Review of photovoltaic technologies

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ABSTRACT

This paper is a full review on the development of existing photovoltaic (PV) technology. It highlights the four major current types of PV: crystalline, thin film, compound and nanotechnology. The aim of continuous development of PV technology is not only to improve the efficiency of the cells but also to reduce production cost of the modules, hence make it more feasible for various applications. Moreover, such variety in technology is needed to enhance the deployment of solar energy for a greener and cleaner environment. Devices such as space PV cell technology were also described and the progress in this field is expanding. In addition, a quick overview of the application of PV installations is described.

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Contents

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Nomenclature

V	terminal voltage (V)
I_0	reverse current (A)
γ	shape factor (measure of cell imperfection and completion)
R_S	series resistance (Ω)
q	electron charge 1.602×10^{-19} (C)
k	Boltzman constant 1.38×10^{-23} (J/K)
T_c	absolute temperature (K)
D	diode diffusion factor
ε_G	material band gap energy (1.12 eV for Si, 1.35 eV for GaAs)
A	cross sectional (m^2)
N_S	cells in series
N_p	cells in parallel
I_{ph}	cell photocurrent proportional to insolation (A)
V_{oc}	open circuit voltage (V)
I_{sc}	short circuit current
V_{mp}	cell voltage at which cell power is maximum (V)
I_{mp}	cell vurent at which cell power is maximum (A)
W_p	peak" watts (W)
FF	fill factor
η	power conversion efficiency

1. Introduction

In ancient times, the sun was worshipped as a life-giver planet. Later, as education and the industrial age evolved, the knowledge of the sun as energy source was understood. The importance of such a discovery reached its peak in the current era, where the extraction of fossil fuel for energy production has been proven to affect the planet's ambient temperature. Each day the sun provides 10,000 times the energy needed on the planet. Water, bio-energy, or wind powers were all sources used in early human societies and they are in one way or another derived from solar power. Technologies which can harness the powers of the sun continued to improve right up to the early years of the industrial revolution. Since that time, as communities developed activities, greenhouse gases in particular carbon dioxide (CO2) emissions increases, causing global warming, a factor of which is temperature rise of 0.6 °C (Fig. 1) [1]. Future predictions indicate that the surface temperature could increase to between 1.4 °C and 5.8 °C if action is not taken. Such developments will probably cause droughts, floods, sea level rise, glacier melting, and serious disruptions to agriculture and natural ecosystems hence, the mounting consensus on the need to reduce such emissions. This needed reduction of emissions can be achieved by switching many traditional energy applications to renewable energy technologies (Fig. 1).

Renewable energy sources can be defined as "energy obtained from the continuous or repetitive currents on energy recurring in the natural environment" [2] or as "energy flows which are replenished at the same rate as they are used" [3]. All the earth's renewable energy sources are generated from solar radiation, which can be converted directly or indirectly to energy using various technologies (Fig. 2). This radiation is perceived as white light since it spans over a wide spectrum of wavelengths, from the short-wave infrared to ultraviolet. Such radiation plays a major role in generating electricity either producing high temperature heat to power an engine mechanical energy which in turn drives an electrical generator or by directly converting it to electricity by means of the photovoltaic (PV) effect. It is well known that PV is the simplest technology to design and install, however it is still one of the most expensive renewable technologies. But its advantage will always lie in the fact
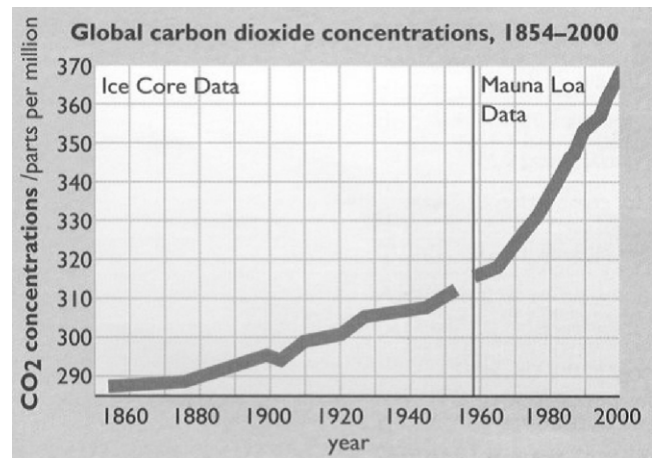

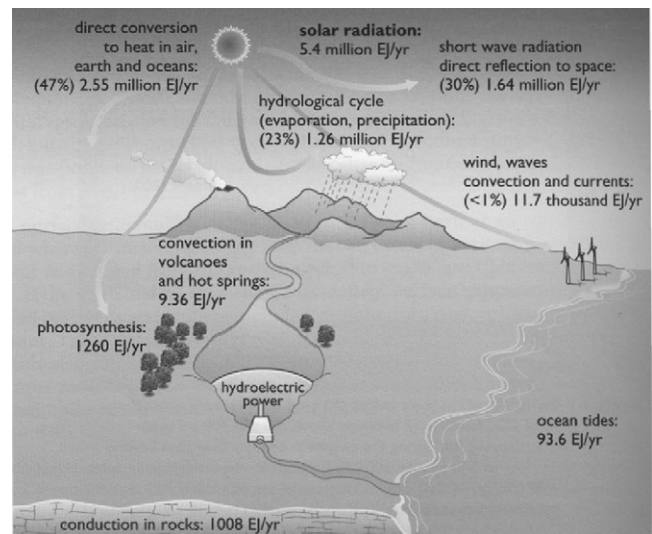Fig. 1. Atmospheric concentrations of CO_2 [1].

Fig. 2. Various forms of renewable energy depend primarily on incoming solar radiation [4].

it is environmentally friendly and a non-pollutant low maintenance energy source. This paper will briefly describe the principles and history of photovoltaic energy systems and will explore in details the various available technologies while reflecting on the advancement of each technology and its advantages and disadvantages.

2. Brief history

PV history starts in 1839, when Alexandre-Edmund Becquerel (physicist) observed that "electrical currents arose from certain light induced chemical reactions" [5] and similar effects were observed by other scientists in a solid (selenium) several decades later. But it was not till the late 1940s when the development of the first solid state devices paved the way in the industry for the first silicon solar cell to be developed with an efficiency of 6% [5].

Table 1 describes dates of relevance to PV solar energy technology development. The development of the first silicon solar cell was fundamental in the initiation of solar technologies as it represented the power conversion unit of a PV system but with practical implications. These Si cells are not used separately rather they are assembled into modules. Presently, various types of solar cells on industrially available, however, the strive for research and development is continuing to expand and improve this energy collector.

