighted reflectivity to 4%, half of that given by anisotropic etching and the same AR coating. Adjustments have been made to obtain smoother and smaller grooves, in order to adapt the technique to a screen-printed process.

7.6.3.3 Reactive ion etching (RIE)

Reactive ion etching (RIE) texturization of silicon in chlorine plasma is a dry isotropic etching process that creates a surface with a high density of steep etching pits, with typical dimensions below 1 μm (see Figure 7.13) [111]. Increases of up to 1.4 $mA \cdot cm^{-2}$ in short-circuit current compared to anisotropic texture have been reported with a maskless technique [112]. RIE can also be performed in conjunction with a masking layer to produce more regular features [113]. The main obstacle in industrial implementation is too

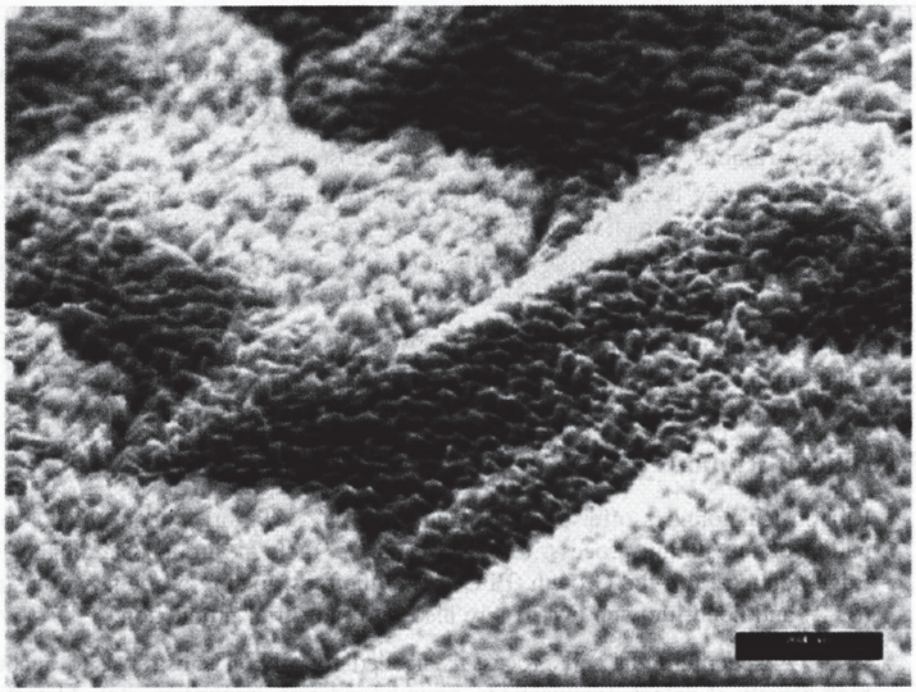


Figure 7.13 Mc-Si surface after RIE. (Reprinted from *Solar Energy Materials and Solar Cells*, **74**, Szulfcik J, Duerinckx F, Horzel J, Van Kerschaver E, Dekkers H, De Wolf S, Choulat P, Allebe C and Nijs J, "High-efficiency low-cost integral screen-printing multicrystalline silicon solar cells", 155–164, (2002), with permission from Elsevier Science)

low process throughput. Alternatives to the use of toxic and corrosive Cl_2 are also being investigated [114].

7.6.3.4 AR coating and encapsulation

It has to be taken into account that cell reflection properties differ from those of texturing because it is usually complemented by AR coating (typically, by atmospheric pressure CVD deposition of TiO_2 or TiO_2/SnO_2 or by PECVD of SiN_x), and cell encapsulation, so that the relative difference between several texturing methods normally reduces, as can be noticed in Table 7.4.

Table 7.4 Comparison of weighted AM1.5 reflectivities for mc-Si wafers with several surface treatments [115]

Reflectivity [%]	Alkaline textured	Acidic textured	Maskless RIE
Bare	34.4	27.6	11.0
With SiN AR coating	9.0	8.0	3.9
SiN & encapsulated	12.9	9.2	7.6

7.7 OTHER INDUSTRIAL APPROACHES

Other commercially available technologies will be described in this section. They all look for a decrease in the \$ W^{-1} figure of merit, following different approaches:

- using ribbons, presented in Chapter 6, as substrates;
- implementing techniques that do not need high-temperature processes: HIT, based on a-Si/*x*-Si heterojunction emitter;
- substituting screen-printing metallization by a more efficient technique: LGBG, based on the buried contact concept;

These only cover a small fraction of the PV market today, but they all have big expansion plans for the next few years.

7.7.1 Silicon Ribbons

Ribbon technologies offer a cost advantage over crystalline silicon, thanks to the elimination of the slicing process. They cover at the moment around 5% of the PV market, Edge-defined-Film-fed Growth (EFG) being the most mature of them, while string ribbon (STR) and dendritic web (WEB) are also into industrial production.

A specific solar cell process is needed for ribbon substrates, to account for the high density of defects (dislocations, grain boundaries, impurities, etc). Al paste is usually printed to create a deep BSF and to benefit from gettering, and silicon nitride is deposited by PECVD for bulk defect passivation and anti-reflection coating.

