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Survey on PV panels: materials and types

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Abstract

With the growth of PV panels, many semiconductors are studied and exploited. New forms and generations of PV cells are produced presenting original and special features. Each PV technology is developed striving increase in efficiency or simplicity in production process. In this article, we will present a survey on PV panels. State of the art of each technology will also be presented. We will focus on materials used and on the operating principle of each type. The main interest in this analysis, for our future work, is how to manage the use of PV panels to increase their life span? Which technology is more suitable to include ICT (Information and Communication Technologies) for monitoring, maintenance and life cycle extension by means of adequate control techniques?

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Keywords: semiconductors; crystals; thin film; absorption; band gap; efficiency.

1. Introduction

The world's total installed PV panels' power has reached 100GWp in 2014 [1]. This growth is based on existing and new technologies. In PV technology, we can find numerous semiconductors (Si, In, Ga, Se, Cd, Te) and numerous forms (wafers, single crystal (sc), multi-crystalline (MC), poly-crystalline (PC), thin films (TF)). Combination of these semiconductors and materials generate different types and generations of PV panels. In this paper we will try to summarize materials and types used in PV panels. We will show their application fields, their principle of operation, and their technologies.

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Nomenclature

n_{si}	refractive index of silicon (3.48)
n_{air}	refractive index of air (1)
ω	thickness of the cell (m)
D	carrier diffusivity ($\text{cm}^2 \cdot \text{s}^{-1}$)
τ	carrier lifetime (s)
L	diffusion length (m)

2. Silicon based PV Panels

Silicon (Si) is an indirect band gap semiconductor with a band gap energy of 1.11 eV. It is the most abundant material of the earth crust after oxygen. Si based PV panels dominate the market [1] and are chosen for our future work because of history processing of Si in electronics, and because the maximum efficiency of PV panels can be reached for a semiconductor having a band gap of 1.1eV [2]. Moreover, most of the research works are done on Si panels, and it is used for power generation. How to increase their life span may be a good challenge of using ICTs.

2.1. Silicon crystals

Silicon used in PV panels can be divided into different categories according to its crystal organization or grain size. The manufacturing process is responsible in generating different grain size. PV panel efficiency varies with the obtained crystal.

Single crystal (or mono-crystal) silicon solar cells are made from the microelectronic industry rejects through the Czochralski process. The grain size of single crystal solar cells is around 15 cm. The Czochralski process is complex and expensive. Single crystal is a high-quality material, it constitutes efficient PV modules (up to 18%) and is stable in electric production. Its lifetime ranges between 20 and 30 years. It is used in aerospace shuttles and home power production [1].

Multi-crystalline (mc-Si) or polycrystalline (pc-Si) or microcrystalline ($\mu\text{c-Si}$) silicon solar cells are made of lower quality silicon feedstock via less expensive processes (Bridgman and block-casting). The multi-crystalline (1mm), polycrystalline (1 μm), and microcrystalline (<1 μm) grain size present defects or discontinuations that increase recombination. This limits multi-crystalline or polycrystalline PV panels efficiency (up to 15%). Their lifetime ranges between 20 and 30 years. They are mass produced and cover 50% of the market. They are used in home power production and in power plants.

Silicon ribbons solar cells are made via EFG (Edge-defined Film-fed Growth), STR (String Ribbon), SF (Silicon Film) ... which are characterized by low cost processes. The grain size and the optimum thickness of the cell vary with the manufacturing process.

2.2. Wafer silicon cells

A silicon crystal cell structure is optimized to reach the following objectives:

- Decrease of incident light reflection
- Increase of refracted light absorption
- Decrease of recombination
- Decrease of surface recombination
- Decrease of contact resistance

In figure 1, we can find the structure of a PERL (Passivated Emitter and Rear Locally diffused) Cell [1]. This model presents a typical optimization of a cell that responds to the cited objectives. A metallic grid of Silver, Titanium, and Palladium is mounted onto the cell. Its role is to collect electrons generated in the n-type material. The most negative side effects of the grid are partial shading and series resistance increase. If the width of the metallic grid is increased, we obtain a low series resistance but high partial shading. If the width of the metallic grid is decreased, we obtain a high series resistance but low partial shading. A trade off recommends that thin metal fingers are formed with a width of 15 μm [1].

