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"High Efficiency Solar Cells with Concentration"

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These are preliminary lecture notes, intended only for distribution to participants.

HIGH EFFICIENCY SOLAR CELLS WITH CONCENTRATION

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1.-Introduction.

The final objective of photovoltaics is to obtain electricity from the Sun that be cost competitive and even advantageous with other energy sources. This is already a reality in some environments as the space, in the rural electrification of remote places, in small applications as calculators, watches, etc., but it is still far from contributing significatively to mass energy production. High efficiency solar cells with concentration can provide a way to help in achieving this objective.

2.-Flat module and concentrator systems.

The starting point for designing a photovoltaic system is some available area, that is going to be exposed to the Sun and from which, by using solar cells, it is desired to obtain electricity at a cost competitive price. This is a complex problem because it will be influenced by a great number of aspects: climatology, periodicity of production considered (months, year or years...), degradation of the devices, ecological concerns, the availability of other resources, etc. Anyway, there are two main strategies for attaining the competitiveness goal:

a) *Flat module approach*. In this approach, the *available area* is covered with solar cells as completely as possible resulting in what is usually called a *flat module*. Of course, it would be desirable to use in this modules cells with an efficiency as high as possible. As it will be seen in the next paragraphs, such a cells already exit but they are expensive and, in consequence, the final cost of the energy produced would not be cost competitive. Hence, it results more advantageous to sacrifice some points of the achievable efficiency in order to greatly reduce the cost of the cells. Obviously, each time the efficiency is increased without increasing or even reducing the cost, an important break-through is reached in this field. Some materials are generally used in this approach:

-*Amorphous silicon*. Both α-Si:H and α-Si:F are being currently studied. When alloyed with either Ge or C, double and triple multijunction structures can be manufactured. Degradation is one of the main concerns of this technology.

-*Polycrystalline thin films*. It is mainly based in II-VI compounds and most of the structures include heterojunctions (CdS/CdTe, $CdS/CuInSe_2$).

-*Crystalline Si.* Although crystalline silicon plays an important role in high efficiency concentrator cells, silicon cells for flat panels can be regarded as simplified and cheaper versions of the concentrator cells. They are based in the well known silicon technology. A silicon material not as pure (*solar grade*) as the usually required in microelectronics can be used to reduce costs. The development of these cells has been often benefited from the research in high efficiency silicon cells for concentration.

A good and brief summary of the main aspects concerning the above technologies can be found in [1].

b) *Concentration approach.* A basic unit of a concentrator module is sketched in Fig.1. In this structures, the light is collected by optical means (a *concentrator*) and directed over one cell.

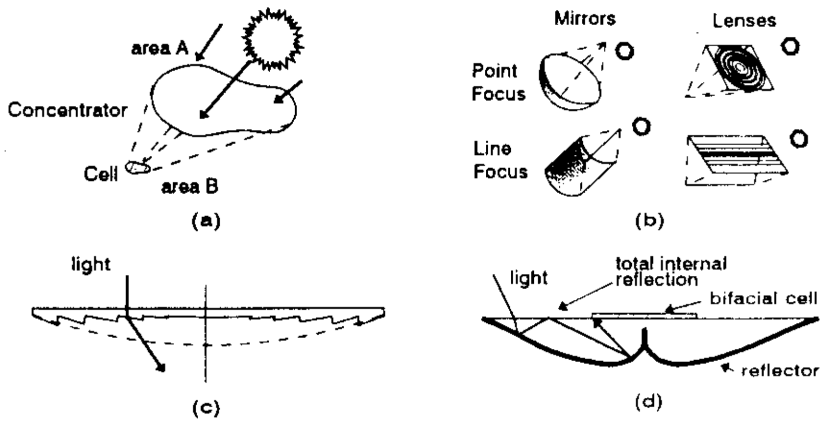

Fig 1. *(a) Sketch of a concentrator system. The ratio A/B defines the geometrical concentration (b) Basic structures for concentrators. (c) Sketch of a Fresnel lens. (d) Concentrator designed to operate in a static module with bifacial cells, [2].*

Based on mirrors or lenses, several types of concentrators can be designed (Fig.1b). Fresnel lenses (Fig.1c) provide a way for manufacturing unexpensive lenses. One of the most important concepts involved in the design of concentrators refers to the fact that there is no need for the concentrator to be an *imaging* system: it has only to be able to collect the energy from the surface exposed to the Sun and to *put it* (concentrate) on the cell. Therefore, these designs, specially when static concentrators are involved, use the tools derived from the theory of non-imaging optics, [3],[4]. An important example are the static concentrators that are used with bifacial cells [5],[6] (cells which are able to collect light from both sides), Fig 1d.

The ratio between the area of the external surface that collects the sunlight and the area of the cell is often referred to as *geometrical concentration*. Most commonly, by concentration it is mean the ratio between the power per unit area that impinges over the external surface (which is taken as reference and designed as *one sun*) and the power per unit area impinging at the cell surface (that is said, then, to operate at *X suns*). Both definitions agree when the concentrator has no losses (it does not only mean that the material with which the concentrator has been manufactured is perfectly transparent but also that every ray of light entering the concentrator reaches the cell). However, from the brightness conservation theorem [5], it can be proved that the maximum achievable concentration with the later definition is $n^2/\sin^2\theta_S$ where 'n' is the refraction index of the media surrounding the cell and θ_S is the angle of the solar dish seen from the Earth (0.267°). This result would take us to a maximum concentration of about 46050 suns when the media surrounding the cell is air (n=1).

As it becomes clear from the discussion above, the main idea behind the concentrator approach is to collect with only one cell the same light for which it would have been necessary approximately to use X cells. For the success of the approach, there are, however, some potential *drawbacks*:

- The cost of a *concentrator cell* is higher than the cost of a *one sun* cell. This is due to the fact that the cell has to be carefully designed and manufactured because of the high current densities involved. Special attention has to be paid to minimize the series resistance of the devices and to the dissipation of the unconverted energy. Moreover, cells often show problems of stability.
- The optical system introduces some losses.
- The supporting structures, such as for example the need of the concentrator itself and the use of trackers and their maintenance are more expensive than the ones required for flat modules.
- Although static concentrators are able to collect some diffuse light, climatic conditions with good direct radiation component are required.
- Nowadays, there is still a low market for concentrator cell that unnaturally increases the costs.

