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Photovoltaic Systems and Applications

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1. Introduction

Improvements in quality of life and rapid industrialization in many countries are increasing energy demand significantly, and the potential future gap between energy supply and demand is predicted to be large. Interest in sustainable development and growth has also grown in recent years, motivating the development of environmental benign energy technologies. Research on applications of solar energy technologies have as a consequence expanded rapidly, exploiting the abundant, free and environmentally characteristics of solar energy. However, widespread acceptance of solar energy technology depends on its competitiveness, considering factors such as efficiency, cost-effectiveness, reliability and availability (Kumar and Rosen, 2011).

Renewable energy sources can be defined as “energy obtained from the continuous or repetitive currents on energy recurring in the natural environment” or as “energy flows which are replenished at the same rate as they are used”. All the earth’s renewable energy sources are generated from solar radiation, which can be converted directly or indirectly to energy using various technologies. 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 it is environmentally friendly and a non-pollutant low maintenance energy source (Chaar et. al., 2011).

Some solar thermal systems, such as solar water heaters, air heaters, dryers and distillation devices, have advance notably in decades in terms of efficiency and reliability. Efficiencies of these devices typically range from about 40% to 60% for low- and medium-temperature applications (Thirugnanasambandam et al., 2010). Also, the direct conversion of solar energy to electricity has advanced markedly over the last two decades, leading to significantly reduced prices of photovoltaic modules, and applications have increased especially due to the availability of incentives in many parts of the world (Branker and Pearce, 2010). However, the efficiency of mono crystalline silicon based module is still around 20% and the cost of production of PV power remains considerably higher than the cost of generating solar thermal heat (Liou, 2010). The efficiency of photovoltaic cells or modules is measured under controlled conditions (solar irradiance 1000 W/m^2, cell temperature 25 ^{o}C, air mass 1.5), although the nominal operating cell temperature (NOCT) in actual applications is much higher than the reference cell temperature 25 ^{o}C; the higher NOCT is considered a major cause of reduced efficiency and electrical power output of photovoltaic modules (Garcia and Balenzategui, 2004). To enhance and possibly maximize the output of photovoltaic modules, the heat generated in the module can be extracted by passing a heat recovery fluid (water, oil, glycol, air) under and/or over the module (Tonui and Tripanagnostopoulos, 2007).

Photovoltaic conversion is the direct conversion of sunlight into electricity without any heat engine to interfere. Photovoltaic devices are rugged and simple in design requiring very little maintenance and their biggest advantage being their construction as stand-alone systems to give outputs from microwatts to megawatts. Hence they are used for power source, water pumping, remote buildings, solar home systems, communications, satellites and space vehicles, reverse osmosis plants, and for even megawatt scale power plants. With such a vast array of applications, the demand for photovoltaics is increasing every year (Parida et al., 2011)

PV history starts in 1839, when Alexandre-Edmund Becquerel observed that ''electrical currents arose from certain light induced chemical reactions" 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%. 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 (Chaar et al., 2011).

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 and absorption after reflection (Fig. 1).

This chapter will briefly describe the principles and history of photovoltaic (PV) energy systems and will explore in details the various available technologies while reflecting on the advancement of each technology and its advantages and disadvantages and photovoltaic applications. Included are discussions of the status, development and applications of various PV and solar thermal technologies. This chapter 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, the applications of PV installations are described.

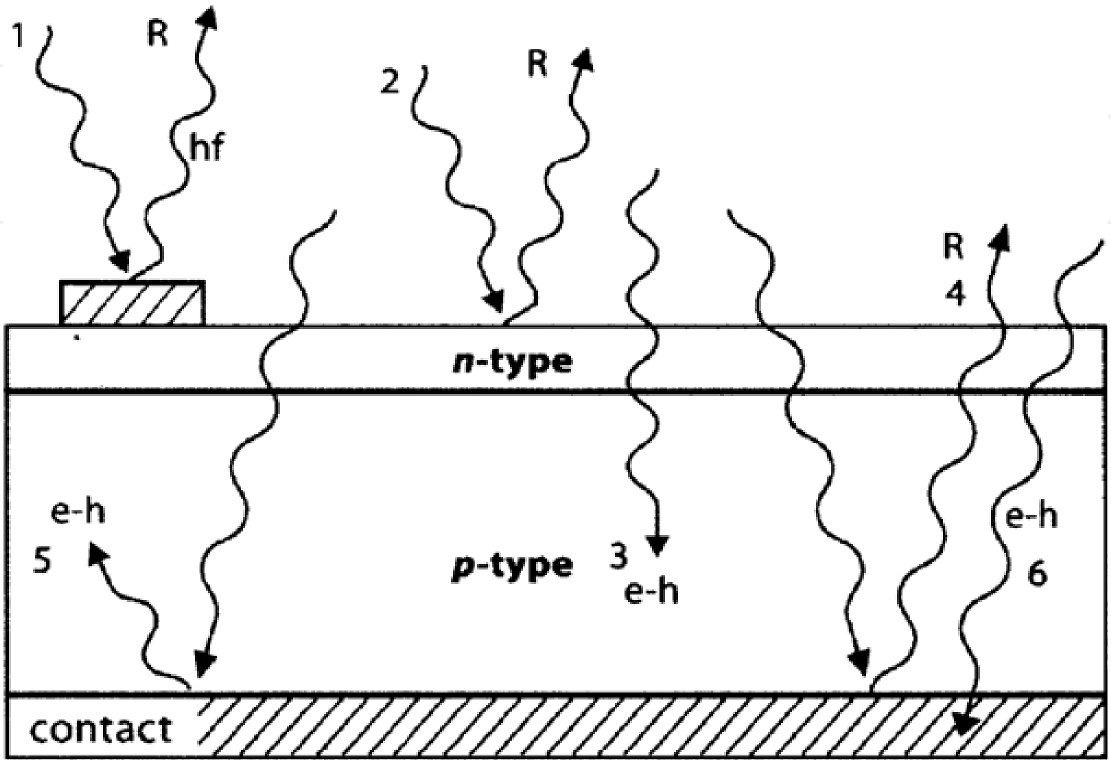


Fig. 1. Behavior of light shining on a solar cell: (1) Reflection and absorption at top contact. (2) Reflection at cell surface. (3) Desired absorption. (4) Reflection from rear out of cell. (5) Absorption after reflection. (6) Absorption in rear contact (Chaar et al., 2011).

2. Photovoltaic systems

The photovoltaic phenomenon has been recognized since 1839, when French physicist Edmond Becquerel was able to generate electricity by illuminating a metal electrode in a weak electrolyte solution. The photovoltaic effect in solids was first studied in 1876 by Adam and Day, who made a solar cell from selenium that had an efficiency of 1–2%. The photovoltaic effect was explained by Albert Einstein in 1904 via his photon theory. A significant breakthrough related to modern electronics was the discovery of a process to produce pure crystalline silicon by Polish scientist Jan Czochralski in 1916. The efficiency of first generation silicon cells was about 6%, which is considerable lower than that of contemporary solar cells (about 14–20%). Early efforts to make photovoltaic cells a viable method of electricity generation for terrestrial applications were unsuccessful due to the high device costs. The ''energy crises'' of 1970s spurred a new found of initiatives in many countries to make photovoltaic systems affordable, especially for off-grid applications. The significant reductions in the prices of photovoltaic cells in more recent years has rejuvenated interest in the technology, e.g., the annual growth since 2000 in the production of PV system has exceeded 40% and present total installed capacity worldwide has reached about 22 GW (Kumar and Rosen, 2011).

3. Types of photovoltaic installations and technology

Four main types of PV installations exist: grid-tied centralized (large power plants); grid-tied distributed (roof/ground mounted small installations); off-grid commercial (power plants and industrial installations in remote areas); and off-grid (mainly stand alone roof/ground based systems for houses and isolated applications). The balance-of-system requirements of each installation differ significantly. For example, off-grid stand alone applications often require a battery bank or alternative electrical storage capacity (Kumar and Rosen, 2011).

Photovoltaic systems can be further distinguished based on the solar cell technology (Fig. 2). Silicon (Si) based technologies can be categorized as a crystalline silicon and amorphous silicon or thin film, and are considered the most mature. Crystalline silicon cells can have different crystalline structures: mono-crystalline (mono- crystalline) silicon, multi-crystalline silicon and ribbon cast multi-crystalline silicon (Kumar and Rosen, 2011).

A key feature of photovoltaic systems is their ability to provide direct and instantaneous conversion of solar energy into electricity without complicated mechanical parts or integration (Phuangpornpitak and Kumar, 2011).