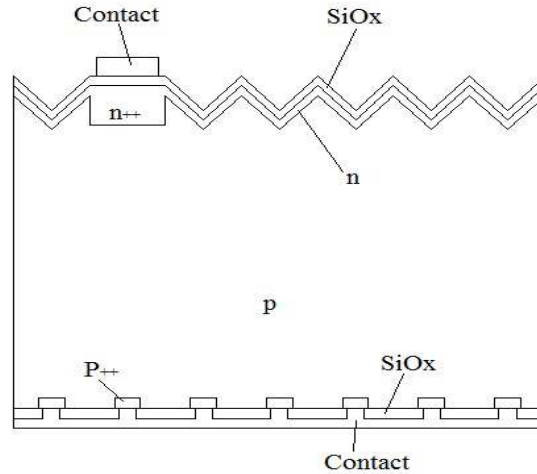


Figure 1 Scheme of a PERL.

The exposed surface of the cell is textured in the form of inverted pyramids allowing increase in the refraction of incident light. This mechanism is called light trapping. The effective length traversed by the refracted light is multiplied by a factor of:

$$4 \times \left(\frac{n_{si}}{n_{air}} \right)^2 \cong 50 \tag{1}$$

The side effect of texturing the surface is an increase of the SRV (Surface Recombination Velocity).

An ARC (Anti Reflective Coating) is added to the surface of the silicon substrate. Without the ARC, 30% of the incident light is reflected to the air because of the high refractive index of the silicon.

The thickness ω of the PV cell is calculated in a manner allowing collection of the generated carriers. In fact, when carriers are generated, they diffuse (pass through the silicon substrate) and then are collected or recombine. The most important recombination is called SRH (Shockley-Real-Hall), it occurs in silicon crystal defects. The diffusion length is defined by:

$$L = \sqrt{D\tau} \tag{2}$$

The thickness ω of a PV cell must be less than the diffusion length so that the carriers can be collected and do not recombine. At the same time, ω must be high to increase the generation of electron hole pairs. Optimum ω values ranges between 150 to 200 μm .

A BSF (Back Surface Field) is implemented to reduce SRV; a heavily doped p-type region is formed between the emitter and the back contact. Similarly, a heavily doped p-type region is formed under the metallic grid and a SiO_x layer covers non contact areas.

The back contact is made to collect generated holes. Silver is used as back contact by printing process.

Many structures of Si wafer based PV cells are developed; we have only presented the PERL in this paper.

2.3. Thin film Si cells

The main purpose of developing thin film (TF) cells remains in decreasing the total quantity of silicon used. Silicon being an indirect band gap semiconductor, a thick wafer (up to 700μm) is required to absorb the solar spectrum. Raw material used in TF cells may be less pure. At first look, the photocurrent generated by a TF cell will appear to be low. However, with technological enhancement, TF cell of 10μm thickness can reach 10% efficiency.

Efficient TF solar cells must complete the following requirements:

- Efficient photo-generation
- Efficient carrier collection
- Efficient mechanical support.

Reducing the thickness increases the surface recombination part in total recombination. To mitigate the SRV, surface fields are created and oxide isolator covers the illuminated areas. A superior light trapping technique is applied to TF cells. Both the illuminated surface and the back surface are textured. One side effect of surface texturing resides in the increase of total surface area that increases recombination. A trade off must be taken in consideration. Reflective metal constitutes the back contact to increase effective thickness, but some light is lost by metal absorption. A comparison between a 300μm wafer silicon cell and a 10μm silicon TF cell proves that light absorption is 3 times more important in TF cell.

A 10μm TF cell cannot self stand, TF are deposited over a substrate that acts as a mechanical support.

Additional enhancements of TF silicon cells can be noted. A back contact made of Aluminum can serve as an impurity-gettering material. Besides, a high grain to thickness ratio presents upper efficiency regarding V_{OC} and FF.

In summary, TF solar cells offer:

- A reduction in recombination allowing lower dark current, higher V_{OC}, and higher FF
- Low quality and low quantity of feedstock
- Low cost and low energy for fabrication
- Low cost module
- Low weight module
- Flexible solar cells

2.4. Amorphous silicon cells

a-Si:H (hydrogenated amorphous silicon) solar cells represent a simple and inexpensive type of solar cells. The properties of amorphous silicon are suitable for photo-generation. A thickness of only 500nm can reach 11% efficiency.