Table 1
Dates of relevance to photovoltaic solar energy conversion.

| Scientist and innovation	Year
Becquerel discovers the photovoltaic effect	1839
Adams and Day notice photovoltaic effect in selenium	1876
Planck claims the quantum nature of light	1900
Wilson proposes Quantum theory of solids	1930
Mott and Schottky develop the theory of solid-state rectifier (diode)	1940
Bardeen, Brattain and Shockley invent the transistor	1949
Charpin, Fuller and Pearson announce 6% efficient silicon solar cell	1954
Reynolds et al. highlight solar cell based on cadmium sulphide	1954
First use of solar cells on an orbiting satellite Vanguard 1	1958
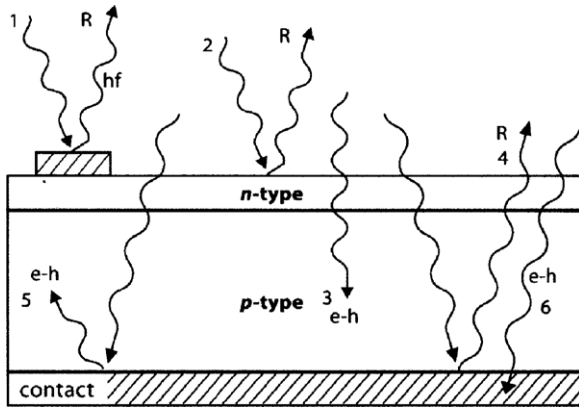
Fig. 3. Behavior of light shining on a solar cell: (3.1) Reflection and absorption at top contact. (3.2) Reflection at cell surface. (3.3) Desired absorption. (3.4) Reflection from rear out of cell. (3.5) Absorption after reflection. (3.6) Absorption in rear contact [6].

The growth of such technology depends on materials and structure development; however the goal will always be maximum power at minimum cost. In any structure, solar cells, which are connected in series and in parallel in order to form the desired voltage and current levels, remain the basic semiconductor components of a PV panel. To maximize the power rating of a solar cell which ensures the highest efficiency, hence designed to raise the desired absorption (Fig. 3.3) and absorption after reflection (Fig. 3.5). The primary solar cell equivalent circuit (Fig. 4) is modeled as a current source with a parallel diode. Shockley equation provides the diode current:

$$I_D = I_0 \left[\exp \left(\frac{q(V + IR_S)}{\gamma k T_c} \right) - 1 \right] \tag{1}$$

The reverse saturation current is

$$I_0 = D T_c^3 \exp \frac{q \varepsilon_G}{A k T_c} \tag{2}$$

To achieve the desired voltage and current levels, solar cells are connected in series and parallel combinations hence the $I_g - V_g$ equation of the solar cell generator is given by:

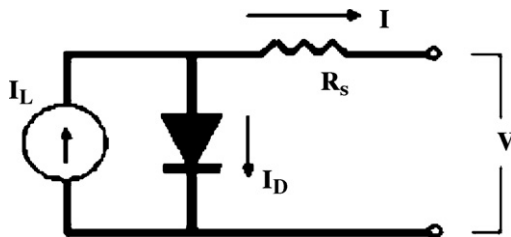$$V_g = I_g R_S \frac{N_s}{N_p} \ln \left(1 + \frac{N_p I_{ph} - I_g}{N_p I_0} \right) \tag{3}$$

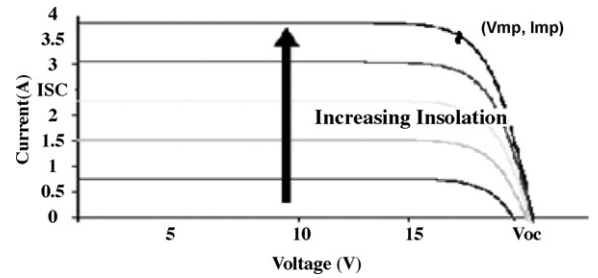**Fig. 4.** Equivalent solar cell electrical model.

Fig. 5. $I_g - V_g$ characteristics at varied solar intensities.

$$I_g = I_{ph} - I_0 \exp \left(\frac{q V_g}{kT} - 1 \right) \tag{4}$$

The PV cell has two limiting components (Fig. 5): V_{oc} and I_{sc}. To determine the short circuit current, set $V_g = 0$ and $I_{sc} = I_{ph}$ (4) and this value changes proportionally to the cell irradiance. To determine the open circuit voltage, the cell current $I_g = 0$ hence (3) leads to

$$V_{oc} = \frac{kT}{q} \ln \left[\frac{I_{ph}}{I_0} \right] \tag{5}$$

The PV module can also be characterized by the maximum power point when the product ($V_{mp} \times I_{mp}$) is at its maximum value. The maximum power output is derived by

$$\frac{d(V_g \times I_g)}{dt} = 0 \tag{6}$$

and

$$V_{mp} = V_{oc} - \frac{kT}{q} \ln \left[\frac{V_{mp}}{kt/q} + 1 \right] \tag{7}$$

A PV module is normally rated under its W_p which is normally 1 kW/m^2 under standard test condition (STC). The product ($V_{mp} \times I_{mp}$) is related to the product generated by ($V_{oc} \times I_{sc}$) by a FF which is a measure of the junction quality and series resistance and it is given by:

$$FF = \frac{V_{mp} \times I_{mp}}{V_{oc} \times I_{sc}} \tag{8}$$

and the closer the FF is to unity the higher the quality of the PV module.

Finally the last and most important factor of merit for a PV module is its η, defined as

$$\eta = \frac{FF \times V_{oc} \times I_{sc}}{P_{in}} \tag{9}$$

where P_{in} represents the incident power depending on the light spectrum incident upon the PV cell.

Global warming issues and reduction of green house gases emission are becoming a major concern worldwide. In addition the aim of current energy policies is to decrease the consumption of primary sources (related to fossil fuels) while keeping up with the energy demand. Renewable energy sources in general and solar PV in particular, are expanding rapidly.

All technologies related to capturing solar energy for a direct electricity generator are described as photovoltaic. However this technology is subdivided into crystalline, thin film, compound semiconductor and nanotechnology.

3. Silicon crystalline structure

The first generation of PV technologies is made of crystalline structure which uses silicon (Si) to produce the solar cells that are combined to make PV modules. However, this technology is

not obsolete rather it is constantly being developed to improve its capability and efficiency. Mono-crystalline, poly-crystalline, and emitter wrap through (EWT) are cells under the umbrella of silicon crystalline structures and are discussed in the following sections.

3.1. Mono-crystalline photovoltaic cells/panels

This type of cell is the most commonly used, constitutes about 80% of the market and will continue to the leader until a more efficient and cost effective PV technology is developed. It essentially uses crystalline Si p–n junctions. To manufacture monocrystalline silicon, a single crystal ingot, is cultivated using the Czochralski method [7]. Due to the silicon material, currently attempts to enhance the efficiency are limited by the amount of energy produced by the photons since it decreases at higher wavelengths. Moreover, radiation with longer wavelengths leads to thermal dissipation and essentially causes the cell to heat up hence reducing its efficiency. The maximum efficiency of mono-crystalline silicon solar cell has reached around 23% under STC, but the highest recorded was 24.7% (under STC). Due to combination of solar cell resistance, solar radiation reflection and metal contacts available on the top side, self losses are generated. After Si ingot is manufactured to a diameter between 10 to 15 cm, it is then cut in wafers of 0.3 mm thick to form a solar cell of approximately 35 mA of current per cm^2 area with a voltage of 0.55 V at full illumination. For some other semi-conductor materials with different wavelengths, it can reach 30% (under STC). However module efficiencies always tend to be lower than the actual cell and Sunpower [8] recently announced a 20.4% full panel efficiency which is a record efficiency as determined by measurements done by National Renewable Energy Laboratory (NREL) [9]. This panel is expected to have better life, and its price is well compatible with other existing sources. Solar silicon processing technology has many points in common with the microelectronics industry, and the benefits of the huge improvements in Si wafer processing technologies used in microelectronic applications are to improve the performance of laboratory cells, hence made this technology most favorable.