But there are also important *advantages*:

- The weight of the cost of the cell in the system is approximately reduced by a factor X.
- The potential conversion efficiency of a cell operating in concentration is higher than when operated at one sun (this will be illustrated inside the context of Fig. 3).
- Within these systems, the utilization of high efficiency cells can be cost competitive. This fact opens the possibility to a practical utilization in terrestrial applications of an increased number of materials (for example GaAs or the ones used for multijunction cells) with complex designs that greatly improve the efficiency.

The discussion about if advantages can overcome the disadvantages is rather complex. However, a recent and detailed work by Luque et al. [7] indicates that if the market were large enough, the cost of concentrator plants (estimated in 0.08 ECUs/kWh) would be 1/3

minor than the cost of a flat module plant.

3.-Fundamentals of solar cell operation and design.

The fundamentals involved in solar cell operation can be studied in any general book dealing with semiconductor device physics (See for example Ref. [1] or [8]) and in specialized books ([3],[9],[10]). More detailed, exhaustive and advanced topics are discussed and continuously reviewed in the proceedings of several international conferences that deal with photovoltaics (For example the IEEE Photovoltaic Specialist Conference or the European Community Photovoltaic Solar Energy Conference). We want here, however, to summarize the most relevant aspects involved in solar cell operation to facilitate the description of the main features that characterize the high efficiency solar cells that will be described in later paragraphs.

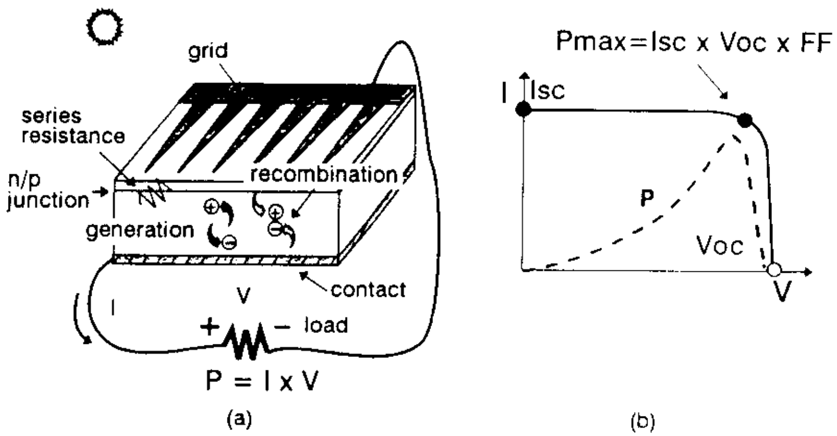

Fig.2 *(a) General sketch of an operating solar cell and (b) current-voltage characteristic.*

Fig. 2 represents a general sketch of an operating solar cell. Basically it consists in a pn junction in which the front contact has been substituted by a metallic grid to allow the sunlight to penetrate into the bulk semiconductor. Photons with energy greater than the semiconductor bandgap can generate electron-hole pairs. The design of the cell must avoid the recombination of this pairs before they can be extracted as electrical current and made circulate across the external load. The recombination depends greatly on the operating voltage and increases when voltage increases. Therefore, the current extracted from the cell is maximum in short circuit conditions (shortcircuit current, I_{sc}) and is null at a certain voltage (open circuit voltage, V_{oc}). At this two characteristic points, the power delivered to the load vanishes and reaches its maximum value at some intermediate point called *maximum power point* (P_{max}). The power delivered at this maximum point is usually referred to I_{sc} and V_{oc} by means of the fill factor, FF:

$$P_{max} = I_{sc} \cdot V_{oc} \cdot FF \qquad (1)$$

The efficiency of the cell is increased if these parameters, I_{sc}, V_{oc}, and FF are increased: the short circuit current will increase if the carrier generation is maximized; the open circuit voltage will increase if recombination is minimized and, although several factors can influence the fill factor, this will be increased if ohmic losses are minimized. Unfortunately, not all these factors can be independently optimized. There are some design constrains that sometimes can be relaxed with innovative ideas. We shall describe now some of these trade-offs and the ideas that have been proposed to relax them to obtain the maximum profit.

a) *The optimum bandgap*. From a basic point of view, the selection of the optimum bandgap constitutes the most important trade-off for starting the design of a solar cell although practical reasons (availability, price, etc.) can determine the right selection. As it is known, photons with energy lower than the semiconductor bandgap will not create electron-hole pairs. Therefore, in order to produce the highest shortcircuit current, the lowest bandgap materials should be chosen. Fig. 3a plots the shortcircuit current as a function of the semiconductor bandgap for different solar spectra if all the photons with energy greater than the gap were absorbed. Unfortunately, semiconductor intrinsic concentration increases exponentially when bandgap decreases and therefore, the recombination rate. In consequence, the open circuit voltage will decrease when bandgap increases (See Fig. 3b) and, since the fill factor does not vary drastically with bandgap, it exists an optimum bandgap at which efficiency is maximum. These results are plotted in Fig. 3c as a function of the concentration and for different spectra. They have been computed assuming the total conversion into electron-hole pairs of those photons with energy above the bandgap. Additionally, only radiative recombination has been assumed to take place in the semiconductor and the area exposed to the Sun has been considered to be the same than the area from which photons are emitted (this can be regarded as if a back reflector had been placed at the rear side of the cell). Further details can be found in references [11],[12].

In consequence, these results are not strictly applicable for example to Si, for which Auger recombination is dominant, but for some other material with the same bandgap but direct, with radiative recombination as the main recombination mechanism, maybe some ternary compound in the InGaAs family. Additionally, it is not usually pointed out how the optimum bandgap shifts towards lower values as concentration increases. It has to be mentioned that the same results could be obtained, instead of applying concentration, by restricting the angle with which photons are emitted from the cell [13] to an angle θ_E. In this case, the value of X that labels the curves in Fig. 3c must be read as the quotient $X/\sin^2\theta_E$.

b) *Reducing reflecting losses*. When light impinges over an untreated cell surface it is partially reflected. This reflection constitutes a primary source for losses. However, this is maybe the losses mechanism that can be attacked more easily. Often, the solution is simply to deposit some antireflecting coating over the cell. Sometimes, as it is almost exclusively made in silicon, the surface is textured [14]. The texturing is produced by chemical etchants which etch some crystallographic directions of the semiconductor faster than others and can be used, for example, to produce pyramids (Fig. 4a) or V grooves (Fig. 4b). Basically, reflection is reduced because of light is not reflected outside the cell but it is directed again over a nearby pyramid (or groove) where the process can continue indefinitely. Light trapping, that will be described below, is also greatly benefited from texturing.