As they are less than $1\mu\text{m}$ thick, a-Si:H cells need a mechanical support. A superstrate or a substrate is used. A superstrate is a transparent plastic or glass layer. The light first propagates through the superstrate before reaching the cell. A substrate is a traditional back support of the cell made of stainless steel.

Amorphous silicon is made of unorganized lattice structure of silicon atoms. Hydrogen is added to the crystal. In this way, a percentage of silicon atoms make 3 covalent bounds with Si atoms and one bound with an H atom. When a-Si:H is heated, H atoms are detached leaving one unbounded electron. This is called a dangling bond. This is why the efficiency of amorphous silicon solar modules increases with temperature. a-Si:H solar modules lose 15% to 30% of their efficiency after 1000h of illumination. This is called the Staebler-Wronski Effect (SWE). In fact, the excessive light soaking increases the dangling bonds which increase the recombination rate. Light soaking also damages the PV panel material and the Si network [3].

The general architecture of a pin (p-intrinsic-n) amorphous silicon cell represents a thin p-layer, a relatively thick intrinsic layer, and at the bottom a thin n-layer. Sun light enters from the p-layer which is called the window layer. In amorphous silicon, doping is not efficient, the Fermi energy is not raised and each generated electron is collected by a dangling bond. This is why the p-layer is made with a high band gap to reduce its absorption coefficient and increase the built in voltage. Efficient photo-generation occurs in the intrinsic layer.

As all cells, a-Si:H cells are textured and a back reflector is used to increase the effective thickness of the cell.

a-Si:H cells absorb photons with energy $h\nu > 1.9\text{eV}$. It means that an a-Si:H solar cell can act as a low pass filter. Instead of wasting low frequency photons, a second a-Si:Ge PV cell is added. The obtained cell is called a multi-junction cell; we can also form an a-Si/a-SiGe/a-SiGe triple-junction cell. The key principle of multi-junction cells is the spectrum splitting. As each cell will absorb a portion of the solar spectrum, the intrinsic layer is thinner than that of single junction cell. A higher voltage is generated with a lower current; a lower voltage drop is then induced. The V_{OC} of the multi-junction cell is the sum of the V_{OC} of each cell. The current is limited by the cell generating the minimum current. The FF is limited by the cell having the smallest FF. To optimize multi-junction cells, the thickness of i-layers and the band gaps must be arranged. We can reach an ideal efficiency of 56% with triple-junction cells to be used under concentrated sun light [1].

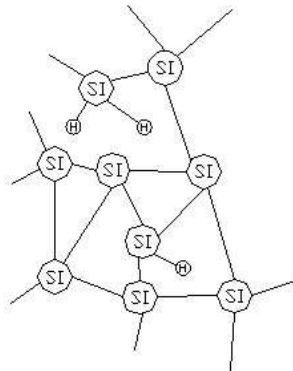


Figure 2 a-Si:H crystal.

a-Si:H based solar cells are used because of their low cost fabrication. They are light, flexible, and resistant to radiation. They are rather used for terrestrial applications and in warm regions because their

efficiency increases with temperature. Superstrate cells are integrated in buildings and substrate cells are made for flexible design.

3. Multi-junction GaInP/GaAs/Ge cells

When talking about multi-junction GaInP/GaAs/Ge cells (or III-V multi-junction cells) we mean high efficiency high cost solar cells. They are designed to work under concentrated sun (up to 2000 suns). Their efficiency can reach 34% [1].

III and V groups of semiconductor present an attraction for solar application. In fact, many of them are direct band gap semiconductor with a high absorption coefficient. Their energy gap ranges between 1 and 2 eV. In addition N and P doping is simple for III-V semiconductors. Se and Si are examples of n-type dopants. Zn, Mg, and C are examples of p-type dopants.

The key operation of multi-junction solar cells relies on spectrum splitting. The solar spectrum is divided into regions $[h\nu_i, h\nu_{i+1}]$ and each region is redirected to a dedicated subcell ($E_{gi}=h\nu_i$). Theoretically, increasing the number of subcells increases the overall efficiency of the cell [4]. To divide the spectrum and redirect the regions to their dedicated subcell, we must simply mount the subcells one onto the other respecting order of band gaps and illuminating first the subcell of the highest band gap. A subcell with a high band gap will act as a low pass filter; it will absorb only photons with high frequency. The next subcell (E_{gi}) will receive a spectrum with photons of maximum energy $h\nu_{i+1}$ and will absorb photons of the region $[h\nu_i, h\nu_{i+1}]$. Optimum efficiency of multi-junction solar cells relies on band gap matching of subcells.