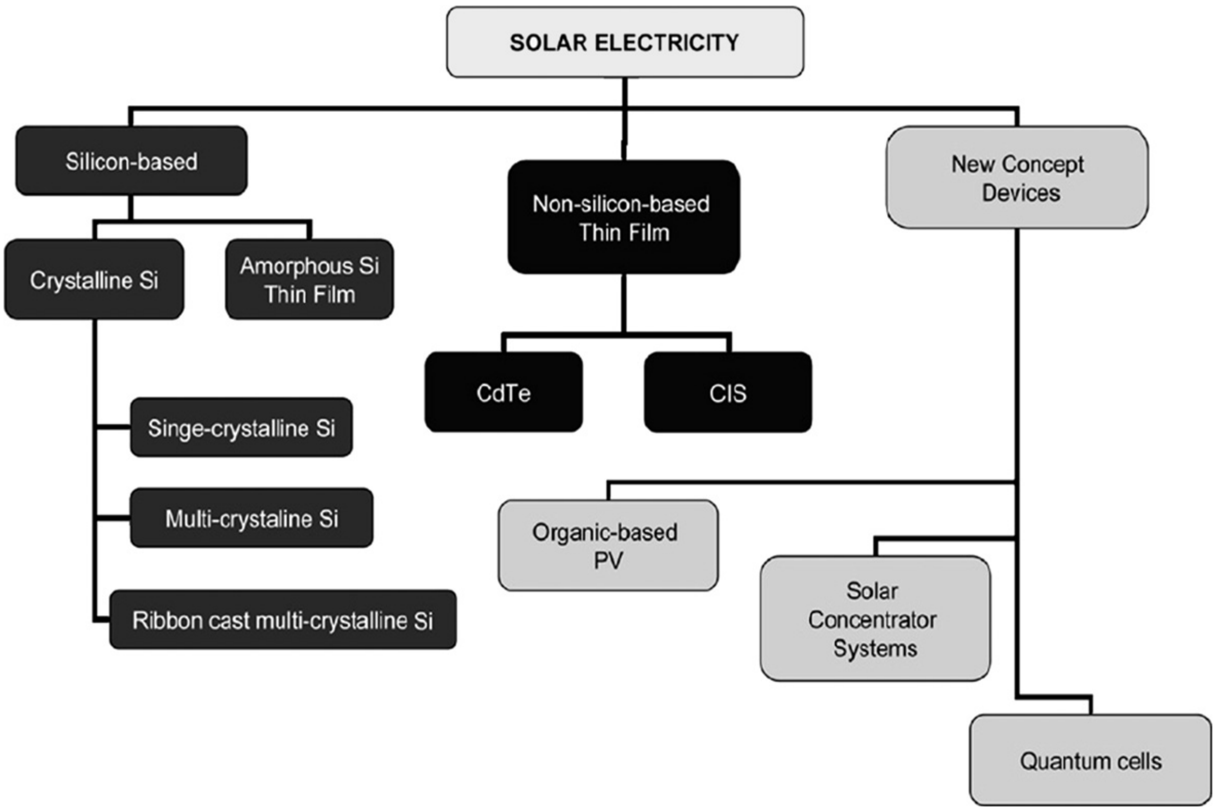


Fig. 2. Various PV technologies.

Most photovoltaic cells produced are currently deployed for large scale power generation either in centralized power stations or in the form of 'building integrated photovoltaics' (BIPV). BIPV is receiving much attention, as using photovoltaic cells in this way minimizes land use and offsets the high cost of manufacture by the cells (or panels of cells) acting as building materials. Although crystalline Si solar cells were the dominant cell type used through most of the latter half of the last century, other cell types have been developed that compete either in terms of reduced cost of production (solar cells based on the use of multicrystalline Si or Si ribbon, and the thin-film cells based on the use of amorphous Si, CdTe, or CIGS) or in terms of improved efficiencies (solar cells based on the use of the III-V compounds). The market share of the different cell types during 2006 are given in Fig. 3.

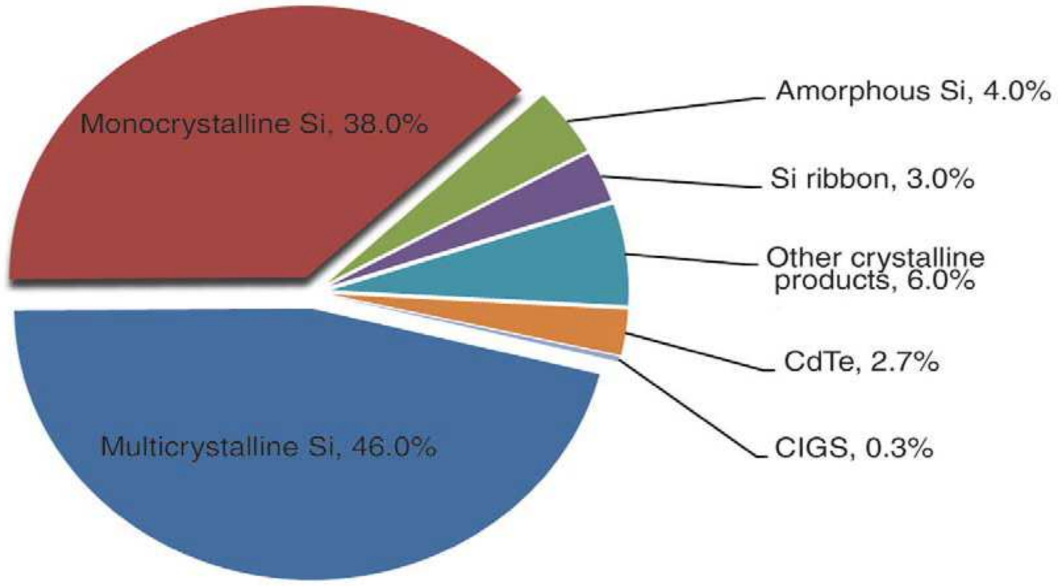


Fig. 3. Market share for various photovoltaic cell technologies in 2006.

3.1 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, multi-crystalline, and emitter wrap through (EWT) are cells under the umbrella of silicon crystalline structures and are discussed in the following sections.

3.1.1 Mono (single)-crystalline photovoltaic cells/panels

This type of cell is the most commonly used, constitutes about 80% of the market recently and will continue to the leader until amore efficient and cost effective PV technology is developed. It essentially uses crystalline Si p–n junctions. 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 0.3mm thick to form a solar cell of approximately 35mA of current per cm^2 area with a voltage of 0.55V 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 Sun power recently announced a 20.4% full panel efficiency. 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 (Chaar et. al., 2011).

Current PV production is dominated by mono-junction solar cells based on silicon wafers including mono crystal(c-Si) and multi-crystalline silicon (mc-Si). These types of mono-junction, silicon-wafer devices are now commonly referred to as the first- generation (1G) technology, the majority of which is based on a screen printing-based device similar to that shown in Fig. 4. (Bagnall and Boreland, 2008)

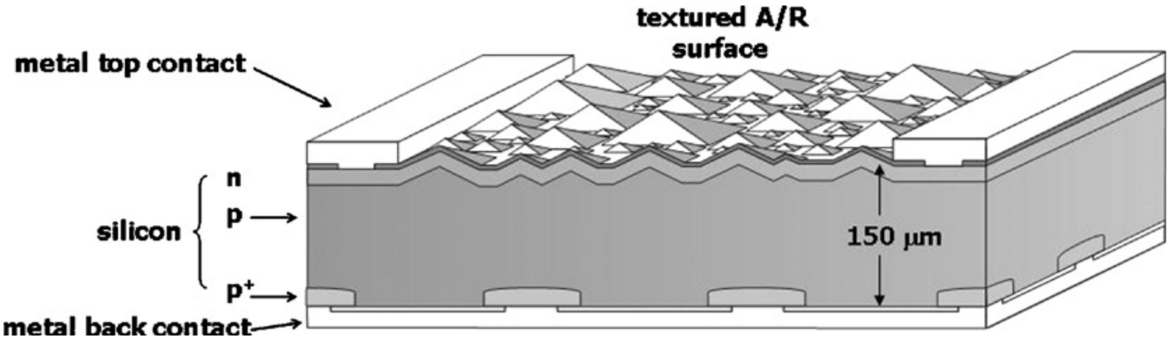


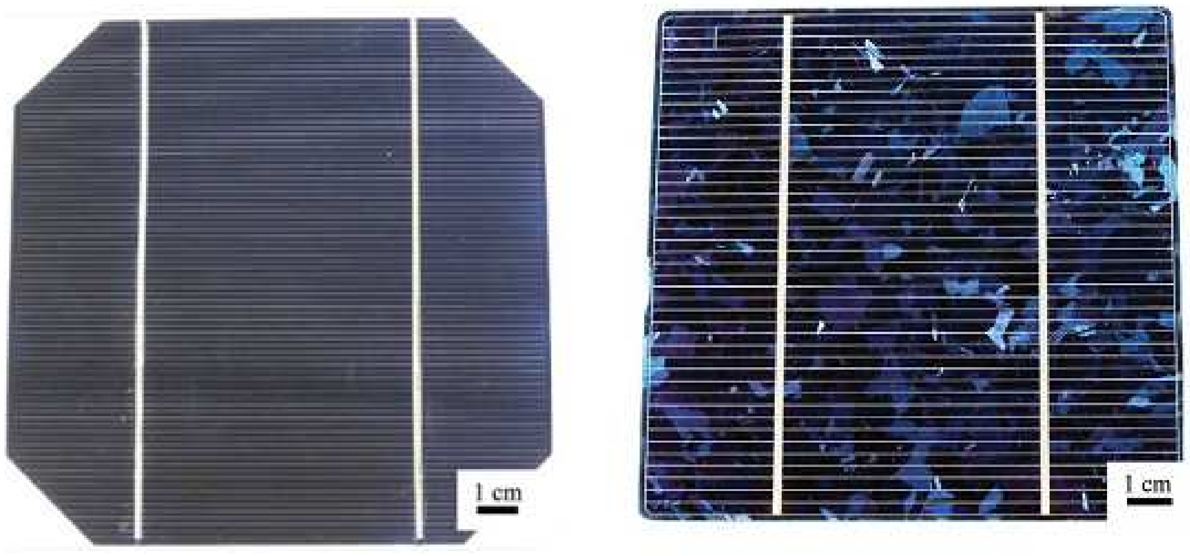
Fig. 4. Schematic of a mono-crystal solar cell. (Bagnall and Boreland, 2008)

3.1.2 Multi (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, multi-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. Multi-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 multi-crystalline silicon. This technology was developed by Evergreen Solar uses (Chaar et al., 2011). A photograph of a cell is given in Fig. 5.

3.1.3 Emitter wrap-though cells

Emitter wrap-through (EWT) 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 showed that (Chaar et al., 2011) there are manufacturing gains by putting the contacts on the backs of the cell. 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.



(a) (b)

Fig. 5. Photographs of (a) crystalline Si, and (b) multicrystalline Si solar cells.