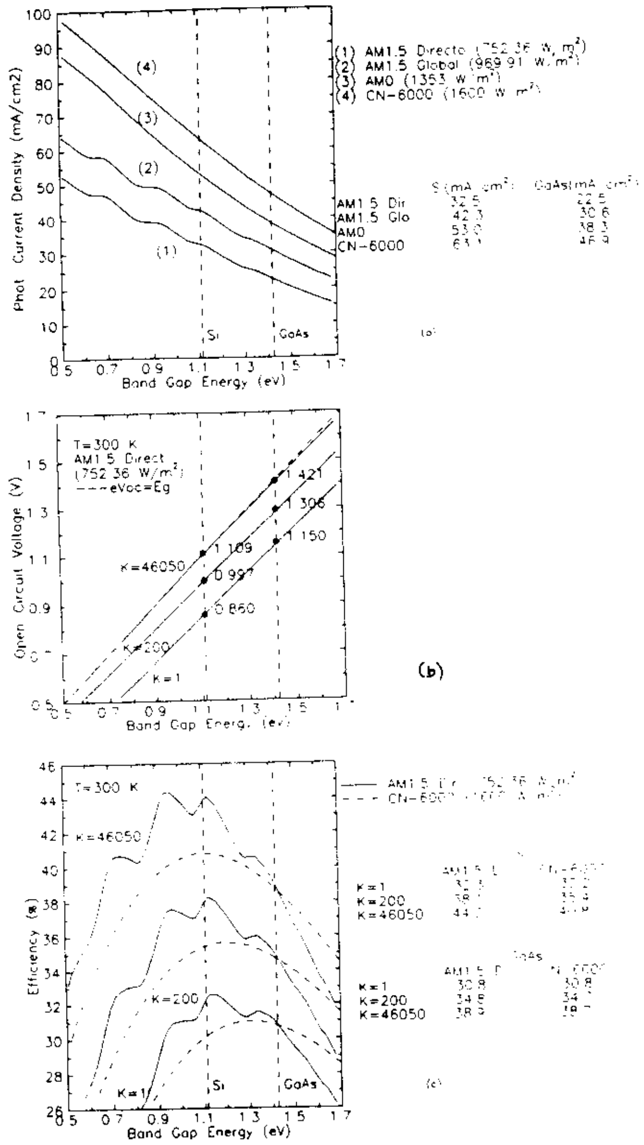

Fig. 3 *(a) Maximum shortcircuit current of a solar cell at one sun as a function of the bandgap for different solar spectra: AM1.5 Direct [15], AM1.5 Global [15], AM0 [16] and Black Body at 6000 K. (b) Open circuit voltage at different concentrations for AM1.5 Direct spectrum. (c) Maximum efficiency plots for AM1.5 Direct and Black Body at 6000 K spectra. Only radiative recombination was considered in the efficiency and V_{oc} computations.*

c) *Avoiding unnecessary recombination.* Good quality materials, free of defects and undesirable recombination centres, are required for manufacturing a high efficiency solar cell. Special attention has to be paid to surfaces that should be passivated. However, there are certain recombination mechanisms, such as Auger and radiative, that are fundamental processes in the semiconductor physics and that technology cannot avoid. Often, compromises have to be adopted in relation with other losses mechanisms. For example, while high doping levels decrease resistivity and therefore, series resistance, they increase recombination. Complexity is added if heavy doping effects have to be considered.

d) *Grid trade off.* The grid of the cell has to be carefully designed: if it were too dense, light could not go inside the semiconductor; if it were too sparse, the series resistance of the cell and consequently the ohmic losses would boost because of the longer distance that carriers have to travel laterally through the emitter before they be collected in the contacts. Some ideas can soften this trade off. One of them is based on the utilization of prismatic covers [17], Fig. 3d, that steer the incoming light away from the cell metallic grid. Another, is to move the front contact somehow to the rear side of the cell as, for example, it will be described below for the silicon Back Point-contact solar cell. The constrain can also be relaxed with light confining cavities ([18],[19],[20]) that can direct again the light reflected in the metal over the cell.

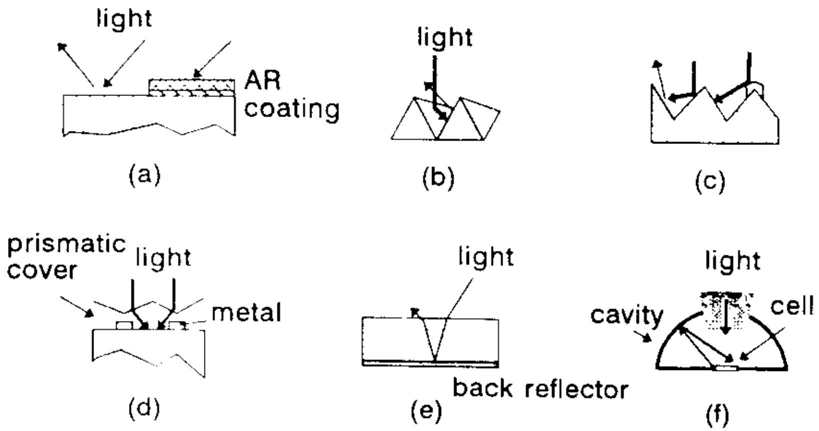

Fig. 4 *Sketches illustrating the principles of (a) antireflecting coatings, (b) textured surfaces, (c) V-grooves, (d) prismatic covers, (e) back reflector, (f) light confining cavities.*

e) *Light trapping.* Specifically, light trapping techniques are procedures that achieve the same carrier photogeneration with less semiconductor volume. An immediate benefit is therefore obtained from the reduction in the volume recombination. The simplest *light trapping* is produced by means of a back reflector and it is enhanced if some texturing exists on the front surface. It must be emphasized that the back reflector must be placed behind the photovoltaically active layers of the cell. Sometimes, as it occurs in conventional GaAs cells, these layers, a few microns depth, have to be grown over a photovoltaically inactive substrate, that later is only used for mechanical support, and are not directly accessible. Light confining cavities are a recent approach. They can be somehow integrating spheres that

collect the light that is reflected from the cell and direct it again over it. They require a certain aperture to allow the light to come in but it is remarkable how they can also be designed to restrict the angle of emission of the escaping rays (*angular* restricted cavities [20]).