Each subcell is now considered to act as an independent current source. However, when they are electrically connected in series, they must have the same polarity and the same generated photocurrent. In fact, the cell current will be limited by the smallest photocurrent of the stack. This requires subcells matching. The output voltage of the multi-junction cell is the sum of the voltage of each subcell. Optimum matching of multi-junction cells occurs when subcell have the same I_{mpp} . In this case, the maximum power output of the cell is the sum of all subcells maximum power ($I_{mppi} * V_{mppi}$). Top cell thickness affects current matching. In fact, varying the thickness of the top subcell affects the light transmission to the bottom subcell. And thus an optimum thickness is elaborated when top and bottom photocurrent matches.

In general, high efficiency multi-junction solar cells are used with concentrators because of their high cost. The efficiency of such cells increases when they are illuminated with 100 suns or 1000 suns. In reality, the photocurrent increases and according to the I-V characteristic, V_{OC} increases, thus giving a push to the cell efficiency. Lattice matching is also important when dealing with multi-junction solar cells.

Ge is used as substrate in multi-junction GaInP/GaAs/Ge cells. Its lattice constant is close to that of Ga/As, it is rigid, I_{SC} of Ge subcell is higher than that of the GaAs.

One last difficulty in multi-junction design is the interface between subcells called the TJIC (Tunnel-Junction Interconnect). As first approach, the polarity of a TJIC is opposite of that of the PN junction, which will reduce the V_{OC} . In reality, the TJIC is made of a tunnel junction or a narrow heavily doped P and N regions. A tunnel junction will act as a resistor for current values not exceeding the peak tunneling current.

In summary, III-V solar cells are expensive for one sun use. They are commonly used with concentrators and in spacecrafts [5]. They enjoy a high V_{OC} and a low I_{SC} , an excellent radiation resistance, and a small temperature coefficient. Their temperature may increase under concentrate sun which require intervention and control for cooling.

4. Cu(InGa)Se₂ cells

Cu(InGa)Se₂ solar cells power small equipments like calculators. Their fabrication is costly. Their surface is of the order of 0.5cm². They have a high radiation resistance, they are light, and can be made flexible. Their efficiency can reach 18.8%.

The Cu(InGa)Se₂ composition can vary in function of In and Ga concentration. This concentration affects the band gap of the p-type Cu(InGa)Se₂ material. The maximum efficiency is obtained with a band gap of 1.12eV. Cu(InGa)Se₂ is a direct band gap semiconductor with high absorption coefficient. Its grain boundaries do not increase the surface recombination.

A Cu(InGa)Se₂ solar cell is formed over a soda-lime glass. Then a molybdenum (Mo) layer is added acting as a back contact. The Cu(InGa)Se₂ layer is then deposited. The PN junction is formed by adding a thin layer of CdS. A heavily doped ZnO layer and an intrinsic layer of ZnO are deposited to the stack. At the end a metallic grid is added for collection [1].

The defects between p-type (Cu(InGa)Se₂) and n-type (CdS) lattice structures does not affect the behavior of the cell or reduce V_{OC}. The role of the ZnO layer is to minimize the defects of Cu in the PN junction interface [1]. The substrate (soda-lime glass) is suited to Cu(InGa)Se₂. In fact, the thermal expansion coefficients of the two materials are similar ($9 \times 10^{-6} K^{-1}$). After deposition, the temperature decreases of about 500oC. Soda-lime glass is also chemically suited for Cu(InGa)Se₂.

The absorption coefficient of Cu(InGa)Se₂ is high and the open circuit increases when the band gap is increased.

The device losses can be enumerated:

- Optical losses (Shading and reflection)
- Recombination losses
- Resistive losses
- Light absorption in ZnO and in CdS (electrons and holes in the CdS region are not collected)
- Incomplete absorption and collection in the Cu(InGa)Se₂ layer

Cu(InGa)Se₂ fabrication is delicate; Cd is carcinogenic. It is recommended, because of environmental and health concerns, that PV panels becomes Cd-free. When talking about materials availability, In is the least available material. This causes mandatory recycling of Cu(InGa)Se₂ modules [6].