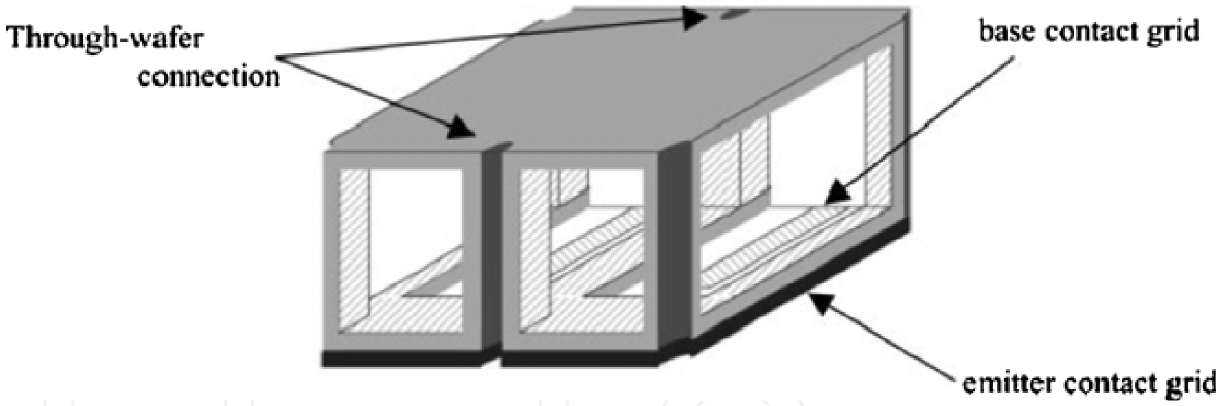


Fig. 6. Schematic representation of an emitter wrap-through solar cell (Chaar et al., 2011).

3.1.4 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 kWh delivered by PV technologies on par with the kWh 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 (Chaar et al., 2011).

3.2 Thin film technology

Thin-film solar cells are basically thin layers of semiconductor materials applied to a solid backing material. Thin films greatly reduce the amount of semiconductor material required for each cell when compared to silicon wafers and hence lowers the cost of production of photovoltaic cells. Gallium arsenide (GaAs), copper, cadmium telluride (CdTe) indium diselenide ($CuInSe_2$) and titanium dioxide (TiO_2) are materials that have been mostly used for thin film PV cells (Parida et al.,2011).

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 (Chaar et al., 2011).

Four kinds of thin film cells have emerged as commercially important: the amorphous silicon cell (multiple-junction structure), thin multi-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 (Chaar et al., 2011).

3.2.1 Amorphous silicon

Amorphous (uncrystallized) silicon is the most popular thin film technology with cell efficiencies of 5–7% and double- and triple-junction designs raising it to 8–10%. But it is prone to degradation. Some of the varieties of amorphous silicon are (Parida et al., 2011) amorphous silicon carbide (a-SiC), amorphous silicon germanium (a-SiGe), microcrystalline silicon (µc-Si), and amorphous silicon-nitride (a- SiN).

Amorphous silicon (a-Si) is one of the earliest thin film Technologies developed. This technology diverges from crystalline silicon in the fact that silicon atoms are randomly located from each other. 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.

3.2.1.1 Amorphous-Si, double or triple junctions

Since a-Si cells have lower efficiency than the mono- and multi-crystalline silicon counterparts. With the maximum efficiency achieved in laboratory currently at approximately 12%, mono 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. 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. 7). 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%.

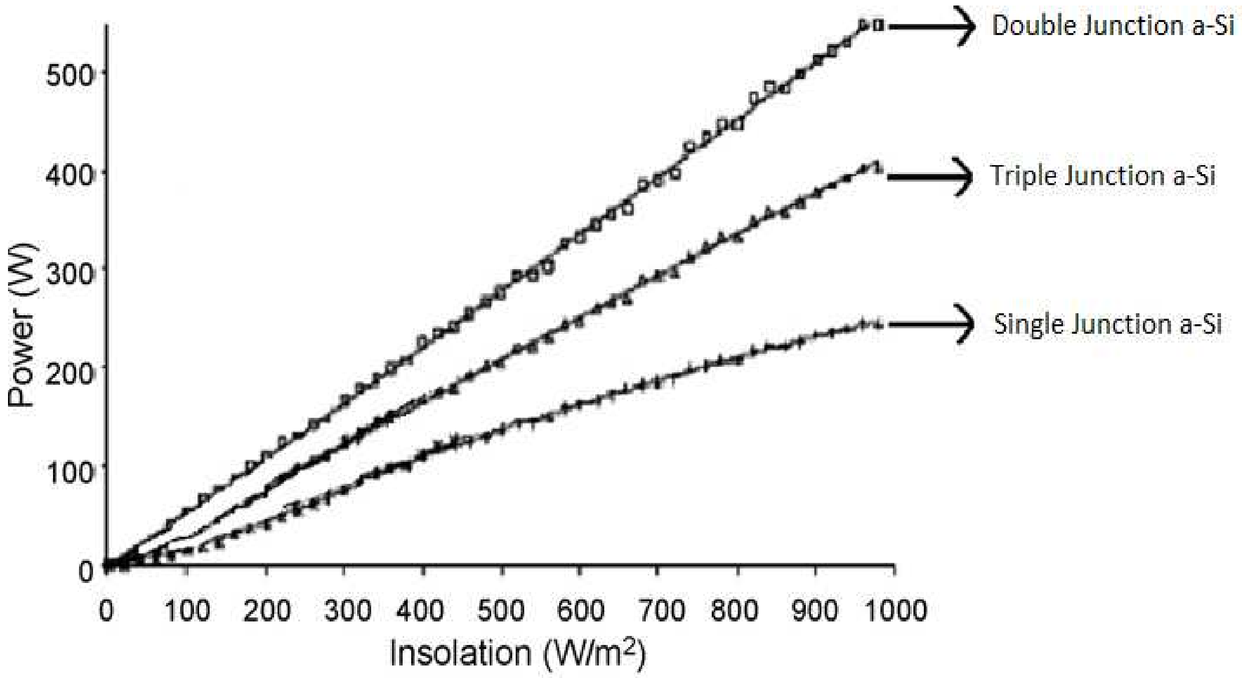


Fig. 7. Variation of output with insolation for representative sub-arrays.

3.2.1.2 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, also called micro morph thin film. 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.

3.2.2 Cadmium telluride or cadmium sulphide

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% and CdTe modules with efficiencies of greater than 9% have been demonstrated. CdTe, unlike the other thin film technology, is easier to deposit and more apt for large-scale. 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 (Chaar, 2011).

Ferekides et al. (2000) presented work carried out on CdTe/CdS solar cells fabricated using the close spaced sublimation (CSS) process that has attractive features for large area applications such as high deposition rates and efficient material utilization. Pfisterer (2003) demonstrated the influence of surface treatments of the cells (Cu2S–CdS) and of additional semiconducting or metallic layers of monolayer-range thicknesses at the surface and discussed effects of lattice mismatch on epitaxy as well as wet and drytopotaxy and preconditions for successful application of topotaxy.

3.2.3 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 contain 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 and about 13% for large area modules. 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 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.

The obvious step in the evolution of PV and reduced $/W is to remove the unnecessary material from the cost equation by using thin-film devices. Second-generation (2G) Technologies are mono-junction devices that aim to useless material while maintaining the efficiencies of 1GPV. 2G solar cells use amorphous-Si (a-Si),CuIn(Ga)Se2 (CIGS), CdTe/CdS(CdTe) or multicrystalline-Si(p-Si) deposited on low-cost substrates such as glass (Fig. 8). These Technologies work because CdTe,CIGS and a-Si absorb the solar spectrum much more efficiently thanc-Sior mc-Si and use only 1–10 mm of active material. Mean while, invery promising work of the last few years, p-Si has been demonstrated to produce _10% efficient devices using light-trapping schemes to increase the effective thickness of the silicon layer (Fig. 9) (Green et al.,2004; Bagnall and Boreland, 2008)

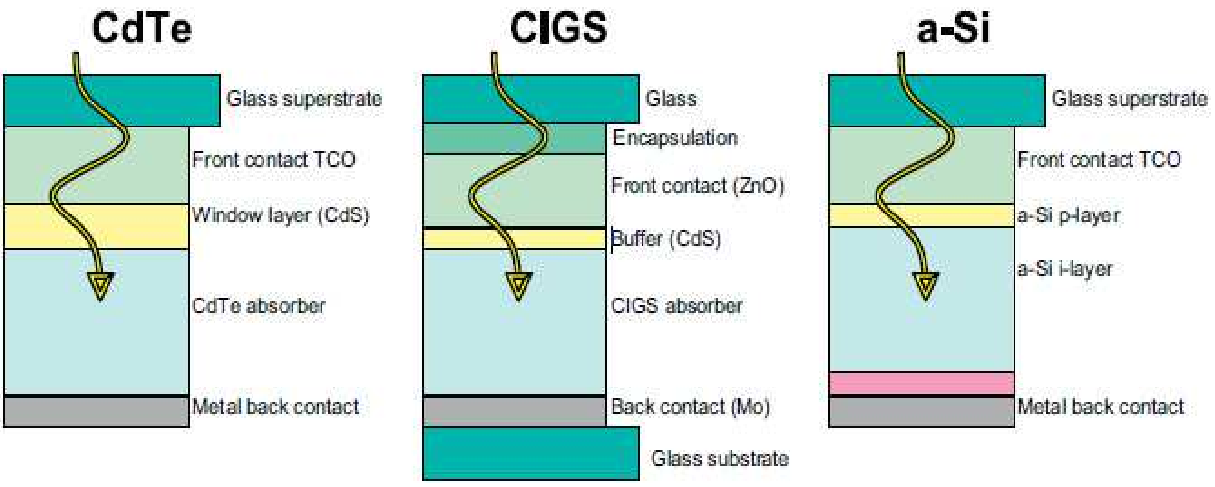


Fig. 8. Schematic diagrams of thin-film CdTe, CIGS and a-Si thin-film PV devices.