4.-Silicon concentrator cells.

The first modern silicon cell is devoted to Chapin [21] in 1954. The development of Si cells was encouraged during the first years of research thanks to its applicability to space satellites. A condensed history of photovoltaics and Si cells can be found in Ref. [22] and [23]. According to a review made by Wolf in 1980 [24], the state of the art of a silicon cell in 1970 was based in the following premises:

- Surface recombination approaches infinity under the ohmic contacts and was almost not influenceable at the open front surface,

- Auger recombination and bandgap narrowing effects were not recognized,

- The cell was being analyzed inside the wide-base diode approach that assumes that carrier diffusion length is much lower than the base width. Therefore, no back surface field (BSF) was considered.

Considering the achievements from 1970 to 1980, Wolf also summarized the theoretical background for the date cells which were already based in the BSF structure (Fig. 5a):

- Good quality materials with long diffusion lengths (in the order of mm) could be achieved and therefore, the narrow-base diode approach should be used.

- The surface recombination could be influenceable (for example by applying inversion layers or wide-bandgap windows).

- The texturing and the optical internally reflecting back surface was taken into account.

- The influence of Auger recombination and band gap narrowing received attention.

Maybe only the *know how* and the leak of more accurate data about the Auger recombination and heaving doping effects separated those days cells from the recent high efficiency silicon solar cells that will be described in the next paragraphs. In this development, the research group at the University of South Wales (UNSW) and the group at the Stanford University played an essential role. An alternative description of the structure and features of some of the cells that follow can also be found in some other proceedings of this workshop series [25].

a) *Metal Insolating NP junction (MINP) and Passivated Emitter Solar Cell (PESC).* When it was recognized that bulk material quality had reached his limit and that it was dominated by Auger recombination, most effort was dedicated to reduce surface recombination and to control the emitter profile. Two structures were suggested and developed around 1983-1984 [26] by the group at the University of New South Wales: the MINP and the PESC cells (Fig. 5b) with an efficiency of 18.0%[1] and 18.3% (improved to 19% two years later) [27] respectively. The approaches consisted in completely passivating the front surface, including the area under the contacts, with a thin oxide layer (MINP) or in leaving small areas under the contacts without covering (PESC). In the first approach, electrons should trespass the oxide by tunnelling. The manufacturing process of the MINP structure was found to be more difficult to carry out than the PESCs because it was found that the oxide that was suitable for passivating was not appropriate for tunnelling what introduced additional photolithographic steps.

b) *Microgrooved PESC (μg PESC)*. The UNSW group improved significatively the PESC solar cell performance by means of what they called microgrooved PESC [27] (Fig. 5c). The microgrooves were manufactured by photolithographic masking the wafer and using and anisotropic etch that exposed the (111) planes. The V grooves reduced the cell reflection (below 1%), provided some light trapping and reduced the series resistance losses by ↓3 when compared with a textured surface. This structure reached an efficiency of 20.8 % at one sun [28].

The design was modified and even simplified for operation in concentration (Fig.5d) by making an obliquely transversing top contact metallization. This designed pursued a higher cell metal coverage without adversing the collection of light by collecting the light that was reflected in the metal grid. An efficiency of 25% at 80-100 suns was reported [29] although, probably, overestimated. With the same purpose, prismatic covers were used and an efficiency of 24% at 102 suns was reported [30].

c) *Passivated Emitter Rear Locally diffused solar cell (PERL)*. It was also developed by the UNSW group [31]. In Fig. 5e it has been represented an sketch of this cell. Its main features are:

- the inverted pyramids, that improve the reduction of the light that is reflected from the cell and the light trapping,

- the oxide passivation of most of the top and the rear surface with the metallic contact made to only a small fraction of both surfaces.

- the contact area is heavily diffused to screen recombination.

This cell showed an efficiency greater than 23% [28],[32] at one sun, which constitutes the world record for the efficiency of a Si operating at one sun, and 24.8% at 21 suns with the use of prismatic covers.

d) *Buried Contact Solar Cell (BCSC)*. Developed by the UNSW, this cell represents a way of practical implementation of high efficiency features into commercial cells. A sketch of the cell is represented in Fig 5f. From the point of view of manufacturing, this cell has the advantage that it does not require any photolithographic process. First, the cells are

[1].-All the efficiencies showed in the text have been corrected to take into account the standarization occured in 1991 between different recognized testing laboratories. See Table I for further details.

pyramidally textured, diffused and oxidised [27]. Then, slots about 40 μm depth and 20 μm width are scribed through the oxide and diffusion layer by means of a laser. Using the remaining oxide as a mask, the slotted areas are heavily diffused to shield the high recombination of the contact area. Finally, the cell is electroless platted in the slotted areas and in the rear side of the cell. This process results in a very high aspect ratio metallization. The efficiency of this structure seems to be limited to 20% [33] at one sun. Efficiencies of 21.6% have been reported at 11 suns [31] and with large area devices ($20cm^2$).

Improved results are expected with the modified structure of Fig. 5g which is buried in both sides. Ar additional advantage of this cell is that it can be used in bifacial static concentrator ([2],[6],[34]). To evaluate the potential of the previous structure the hybrid buried contact/PERL cell (Fig.5h), which has already shown efficiencies above 21%, [35] is being investigated.