5. CdTe cells

CdTe alloy is suited for solar spectrum. With a direct band gap (E_g=1.5eV) and a high absorption coefficient, CdTe can absorb 99% of photons ($h\nu \geq 1.5$) with a 2 μm of thickness. CdTe PV panels present only 10% efficiency and need pollutant materials as Cd. They are typically used for small appliances like calculators. CdTe cells can also be used in space power generation, infrared detection, gamma radiation detection, and thermal imaging.

Cd excess in CdTe provides n-type material and Te excess in CdTe provides p-type material. CdTe solar cells are made with substrate or superstrate structure. The superstrate structure is the most dominant. A TCO (Transparent Conductive Oxide) and a high resistance oxide layer are deposited. Then a thin layer of CdS is deposited acting as an n-region. Then the CdTe layer acts as a p-region. At the end a contact is made to collect the carriers [1].

The CdS layer is thin to permit photons to reach the CdTe layer and produce higher photocurrent. The back contact is made of two layers. The layer attached to CdTe is enriched with Te and Cu to form a heavy p-region. The second layer is a normal metal contact.

The poor efficiency of CdTe solar cells and their carcinogenic composing material Cd mark some disadvantage of this technology. However, CdTe present the best market price inducing low payback time. This emphasizes the interest they can give for enhancement of their life time by use of the new control and diagnosis technologies.

6. Dye-sensitized cells

Dye-sensitized solar cells (DSSC) are Photoelectrochemical cells. They are fundamentally an oxide semiconductor immersed in an electrolyte. Their efficiency can reach 10%. They have low cost fabrication and need low cost materials. They can be made transparent or colorful they can be used as window glass. They are not pollutant and easily recyclable.

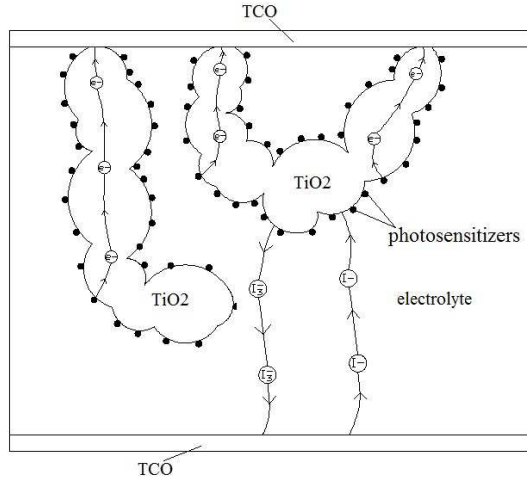
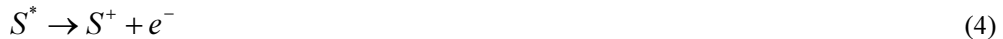


Figure 3 Structure of a DSSC.

Dye-sensitized solar cells are first encapsulated by two TCO layers that form the front and back contacts. SnO₂ is typically used as TCO. A thin film of TiO₂ is deposited near the front contact. The thickness is about 10 μm with nanoparticles of 10-30 nm. This structure yields a high porosity and a high effective surface compared to the apparent surface. The TiO₂ film will be immersed in an electrolyte containing I⁻ and I₃⁻ ions. Complex structures of photosensitizers will be attached on the large surface of the TiO₂. The stack must be sealed to prevent leakage and evaporation.

Photosensitizers at their ground state (S) will absorb light and become in the excited state (S^{*}). Then they will release an electron in the TiO₂ electrode [1].



The electrons will be transported via the TiO₂ to the front contact. They will pass through the load and reach the back contact. I₃⁻ will receive electrons at the back contact and generate I⁻. S⁺ will gain an electron from I⁻ to become in the ground state and generate I₃⁻.



No recombination is noted in DSSC. In fact, electrons are conducted by the TiO_2 crystal and no holes are formed in the valence band. But a recombination dark current is noted when I_3^- receives electrons at the level of TiO_2 . To reduce the dark current TBP (*tert*-butylpyridine) is used on the TiO_2 surface. Voltage is then increased but current is decreased.

Even their low cost fabrication and low cost raw materials, DSSC need some improvements to become commercialized like efficiency improvement, stability for outdoor use, and solid electrolyte. The latter discourage us in searching for increasing their life span.

7. Organic cells

Organic solar cells are formed with polymers. Polymers have conjugated systems. In conjugated systems, atoms bonds by alternating single and multiple bonds. π bonds and π^* bonds are formed. π bonds corresponds to the HOMO (Highest Occupied Molecular Orbital) and π^* bonds corresponds to LUMO (Lowest Unoccupied Molecular Orbital). The energy gap between the HOMO and the LUMO is defined to be the band gap. The band gap of organic cells is generally greater than 1.8eV.