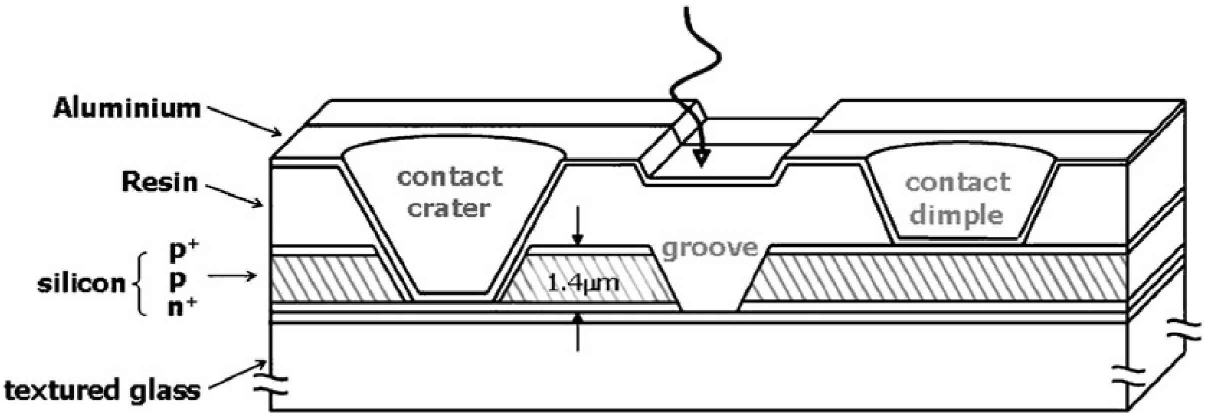


Fig. 9. Key features of the crystalline silicon on glass (CSG) technology . (Bagnall and Boreland, 2008)

4. 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 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 have reached the highest efficiency of 39% with NREL recently announcing 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 mono 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 were grown in order to capture a larger band of the solar spectrum therefore increasing the efficiency of the cells (Chaar, 2011).

4.1 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. 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 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. In the 1950s, Si cells were p–n containing base layers of mono 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. 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%. 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 2mm×2mm) 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.

4.2 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. 10). Using dye sensitized cells for photovoltaic application goes back several decades as scientists were trying to emulate chlorophyll action in plants. 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.

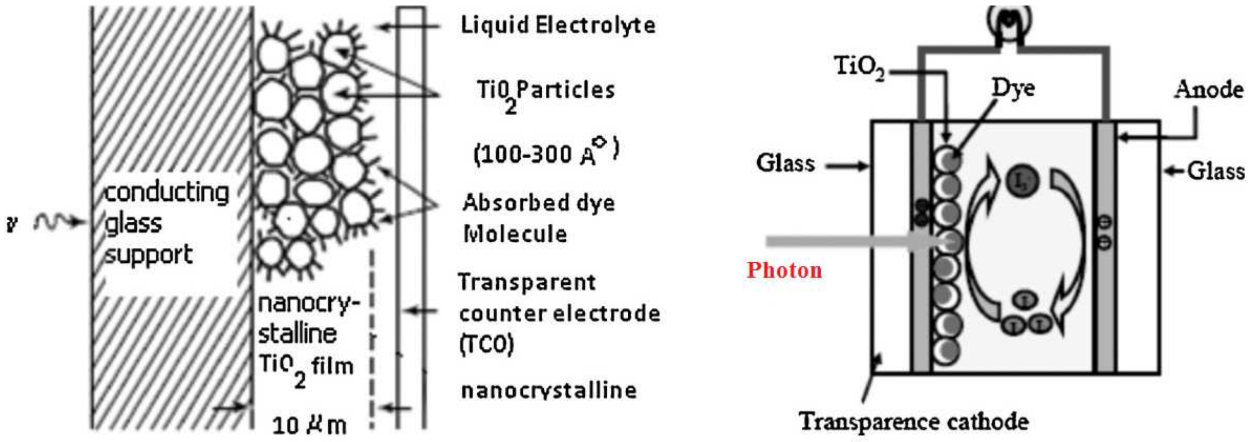


Fig. 10. Cross section of dye-sensitized solar cell (Chaar, 2011).

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 (200–300m²/g TiO_2, as compared to approximately 10m²/g of flat mono 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.

4.3 Organic and polymer PV

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, multiphenylene 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 highvacuum 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. A typical cross section of an organic solar cell is shown in Fig. 11. “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%”. 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.

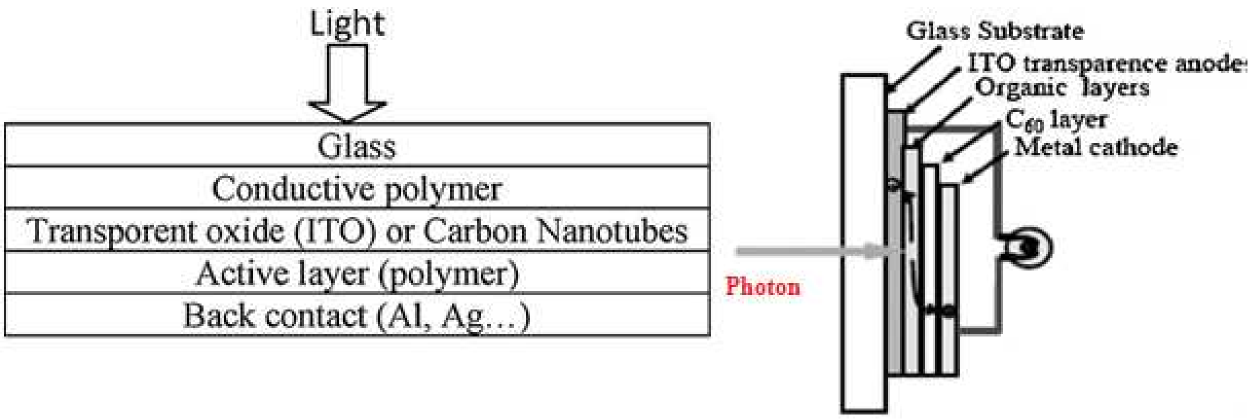


Fig. 11. Organic solar cell.

Organic photovoltaic (OPV) devices are increasingly pursued in view of their low fabrication costs and fairly easy processing. Their light weight, mechanical flexibility and large-scale roll-to-roll production capability are additional advantages compared to traditional Si-based photovoltaics. In a typical OPV device, a blend of conjugated polymer (electron donor) and a fullerene derivative (electron acceptor) is normally used as an active layer sandwiched between the cathode and the anode. The interpenetrating network of donor and acceptor components forms the bulk hetero-junction (BHJ) system for the separation of charge carriers upon illumination and subsequently transports the opposite charge carriers towards the electrodes. Among the various active layers, multi(3-hexylthiophene) (P3HT)/-phenyl-C61-butyric acid methyl ester(PCBM) combination remains the promising system researched till date and shows greater than 5%power conversion efficiency. The performance of the device, however, critically depends on the nano-scale morphology and phase separation of the blend components (Chang Li et al., 2011).

Many strategies are employed to optimize the morphology of constituting domains (P3HT or PCBM) in terms of their size, composition, crystallinity and their connectivity to get the best device efficiency. Among them, the use of suitable solvent for both components of the blend, thermal annealing of the films before/after the deposition of electrodes [8,9], slow drying or solvent vapor treatment of blend films, the use of additives, etc., have significant impact on the thin-film morphology and hence the device performance. All these processing conditions essentially contribute to a self organization mechanism in which the P3HT chains initially crystallize as ordered domains and then PCBM molecules diffuse into the polymer chains to grow as aggregates. The characterization of this nano-scale phase separation is usually done by advanced microscopy techniques, X-ray or electron diffraction methods and recently by electron tomography as well. Since the phase segregation is at the nano-scale dimension, the packing order of P3HT and PCBM phases should also manifest in the local mechanical properties. Therefore, we consider it would be more relevant and appropriate to carry out the measurement of the nano-scale mechanical properties of the blend films to identify their correlations with the device performance if any. In this manuscript, the mechanical properties of P3HT:PCBM active layers prepared from different processing conditions are evaluated by nano indentation. We observed the lowest Young's modulus (20.73GPa) and hardness (649MPa) for P3HT:PCBM active layer films that were processed under optimum conditions to show the best power conversion efficiencies as devices. The correlations for the degree of nano-scale phase separation in the P3HT:PCBM blends as well as the device performances with the mechanical properties in the nano dimension could be estimated by nanoindentation. the P3HT:PCBM blends as well as the device performances with the mechanical properties in the nano dimension could be estimated by nanoindentation (Chang Li et al., 2011).

5. 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 (Serrano et al., 2009) in addition to enhancing the probability of charge recombination.

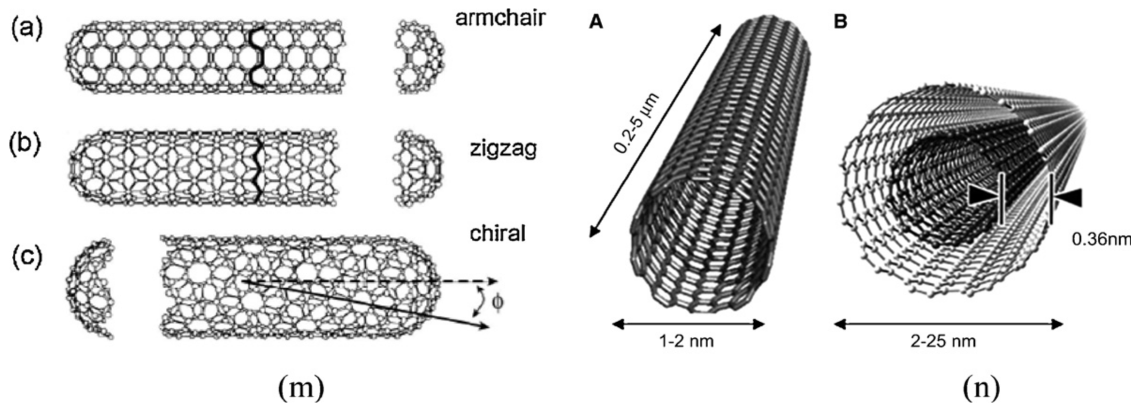
5.1 Carbon nanotubes

Carbon nanotubes (CNT) are constructed of a hexagonal lattice carbon with excellent mechanical and electronic properties. 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. Nano-tubes can be either metallic or semiconducting and they belong to two categories: mono walled or multi-walled (Fig. 12).