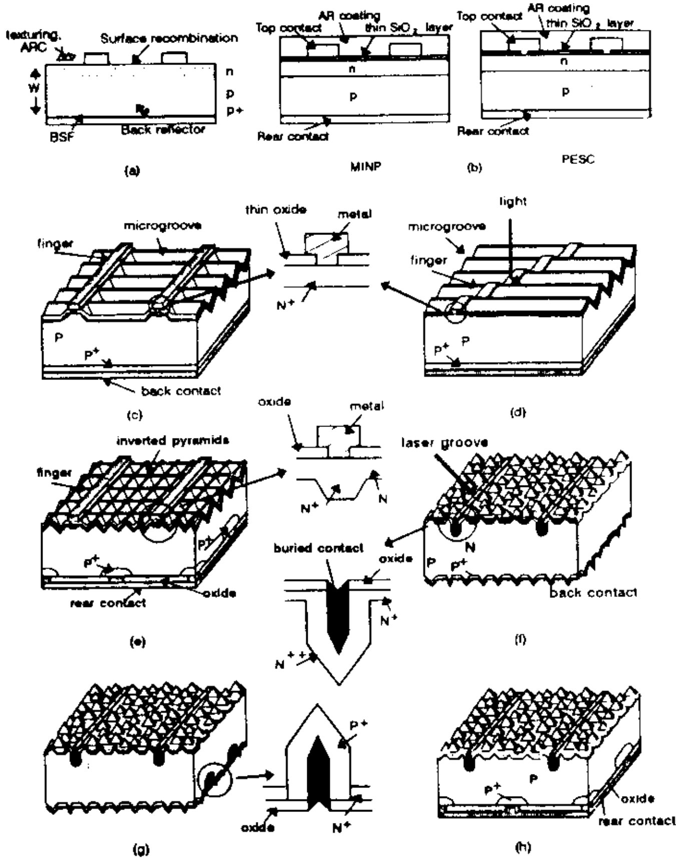

Fig. 5 (a) *Basic BSF solar cell structure, (b) MINP and PESC cells, [26], (c) μg PESC, [27] (d) μg PESC with obliquely transversing metallization, [29] (e) PERL solar cell, [31] (f) BCSC, [27], (g) doubled buried, [33] (h) hybrid buried/PERL [33].*

e) *Back Point Contact solar cell (BPC).* A first hand description of this cell, precursors and context can be found in [36]. This cell was originally developed by researchers at Stanford University. In short, the main idea involved in the approach is to move the front contact of the cell to the rear side avoiding in this way the front obscuration introduced by the grid. The precursor of the BPC cell was the Interdigitated Back Contact solar cell (IBC) [37], Fig. 6a. However, the first cells of this type showed a low short circuit current due to recombination in the bulk and in the front surface. The BPC is similar to the IBC but the contacts are made by small points etched through the back passivation, Fig.6b. This cell requires a careful design [38],[39] to compromise between the spreading resistance loss in the contacts and the minimizing of the contact coverage fraction. Moreover, to allow for good carrier collection at the back, the cell cannot be very thick and therefore, light-trapping plus special care during the manufacturing process to avoid contaminants that decrease diffusion length is specially important. This cell achieved a 26.5% efficiency ([33],[38]) at 140 suns which is the highest efficiency ever measured and contrasted to date for a silicon cell. This are, however some of the problems related to this cell and the solutions reported:

- *Stability.* This problem is caused by an increase in the surface recombination induced by the ultraviolet light. To reduce this effect, front diffusion and thermal oxide are used [40].

- *Complexity.* The cell is very complex to fabricate, and therefore, expensive. Simplicity can be enhanced with the Trench cell [41]

- *Large area.* Multilevel metallization allows to increase the area of the cell without increasing the series resistance introduced by the rear grid [42].

A challenging application of this cells is currently under way at Sunpower. Using the integrated circuit technology, a single wafer integrated 140 W silicon concentrator module is being researched for concentrating dish applications. Efficiencies of 20.8% at 70 suns and 39°C have been reported [43].

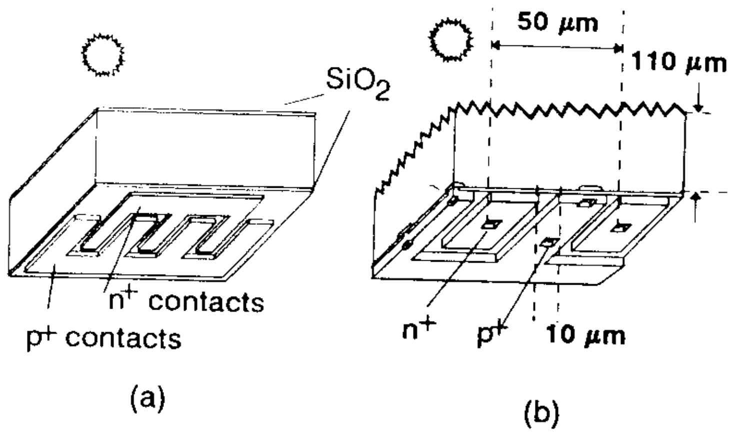

Fig.6 *(a) IBC solar cell (b) BPC solar cell.*

5.-III-V compound cells.

We shall focus our preliminary description in the GaAs cell because it has the highest developed technology. However, essentially the same concepts involved in the description of this cell are applicable to any cell based on III-V compounds. It has to be mentioned that the cost of these cells results too high for terrestrial applications unless concentration be used. The use of concentration is encouraged because of the greater potential of these cells to operate at higher concentrations than silicon cells.

a) *Basic III-V cell.*

Fig. 7 (a) represents the general structure of a GaAs cell. When compared with silicon cells, these are the main differences:

- The front passivation, which in Si was generally made with SiO_2, now has to be made by means of a heterojunction that reflects the minority carrier flux that flow towards the surface. The passivating material has to be transparent to solar radiation (it is actually named *window* layer) and with a lattice constant similar to that of the bulk material to avoid defects in the interface that increase recombination. This passivation is specially important since these materials are very absorbent and carriers are generated close to the surface. AlGaAs is commonly used as window layer for GaAs cells although the best results for operation at one sun have being obtained with $GaInP_2$ as window layer [44].