For EFG solar cells, the uneven surface of the sheets precludes the use of screen-printing metallization, and back and front contact formation is done by pad-printing and direct writing (extrusion) of silver pastes and inks. Efficiencies exceeding 14% on an average have been produced in the manufacturing line, achieving more than 14.7% in some cases [116]. Further reduction of production costs is expected by the growth of large-diameter EFG cylinders, which reduce thermoelastic stresses and can result in thinner and more uniform wafers. Thin curved wafers will require new technology for solar cell processing.

In the case of STR, 14.7% efficiencies have been reported for a process including screen-printed contacts fired with RTP [117], and 50 and 100 W modules are commercially available [118]. Regarding dendritic web, an $n^+ np^+$ structure (phosphorus front diffusion and rear Al alloyed emitter) is implemented on a high-resistivity antimony-doped substrate. Because of the low substrate thickness (100 μm), it can benefit from the location of the *p-n* junction at the back, performing an effective front surface field, enabling a high diffusion length and immunity to light-induced degradation. Using only production-worthy, high-throughput processes, dendritic web cells have been fabricated with efficiencies of up to 14.2% [119].

7.7.2 Heterojunction with Intrinsic Thin Layer

A new structure called HIT has been developed recently, which makes use of the cheaper amorphous silicon (a-Si) technology, depositing a-Si layers on crystalline silicon by

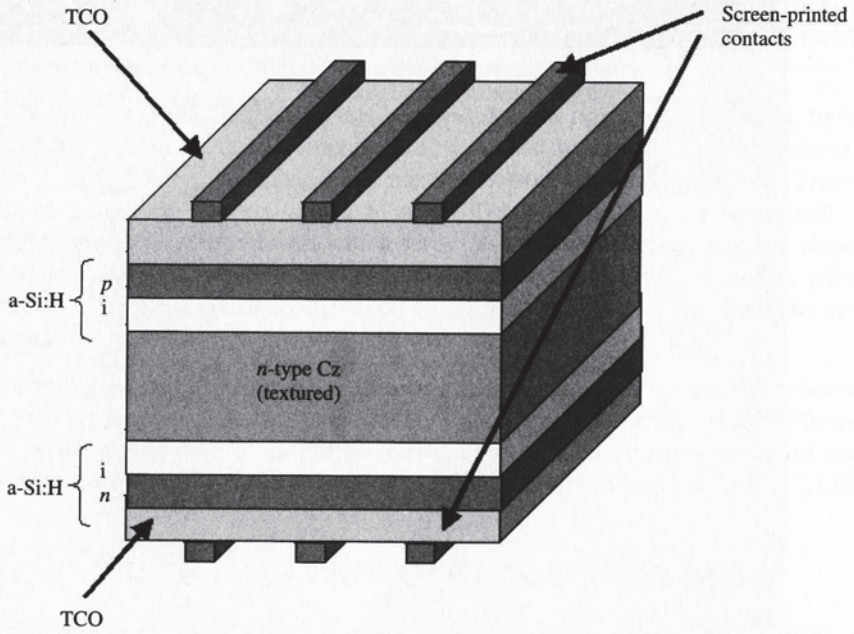


Figure 7.14 Structure of the HIT cell

PECVD [120]. It provides an excellent surface passivation with very low temperature processes (below 200°C), avoiding lifetime degradation of the bulk material. Figure 7.14 shows the structure of the HIT cell. A textured *n*-type Cz-Si substrate is used. The emitter and BSF are made of *p*-type and *n*-type a-Si layers, respectively. Very thin intrinsic a-Si layers are inserted between a-Si and the crystalline substrate, to improve the characteristics of the a-Si/c-Si interface. Thickness of these amorphous layers is on the order of 10 to 20 nm. On both doped layers, transparent conductive oxide (TCO) layers are formed, by sputtering, and metal fingers are screen printed. Back metallization is also comblike to reduce thermal and mechanical stresses, making the cell symmetrical and enabling it to perform as a bifacial cell.

In 1994, 20% efficiency was achieved with a similar HIT structure on a 1 cm^2 cell. Mass production of HIT cells started in 1997, with conversion efficiencies of 17.3% on 100 cm^2 substrates. 180 W modules are fabricated, and special modules exist for roof-tile and bifacial applications.