Carbon nanotubes can be used as reasonably efficient photosensitive materials as well as other PV material. PV nanometer-scaletubes 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".

Currently nanotubes are used as the transparent electrode for efficient, flexible polymer solar cells. Naphthalocyanine (NaPc) dye-sensitized nanotubes have been developed and resulted in higher short circuit current however the open circuit voltage is reduced (Kyamis and Amaratunga, 2006). 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 stil in the 3–4% range but much research is being conducted in this field.



(m) (n)

Fig. 12. (m) Mono walled nanotube and (n) double-walled (Chaar et al., 2011)

5.2 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_3N_4). Fig. 13 shows the difference in voltage band-gap widths of each of the three Si based technology.

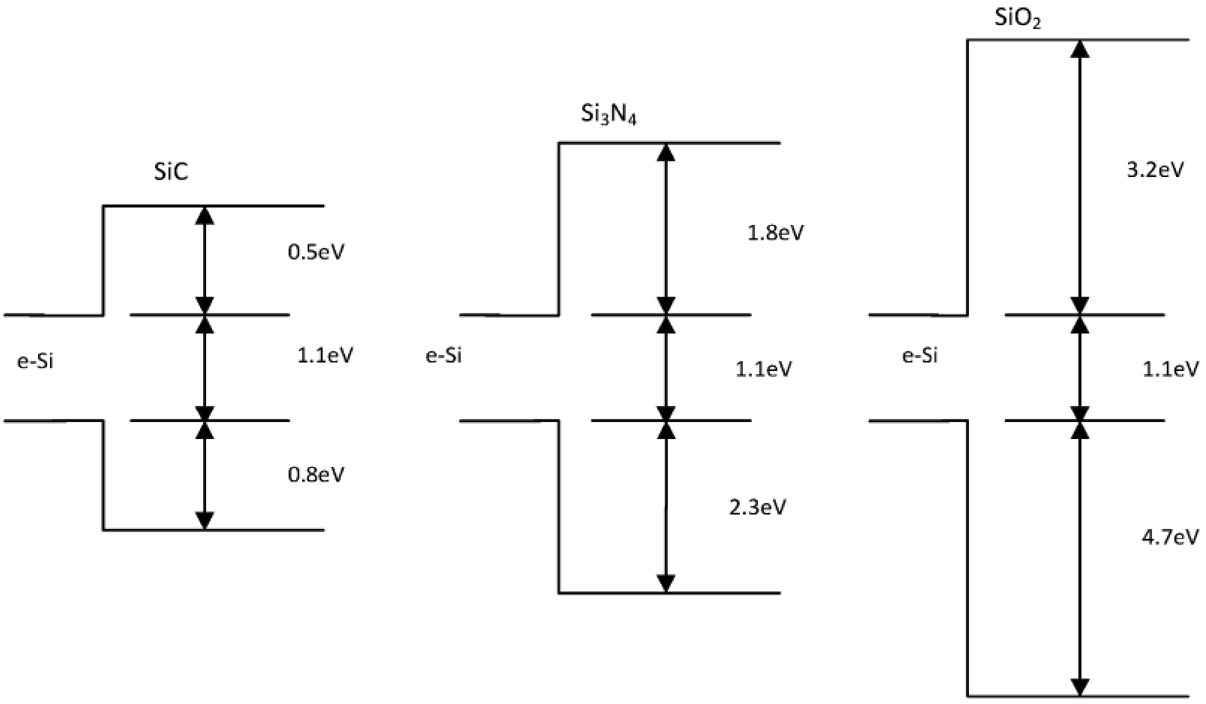


Fig. 13. Bulk band alignments between silicon and its carbide, nitride and oxide.

5.3 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. 14). 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.

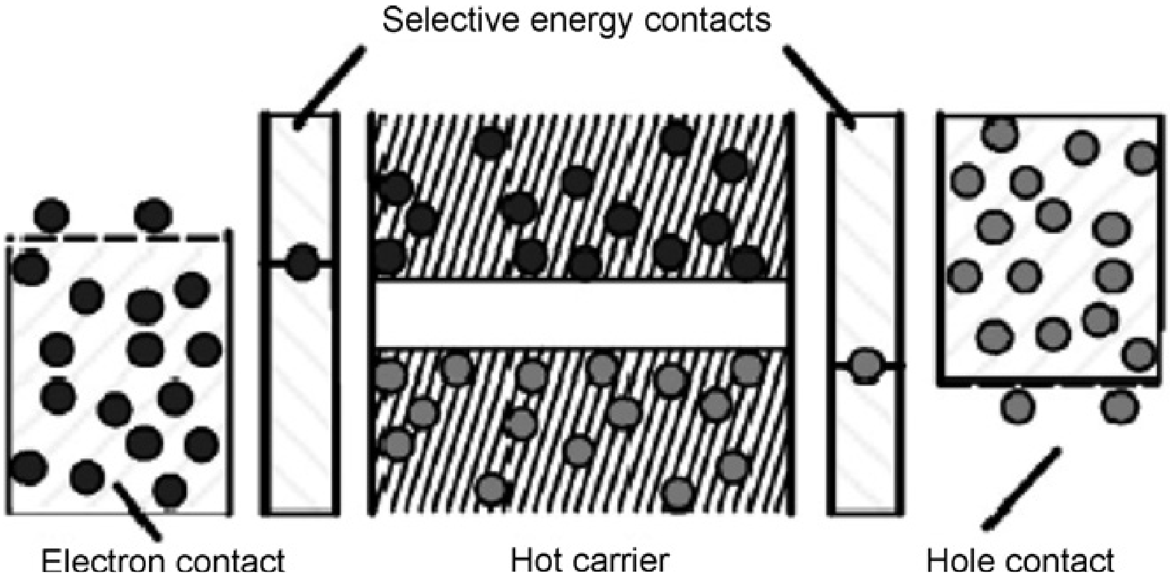


Fig. 14. Schematic and band diagram of an ideal hot carrier solar cell (Chaar et al., 2011)

6. Hybrid photovoltaic cell

Itoh et al. conducted electrical output performances of 'democratic module photovoltaic system' consisting of amorphous-, multicrystalline- and crystalline-silicon-based solar cells that reveal significant differences, mainly with respect to seasonal variation and found that the annual output energy generated by amorphous-Si-based solar cell is about 5% higher than that of crystalline-Si-based arrays (Itoh et al., 2001). Wu et al. proposed a new technique of maximum power point controller, through which the proposed hybrid PV system could adopt amorphous Si solar cell together with crystalline Si solar cell to realize a PV system with higher ratio of performance to cost (Wu et al., 2005).

7. Some other solar cells

Mainz et al. demonstrated that rapid thermal sulphurisation of sputtered Cu/In precursor layers is suitable for industrial production of thin film photovoltaic modules. Yoosuf et al. (2005) investigated the effect of sulfurization temperature and time on the growth, structural, electrical and photoelectrical properties of b-In2S3 films. Nishiokaa et al. (2006) evaluated the temperature dependences of the electrical characteristics of InGaP/InGaAs/Ge triple junction solar cells under concentration and found that for these solar cells, conversion efficiency decreased with increasing temperature, and increased with increasing concentration ratio owing to an increase in open-circuit voltage (Nishiokaa et al., 2006). Phani et al. (2001) described the titania solar cells that converts sunlight directly into electricity through a process similar to photosynthesis and has performance advantages over other solar cells, which include the ability to perform well in low light and shade, and to perform consistently well over a wide range of temperatures and low cost.

Some commercial manufacturers use self-organised nanostructured glass surfaces to improve system efficiencies b yaround 10%. More carefully constructed silicon nanostructure that mimic the eyes of species of moth promise further improvements but are currently too expensive to implement (Bagnall and Boreland, 2008). However, nano-embossing and nano-imprinting technologies are rapidly developing and it is now possible to envisage regular commercial use of nanostructured broad-band antireflective surfaces within the near future, enhancing system efficiencies by more than10%(Fig.15).

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.

8. Performance and reliability

Researchers and scientists had developed and proposed various methods for evaluation of performance of a photovoltaic system. A brief review of these methods is presented here.

Li et al. (2005) investigated the operational performance and efficiency characteristic of a small PV system installed at the City University of Hong Kong and the amount of solar irradiance data falling on the PV panel was determined using the luminous efficacy approach. Yu et al. (2004) developed a novel two-mode maximum power point tracking (MPPT) control algorithm combining the modified constant voltage control and incremental conductance method (IncCond) method to improve the efficiency of the 3 kWPV power generation system at different insolation conditions that provides excellent performance at less than 30% insolation intensity, covering the whole insolation area without additional hardware circuitry. Huang et al. (2006) proposed a PV system design, called "near-maximum power-point-operation" (nMPPO) that can maintain the performance very close to PV system with MPPT (maximum-power-point tracking) but eliminate the hardware of the MPPT and the long term performance simulation shows that the overall nMPPO efficiency is higher than 93%. Jaber et al. (2003) developed a computer-simulation model of the behavior of a photovoltaic (PV) gas-turbine hybrid system, with a compressed-air store, to evaluate its performance as well as to predict the total energy-conversion efficiency and found that hybrid plant produces approximately 140% more power per unit of fuel consumed compared with corresponding conventional gas turbine plants and lower rates of pollutant emissions to the atmosphere per kWh of electricity generated. Stoppato (2008) presented the results of a life cycle assessment (LCA) of the electric generation by means of photovoltaic panels. Wiemken et al. (2001) studied effects of combined power generation by monitoring data from 100 PV systems that reveals a considerable decrease in power fluctuations compared to an individual system and the energy spectrum of combined power generation showed that produced energy is generated in a range below65%of the overall installedpower. Keogh et al. (2004) presented a new tester (commonly used for measuring solar cells and modules) design that is simple, low cost, and reduces transient errors by use of a constant voltage cell-bias circuit and it extracts a family of I–V curves over a decade range of light intensity, which provides comprehensive information on cell performance.

