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A Study of Materials for Solar PV Technology and Challenges

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ABSTRACT

The current global energy scenario and consumption rate is alarming greatly as the tremendous increase in population causes a sharp increase in electrical energy demand. The exhaustive extraction and production of fossil energy is the main reason and contributor to many environmental issues. As these fuels will ultimately get depleted resulting into increased energy shortfall, climate change and energy insecurity. In this regards every country is putting an effort to increase energy efficiency as well as switching over to new and renewable energy technologies. Among such solar energy from the sun is free and abundant. It offers number of strategic benefits which replaces the fossil-fuel combustion for the various electrical and thermal needs by minimizing the emissions of harmful gases and air pollutants. Currently, solar energy's contribution to the total global energy supply is very low and small but the potential is enormous. Historically solar systems suffer from huge initial cost than conventional energy sources but once the solar technologies are installed, they have very low operating costs and require minimal input this provides security against conventional fuel supply disruptions and their prices. However present innovation and supports for solar manufacturing and sales prices have dropped greatly from the past few decades resulting into at energy price parity. Shockley-Queisser limit is the theoretical maximum efficiency that a single junction solar cell can exhibit. The current research in this direction is going on to find out the best substitute materials and technology to improve the performance of solar cells. The study of light spectrum and different absorption levels in semiconductor material, special coating, application of nano technology and use of organic polymers have led to greater saving and rapid production.

Keywords: Energy Scenario, Renewable Energy Systems, Solar PV materials, Technology, Environmental impacts

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INTRODUCTION

Every location on the Earth receives sunlight to a very good extent of the year and the quantity of solar radiation reaching any one point on the Earth's surface varies with respect to the followings namely, Geographic location, Time of day, Season, Local weather and landscape. A particular point on the Earth's surface gets maximum possible energy when sun is closer and rays are vertical as well varies with slant angles. The radiation data required for solar photovoltaic systems is expressed in terms of kilowatt-hours per square meter (kWh/m^2) and for solar heating systems it is British thermal units per square foot (Btu/ft^2). French physicist Edmond Becquerel discovered the concept of Photovoltaic conversion early in the year 1839. Solar PV cells are the basic building blocks of all PV systems made up of Photovoltaic (PV) materials and devices to convert sunlight into electrical current by photoelectric effect. Several PV cells of various sizes and shapes, from a smallest postage stamp to several centimetres drawn from semiconducting materials are often connected to form PV modules and in turn Arrays [1]. The other accessories like, electrical connections, mounting mechanisms, power-handling and conditioning and batteries to store energy. The efficiency of solar PV cells depends on absorbed light transferring electrons into the atoms of the PV cell semiconductor material, doping, band gap and its structure by the driving force known as built in electric field of PV cell [1,2]. Numbers of technologies are being researched, adopted and undergoing tremendous continual advancements to achieve higher efficiencies. Shockley-Queisser limit refers to the theoretical maximum efficiency that can be obtained from a solar cell which uses a p-n junction. When the incident photon energy is greater than the band gap of the semiconductor then the photon absorbed increases the energy of the valence band electrons and causes the jump of electrons into the conduction band. The increase in temperature of the PV cells cause the decrease in band gap and the overall effect is the reduction of the power supplied by the panel [3].

Historical view of silicon Pn junction and current state

The literature and historical developments in silicon material and application is represented in the Table 1. The great contribution, developments, tremendous growth in material and technology is observed in the last decades. The theoretical limits of the components are proposed by the study and counter acting many factors are also studied and found.

Table 1: Historical view of inventions in semiconductors

YEAR	INVENTION	INVENTOR
1839	Photo electric effect	Becquerel
1876	Photo electric effect in selenium	Adam and Day
1900	Quantum nature of light	Planck
1927	Selective conductivity	Bose
1930	Quantum theory of solids	Wilson
1940	Theory of solid state rectifier(Diode)	Mott and Schotky
1949	Transistor	Barden, Brattain and Shockley
1954	6% efficient solar cell	Chapin, Fuller and Pearson
1954	Cadmium sulfide based solar cell	Reynolds and others
1958	First use of solar cell on orbiting satellite	Launched by the US

Basic working of solar photovoltaic cell

The basic principle of working of solar PV cell is photovoltic effect exhibited by semiconducting material when exposed to solar flux. The effect is analysed considering the PN junction diode concept, (Figure 1). PV cells are availabe in many sizes and shapes from a smaller postage stamp to several meters wide across. Generally connected together to form PV modules and inturn array to handle huge power requirements. Along with these proper electrical connections, mounting hardware, power-conditioning equipment and batteries togather constitute a solar PV system.