7.7.3 Buried Contact Technology

The buried contact solar cell process was developed at the University of New South Wales [50]. It is based on forming grooves in the silicon surface, where the metal is deposited by electroless plating, so that high aspect ratios and low metal shading losses are achieved. Several techniques have been proposed for groove formation, laser scribing being the most attractive for large-scale production. A metallized groove, typically 40-μm deep and 20-μm wide, is presented in Figure 7.15. Additionally, other high-efficiency

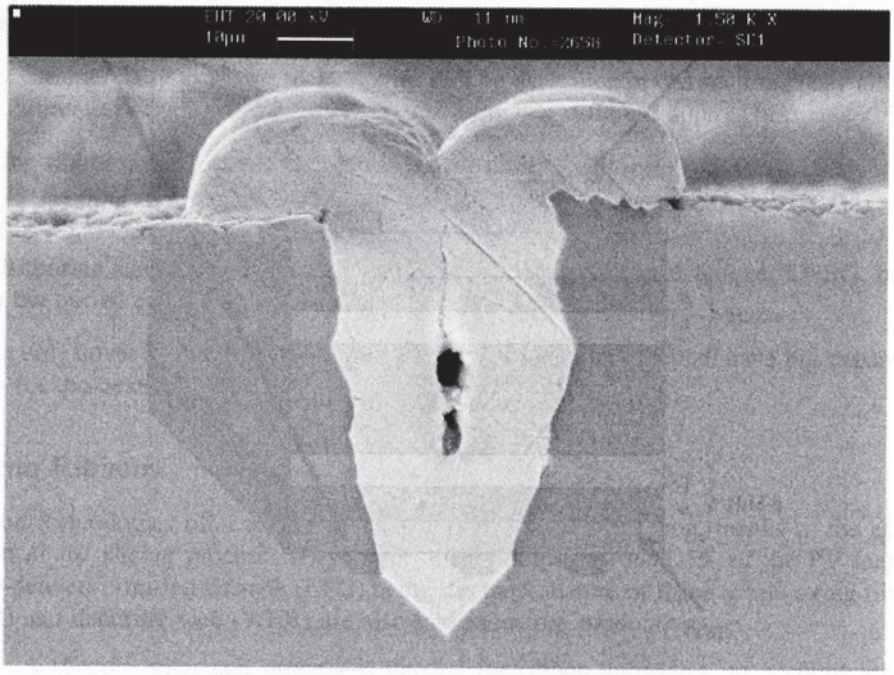


Figure 7.15 Cross-section of a buried contact. (Reprinted with permission from BP Solar)

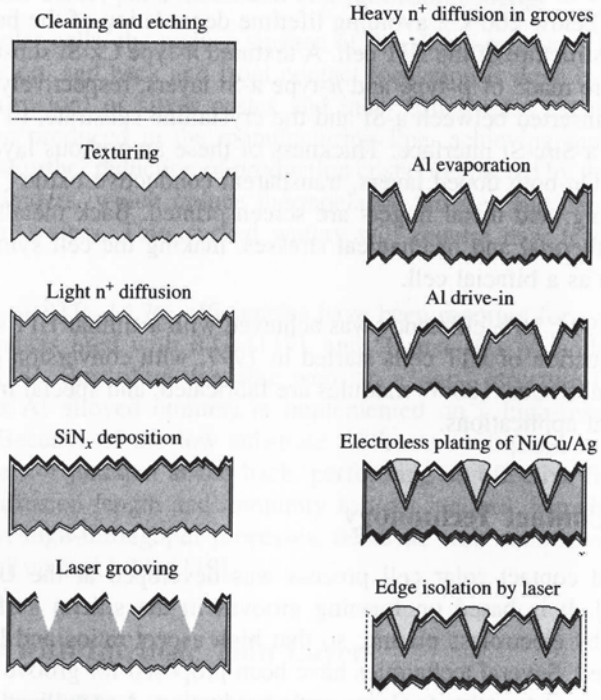


Figure 7.16 Laser-grooved buried-grid solar cell process

features are implemented, such as a selective emitter (highly doped under the metal fingers and low-doped and surface-passivated in the active area) and a Back Surface Field by Al evaporation and alloying, which also produces gettering effect.

The buried contact solar cell has been licensed to many manufacturers, but for the moment only one of them has implemented it at the industrial level, commercializing it as the LGBG solar cell. The LGBG process is sketched in Figure 7.16. Three high-temperature steps are needed, and a number of wet steps must be performed. A key element is the silicon nitride layer, which serves as a masking layer for heavy phosphorus diffusion and plating, and also performs as an antireflection coating and surface passivator. Efficiencies of 17% are routinely achieved with Cz-Si [121], and improvements are being researched and implemented to further increase cell efficiency [122].

The buried contact approach relies on compensating the increase in process complexity as compared to screen-printed technology with an increase in cell efficiency. A midway is proposed with a simplified buried contact solar cell process, with only one high-temperature step, TiO_2 antireflection coating and screen-printed Al BSF [123].

7.8 CRYSTALLINE SILICON PHOTOVOLTAIC MODULES

The power of a single solar cell being small, several of them must be electrically associated to make a practical generator. The module is the building unit for generators that can be purchased in the market, that is, it is the real PV product. Performance and lifetime of PV systems depend on the protection that module construction offers to the active photovoltaic devices.

The basic module fabrication procedure used by most manufacturers was developed three decades ago and is described below briefly. Modules for special applications (building integration, marine operation, etc) require slight modifications of the process and the materials.

7.8.1 Cell Matrix

In a module, the cells are usually arranged in series. After cell finishing, tinned copper ribbons (tabs) are soldered to the bus bars at the front (Figure 7.17a). It has to be noted that tabs must overlap a long distance along bus bar length since the conductance of the printed bus bars is too low. Conductive epoxies can replace conventional solder alloys and illumination used instead of iron heating.