3.2. Poly-crystalline photovoltaic cells/panels

The efforts of the photovoltaic industry to reduce costs and increase production throughput have led to the development of new crystallization techniques. Initially, poly-crystalline was the dominant solar industry while the cost of Si was $340/kg. However, even with a silicon price reduction to $50/kg, such technology is becoming more attractive because manufacturing cost is lower even though these cells are slightly less efficient (15%) than mono-crystalline. The advantage of converting the production of crystalline solar cells from mono-silicon to multi-silicon is to decrease the flaws in metal contamination and crystal structure [10]. Poly-crystalline cell manufacturing is initiated by melting silicon and solidifying it to orient crystals in a fixed direction producing rectangular ingot of multi-crystalline silicon to be sliced into blocks and finally into thin wafers. However, this final step can be abolished by cultivating wafer thin ribbons of poly-crystalline silicon. This technology was developed by Evergreen Solar uses [11].

3.3. Emitter wrap-though cells

Emitter wrap-through cells (Fig. 6) have allowed an increase in efficiency through better cell design rather than material improvements in this technology, small laser drilled holes are used to connect the rear n-type contact with the opposite side emitter. The removal of front contacts allows the full surface area of the cell to absorb solar radiation because masking by the metal lines is no longer present. Several tests [12] showed that there are man-
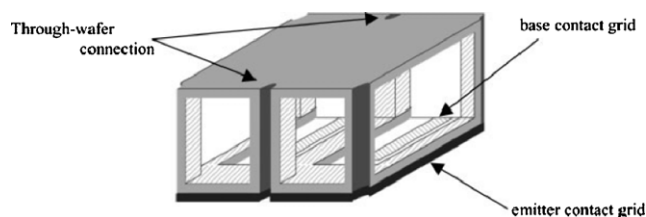

Fig. 6. Schematic representation of an emitter wrap-through solar cell [12].

ufacturing gains by putting the contacts on the backs of the cell. Examples of companies using EWT technology are Advent Solar [13] and Sunpower Corp. [8] in the US. Using EWT has allowed a 15–20% increase in efficiency. One major disadvantage of such a technology is evident on large area EWT cells where this technology suffers from high series resistance which limits the fill factor.

3.4. Silicon crystalline investment

Photovoltaic systems have large initial capital costs but small recurrent costs for operation and maintenance. The price of delivered energy varies inversely as the lifetime of the system. The above described silicon based technology modules exhibit lifetimes of 20–30 years. In most systems unless there are extremely aggressive government incentives the payback periods remain long. For that reason, several groups have been researching ways of lowering the initial capital investment, therefore shortening payback periods and as a result making photovoltaics a viable technology that can stand on its own without heavy government subsidies. The need to reduce the manufacturing, and therefore module cost, is the main reason behind the move toward thin film solar cells. The ultimate goal being the achievement of "grid parity", which would make the cost of the kW h delivered by PV technologies on par with the kW h delivered by traditional means. A goal that remains elusive to this day, although improvements in the technologies have allowed in impressive drop in the cost per watt.

4. Thin film technology

In comparison with crystalline silicon cells, thin film technology holds the promise of reducing the cost of PV array by lowering material and manufacturing without jeopardizing the cells' lifetime as well as any hazard to the environment.

Unlike crystalline forms of solar cells, where pieces of semiconductors are sandwiched between glass panels to create the modules, thin film panels are created by depositing thin layers of certain materials on glass or stainless steel (SS) substrates, using sputtering tools. The advantage of this methodology lies in the fact that the thickness of the deposited layers which are barely a few micron (smaller than 10 μm) thick compared to crystalline wafers which tend to be several hundred micron thick, in addition to the possible films deposited on SS sheets which allows the creation of flexible PV modules. The resulting advantage is a lowering in manufacturing cost due to the high throughput deposition process as well as the lower cost of materials. Technically, the fact that the layers are much thinner, results in less photovoltaic material to absorb incoming solar radiation, hence the efficiencies of thin film solar modules are lower than crystalline, although the ability to deposit many different materials and alloys has allowed tremendous improvement in efficiencies. Furthermore, the versatility and temperature robustness of thin film PV modules resulted in a large gain in market share from non-existing to about 15–20% as shown in the graph below (Fig. 7).

Four kinds of thin film cells have emerged as commercially important: the amorphous silicon cell (multiple-junction struc-
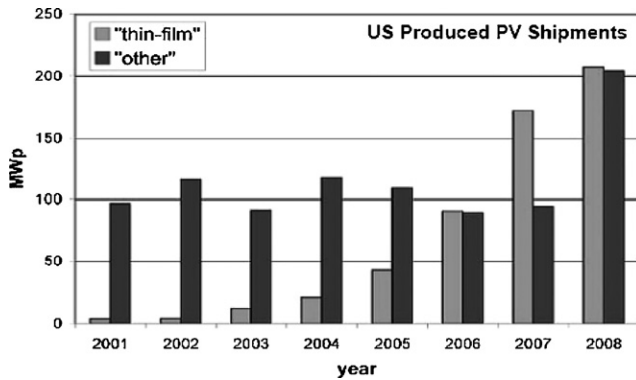
Fig. 7. US produced Modules through 2007, counting First Solar, Uni-Solar and Global Solar as "thin Film" PV and the rest as "other." Projections for 2008 use 2/3 of PV News reported end of 2008 capacity figures [14].

ture), thin poly-crystalline silicon on a low cost substrate, the copper indium diselenide/cadmium sulphide hetero-junction cell, and the cadmium telluride/cadmium sulphide hetero-junction cell.

4.1. Amorphous silicon

Amorphous silicon (a-Si) is one of the earliest thin film technologies developed [15]. This technology diverges from crystalline silicon in the fact that silicon atoms are randomly located from each other [16]. This randomness in the atomic structure has a major effect on the electronic properties of the material causing a higher band-gap (1.7 eV) than crystalline silicon (1.1 eV). The larger band-gap allows a-Si cells to absorb the visible part of the solar spectrum more strongly than the infrared portion of the spectrum. There are several variations in this technology where substrates can be glass or flexible SS, tandem junction, double and triple junctions, and each one has a different performance.