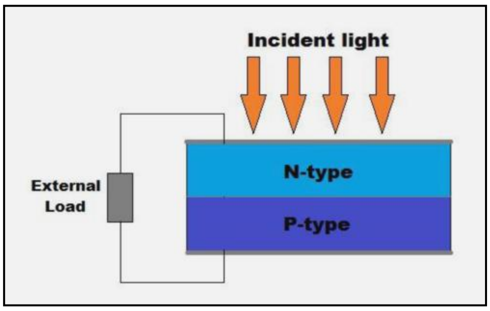

Figure 1: Basic working of Solar PV cell

Spectrum of light

The spectrum of light throw a light on the relationship between the energy in wave and wavelength. Generally the solar cell operte in the range 400 nm to 750 nm wavelength scale to absorb and convert solar flux into photoelectric current (Figures 2 and 3) [3].

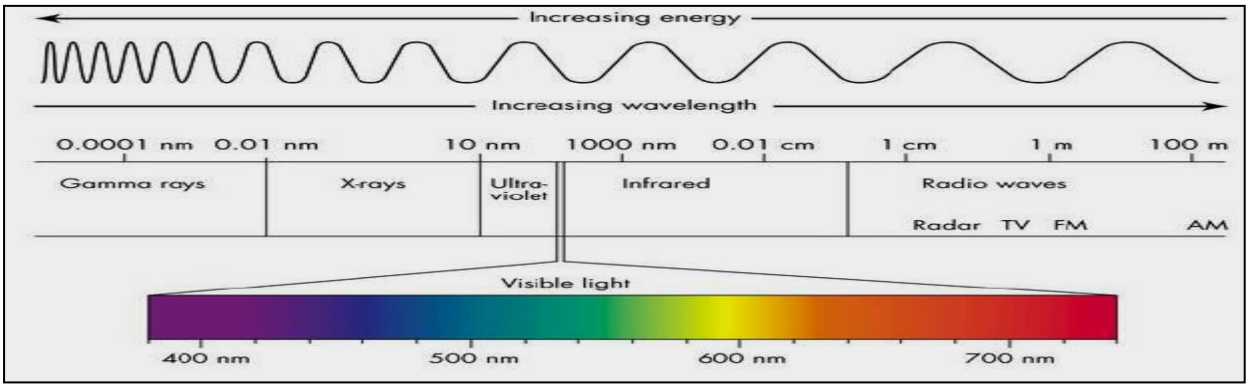

Figure 2: Spectrum of light and energy

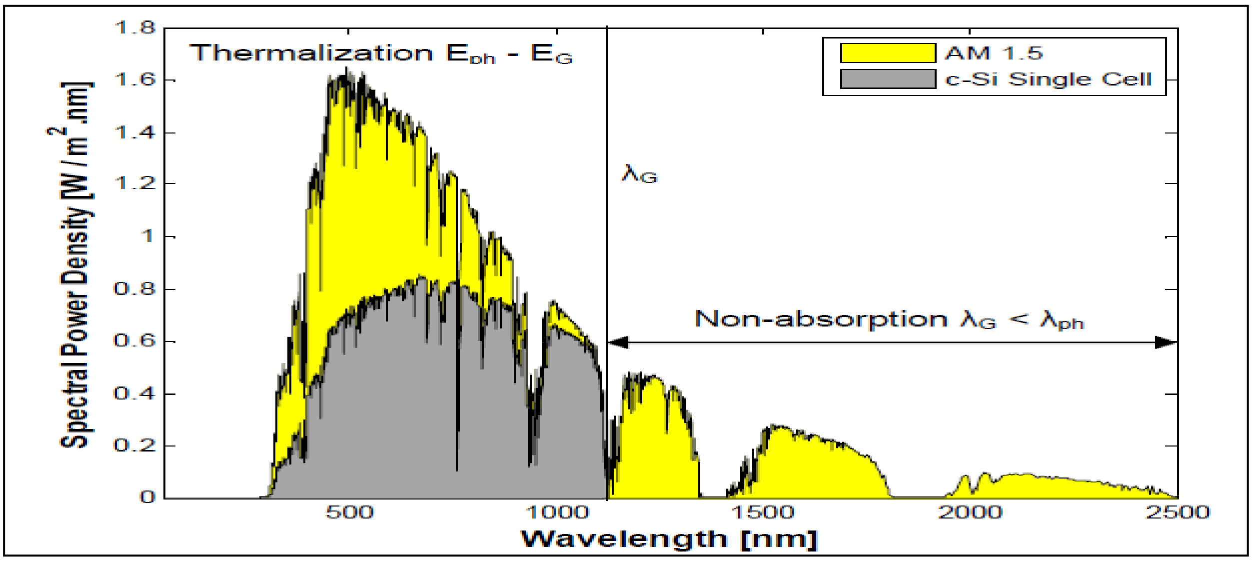

Figure 3: Spectral power density and wavelength

Response to solar flux and factors influencing

The magnitude of current generated in the PV cell is dependent on the intensity of incident light and the wavelength of the incident rays. The semiconductor materials used in solar PV cells absorb limited amount of radiation and energy of a photon is determined by the wavelength but not on intensity of light where in shorter wavelength possess larger energy in compariosion with larger one. Generally Solar cells are coated with an anti-reflective material to capture the maximum radiation possible to increase light intensity resulting proportional increased photoelectron emission rate in the photovoltaic material [4] (Figure 4).

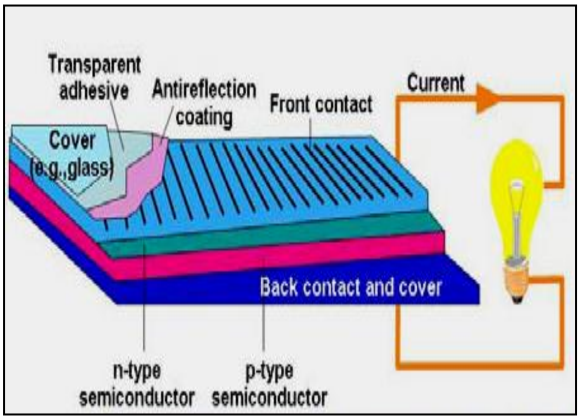

Figure 4: Photovoltaic effect

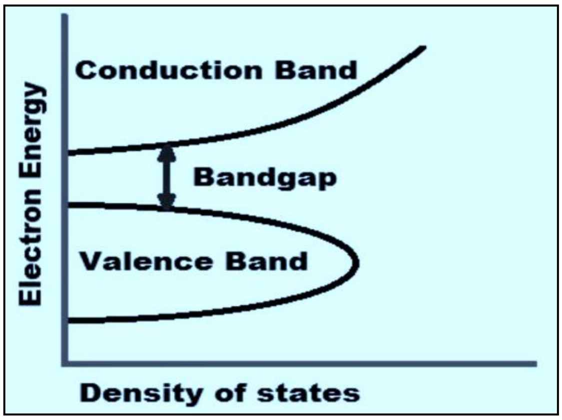

Figure 5: Electron energy and density of states

The effects of temperature on the solar cell plays an important role as the rise in temperature increases the band gap of cells and in turn decrease the output power of the cell (Figure 5). Certainly the manufacturers of solar cell specify the cell temperature as 25°C. The solar panel output power and efficiency are defined under Standard Test Conditions (STC) likely to say, 1,000 W/m^2 of sunlight at 25°C cell temperature and Spectrum at air mass of 1.5. For example, if the temperature coefficient of given solar panel is -0.5%/°C and the ambient temperature is 40°C then the cell temperature is expected to be roughly 15°C higher than the ambient one due to panel encapsulation. Then the loss in solar panel output at 40°C is 0.5%/°C*(55-25)=15%. In other words, a panel rated at 100 W under STC (25°C cell temperature) would produce only 85 W at 40°C ambient temperature. Similarly the shading or cloud cover, dust and proper installation play a good role otherwise leading to inefficiency (Figure 6). Various experiments conducted to find out the effects of partial or full shading have shown the poor performance of solar systems. Lot work is being carried out to eliminate or to clean the panel due to the accumulation of dust by incorporating intelligent controller, cooling and cleaning mechanisms to improve the collection efficiency of the solar PV system (Figure7) [5].