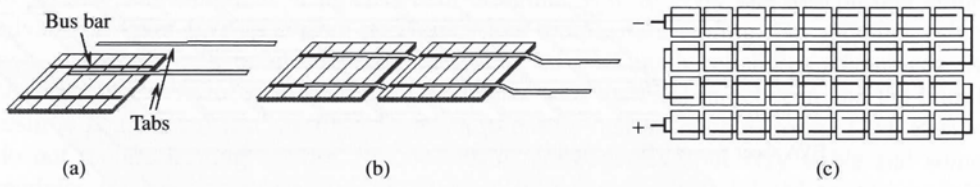


Figure 7.17 (a) Cell interconnection with tabs; (b) two cells in series; and (c) layout of 36 series-connected cells

Two tabs per cell are employed thus providing redundancy that allows current to flow in case electrical continuity is broken because of some failure [124]. Besides, the effective length of grid fingers is one-fourth the cell side and series resistance is alleviated. Tabs provide a nonrigid link between cells that allow thermal expansions to be accommodated.

Series interconnection of strings by soldering the tabs to the rear side of another cell follows (Figure 7.17b). The strings are interconnected with auxiliary tabs to form the cell matrix. This can consist of a single series string or several strings (Figure 7.17c). If the strings are not internally paralleled, their terminals are brought outside the module to permit flexible circuit configuration.

A common module configuration uses 36 series-connected cells, which, under operating conditions, would produce around 15 V at maximum power, appropriate for 12 V battery charging [125]. As building-integrated, grid-connected applications grow, modules with different electrical configurations enter the market.

A few years ago these operations were performed manually, but current factories use sophisticated equipment that performs most of the operations automatically. Both throughput and yield benefit from automation since the connected cells are very fragile and difficult to handle.

7.8.2 The Layers of the Module

The array of cells must be properly encapsulated for reliable outdoor operation for more than 20 years, paying attention to factors like rigidity to withstand mechanical loads, protection from weather agents and humidity, protection from impacts, electrical isolation for the safety of people and so on.

The different layers that the module is made up of are then stacked. A common structure is sketched in Figure 7.18.

A 2- to 3-mm thick soda lime glass is used as a superstrate that provides mechanical rigidity and protection to the module while allowing light through. It must have low iron content or otherwise the light transmission will be low. Modern modules use glass with cerium that absorbs UV radiation to enhance reliability [126]. Tempered glass must be employed to increase the resistance to impacts.

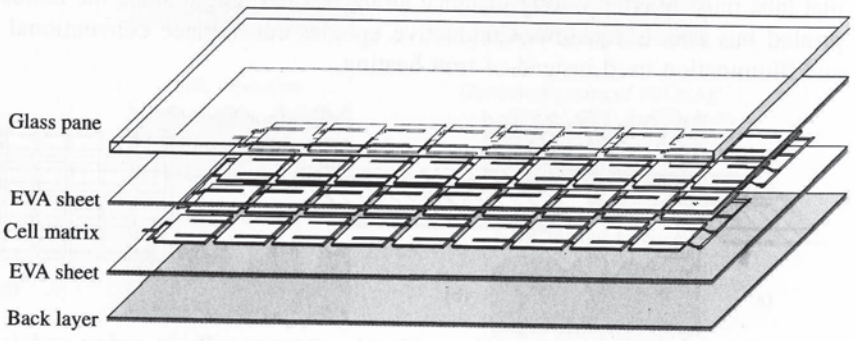


Figure 7.18 Stack of materials to be laminated

The cell matrix is sandwiched between two layers of the encapsulant or pottant material. The most popular encapsulant is the copolymer ethylene-vinyl-acetate (EVA), a plastic composed of long molecules with a backbone of carbon atoms with single covalent bonding. EVA is a thermoplastic, that is, shape changes made under heating are reversible. It is sold in rolls of extruded film around 0.5-mm thick. Along with the polymer, the film contains (1) curing agents and (2) stabilizers whose role will be described later.

The outer layer at the nonilluminated module side is usually a composite plastic sheet acting as a barrier for humidity and corroding species. Some manufacturers use another glass, which increases protection.

7.8.3 Lamination and Curing

These steps are carried out in a laminator, a table that can be heated and furnished with a cover that closes the edges tightly. The cover has an internal chamber and a diaphragm that separates this from the chamber containing the module. Both chambers can be independently evacuated: this configuration allows the module to be kept in a vacuum while mechanical pressure is exerted on it.

In the lamination stage, both chambers are evacuated while temperature is raised above the EVA melting point at around 120°C. Vacuum is important to extract air – to prevent voids from forming – and moisture and other gases. The EVA flows and embeds the cells. After a few minutes, with the module chamber still in vacuum, the upper chamber is filled with air so that the diaphragm presses the laminate. The temperature is increased to 150°C and the curing stage begins: the curing agents induce cross-linking of the EVA chains, that is, chemical bonds are formed transversely among the long molecules that before curing are only weakly linked to one another. The plastic then acquires elastomeric, rubberlike properties and indeed the curing step is analogous to the vulcanization of rubber. This stage takes up to 60 min for standard cure EVA [127]. After cooling down, the laminates are unloaded from the laminator.