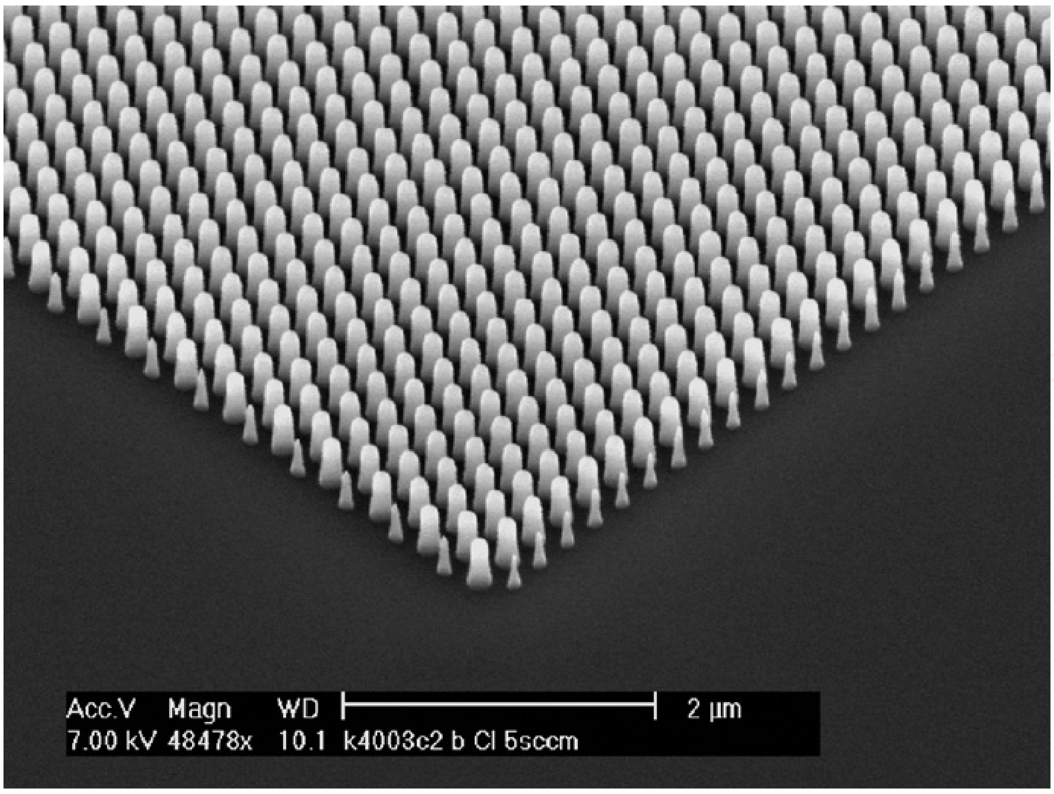


Fig. 15. SEM micrographofasilicon'moth-eye'antireflective surface (Bagnall and Boreland 2008).

9. Environmental aspects

Tezuka et al. (2002) proposed a new method for estimating the amount of CO2-emission reduction in the case where the carbon-tax revenue is used as the subsidy to promote PV-system installations and concluded that the amount of CO2-emission reduction increases by advertising the PV system with subsidy policy even under the same tax-rate and the CO2-payback time of the PV system reduces by half if the GDP is assumed not to change after the introduction of carbon taxation. Krauter et al.(2004) examined a CO2 comprehensive balance within the life-cycle of a photovoltaic energy system and found that the actual effect of the PV system in terms of net reduction of carbon dioxide is the difference between the sum of electrical yield related to the local grid and the value for recycling and the sum of the production requirements and the transport emissions. Fthenakis and Kima (2007) studied solar- and nuclear-electricity-generation technologies' entire lifecycle of energy production; carbon dioxide and other gases emitted during the extraction, processing, and disposal of associated materials and determined the greenhouse gas (GHG) emissions, namely, CO2, CH4, N2O, and chlorofluorocarbons due to materials and energy flows throughout all stages of the life of commercial technologies for solar–electric and nuclear-power generation. Kannan et al. (2006) performed life cycle assessment (LCA) and life cycle cost analysis for a distributed 2.7kWpgrid-connected monocrystalline solar PV system operating in Singapore and provided various energy payback time (EPBT) analyses of the solar PV system with reference to a fuel oil-fired steam turbine and their greenhouse gas (GHG) emissions and costs are also compared revealing that GHG emission from electricity generation from the solar PV system is less than one-fourth that from an oil-fired steam turbine plant and one-half that from a gas-fired combined cycle plant. Tsoutsos et al. (2005) presented an overview of an Environmental Impact Assessment for central solar systems, to estimate the magnitude of potential environmental impacts and proposed appropriate mitigation measures, can play a significant role to proper project design and to a subsequent project public acceptance.

10. Parametric effects on PV module efficiency

The electrical efficiency of photovoltaic modules is influenced by module construction and climatic parameters, with the primary parameters being solar irradiance, packing factor and module temperature. PV cell efficiency increases with solar irradiance, as the greater number of photons associated with higher solar irradiance creates more electron–hole pairs and consequently more current in the photovoltaic cell. The packing factor of a PV, defined as the fraction of absorber area occupied by the photovoltaic cells, significantly affects electrical output. A higher packing factor increases the electrical output per unit collector area, but also increases the module temperature. PV efficiency decreases as PV temperature increases, mainly because a higher cell temperature decreases the voltage significantly (even though it increases current by a very small amount).

Many correlations have been developed for the cell temperature (T_c) as a function of climatic parameters (solar radiation, ambient air temperature, wind speed, etc.). Also, numerous correlations are available to calculate the influence of cell temperature on the efficiency of a PV cell (η_c), but in most practical applications the following linear relation for the cell efficiency can be used without incurring significant loss in accuracy (Skoplaki and Palyvos, 2009):

$$\eta_c = \eta_{ref}\left[1 - \beta_{ref}(T_c - T_{ref})\right] \tag{1}$$

where η_{ref} is the efficiency of the photovoltaic cell at temperature T_{ref}. The temperature coefficient β_{ref} is mainly determined by the cell material, which usually is provided by the manufacturer, and on the T_{ref}, and can be written as (Agarwal and Garg, 1994):

$$\beta_{ref} = \frac{1}{(T_0 - T_{ref})} \tag{2}$$

Here T_0 is the maximum temperature at which the efficiency of the PV cells decreases to zero. For a crystalline Si cell this temperature is about 270° C (Kumar and Rosen, 2011). A range of values of β_{ref} are suggested for silicon based PV technologies.

PV cell type	**Temperature coefficient** [a], β_{ref}, ($^{o}C^{-1}$)
Mono c-Si	0.003-0.005
Multi c-Si	0.004
a-Si	0.0011-0.0026
PV/Thermal	0.00375-0.0063

[a]The reference temperature for each case is 25° C.

Table 1. Temperature coefficients for various PV Technologies.

11. Applications

The increasing efficiency, lowering cost and minimal pollution are the boons of the photovoltaic systems that have led to a wide range of their application.

11.1 Building integrated photovoltaic systems

The PV system is composed of a number of individual PV modules that can be connected either in series (to increase the dc output voltage up to the desired value) to form a string. Then, multiple strings are connected in parallel to increase the output current. The possibility of using multiple strings ensures the PV system modularity, which is one of the most important features of the PV technology. The arrangement of the PV modules in strings also allows for using different solutions for the dc/ac conversion. Available solutions include the centralised inverter, collecting the dc output from the whole array of PV modules, string inverters (with one inverter for each string) or module-integrated inverters (with a mono inverter for each PV module). The centralised inverter is a solution most suitable for PV systems with rated power indicatively above 20kW, connected to the supply system through a three-phase inverter. The other solutions are typical of residential installations, where the power is usually not higher than 5–10kW and the inverters are mono-phase. The adoption of module-integrated inverters requires the installation of a relatively high number of inverters, each one with its protections, directly on the field, paying attention to the fact that the inverters have to withstand different climatic conditions. Yet, the adoption of module-integrated inverters allows for individual and independent control of the mono inverters, with possibility of minimising the losses due to different electrical behavior of the modules (that is, the mismatching of the current/voltage characteristics) and may bring some benefits in increasing the system availability, since the occurrence of an inverter failure affects only a mono module and the relatively low failure rate of the inverter may prevail over the increase of the number of inverters installed with respect to the other solutions (Andrei et al., 2007).

Building-integrated photovoltaic (BIPV) systems incorporate photovoltaic properties into building materials such as roofing, siding, and glass and thus offer advantages in cost and appearance as they are substituted for conventional materials in new construction. Moreover the BIPV installations are architecturally more appealing than roof-mounted PV structures. Yoo et al. (2002) proposed a building design to have the PV modules shade the building in summer, so as to reduce cooling loads, while at the same time allowing solar energy to enter the building during the heating season to provide daylight and conducted an analysis of the system performance, evaluation of the system efficiency and the power output. Bakos et al. (2003) described the installation, technical characteristics, operation and economic evaluation of a grid-connected building integrated photovoltaic system (BIPV) and the technical and economical factors were examined using a computerized renewable energy technologies (RETs) assessment tool. Xu et al. (2008) developed and evaluated the performance of an Active Building Envelope (ABE) systems, a new enclosure technology with the ability to regulate their temperature (cooling or heating) by interacting with the sun which integrates photovoltaic (PV) and thermoelectric (TE) Technologies. Chow et al. (2003) described effectiveness of cooling by means of a natural ventilating air stream numerically based on two cooling options with an air gap between the PV panels and the external facade: (i) an open air gap with mixed convective heat transfer, and (ii) a solar chimney with buoyancy induced vertical flow and found that effective cooling of a PV panel can increase the electricity output of the solar cells. Wong et al. (2008) proposed semi-transparent PV top light material for residential application with 50% radiation transmission rate contributing to a maximum of 5.3% reduction in heating and cooling energy consumption when compared with a standard BIPV roof. Cheng et al. (2005) developed an empirical approach for evaluating the annual solar tilted planes irradiation with inclinations from 0 to 90◦ and azimuths from 0 to 90◦ on building envelopes for BIPV applications in Taiwan. Ruther et al. (2008) studied the behavior of grid connected, building integrated photovoltaic(BIPV) solar energy conversion in the urban environment of a metropolitan area in a Brazilian state capital, aiming at maximizing the benefits of the distributed nature of PV generation. Jardim et al. (2008) Studied the behaviour of grid-connected, building integrated photovoltaic solar energy conversion in the built environment of ametropolitan area in Brazilian state capital, aiming at maximising the benefits of the distributed nature of PV generation.