4.1.1. Amorphous-Si, double or triple junctions

Since a-Si cells have lower efficiency than the mono- and poly-crystalline silicon counterparts. With the maximum efficiency achieved in laboratory currently at approximately 12%, single junction a-Si modules degrades after being exposed to sunlight and stabilizing at around 4–8%. This reduction is due to the Staebler–Wronski effect which causes the changes in the properties of hydrogenated amorphous Si [17]. To improve the efficiency and solve the degradation problems, approaches such as developing multiple-junction a-Si devices have been attempted and are shown in the graph (Fig. 8) [18]. This improvement is linked to the design structure of such cells where different wavelengths from solar irradiation (from short to long wavelength) are captured. The STC rated efficiencies of such technologies are around 6–7%.
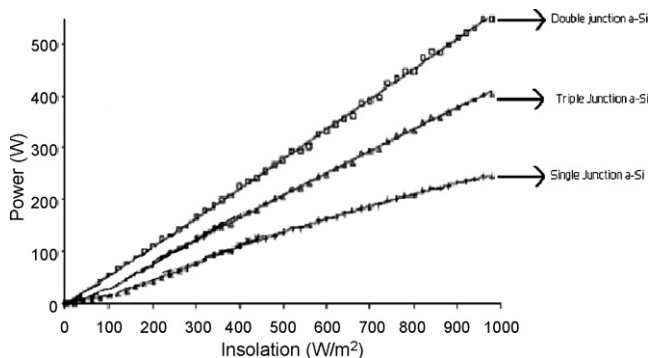

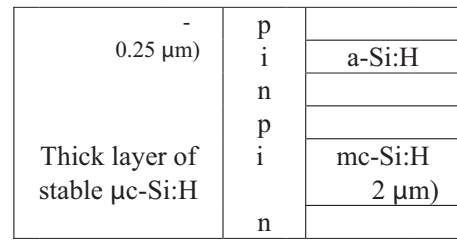Fig. 8. Variation of output with insolation for representative sub-arrays.

Fig. 9. Schematic of the cross section of a multiple crystalline junction thin film.

4.1.2. Tandem amorphous-Si and multi-crystalline-Si

Another method to enhance the efficiency of PV cells and modules is the "stacked" or multi-crystalline (mc) junctions (Fig. 9), also called micromorph thin film [19]. In this approach two or more PV junctions are layered one on top of the other where the top layer is constructed of an ultra thin layer of a-Si which converts the shorter wavelengths of the visible solar spectrum. However, at longer wavelength, microcrystalline silicon is most effective in addition to some of the infrared range. This results in higher efficiencies than amorphous Si cells of about 8–9% depending on the cell structure and layer thicknesses. There has been a great push to move thin film Si solar panels in this direction and two deposition companies in particular provide the tools for such process: Oerlikon [20] and Applied Materials (AMAT) [21]. AMAT have developed tools that can produce thin film a-Si and micromorph panels of up to 5.5 m^2 (Fig. 10).

4.2. Cadmium telluride or cadmium sulphide/cadmium telluride

Cadmium telluride (CdTe) has long been known to have the ideal band-gap (1.45 eV) with a high direct absorption coefficient for a solar absorber material and recognized as a promising photovoltaic material for thin-film solar cells. Small-area CdTe cells with efficiencies of greater than 15% [22] and CdTe modules with efficiencies of greater than 9% [23] have been demonstrated. CdTe, unlike the other thin film technology, is easier to deposit and more apt for large-scale production (40 MW plant – Ohio (USA), 10 MW – Germany, 5 MW – Abu Dhabi (UAE), in addition to its hetero-junction potential, as illustrated by First Solar [24] and Antec Solar [25]. The toxicity of cadmium (Cd) and the related environmental issues remain somewhat of a problem for this technology, which is why First Solar has introduced a recycling program for decommissioned PVs. First Solar has made this technology extremely popular in the thin film domain because of the efficiency of their manufacturing process, and has the capability to reduce the cost of manufacturing to make this technology extremely cost competitive. The other potential issue is the availability of Te which might cause some raw material constraints that will then affect the cost of the modules.

4.3. Copper indium diselenide or copper indium gallium diselenide

Copper indium diselenide (CuInSe2) or copper indium selenide (CIS) as it is sometimes known, are photovoltaic devices that con-
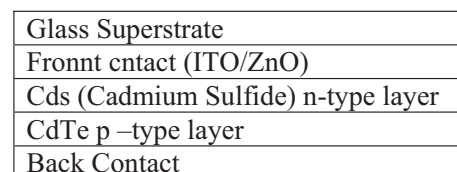
Glass Superstrate
Fronnt cntact (ITO/ZnO)
Cds (Cadmium Sulfide) n-type layer
CdTe p –type layer
Back Contact

Fig. 10. Typical cross section of a CdS/CdTe cell.

| ZnO transparent oxide |
| Cds buffer layer (or Indium Sulfide (InS) |
| CIGS (absorber) |
| Mo contact layer |
| Glass |

Fig. 11. Cross section for copper indium gallium di-selenide.

tain semiconductor elements from groups I, III and VI in the periodic table which is beneficial due to their high optical absorption coefficients and electrical characteristics enabling device tuning. Moreover, better uniformity is achieved through the usage of selenide, hence the number of recombination sites in the film is diminished benefiting quantum efficiency and hence the conversion efficiency. CIGS (indium incorporated with gallium - increased band gap) are multi-layered thin-film composites. Unlike basic p–n junction silicon cell, these cells are explained by a multifaced hetero-junction model. The best efficiency of a thin-film solar cell is 20% with CIGS [26] and about 13% for large area modules [27]. The biggest challenge for CIGS modules has been the limited ability to scale up the process for high throughput, high yield and low cost. Several deposition methods are used: sputtering, "ink" printing and electroplating [28,29] with each having different throughput and efficiencies. Both glass of stainless steel substrates are used, obviously the stainless steel substrates yield flexible solar cells. The biggest worry of this technology is indium shortage. Indium is heavily used in indium tin oxide (ITO), a transparent oxide that is used for flat screen displays such as TVs, computer screens and many others. Nanosolar as seen in reference [30], dissipates only 5% of indium in its manufacturing process compared to the 60% lost in DayStar's vacuum sputtering technology [31]. Recycling from decommissioned PV modules of indium is easily achieved as can be seen in a program that is currently undertaken in Germany supporting not only recycling but industrial regenerative strategies. A typical cross section for a CIGS cell is shown in Fig. 11.

Both CdTe and CIGS modules show degradation in high heat/damp conditions and need additional barrier coatings to protect them from such degradation. Particularly damp heat stress will cause degradation in the junction transport properties and minority carrier transport characteristics of the cell absorber [32].

Generally most of the research now is going into deposition processes that can make this technology more cost effective from a commercial point of view in order to compete with Si based modules [33].

5. Compound semiconductor

The result is a complicated stack of crystalline layers with different band gaps that are tailored to absorb most of the solar radiation. Also compound semiconductor cells have been shown to be more robust when expose to outer space radiation.