Lamination used to be a bottleneck in the module fabrication process. To improve throughput several solutions have been followed by the industry: (1) commercial fast-curing EVA formulations allow drastic reductions of curing time to less than 10 min [128], (2) performing the curing step in a separate oven decreases the residence time in the laminator and (3) a large lamination area – up to several square meters – enables simultaneous process of several modules or very large ones.

Another polymeric material, poly vinyl butyral (PVB), was used in early times of module fabrication. It is processed in a similar way to EVA and can present some advantages over EVA [129] but it requires low temperature storing. For modules using two glass panes, resin fill-in is an alternative to EVA with reliability advantages. A sealed cavity is formed between the glass panes with the cells in-between and the liquid resin is poured into it. Care must be taken to ensure that no bubbles form [125]. Resins do not require heating to cure. Silicone resins are expensive but very stable and some modules for building integration use them. Yet curing can be inhibited by the module sealant so that they are difficult to handle. Acrylic resins with UV curing are being investigated.

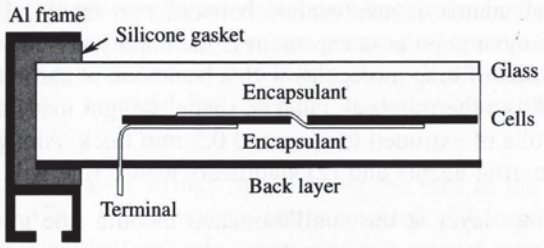


Figure 7.19 Cross-section of a standard module

7.8.4 Postlamination Steps

These include (1) trimming the edges of the laminate to remove spread-out encapsulant, (2) sealing them with silicone rubber to close this potential path of moisture penetration in the module, (3) sticking the plastic junction box at the back of the laminate and performing the connections and (4) when required, installing the anodized aluminum frame (Figure 7.19). The frame must be electrically insulated from the active cell circuit so that high-voltage differences can be sustained between the electrical terminals and the frame without current flow.

Besides, among other final tests, the $I-V$ curve of all modules under standard conditions is measured in a solar simulator to check if they fulfill specifications. Flash simulators are commonly utilized to save energy, with the electronic equipment able to record a complete $I-V$ curve in a fraction of a second. They must have a spectral content matched to the AM1.5 standard, or else, they must be calibrated with a calibrated cell of the same technology.

7.8.5 Special Modules

7.8.5.1 BIPV products

Building integration of PV modules (BIPV) has emerged as one of the most important – by volume – applications of Photovoltaics. Modules perform two tasks: as constructive materials as well as power generators. Modules can be incorporated to a building in a number of ways and special products are being developed so that the typical framed module is no longer the only PV product. Very large modules with special fixing for roof or façade integration, roof tiles with cells and semitransparent modules allowing light through are available. Visual appearance is enhanced by module shape, encapsulation and cell color [130]. Besides, these products must comply with building normative such as fire resistance.

7.8.5.2 Bifacial modules

Several cell structures have been presented that can operate with bifacial illumination. By encapsulation between two glass panes, bifacial modules offering increased power output per unit cell area can be produced without technology changes. In spite of their potential, their presence in the market is very small at the moment.

7.8.5.3 Modules with back contact cells

Several cell structures have been proposed that bring both contacts to the back face, which is usually accomplished by implementing phosphorus diffusions at both faces that are internally connected through processing. They fit the scheme in Figure 7.1(d) [131]. Back contact cells are interconnected without tabs by soldering them to a layer with the connection paths printed, similar to PCB practice in electronic circuits. These experimental designs offer simplified module fabrication and enhanced visual appeal.

7.9 ELECTRICAL AND OPTICAL PERFORMANCE OF MODULES

7.9.1 Electrical and Thermal Characteristics

The voltage of the module is, in principle, the number of series-connected cells times the voltage of the single cell, and the module current the number of paralleled cells times the single cell current. Whatever the combination, the module power equals the power of a single cell times the number of them. Mass-produced modules offered in the catalogues of manufacturers show power ratings that typically range from 50 to 200 Wp, delivered at current levels between 3 and 8 A and at voltages between 20 and 40 V. Lower and higher values are possible for special applications.

The manufacturer usually provides values of representative points (short-circuit, open-circuit and maximum power) of the module $I-V$ curve measured at standard cell conditions (STC), that is, 1 kW·m^{-2} irradiance (=0.1 W·cm^{-2}), AM1.5 spectral distribution and 25°C cell temperature. The maximum power of the module under STC is called the peak power and given in watts-peak (Wp). While efficiency has the greatest importance for a solar cell, for a module it has the less relevant meaning since part of the area is not occupied by the expensive solar cells.