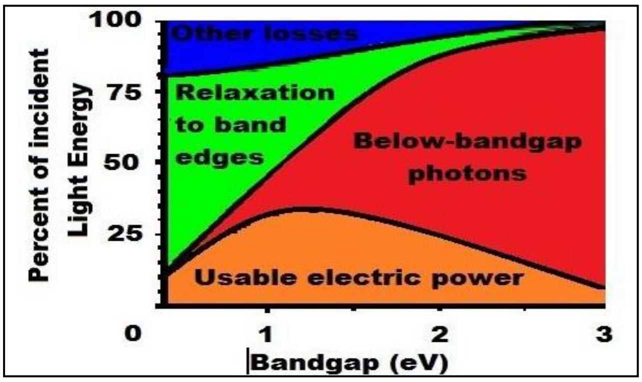

Figure 6: Incident flux and band gap

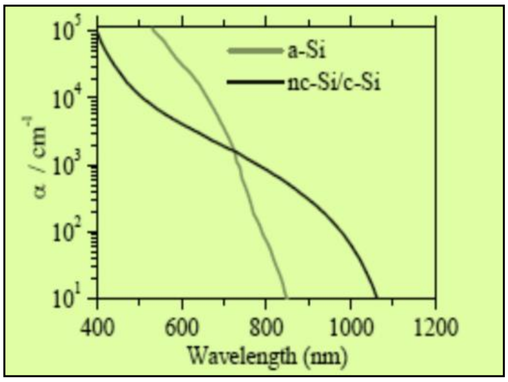

Figure 7: Absorption coefficient wavelength

The choice of material, its band gap, fill factor and effect of temperature on that do matter a lot in photovoltaic energy conversion process (Figure 8). The fill factor clearly defines the efficiency of the conversion based on the technology and material response to the solar insolation (Figure 9).

Cell type	Bandgap (eV)	V_{oc} (V)	FF (%)
Si	1.12	0.71	82.8
GaAs	1.42	1.11	85.9
InP	1.28	0.88	85.4
CIGS	1.15	0.71	79.2
CdTe	1.45	0.84	75.5
a-Si	1.73	0.89	67
DSC (black dye)	1.3	0.74	68
DSC (N719)	1.6	0.82	74
DSC (YD2-o-c8 +Y123)[a]	1.7	0.93	74
Organic Polymer (Konarka)	1.65	0.82	70.2
Organic Small Molecule (Mitsubishi)	1.66	0.90	66.1

Figure 8: PV materials and band gaps

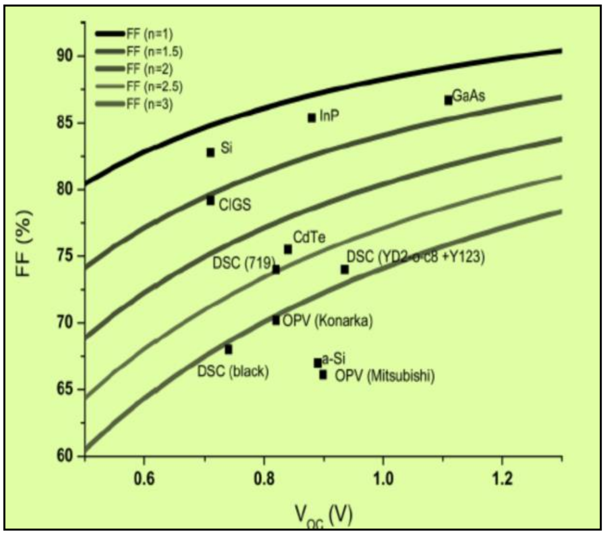

Figure 9: Fill factor and Voc

Classifications of solar PV materials

The main factors influencing the choice of 90% of the World's PV solar cell material are respectively, a minor variation of silicon purity, cost, space and efficiency. The further detailed classification listed is generally used in the commercial manufacturing process [6].