- As it was mentioned before, these materials are direct gap materials which implies they are very absorbent. A few microns of bulk material are enough to absorb all the light. Therefore, the photovoltaically active layers are placed at the top of the substrate from which they have been grown that after the manufacturing process only plays the role of mechanical support. A second consequence of this fact is that the rear side of the active layers is not directly accessible. A great interest exists in developing techniques with the double purpose of making the rear side accessible for processing (for example, to place reflectors or to integrate the cells in multiple gap systems) and for substrate reusage. Some of these techniques will be described with more detail below.

The efficiency of the basic structure just described can be improved by:

- placing a second AlGaAs layer below the active base of the cell to reduce recombination.

- including a contact layer to reduce series resistance.

- setting prismatic covers to allow a more favourable compromise between series resistance and grid coverage.

All this improvements have been represented in Fig.7b. With this structure Varian researchers achieved an efficiency of 27.5 % at 205 suns [45] using Entech prismatic covers.

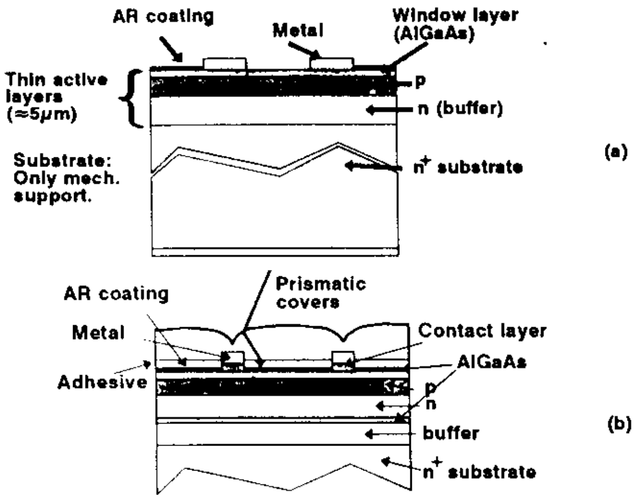

Fig 7. *(a) Basic structure of a III-V solar cell. (b) Improved structure.*

Besides GaAs, InP and InGaAs play an important role as materials for manufacturing solar cells:

-The interest in InP relies mainly in the space applications since this material is more resistant to radiation damage. Efficiencies of 21.9% at one sun [32] and 24.3 % at 100 suns [46] have been reported.

-InGaAs bandgap can be chosen close to the value that gives the maximum efficiency in the plots of Fig.3c for operation with high concentration. It presents a great interest for manufacturing cells that can be used in multigap systems [47]. It has been reported an efficiency of 23.6% at 204 suns for 1.15 eV bandgap and 24.7% at 305 suns for a material with 1.35 eV bandgap.

b) *Cleavage of Lateral Epitaxial Films for Transfer (CLEFT).* This technique was developed by researchers at Kopin [48] for manufacturing thin GaAs solar cells with the following advantages:

- cells are light-weight and in consequence can better couple with the constrains of space applications,
- substrates can be reused and therefore, cell cost reduced,
- the technique provide a way for processing the back active layers of the cells.

Briefly, the CLEFT process includes the following steps (Fig.8a):

- substrate masking and pattering.

- epitaxial growth of a GaAs layer until a continue layer is obtained.
- growth of the active layers that constitute the cell, including the front metallization.
- bonding of the layer surface to a glass superstrate for holding the wafer after separation from the substrate.
- cleavage.
- back processing.
- mounting on a glass substrate.
- separation from the glass superstrate and final processing of the front side.

With this techniques, efficiencies of 23.3% at one sun have been reported [32].

c) *Bragg reflectors.* Bragg reflectors provide a way for placing a reflector at the rear side of the active layers that constitute the cells. Due to the fact that absorption length is smaller than the diffusion length in III-V compound solar cells, almost all the available photons going into the semiconductor volume are converted in carriers and collected in well designed devices. Therefore, minor benefits are usually expected from the application of light trapping techniques to these compounds and efforts are focused in reducing the grid obscuration (for example, by means of prismatic covers) without adversely affecting the series resistance. However, we want to point out [11] that the efficiency of this cells has the potential to be enhanced also with the application of back reflectors or light trapping techniques because of the re-absorption of the photons originated in the radiative recombination processes.

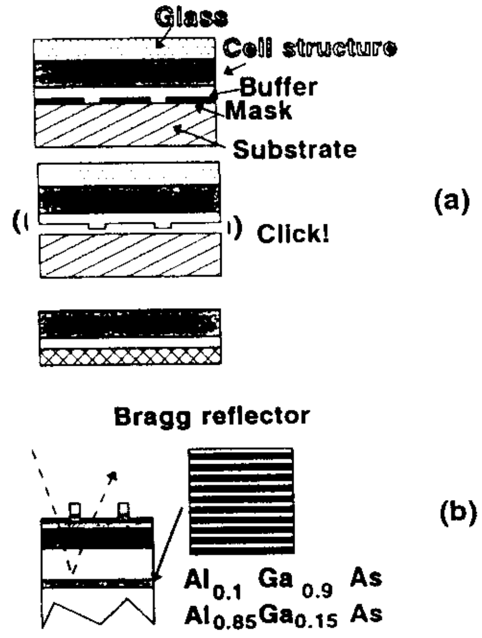

Fig.8 *Sketch illustrating (a) CLEFT process and (b) Bragg reflector.*

A Bragg reflector (Fig.8b) is a multilayer structure in which effective reflection is achieved due to the differences in the refraction index of the layers that constitute the structure. The structure is epitaxially grown over the substrate prior to the active layers of the cell. It is used when it is previewed a reduction in the carrier diffusion length of the cell, as for example it happens in space applications due to radiation damage, and when it is intended to grow GaAs over Si or Ge. Efficiencies of 24.7 % at one sun have been reported [49].

d) *Back contacts.* A back contact scheme produced the highest measured efficiency for a concentrator Si cell. A parallel design for a GaAs cell would be extremely difficult to carry out. Firstly, the back side of the active layers should be processed and therefore, thin film techniques as CLEFT would be required. Secondly, the optimum design of the rear contact layout would need dots less than 1 μm in diameter [50].