The conditions in real operation are not the standard ones; instead, they vary strongly and influence the electrical performance of the cell, causing an efficiency loss with respect to the STC nominal value. This loss can be divided into four main categories [132]:

1. *Angular distribution of light*: Because of the movement of the sun and the diffuse components of the radiation, light does not fall perpendicular to the module, as is the case when measurements are done and the nominal efficiency is determined.
2. *Spectral content of light*: For the same power content, different spectra produce different cell photocurrents according to the spectral response. And the solar spectrum varies with the sun's position, weather and pollution and so on, and never exactly matches the AM1.5 standard.
3. *Irradiance level*: For a constant cell temperature, the efficiency of the module decreases with diminished irradiance levels. For irradiances near one sun, this is primarily due to the logarithmic dependence of open-circuit voltage on photocurrent; at very low illumination the efficiency loss is faster and less predictable.
4. *Cell temperature*: The ambient temperature changes and, because of the thermal insulation provided by the encapsulation, light makes cells in the module heat over it;

higher temperature means reduced performance. This is usually the most important performance loss.

But, prediction of the module response under different conditions is required to correctly assess the yearly production of a PV system in the field. The physical mechanisms of influence of temperature and irradiance on cell performance are well known, so that, in principle, prediction of module output could be rooted in physical models. This is however unpractical and would be a different approach if followed by PV system engineers.

Instead, very simple methods are used for translating the $I-V$ performance to different operating conditions and standardized procedures have been developed for PV modules of industrial technologies [133]. These methods are applicable within a limited range of temperature and irradiance conditions that are not very far from those met when testing the module and which require a small number of easily measurable parameters. The module datasheets from the manufacturers used to include some of these, allowing simplest estimates to be made, such as:

1. The steady-state power balance determines cell temperature: the input is the absorbed luminous power, which is partially converted into useful electrical output and the rest is dissipated into the surroundings. Convection is the main mechanism for heat dissipation in terrestrial, flat plate applications, and radiation is the second nonnegligible mechanism of heat dissipation. A common simplifying assumption is made that the cell-ambient temperature drop increases linearly with irradiance. The coefficient depends on module installation, wind speed, ambient humidity and so on, though a single value is used to characterize a module type. This information is contained in the Nominal Operating Cell Temperature (*NOCT*), which is defined as the cell temperature when the ambient temperature is 20°C, irradiance is 0.8 kW·m^{-2} and wind speed is 1 m·s^{-1}. *NOCT* values around 45°C are typical. For different irradiance values G, this will be obtained by

$$T_{\text{cell}} = T_{\text{ambient}} + G \times \frac{NOCT - 20^{\circ}\text{C}}{0.8\ \text{kW}\cdot\text{m}^{-2}}$$

2. The module short-circuit current is assumed strictly proportional to irradiance. It slightly increases with cell temperature (this stems from a decrease in band gap and an improvement of minority-carrier lifetimes). The coefficient α gives the relative current increment per degree centigrade. By combining both assumptions, the short-circuit current for arbitrary irradiance and cell temperature is calculated as

$$I_{\text{SC}}(T_{\text{cell}}, G) = I_{\text{SC}}(\text{STC}) \times \frac{G}{1\ \text{kW}\cdot\text{m}^{-2}} \times [1 + \alpha(T_{\text{cell}} - 25^{\circ}\text{C})]$$

   For crystalline Si, α is around 0.4% per degree centrigrade.

3. The open-circuit voltage strongly depends on temperature (the main influence is that of the intrinsic concentration), decreasing linearly with it. Knowledge of the coefficient, called β, allows the open-circuit voltage to be predicted by

$$V_{\text{OC}}(T_{\text{cell}}, G) = V_{\text{OC}}(\text{STC}) - \beta(T_{\text{cell}} - 25^{\circ}\text{C})$$

   The irradiance dependence is buried in T_{cell}. For crystalline Si, β is around 2 mV/°C per series-connected cell.

4. A lot of factors affect the variation of the maximum power (or, equivalently, the efficiency) with irradiance and temperature. The parameter γ is defined as the relative decrease in module efficiency per degree centigrade of cell temperature increase

$$\eta(T_{\text{cell}}, G) = \eta(\text{STC}) \times [1 - \gamma(T_{\text{cell}} - 25^{\circ}\text{C})]$$

Usual γ values are near 0.5% per degree centrigrade.

7.9.2 Fabrication Spread and Mismatch Losses

So-called mismatch losses arise when cells with different $I-V$ characteristics are interconnected because of the fewer degrees of freedom left to bias the devices, so that the array output is less than the sum of the powers that the individual cells could deliver. The differences come from the unavoidable fabrication spread or from nonuniform irradiance or working temperature within the array.

To minimize mismatch losses, finished cells are measured and sorted in the factory. For series connection, the important parameter is the current at the maximum power point (mpp). It is the common practice to measure the current before encapsulation at a fixed voltage close to the mpp and to classify the cells accordingly, though other classification criteria are possible [134]. Within each class all devices present similar currents within the specified tolerance that ensures that, when connected in series to form the module, the mismatch loss will be below the desired limit [135]. Depending on the class being processed, the power rating of the resulting module will vary and this explains why manufacturers offer different module families though they are built in exactly the same way.