Mono crystalline silicon solar cells

Mono crystalline solar panels look more aesthetically pleasing as they possess more uniform look compared to the speckled blue colour of polycrystalline silicon. Czochralski process is used to manufacture Mono crystalline solar cells (Figure 10). They are drawn from high grade cylindrical silicon ingots having cut properly on its all four sides representing a very good efficiency 20-21%. The panels of Mono crystalline silicon solar are space-efficient and capable to produce power output 2 to 3 times more than that of thin film technology (Figure 11). Usual life span of these solar panels is about 25 years. Usually solar panel performance is significantly affected by shade, dirt or snow and the entire circuit can break down. Mono crystalline solar panels tend to be more efficient in warm weather and deteriorate in performance as temperature goes up [7].

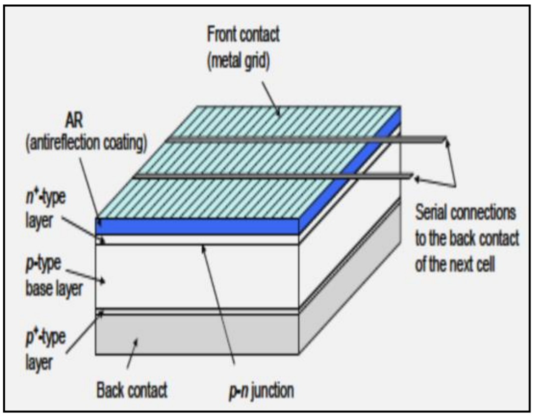

Figure 10: Crystalline silicon solar cell structure

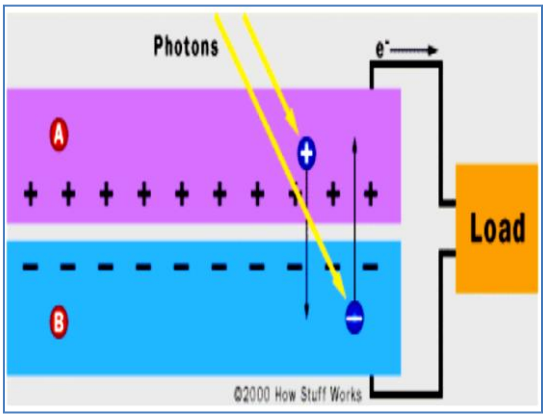

Figure 11: Working of crystalline PV cell

Polycrystalline silicon solar cells

Raw silicon is melted and poured into a square mold and after the cooling they are cut. Polycrystalline solar cells look perfectly rectangular with no rounded edges. Polycrystalline silicon is simple and cheaper. The wastage of silicon is very less compared to mono crystalline manufacturing (Figures 12-16).