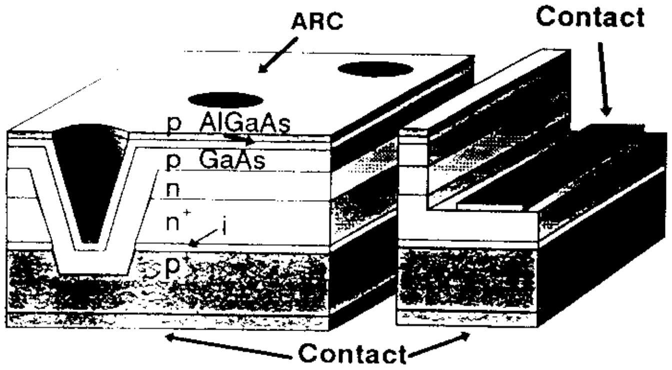

Fig.9. *Back Contacted Emitter GaAs solar cell.*

A rear contact scheme although conceptually very different to the back point contact approach was proposed with the Back Contacted Emitter GaAs solar cell [51],[52] Fig.9. In this solar cell, the minority carriers photogenerated in the photovoltaically active regions, electrons in the emitter and holes in the base, flow vertically and are collected by the p/n junction as in the classical structure. The majority carriers flow laterally through the emitter region and then vertically through the conductive channels to the p-type substrate. Their contribution to the series resistance is small for well designed devices. The majority carriers (electrons) in the n base must flow laterally through the n+ region, but as this region has no photovoltaic role, it can be heavily doped and therefore the metal contacts can be separated a great distance (in the order of mm) to reduce the obscuration factor without adversely affecting the series resistance.

6.-Multijunction cells.

In cells based in one bandgap, photons with energy lower than this bandgap cannot be absorbed for electron-hole pairs generation and therefore, are wasted. Multijunction cells

provide a way for a better utilization of the Sun spectrum. While one gap cell has the potential of achieving 40.7% conversion efficiency (assuming the Sun as a black body at 5759 K and maximum concentration or total restriction of the angle of emission of the photons) two-gap systems have a potential of 55.5 % and three-gap, 63.4 %. The process can be continued until an infinite number of gaps are considered and then, the limiting efficiency of photovoltaic energy conversion is obtained (86.3%) [13].

Similarly to in one-gap cells, it exists some optimum values for the bandgap of the cells for which efficiency is maximum. Fig. 10 plots the limiting efficiency of a two-gap system, with the cells independently connected, as a function of the bandgap of the top and bottom cell, for one sun and for maximum concentration operation. It can be observed how the efficiency is less sensitive to the bandgap of the bottom cell than to the bandgap of the top cell. Optimum bandgap region also shifts to lower bandgaps as concentration increases.

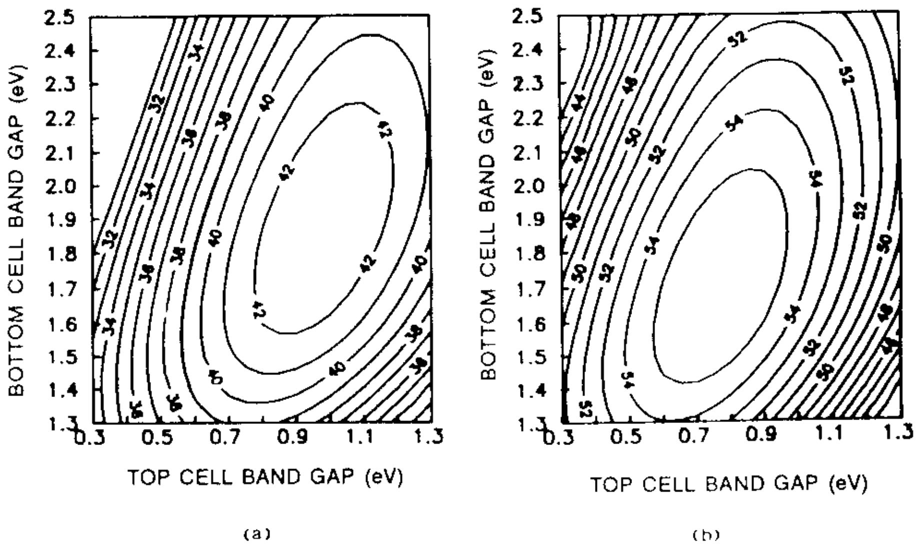

Fig.10. *Limiting efficiency as a function of the gap energy of the top and bottom cell for a two cell system, independently connected, operating at (a) one sun, (b) maximum concentration. The system has been supposed to be illuminated with black body radiation at 5759 K [12].*

Table I. *This table summarizes the main efficiencies which have been referred in the text. The column "reported efficiency" summarizes the efficiency that was published at first. The column "corrected efficiency" summarizes the value of the efficiency after the normalization of the calibration standards that took place between the main calibration centres [28]. This corrected values have been taken from Ref. [28] (indicated by the superscript 1) and [32] (indicated by the superscript 2) when it has been possible. When it has not, based on [28], author has just divided the efficiency by 1.05 when the calibration centre was Sandia and prior to 1991. This correction affects mainly to the shortcircuit current and it has to be* *regarded with care. In any case, it does not represent an assessment of the author about what the final efficiency should be since, for a precise correction, other factors, particular to each case, as the spectral response or the variation of the open circuit voltage with the current and not available to the author in all cases, should be taken into account. Therefore, the corrected data have to be taken as approximative. With these considerations, results for one sun operation should be referred to global AM1.5 spectrum (1000 Wm^{-2}, ASTM E892-87) at 25°C and direct beam AM1.5 spectrum (1000 Wm^{-2}, ASTM E891-87) at 25°C for operation in concentration. Numbers that follow the name of the testing centre refer to different calibrations into the same centre: NREL-1, before October 1985; Sandia 2, before 1991 but later that the middles of 1987; NREL-2 and Sandia 3, after 1991 [28]. Abbreviations: 2T, Two terminals; 3T, Three Terminals; 4T, Four Terminals; Mec. Mechanical Stack; MI, Metal interconnect; TI, Tunnel Interconnect; obl, obliquely transversing metallization.*