7.9.3 Local Shading and Hot Spot Formation

Because of local shading or failure, one or several solar cells can present a much smaller short-circuit current than the rest of devices in the series string. If the defected cells are forced to pass a current higher than their generation capabilities, they become reverse-biased, even enter the breakdown regime, and sink power instead of sourcing it.

Figure 7.20 illustrates this behavior for an 18-cell string with one cell shaded so that its short-circuit current is half that of the remaining devices. String short-circuit is marked with a horizontal line, showing that in this condition the shaded cell is strongly reverse-biased and dissipates the power produced by the unshaded cells. This effect of course severely degrades the efficiency of the module, but more important is the fact that it can get damaged.

Avalanche breakdown is characterized by a nonuniform distribution of current across the junction, breakdown occurring preferentially at localized regions, possibly correlated to damage during processing. Intense local heating can produce very high temperatures (a hot spot). If a temperature of around 150°C is reached, the lamination material becomes degraded and the module irreversibly deteriorated [136, 137]. Because of the localized nature of the process solar cells show large scattering in their reverse characteristics so that the module behavior under partial shading is not accurately predictable.

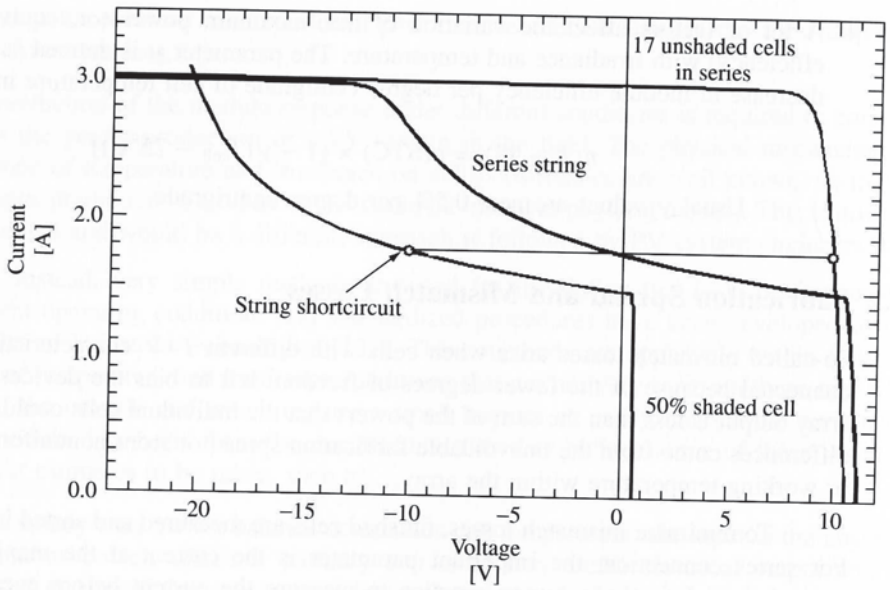


Figure 7.20 Computer simulation of the $I-V$ curves of a 50% shaded cell, showing the typical "soft" reverse breakdown, and of 17 identical cells, unshaded, in series. When series-connected with the shaded cell, the curve labeled "series string" is obtained

In order to devise the means of preventing hot spot failure from occurring, the worst case is considered. This occurs when the N-cell series string is short-circuited and a shaded solar cell is reverse-biased with the voltage of the remaining $N-1$ good devices, as shown in Figure 7.20. The minimum N that will lead to hot spot formation (i.e. the maximum N for safe operation) depends on rather uncontrollable factors, as explained. For Si solar cells of standard technology, it is around 15 to 20.

Since larger series strings are generally used, the approach followed is to put a diode (bypass diode) in parallel, but in opposite polarity, with a group cells. The number of cells in the group is chosen so that hot spots cannot be formed. When one or several cells are shaded, they are reverse-biased only to the point where the diode across the group starts forward conduction. The diode carries away the necessary current to keep the group near short-circuit.

Figure 7.21 illustrates the operation of the bypass diodes. When the current forced through the shaded substring is such that the reverse bias equals the diode threshold voltage, the bypass diode sinks all necessary current to keep the string at this biasing point thus preventing the power dissipated in the shaded cell to increase. It is also apparent that the bypass diode leads to a significant increase of output power allowing the module to keep delivering the power generated by the unaffected groups.

It is clear then that the smaller the number of cells per bypass diode, the lower the efficiency loss for a shading condition, but this means a higher cost and more complex fabrication. It has been proposed to integrate a bypass diode in each cell so that these effects will be minimized at the expense of more complicated cell processing [138].