Many architecture types of organic cells can be noted. The single layer photovoltaic cell or Pochettino cell is made of an organic layer sandwiched between two electrodes the LWFE (Large Work Function Electrode) and the SWFE (Small Work Function Electrode). The LWFE corresponds to the positive electrode it collects holes and the SWFE corresponds to the negative electrode it collects electrons. A schottky junction is formed near the SWFE where excitons are dissociated into electron and holes (figure 4). The second architecture type of an organic cell is the double layer donor/acceptor Heterojunction. A donor and an acceptor organic layers are mounted between two electrodes. A donor/acceptor interface is formed. Electrons and holes are more likely to be collected because they move in different layers. A third architecture type of organic cells is the bulk heterojunction organic cell. Acceptors and donors are randomly distributed in the bulk creating thus delocalized donor/acceptor interfaces.

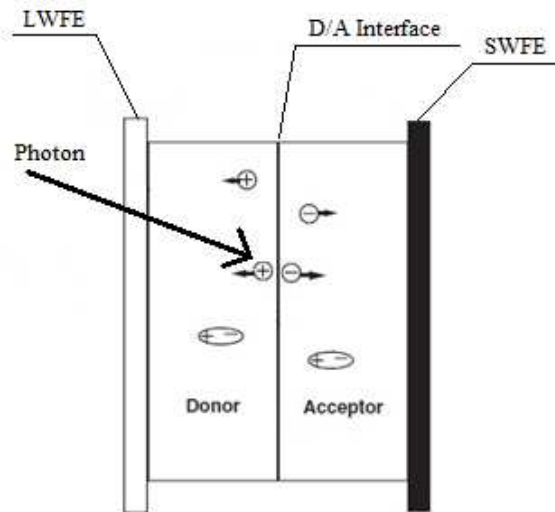


Figure 4. Organic bilayer cell

When a photon with energy equal to the energy of the band gap exits an organic polymer, an electron is transferred from the HOMO to the LUMO. Organic cells are made using thin films which decreases the amount of light absorption. After that the exciton is formed, it will diffuse to the donor/acceptor interface,

the average exciton diffusion length is between 5 and 50 nm. In order to increase the average exciton diffusion length, materials must be defect-free and a large donor/acceptor interface must be built. Once an exciton reaches the donor/acceptor interface, charge carriers (electrons and holes) will dissociate and will start diffusing to the corresponding electrode. The driving force of the charge carriers is generally due to the work function difference between the electrodes. At the end charge carriers will be collected. It is proposed for ideal contact resistance that the acceptor LUMO level matches the SWFE Fermi level and that the donor HOMO level matches the LWFE Fermi level.

Organic solar cells present many advantages: lightweight, flexible, low fabrication cost, integration in decoration, and continuous variation of band gap. They also present disadvantages: low efficiency, low durability, and low stability. The latter discourage us in searching for increasing their life span.

Conclusion

In this paper, we tried to summarize the existing types of PV panels. We talked about various semiconductors like Si, Ga, As, Cd, Te, Se, and Ge. We talked about various forms like wafers and thin films. We also discussed each type of PV panels: its efficiency, its operating principle, and its field of application. This survey summarized the existing technologies of PV cells. In order to point out their features and show which technology is the best suited to use ICT for life span extension by means of optimal control and good maintenance.

Si based solar cells present high efficiency and are the most studied. Multi-junction GaInP/GaAs/Ge solar cells present high efficiency but need cooling mechanism because they operate at concentrated suns. Cd based solar cells present low efficiency and contains carcinogenic and rare materials. Dye-sensitized and organic solar cells represent low cost and low efficiency solutions. Each technology attracts investors for the price of kWh produced. The price of the kWh is related to the lifetime of PV panels. Interested searches must focus on increasing the lifetime of PV panels used in high power generation and having high efficiency.

Our research project has as objective to increase the life span of PV panels via control. This survey helped us to decide which technology to focus on and try to apply a preventive control. Our future work will be based on the degradation modes of Si based solar cells. We will try to build a PV module model that degrades with time [7]. This will lead us to adequate use of ICT and new control technologies to keep the PV panel well managed (every time) and increase their life span.

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