Since each type of semiconductor has a different characteristic band gap energy which then allows the absorption of light most efficiently, at a certain wavelength, hence absorption of electromagnetic radiation over a portion of the spectrum. These hetero-junction devices layer various cells with different bandgaps which are tuned utilizing the full spectrum. Initially, light strikes a wide band-gap layer producing a high voltage therefore using high energy photons efficiently enabling lower energy photons transfer to narrow band-gap sub-devices which absorb the transmitted infrared photons. Gallium arsenide (GaAs)/indium gallium phosphide (InGaP) multi-junction devices (Fig. 12) have reached the highest efficiency of 39% with NREL recently announc-
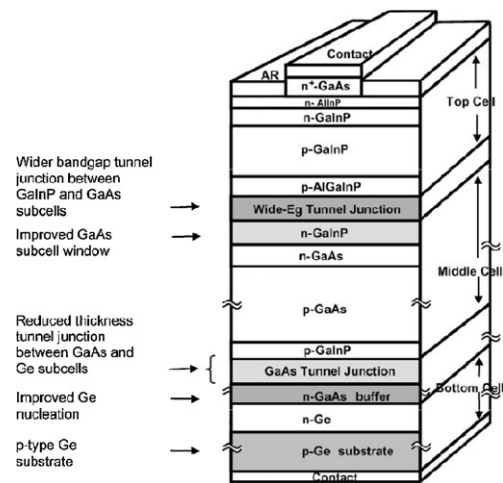

Fig. 12. Epitaxial stacks of multi-junction solar cells [34].

ing a record 40.8% from a metamorphic triple-junction solar cell. Originally these cells were fabricated on GaAs substrates however, in order to reduce the cost and increase robustness and because it is reasonably lattice-matched to GaAs, germanium (Ge) substrates are being used more often. The first cells had a single junction much like the Si p–n junction solar cells, however because of the ability to introduce ternary and quaternary materials such as InGaP and aluminum indium gallium phosphide (AlInGaP) dual and triple junction devices (Fig. 13) were grown in order to capture a larger band of the solar spectrum therefore increasing the efficiency of the cells [35,36].

5.1. Space PV cells

Photovoltaic solar generators have been proven to be the optimal option for providing electrical power to satellites. In 1958, US satellite Vanguard 1 demonstrated the first application [37]. After years of moderate growth of the space PV market, the evolution of large scale applications has increased in the late nineties, where the main applications are dominated by the telecommunication
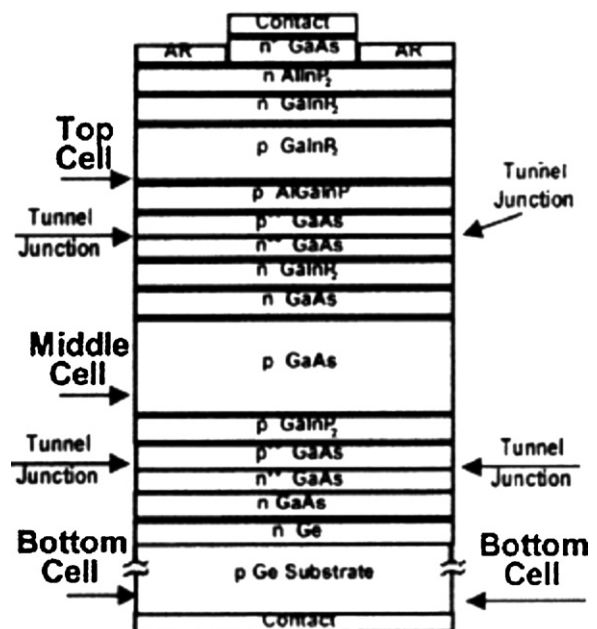

Fig. 13. Schematic cross section of the Spectrolab triple junction cell [34].

satellites, military satellites, and scientific space probes. Solar cells which are designed for space must ensure that their specifications include apriority space environment condition such as spectral illumination and air mass. Issues of concern with terrestrial PV are their high cost while in space, weight, flexibility, efficiency, temperature, and suitable materials [38]. In the 1950s, Si cells were p–n containing base layers of single crystal N–Si with boron diffused P-emitters with an efficiency around 6%. In the 1960s, efficiency was improved to 12% and CdS was investigated because of its flexibility and lightweight, but, its low efficiency and instability left it unfavorable. In the 1970s, although advances in Si growth by float-zoning (Fz) were promising solutions, space cells made from this material suffered additional degradation after radiation exposure. However, Si growth by Czocharaski (Cz) was used extensively in space. Despite all competitive approaches, Si remains the leader in PV technology for space. In the 1980s similar technologies to the seventies were used in addition to the deployment in special air force missions indium phosphate (InP) cells which efficiency reached 18% with high radiation tolerance. In the 1990s, although the high manufacturing cost, GaAs/Ge cells showed significant improvements including reduced area and weight, greater efficiency, and smaller stowage volume per launch. In addition, multi-junction cells have shown great promises with efficiencies reaching almost 30%. Recently, researchers from National Aeronautics and Space Administration (NASA) Glenn Research Center and the Rochester Institute of Technology (RIT) have presented their work on improving space PV cells using QDs and single walled carbon nanotubes [39–42]. The theoretical studies showed high promises in efficiency boosting using 3D arrays of zero dimensional conductors in an ordinary p–i–n solar structure. Moreover, thin film cells when incorporated with nanoparticles polymers showed greater efficiency [39,43].

Due to the expense of the substrate and the growth process, the cost of these cells is extremely high compared to Si cells. For space applications the expense has been acceptable, however for terrestrial/commercial application methods had to be developed to make the cost adequate, and the most successful method of reducing the cost has been to use concentration. Essentially the solar cell wafers are dices into small cells (sometimes as small as 2 mm × 2 mm) and then a large lens is placed above the cell in order to concentrate the solar radiation on the small cell. The cell is placed at the focal length of the lens and the solar radiation incident on the lens will get focused on the PV cell. Effectively the cell is exposed to several times the "normal" radiation which is then quantified by using the terms "100 suns" or "300 suns" which concentrates the sun's radiation 100 and 300 times respectively. The technology is called concentrating PV or CPV. Of course with concentration comes the need for tracking as the lens that is concentrating the sun's radiation needs to track the sun to make sure the radiation is then focused on the cell. The concentrating method has used lenses or mirrors, or a combination of both. The mirrors are curved such that the PV cell is placed at the center of the curvature and the solar radiation is concentrated on the cell.

Several CPV plants have been built over the past 2 years and initial tests are promising, however there are still kinks to be resolved. Examples of companies that are working in CPV are: Solfocus (US) [35], Green and Gold Energy (AUS) [36], Solar Systems (AUS) [44], Concentrix Solar (Germany) [45], Spectrolab [46] and Emcore (US) [47] and many more are emerging. The promise of CPV is huge since the cell efficiency is more than double the one for Si PV. Concentrators have been used on Si PV as well however its main traction is in compound semiconductor based cells. The inclusion of quantum wells or quantum dots [48] in the active layers of solar cells can further improve the efficiency of the cells. Finally these cells use a lot of indium as seen in the epitaxial layers (Figs. 12 and 13) and therefore just like CIGS can be affected by the price/availability of indium metal and precursors in the market.

5.2. Light absorbing dyes

Generally these types of cells consist of a semiconductor, such as silicon, and an electrolytic liquid, which is a conducting solution commonly formed by dissolving a salt in a solvent liquid, such as water. The semiconductor and electrolyte work in tandem to split the closely bound electron–hole pairs produced when sunlight hits the cell. The source of the photo-induced charge carriers is a photosensitive dye that gives the solar cells their name: "dye-sensitized" (most common dye is iodide). In addition, a nanomaterial, most commonly titanium dioxide (TiO_2) is also often used to hold the dye molecules in place like a scaffold (Fig. 14). Using dye sensitized cells for photovoltaic application goes back several decades as scientists were trying to emulate chlorophyll action in plants. The biggest breakthrough occurred in 1991 with the development of a light absorbing dye by Gratzel and O'Regan using nanoparticle TiO_2 sensitized by a more efficient and stable ruthenium (Ru) (11)-complex dye [50].