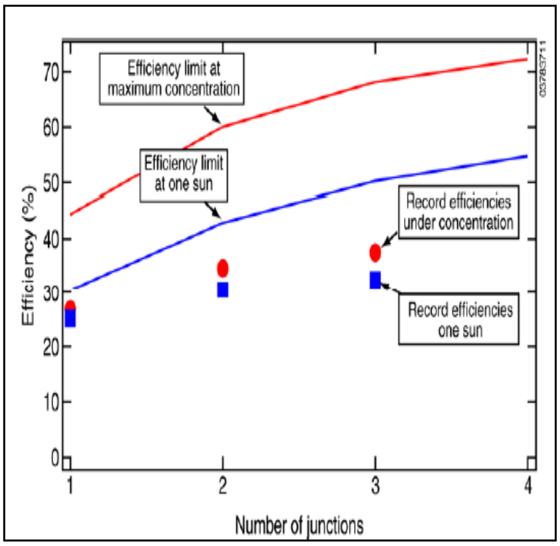

Figure 12: Crystalline silicon solar cell structure

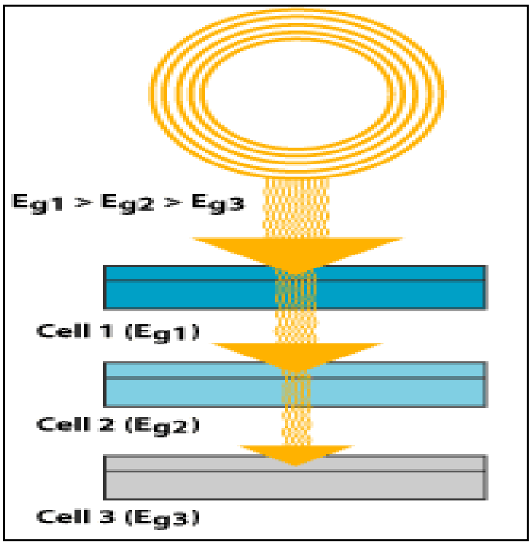

Figure 13: Crystalline silicon solar cell band gap energy

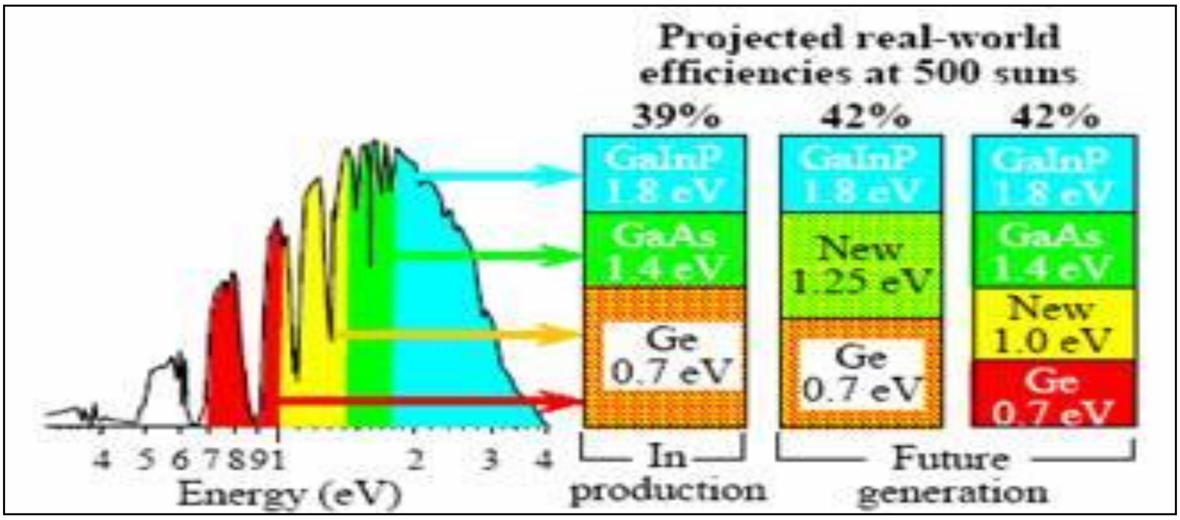

Figure 14: Absorption in multi junction cell by different materials

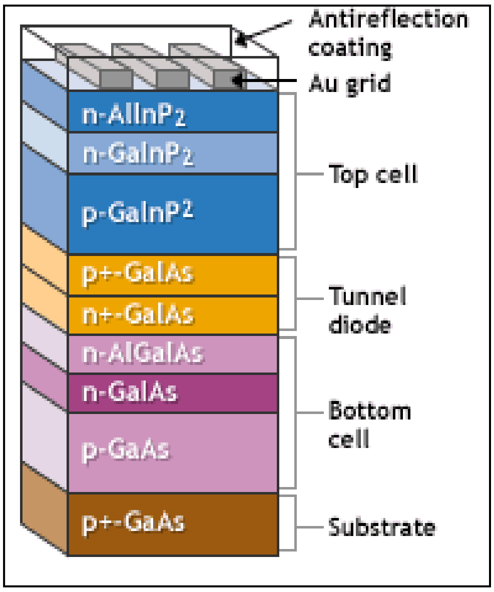

Figure 15: Multi junction PV cell

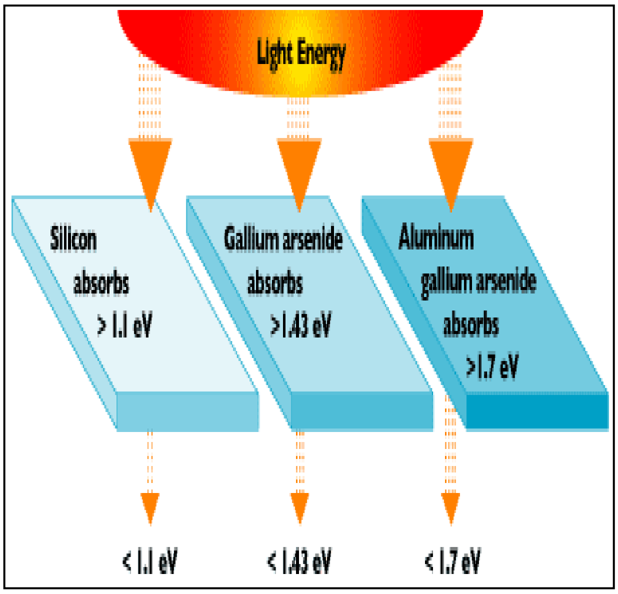

Figure 16: Absorption in multi junction cell

Less heat tolerant, lower space-efficiency than mono crystalline solar panels resulting into 13-16% efficiency and reduced lifespan.

Thin-film solar cells (TFSC)

Alternative to the regular manufacturing process, depositing one or more thin layers of photovoltaic material on a substrate Thin-film photovoltaic