11.2 Desalination plant

Lamei et al. (2008) discussed electricity price at which solar energy can be considered economical to be used for RO (Reverse Osmosis) desalination that is independent of RO plant capacity and proposed an equation to estimate the unit production costs of RO desalination plants that can be used to calculate unit production costs for desalinated water using photovoltaic (PV) solar energy based on current and future PV module prices. A simple mono-effect solar still plant with a capacity of 5.8m3 per day for the treatment of reject brine obtained from Sadous PV-powered RO desalination plant that can be configured as a 100% solar powered desalination system for any location and quality of brackish water and found that the mono effect solar stills for small scale plants is more viable to use in remote area, where the land value is negligible as solar stills are easy to install and maintained and can be fabricated with locally available materials (Parida et al., 2011). El-Sayed modeled desalination by spiral-wound RO membrane modules driven by solar to power photovoltaic converter panels with the purpose of revealing the economic potential of the combination. Weiner et al. (2001) presented the designing, erection and operation process of a stand-alone desalination plant powered by both solar photovoltaic and wind energy.

11.3 Space

A trade-off study in the field of space solar arrays and concentration that defines the parameters to evaluate whether a given concept (cell type, concentrator) becomes appropriate as two different trough concentrators, and a linear Fresnel lens concentrator are compared to rigid arrays and thermal and optical behaviors are analysed. Seboldt et al. a developed a new design for an Earth-orbiting Solar Power Satellite (SPS) called "European Sail Tower SPS" featuring an extremely lightweight and large tower-like orbital system with the capability to supply Europe with significant amounts of electrical power generated by photovoltaic cells and subsequently transmitted to Earth via microwaves (Parida et al., 2011). Girish (2006) studied the possibility of nighttime photovoltaic power generation in planetary bodies like moon using reflected light energy flux from nearby planetary objects based on latest low-intensity low-illumination (LILT) solar cell technology.

11.4 Solar home systems

Bond et al. (2007) described current experience and trials in East Timor with solar photovoltaic (PV) technology by introduction of solar home systems (SHS). Posorski et al. (2003) proposed SolarHomeSystems (SHS) that are commercially disseminated and used them cost efficiently to substitute kerosene and dry cell batteries to reduce

GHG emissions and thus make a significant contribution to climate protection.

11.5 Pumps

Pande et al. (2003) designed and developed a Solar Photovoltaic operated (PV) pump drip irrigation system for growing orchards in arid region considering different design parameters like pump size, water requirements, the diurnal variation in the pressure of the pump due to change in irradiance and pressure compensation in the drippers. Meah et al. (2008) discussed some policies to make solar photovoltaic water pumping (SPVWP) system an appropriate technology for the respective application region as it has proved its aspects technically, economically, and environmentally in developed countries. Short et al. (2003) investigated some of the issues involved in solar water pumping projects, described the positive and negative effects that they can have on the community and proposed an entirely new type of pump, considering the steps that could be taken to ensure future sustainability. Badescu (2003) analyzed the operation of a complex time dependent solar water pumping system consisting of four basic units: a PV array, a battery, a DC motor, and a centrifugal pump.

11.6 Photovoltaic and thermal (PV/T) collector technology

Chow et al. (2007) described an experimental study of a centralized photovoltaic and hot water collector wall system that can serve as a water pre-heating system using collectors mounted at vertical facades preferring natural water circulation over forced circulation and the thermal efficiency was found 38.9% at zero reduced temperature, and the corresponding electricity conversion efficiency was 8.56%. He et al. (2006) proposed the hybrid photovoltaic and thermal (PV/T) collector technology using water as the coolant as a solution for improving the energy performance. Vokas et al. (2006) studied a photovoltaic–thermal system for domestic heating and cooling concluding that the system can cover a remarkable percentage of the domestic heating and cooling demands. Chow et al. (2006) presented a photovoltaic-thermosyphon collector for residential applications with rectangular flow channels and discussed the energy performance.

The merits of photovoltaic technology relative to other power generation technologies include noiseless, relatively environmentally benign, proven, long life (e.g., 20–30 years for crystalline silicon modules) and low maintenance. However, several factors limit the efficiency of photovoltaic module, e.g., 20% or less for crystalline Si and 12% or less for amorphous Si. In particular, the efficiency of PV devices decreases as temperature increases and PV cells utilize only a part of solar spectrum (less than 1.11 μm for c-Si) for electricity generation. Even the total energy collected in the solar spectrum less than 1.11 μm is not converted into electricity, due to the band gap restriction of silicon (1.12 eV) (Helden et al., 2004). Therefore, much of the collected solar energy in a PV module elevates the temperature of its cells. This absorbed heat needs to be extracted to maintain a high electrical output. This requirement creates an opportunity, as the extracted heat can be utilized for many low- and medium-temperature applications.

The concept of photovoltaic–thermal collectors (PV/T) began in the 1970s and now some companies are marketing such collectors. In PV/T collectors, the photovoltaic cells are integral part of the absorber surface. These collectors are known as hybrid solar collectors due to their inherent ability to generate electricity and heat simultaneously. The working principle of these collectors is similar to flat plate solar collectors, except part of the incident solar radiation is converted into electricity. If the heat transfer fluid (air) is flowing through the flow passage attached with the absorber surface, collectors are categorized as a photovoltaic– thermal air collectors or simply PV/T air heaters (Chow, 2010).

The potential of PV/T collectors has been recognized since 1970 and has received increased attention in the past decade. Compared to using separate solar technologies for heat and electricity, the production of heat and electricity from the same collector surface is often considered more cost effective, requires less space and exhibits significantly lower balance-of-system costs (Zondaga, 2003). The potential of PV/T collectors is large, as many potential users have simultaneous requirements for heat and electricity.

11.7 PV/T air heating collectors

Significant research has been performed on PV/T collectors over the last four decades, on such topics as design development, numerical simulation, prototype design, experimental testing and testing methodologies for PV/T collectors. In the subsequent sections we describe major investigations on PV/T solar air collectors.

Hegazy (2000) compared the performances of four commonly used PV/T air collector configurations (Fig. 16). In the four designs, the air flow passage is located above the absorber (model I), below the absorber (model II) and on both sides of the absorber, in a mono- pass (model III) or double-pass (model IV) mode. Numerical solutions of the energy balances indicate that the electrical and thermal outputs for models II–IV are similar and superior to that for model I, and that the pumping power needed is lowest for model III and second lowest for model IV.

Tonui and Tripanagnostopoulos (2007) improved PV/T air collectors by enhancing heat extraction. They addressed some inherent shortcomings of PV/T air collectors, such as the low density, volumetric heat capacity and thermal conductivity of air, by using a thin suspended flat metallic sheet between the absorber surface and back plate and/or by using fins on the back plate of the air duct (Fig. 17). They report energy efficiencies of 30%, 28% and 25%, respectively, for finned, suspended metallic plate and normal air heaters. The choice of particular design depends on location, especially latitude. The use of finned systems is advantageous for higher latitudes where higher heat gains are needed in winter, whereas the PV/T system with a suspended metallic sheet is usually preferable for low latitude or tropical countries.

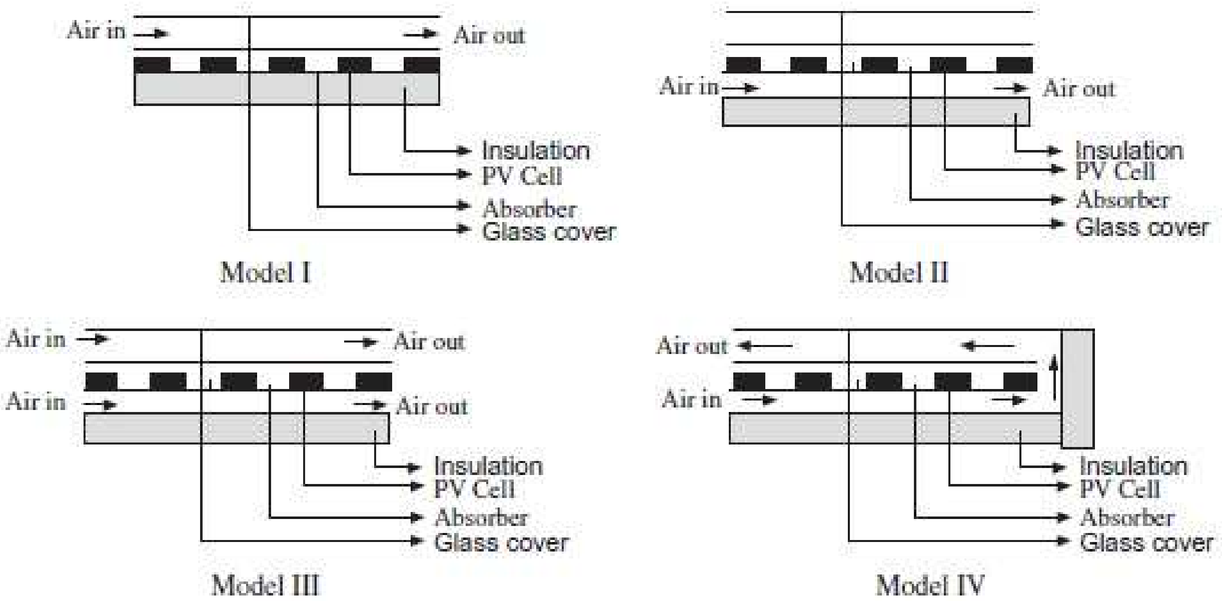


Fig. 16. Various PV/T models (Hegazy, 2000).