While the highest efficiency dye-sensitized solar cell ever made is 11%, this technology contains volatile solvents in their electrolytes that can permeate across plastic (i.e. organic compounds) and also present problems for sealing the cells. Cells that contain these solvents are therefore unattractive for outdoor use due to potential environmental hazards. Researchers have developed solar cells that use solvent-free electrolytes, but the cell efficiencies are too low.
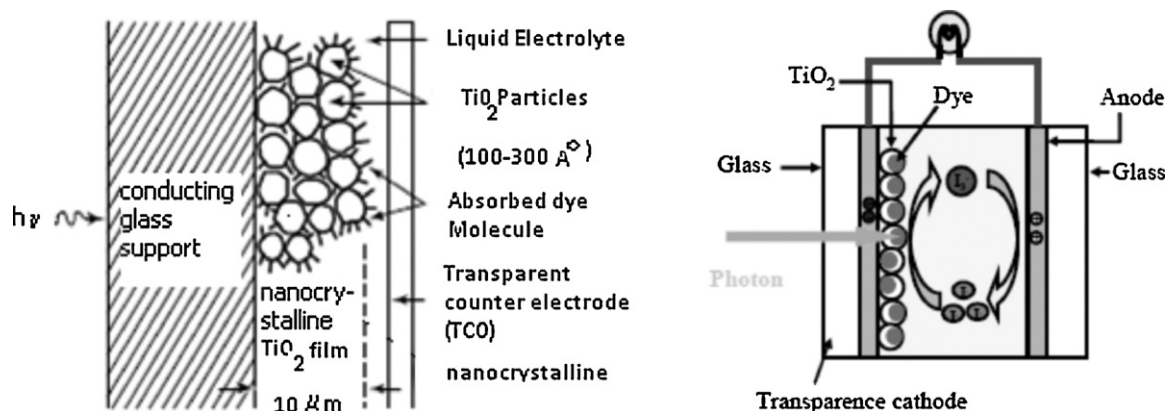

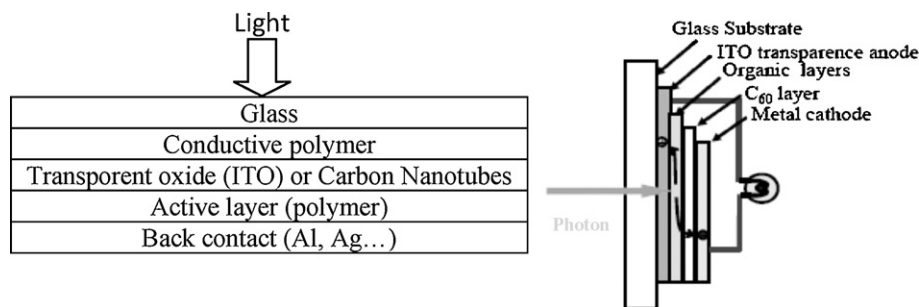**Fig. 14.** Cross section of dye-sensitized solar cell [49].

Fig. 15. Organic solar cell [52].

Lower processing costs along with flexibility of material and type usage achieved by screen printing are the characteristics of dye-sensitized solar cell which depends on a mesoporous layer of nanoparticulate TiO$_2$ to magnify the surface area (200–300 m^2/g TiO$_2$, as compared to approximately 10 m^2/g of flat single crystal). However, heat, ultra-violet (UV) light, and the interaction of solvents within the encapsulation of the cell are negative issues with this technology. Despite all the drawbacks and because of the promise of a low cost potential for cells and incorporation in paints among other things, this technology's future must be observed. Most of the current work is on the development of more efficient light absorbing dyes and on the improvement of the reliability, as well as the elimination of solvents from the electrolytes while maintaining a reasonable efficiency. The efficiencies tend to be between 5 and 10% on a cell level.

5.3. Organic

Organic solar cells and polymer solar cells are built from thin films (typically 100 nm) of organic semiconductors such as polymers and small-molecule compounds like pentacene, polyphenylene vinylene, copper phthalocyanine (a blue or green organic pigment) and carbon fullerenes. 4–5% is the highest efficiency currently achieved using conductive polymers, however, the interest in this material lies with its mechanical flexibility and disposability. Since they are largely made from plastic opposed to traditional silicon, the manufacturing process is cost effective (lower-cost material, high throughput manufacturing) with limited technical challenges (not require high-temperature or high-vacuum conditions). Electron (donor-acceptor) pair forms the basis of organic cell operation where light agitates the donor causing the electron to transfer to the acceptor molecule, hence leaving a hole for the cycle to continue. The photo-generated charges are then transported and collated at the opposite electrodes to be utilized, before they recombine.

Typically the cell has a glass front, a transparent indium tin oxide (ITO) contact layer, a conducting polymer, a photoactive polymer and finally the back contact layer (Al, Ag, etc.). Since ITO is expensive several groups have looked into using carbon nanotube films as the transparent contact layer [51]. A typical cross section of an organic solar cell is shown in Fig. 15.

"The year 2007 has been a turning point for PV thin film technology at least for US-based PV manufacturing with US thin film shipments reaching a market share of about 65%" [53]. However, the search for better efficiency and lower cost has never stopped. Nanotechnology seems to support sustainable economic growth by offering low cost but low efficiency PV which although not ideal offers consumers other alternatives.

6. Nanotechnology for PV cell production

Limitations seen in other PV technologies are lessened by the introduction of nanoscale components due to their ability to control the energy band-gap will provide flexibility and inter-changeability [54] in addition to enhancing the probability of charge recombination. "According to the "Roadmap Report Concerning the use of nanomaterials in the Energy sector from the 6th Framework Program [55,56], the most promising application fields for the energy conversion domain will be mainly focused on solar energy (mostly PV)". Hence to improve the conversion efficiency, structures from nanotechnology products that absorb more sunlight are emphasized: devices such as nanotubes, quantum dots (QDs), and "hot carrier" solar cells.

6.1. Carbon nanotubes

Carbon nanotubes (CNT) are constructed of a hexagonal lattice carbon with excellent mechanical and electronic properties [10]. The nanotube structure is a vector consisting of "n" number line and "m" number column defining how the grapheme (an individual graphite layer) sheet is rolled up [57]. Nano-tubes can be either metallic or semiconducting and they belong to two categories: single walled or multi-walled (Fig. 16).

Carbon nanotubes can be used as reasonably efficient photosensitive materials as well as other PV material. PV nanometer-scale tubes when coated by special p and n type semiconductor materials, form a p–n junction to generate electrical current. Such methodology enhances and increases the surface area available to produce electricity. Recently several articles have reported that "Cornell University researchers have created the basic elements of a solar cell and hope it will lead to much more efficient ways of converting light to electricity than are now used in calculators and on rooftops. The researchers, led by Paul McEuen, the Goldwin Smith Professor of Physics, and Jiwoong Park, assistant professor of chemistry and chemical biology fabricated, tested and measured a simple solar cell called a photodiode, formed from an individual carbon nanotube. The researchers describe how their device converts light to electricity in an extremely efficient process that multiplies the amount of electrical current that flows. According to the team, this process could prove important for next-generation high-efficiency solar cells as reported online by Cornell University and published by the group in Science [60]".