Description	Ref.	Reported Eff. (%)	Testing centre	Corrected Eff. (%)	X (suns)
Silicon:					
MINP (UNSW)	26	18.7	NREL-1	18.0[1]	1
PESC (UNSW)	26	19.1	NREL-1	18.3[1]	1
PESC (UNSW)	27	19.8	NREL-1	19.0[1]	1
μg PESC (UNSW)	28	21.4	Sandia-2	20.8[1]	1
μg PESC obl (UNSW)	29	22.0	indep.	-	1
μg PESC obl (UNSW)	29	25.0	indep.	-	80-100
μg PESC (UNSW)	30	25.2	Sandia-2	24.0	102
PERL (UNSW)	31	24.2	Sandia-2	23.3[1],23.1[2]	1
BCSC (UNSW)	31	22.4	Sandia-2	21.6[2]	11
Hybrid BC (UNSW)	35	21.3	Sandia-3	21.3	21
BPC (Stanford)	38	28.0	Sandia-2	26.5[2]	140
III-Vs:					
GaAs (NREL)	44	25.7	NREL-2	25.1[2]	1
GaAs (Varian)	45	29.2	Sandia-2	27.5[2]	205
InP (Spire)	-	-	NREL-2	21.9[2]	1
InP (NREL)	46	24.3	NREL-2	24.3	100
InGaAs 1.35 eV (Varian)	47	25.9	Sandia-2	24.7	204
InGaAs 1.15 ev (Varian)	47	24.8	Sandia-2	23.6	305
GaAs CLEFT (Kopin)	55	23.3	NREL-2	23.3[2]	1
GaAs Bragg R. (Spire)	49	24.7	Spire	24.7	1
Multijunction:					
AlGaAs/GaAs MI,2T (Varian)	56	27.6	NREL-2	27.6	1
GaInP/GaAs TI,2T (NREL)	57	27.3	NREL-2	27.3	1
GaAs/GaSb Mec. (Boeing)	-	-	Sandia-2	32.6[2]	100
InP/InGaAs 3T (NREL)	58	31.8	NREL-2	31.8[2]	50
GaAs/GaInAsP Mec.4T(NREL)	58	30.2	NREL-2	30.2[2]	40
GaAs/Si Mec. (Sandia)	-	-	Sandia-2	29.6	350
AlGaAs/GaAs/InGaAsP TI+Mec. (Varian/VS C./NREL)	59	25.2	NREL	25.2	1 (AM0)
GaAs-Si Splitt (IES)	54	29.4	IES	-	170

Two are the main configurations for multigap systems (Fig.11):

a) *Stacked systems:* In this approach, cells are placed one behind another with decreasing band gaps (Fig.11a). Photons not absorbed by the former cells can be absorbed by the cells placed behind. The stack is said to be monolithic when all the cells are built in the same wafer and mechanically stacked when cells are manufactured separately and later assembled with the help, for example, of some suitable adhesive.

The major problem involved in the monolithic stack is how to carry out the cell interconnection. One of the approaches is to manufacture a tunnel diode in between the two cells (Fig.12a). However, this connection often introduces a series resistance that results too elevated for cell operation in high concentration. Another strategy consists in using a metal interconnect [53] as showed in Fig. 12b. With this approach, the base of the top cell is connected with the emitter of the bottom cell by a suitable combination of controlled etchings and metallization steps. The major inconvenience of this approach comes from the increase in the obscuration that results from the existence of a second grid. Three terminal devices can also be manufactured within this approach although they find difficulties for a practical application in present photovoltaic installations which are designed for operation with two terminal devices. Fig. 12 describes this procedures.

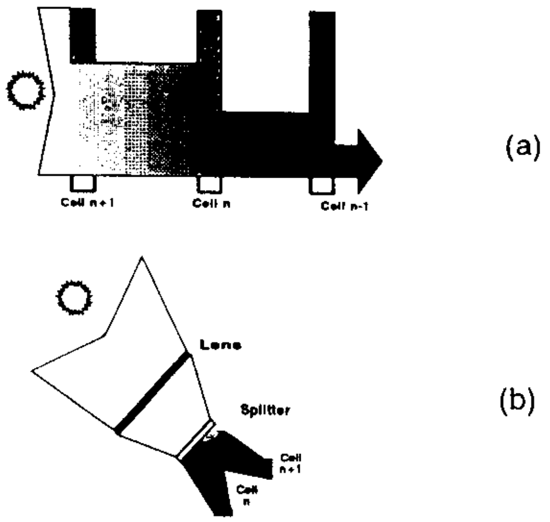

Fig.11 *Representation of an (a) stacked multigap system and (b) splitting system.*

b) *Splitting systems.* In a splitting system, light coming from the Sun is separated in several spectral components and casted by means of a splitting filter (Fig. 10b) over the cells. One of the main advantages of these systems is that technologically well developed one-gap cells can be used. Recently our group has reported [54] an efficiency of 29.4% at 170 suns (outdoor measurement) with a system that used GaAs and Si enclosed in light confining cavities.

Table I includes then main efficiency results referred to multijunction solar cells

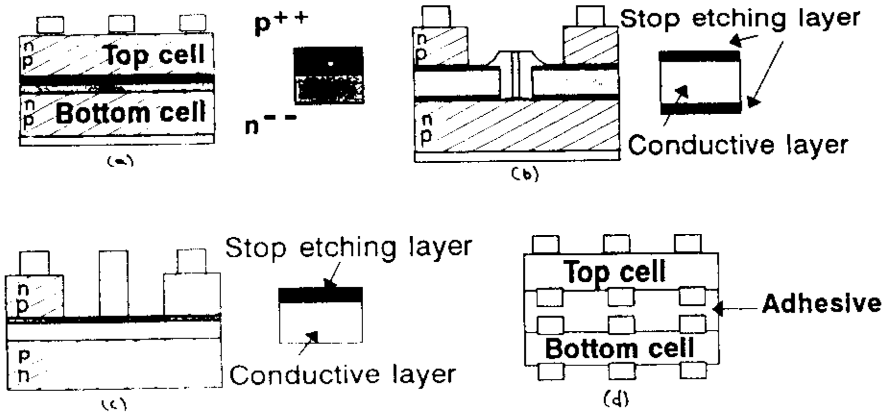

Fig. 12 *Different ways of connecting cells in a multigap system: (a) Two terminal, tunnel diode (b) two or three terminal, metal interconnect, (c) three terminal, (d) two, three or four terminal mechanical stack.*

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