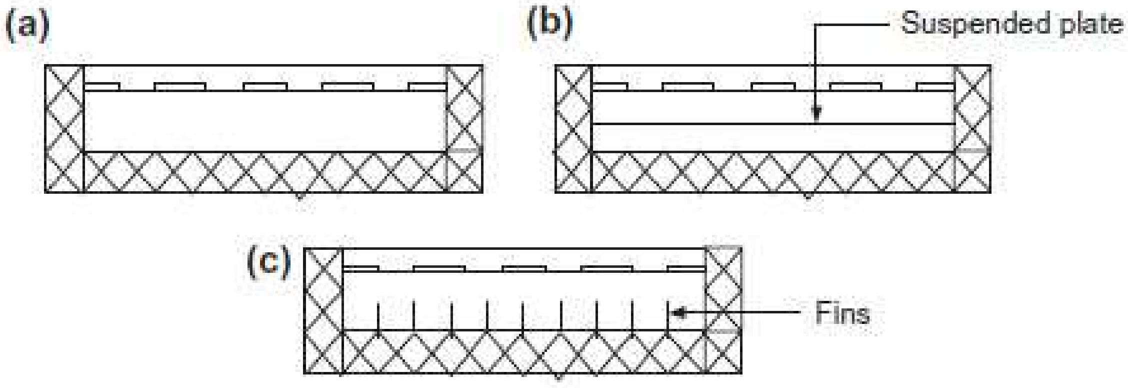


Fig. 17. Cross-sections of (a) a typical PV/T air collector, (b) a PV/T air collector with a suspended plate, and (c) a PV/T air collector with fins. Air flow is perpendicular to the page in all cases. (Tonui and Tripanagnostopoulos, 2007)

The use of a CPC with a double-pass PV/T air heater was examined by Othman et al. (2005). In the considered design, the bottom surface of the absorber has vertical fins (Fig. 18). Electricity production from the PV/T air collector was observed to depend significantly on the air flow rate and to decreases with increasing air temperature. The latter result implies that the air temperature should be maintained at a lower value to generate more electrical energy. These observations are in line with the results reported by Garg and Adhikari (1999) for PV/T air collectors using CPCs.

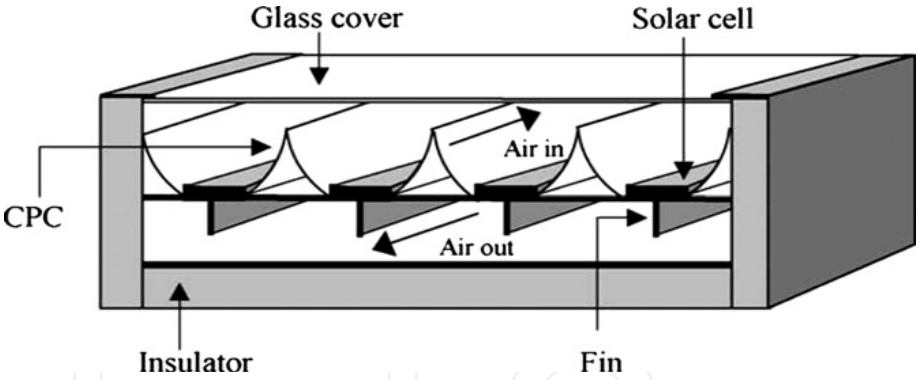


Fig. 18. Double pass PV/T air heater with CPC and fins (Othman et al., 2005).

11.8 Other applications

Mpagalile et al. (2006) fabricated a novel, batch operated oil press, powered by solar PV system designed to suit small-scale oil processors in developing countries with the press providing an opportunity for the processor to use different oilseeds and volumes of the materials being processed by either changing the size of the chamber or adjusting the screw rod to reduce the volume of the upper chamber and for pressing the materials at low or high pressure depending on the expression efficiency required. Xi et al. (2007) presented the development and applications of two solar-driven thermoelectric technologies (i.e., solar-driven refrigeration and solar-driven thermoelectric power generation) and the currently existing drawbacks of the solar-based thermoelectric technology as well as methods to improve and evaluate the performance of the solar-driven thermoelectric devices. Takigawa et al. (2003) developed a new concept of “smart power conditioner” with small storage battery for value-added PV application that has a smoothing function to reduce PV output variation and customer’s load fluctuation, and also has the additional function to compensate for the harmonics current and reactive power caused by customer’s load. Bechinger et al. (1998) developed self-powered electrochromic windows where a semi-transparent photovoltaic (PV) cell provides the power to activate an electrochromic system deposited on top of the solar cell and showed that dye-sensitized solar cells and EC (electrochromic) cells can be easily combined. Chow et al. (2007) developed an energy model of a PV ventilated window system and conducted the overall performance analysis for different window orientations. Ji et al. (2009) presented a novel photovoltaic/thermal solar-assisted heat pump (PV/TSAHP) system, which can generate electricity and heat energy simultaneously and introduced a mathematical model based on the distributed parameter technique for predicting the dynamic system behavior. Ahmad et al. (2006) presented a small PV power system for hydrogen production using the photovoltaic module connected to the hydrogen electrolyzer with and without maximum power point tracker .

12. Conclusion

Electricity produced from photovoltaic (PV) systems has a far smaller impact on the environment than traditional methods of electrical generation. During their operation, PV cells need no fuel, give off no atmospheric or water pollutants and require no cooling water. Unlike fossil fuel (coal, oil, and natural gas) fired power plants, PV systems do not contribute to global warming or acid rain. The use of PV systems is not constrained by material or land shortages and the sun is a virtually endless energy source. The cost of PV systems has decreased more than twenty times since the early 1970’s, and research continues on several different technologies in an effort to reduce costs to levels acceptable for wide scale use. Current PV cells are reliable and already cost effective in certain applications such as remote power, with stand-alone PV plants built in regions not reached by the utility networks. Besides that, integration of PV systems into buildings in residential areas, where the PV system is also connected to the electricity grid to provide an alternative supply source to the load, is becoming even more attractive. Various alternatives have been designed for building-integrated PV systems, including roof-top, facade and sun-shield systems. Early solutions were aimed at superposing the PV modules onto the building structures. Yet, nowadays an increasing attention is paid to the integration of the PV modules into the structural elements that form the building architecture. Although at present the costs of the PV solutions are still not competitive in comparison to other energy sources, the adoption of building-integrated solutions and some incentives provided by national regulations and installation programs could make the investment on PV systems affordable. The future extent of using PV systems will strongly depend upon research to reduce costs and on the value societies place on the negative environmental impacts associated to other forms of electricity generation.

The PV module technology and the type of installation affect significantly the performance of the PV systems. Experimental studies aimed at characterizing the electrical behavior of the PV systems are then essential to understand the peculiarities of the different solutions and to provide operators and customers with unbiased information on the potentials of purchasing and operating a PV system. This paper deals with presenting various aspects concerning the experimental analysis of grid-connected PV systems integrated into the buildings, with the focus on technical aspects related to data acquisition, monitoring and connection to the grid. The use of “virtual instruments” for monitoring the electrical quantities, the power quality assessment and the need for excluding the PV system from operation in case of lack of supply from the grid are specifically addressed, showing examples of applications taken from two real PV systems in operation for some years. Some cases with uncommon behavior of the PV system are highlighted and discussed.

A review of major solar photovoltaic technologies comprising of photovoltaic systems, performance and reliability of PV system, environmental aspects and PV applications is presented. The different applications of solar PV system such as building integrated system, desalination plant, space, solar home systems, photovoltaic and thermal(PV/T) collectors, PV/T air heating collectors, pumps are also presented.

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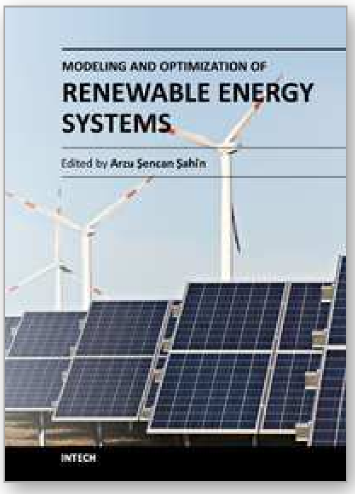

Modeling and Optimization of Renewable Energy Systems

Edited by Dr. Arzu Şencan

ISBN 978-953-51-0600-5
Hard cover, 298 pages
Publisher InTech

Published in print edition May, 2012

This book includes solar energy, wind energy, hybrid systems, biofuels, energy management and efficiency, optimization of renewable energy systems and much more. Subsequently, the book presents the physical and technical principles of promising ways of utilizing renewable energies. The authors provide the important data and parameter sets for the major possibilities of renewable energies utilization which allow an economic and environmental assessment. Such an assessment enables us to judge the chances and limits of the multiple options utilizing renewable energy sources. It will provide useful insights in the modeling and optimization of different renewable systems. The primary target audience for the book includes students, researchers, and people working on renewable energy systems.

Feyza Akarslan (2012). Photovoltaic Systems and Applications, Modeling and Optimization of Renewable Energy Systems, Dr. Arzu Şencan (Ed.), ISBN: 978-953-51-0600-5, InTech, Available from: http://www.intechopen.com/books/modeling-and-optimization-of-renewable-energy-systems/photovoltaic-systems-and-applications

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