Currently nanotubes are used as the transparent electrode for efficient, flexible polymer solar cells [10]. Naphthalocyanine (NaPc) dye-sensitized nanotubes have been developed and resulted in higher short circuit current however the open circuit voltage is reduced [61]. There are also several groups working on totally inorganic based nanoparticle solar cells, based on nanoparticles of CdSe, CdTe, CNTs and nanorods made out of the same material. In this case the scientists are trying to get rid of the complications of using a polymer based solar cells. The efficiencies are still in the 3–4% range but much research is being conducted in this field.
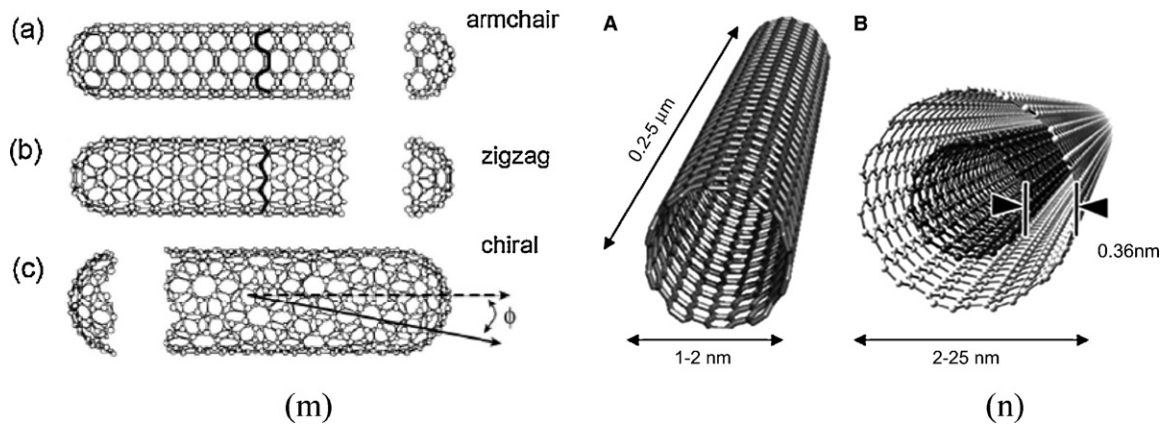
Fig. 16. (m) Single walled nanotube [58] and (n) double-walled [59].

6.2. Quantum dots

Quantum dot (QD) metamaterials are a special semiconductor system that consists of a combination of periodic groups of materials molded in a variety of different forms. They are on nanometer scale and have an adjustable band-gap of energy levels performing as a special class of semiconductors.

The PV cell with larger and wider band-gap absorbs more light hence producing more output voltage, while cells with the smaller band-gap results with larger current but smaller output voltage. The latter includes the band-gap in the red end of solar radiation spectrum. QDs are known to be efficient light emitters with various absorption and emission spectra depending on the particle size.

Currently researchers are focusing on increasing the conversion efficiency of PV cells. For this reason, a 3D array design is needed for strong coupling between QDs in order extend the life of excitons for collecting and transporting "hot carriers" to generate electricity at a higher voltage. The principle of QDs has been implemented using several semiconductor materials and has resulted in the following: when GaAs was used, the cell had a high output advantage

but was more expensive than Si semi-conductive designs such as silicon–silicon dioxide (Si–SiO$_2$), silicon–silicon carbide (Si–SiC) or silicon–silicon nitrite (Si–Si$_3$N$_4$) [62–65]. Fig. 17 shows the difference in voltage band-gap widths of each of the three Si based technology.

6.3. Hot carrier solar cell

This technique is the most challenging method since it utilizes selective energy contacts to extract light generated by "hot carriers" (HC) (electrons and holes) from semiconductor regions without transforming their extra energies to heat. In other words, "hot carriers" must be collected from the absorber over a very small energy range, with selective energy contacts (Fig. 18). This is the most novel approach for PV cell production and it allows the use of one absorber material that yields to high efficiency under concentration.

Ross and Nozik reported that under air mass (AM) of 1.5, the efficiency conversion factor reached a limit of 66% which is 52% higher than that of traditional Si PV cell systems and 33% higher than the
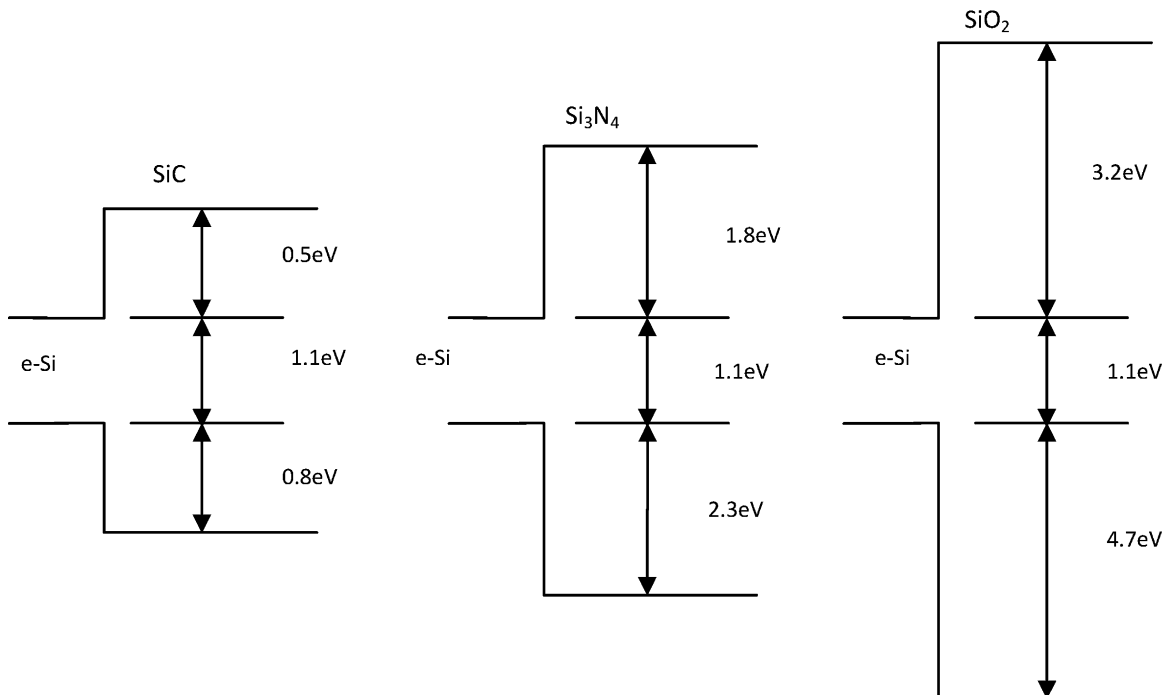

Fig. 17. Bulk band alignments between crystalline silicon and its carbide, nitride, and oxide.
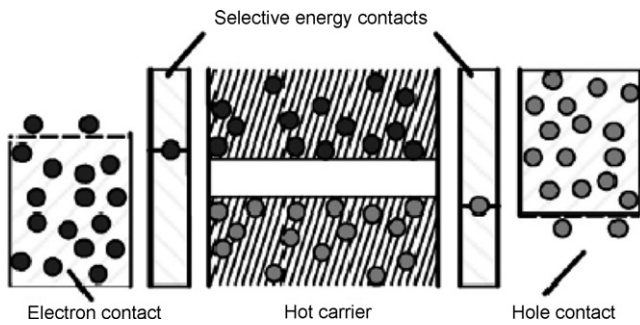
Fig. 18. Schematic and band diagram of an ideal hot carrier solar cell [66].

systems generated using QD principle [67]. Such results were based on the negative chemical potential observed which reduced radiation losses and ensures a high Carnot output which resulted from a high carrier temperature [67,68]. HC achieves high efficiency limit [69].