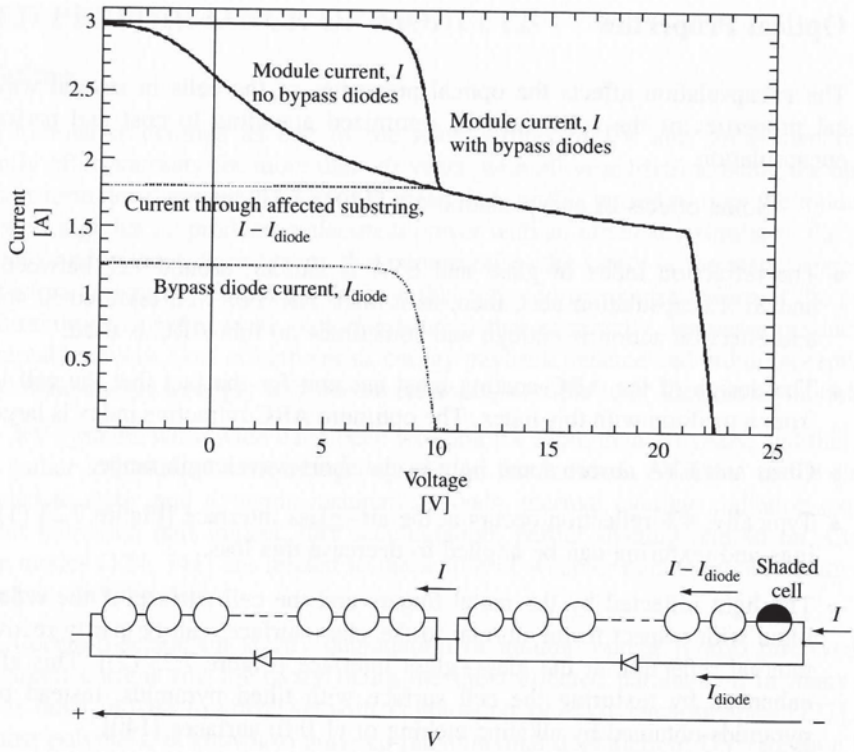


Figure 7.21 Computer simulation of the $I-V$ curves of a 36-cell series string without and with two bypass diodes, connected as shown in the bottom of the figure, when one cell is 50% shaded. The currents through the shaded substring and its bypass diode are also shown

The practice is to take electrical terminals outside the encapsulation not only for the extremes of the series string, but also for intermediate points as well, so that bypass diodes are connected in the junction box 12 or 18 cells each (Figure 7.22). Endurance to shading is a standard test for module qualification.

The influence of local shading on the module output depends on the details of the $I-V$ curve of the cells as well. Under certain circumstances of partial shading, it is beneficial that the cells show some shunt resistance. However, tight control of leakage currents by processing is not easy.

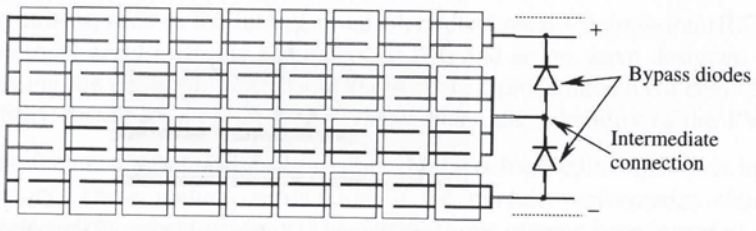


Figure 7.22 Two bypass diodes in a 36-cell module. The connections are done in the junction box

7.9.4 Optical Properties

The encapsulation affects the optical properties of the cells in several ways. The optical properties of the cells must be optimized attending to cost and performance after encapsulation.

Some effects of encapsulation are [139] as follows:

- The refraction index of glass and EVA is similar, around 1.5, between those of air and Si. Encapsulation acts, then, as a thick AR. For well textured Si solar cells, this antireflection action is enough and sometimes no thin ARC is used.
- The design of the ARC coating must account for the fact that the cell is illuminated from a medium with this index. The optimum ARC refractive index is larger than in air.
- Glass and EVA absorb some light in the short-wavelength range.
- Typically, 4% reflection occurs at the air–glass interface [Figure 7.23 (1)]. ARC coatings and texturing can be applied to decrease this loss.
- The light reflected by the metal fingers and the cell surface, if the reflected rays are tilted with respect to the normal to the glass surface, can be partly recovered by total internal reflection at the glass–glass interface [Figure 7.23 (2)]. This effect could be enhanced by texturing the cell surface with tilted pyramids, instead of the upright pyramids obtained by alkaline etching of (1 0 0) surfaces [140].
- Though the trapping capabilities of the cell, due to the lower difference in refractive index, appear to worsen with encapsulation, the escaped rays are trapped in the glass so that the absorption enhancement in the ideal case is not affected.
- For cells without a back metal mirror, the transmitted light can be recovered by putting a reflector, detached from the cell, at the back of the module [Figure 7.23 (3)]. The back plastic layer, if white, serves this purpose.
- The same white layer, since it reflects diffusively, allows some of the light incident between the cells to be collected [Figure 7.23 (4)].

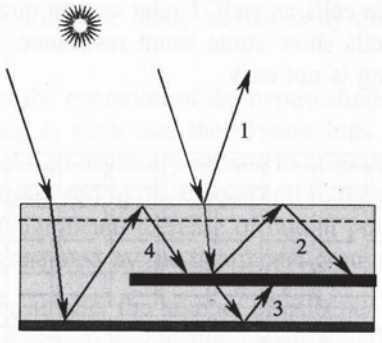


Figure 7.23 Optical effects of encapsulation: (1) glass reflection; (2) trapping of cell reflectance; (3) trapping of cell transmittance; (4) collection of peripheral light