However and until a solution to the main material challenges are found, (finding materials with drastically reduced carrier cooling rates and the realization of selective energy contacts to extract the photogenerated carriers), this technology will never fully develop. In addition, a way of incorporating multiple absorption path devices into a shorter time realization since most of these devices are more suitable for the high energy portion of the spectrum [70], meaning to date that HC solar cells are just experimented technology..

6.4. PV power plant installations

The photovoltaic power systems through research, development and demonstration has developed rapidly in the past decade enabling now dissemination of the information gained. The prime mover for this shift originated with various government incentives to enhance the production and use of PV in order to limit or reduce the global warming effect which helped in creating interest and spreading the deployment of PV as a clean energy source.

In 2003, the photovoltaic industry delivered some 753 MWp was generated from PV systems world-wide (Fig. 19) [71], while in the

past 5 years, 30% increase in deployment makes this energy producer financially viable. The global installations of solar PV reached a record of 2826 MW by June 2007, stated in the annual PV market report authored by Solar buzz [72]. Although the economic downturn of the past two years, has somewhat slowed the pace, planned installations are still high, and several countries are committing to large "solar farm" type installations. Also government incentives in several parts of the globe are making it an enticing investment for the everyday consumer.

Currently, the PV market is going through tremendous fundamental changes. The past years of demand for solar power led by Germany and Spain, stripped the industry of the ability to readily provide product. With the high demand created enurmous shortage of materials such as silicon, wafers and production capacity, also of talent, knowledge and understanding of how to manufacture solar PV and how to install them. However, due to the economic crisis, several construction plans were put on hold which permitted the supply of material to catch up. In 2006–2008, all major manufacuterers were leaning toward scaling up, currently they have diverted their efforts to improve both the manufacturing processes and the end product. Whether crystalline or thin film, everyone is looking for ways to run the lines more efficiently and increase usable cell watts. These improvements and innovations are coming from in-house technology. Whether it is new concepts in manufacturing equipment, improvements in crystalline wafer manufacturing, contact shading reduction, or lamination materials, all these factors will definitly have positive effects on the development of cells. Companies such as Sharp Solar Energy Solutiond Group, Applied Materials, Spire Solar Inc., Sanyo Electric Co. Ltd., Suniva Inc., Georgia Tech's University Center of Excellence in Photovoltaics (UCEP), Oerlikon Solar AG, Solarion AG Photovoltais, Lawrence Berkley National Lab, Sunpower, Suntech, Solar Solutions, Schott Solar, Sun Edison LLC, Rock Systems and Technologies, United Solar Ovonic LLC, First Solar, Wuerth Solar GmbH, Isofloton, Solyndra, BP Solar, and many others are working toward PV innovation. Everyone in this field agrees that the downturn in the PV market in 2009 is going to reap tremendous benefits in the long run since it is causing everyone to look at new ways to operate, new equipment technologies and materials and to evaluate a more cost effective plant operation and better end product.

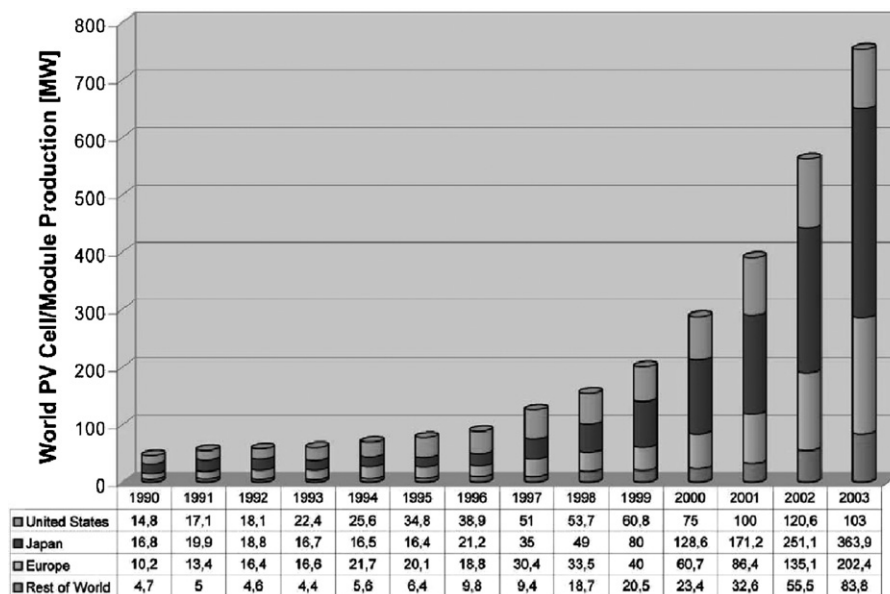|	1990	1991	1992	1993	1994	1995	1996	1997	1998	1999	2000	2001	2002	2003
▣ United States	14,8	17,1	18,1	22,4	25,6	34,8	38,9	51	53,7	60,8	75	100	120,6	103
▪ Japan	16,8	19,9	18,8	16,7	16,5	16,4	21,2	35	49	80	128,6	171,2	251,1	363,9
▢ Europe	10,2	13,4	16,4	16,6	21,7	20,1	18,8	30,4	33,5	40	60,7	86,4	135,1	202,4
▣ Rest of World	4,7	5	4,6	4,4	5,6	6,4	9,8	9,4	18,7	20,5	23,4	32,6	55,5	83,8

Fig. 19. World PV cell/module production from 1990 to 2003.

(Data source: PV News [71]).

7. Conclusion

The importance of photovoltaic was once a questionable issue when fossil fuel was seen as an endless source of energy. However, with growing recognition of the environment impact and the economic instability due to oil and gas price fluctuations, photovoltaic development has the interest of almost all sectors as seen in this paper. Currently PV market consists of a wide range of material and manufacturing processes leading to knowledge transfer regarding the efficiency and suitability of the available technologies. The 1st PV generation is governed by single-junction crystal solar cell based on silicon wafers (single and multi crystalline silicon). The second generation technologies are based on single junction devices aiming to optimize material usage whilst upholding the efficiencies achieved earlier. This generation comprises of CdTe, CiGS and a-Si. While the 2nd generation emphasis is on the reduction of material cost by embracing thinner films, the 3rd generation approach is more concerned with double, triple junction and nanotechnology, which are all showing promising results efficient cells at lower cost.

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