cells are obtained. Large scale production is simple and cheaper as compared to crystalline-based solar cells but occupy larger space as they are moderately efficient. The performance degrades faster than mono- and polycrystalline solar panels. This may be the reason why they come with a shorter warranty period. The homogenous appearance makes them look more appealing good. Higher temperatures and shading have less impact on solar panel performance. The present market for thin-film PV is grown about 55- 60% annual from past 10 years. Again based on the material deposited thin-film solar cells are classified as below (Figure 17) [8,9].

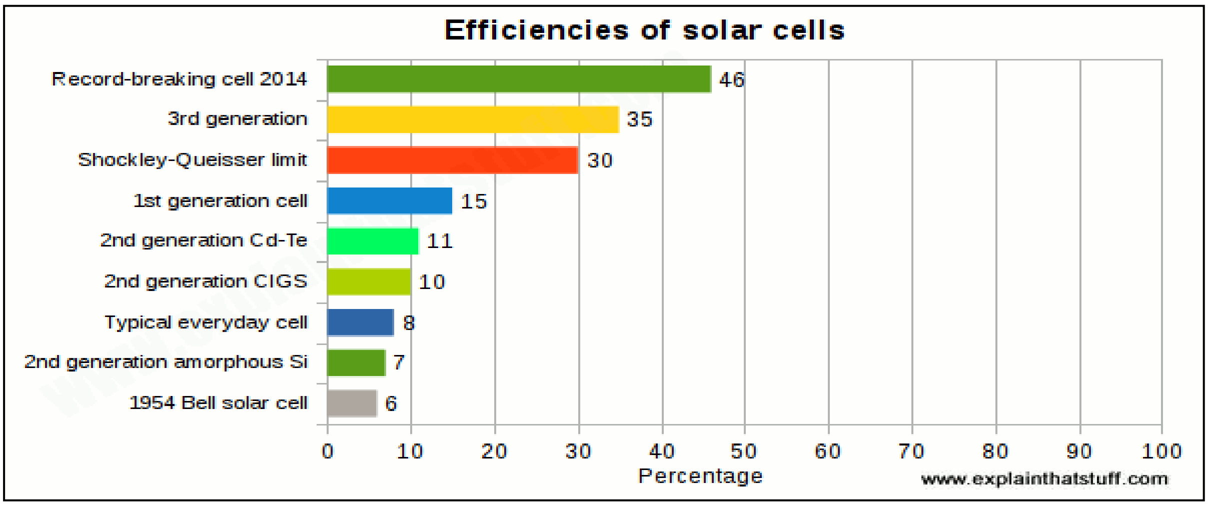

Figure 17: Efficiency of different solar cells

Amorphous silicon solar cells

These are commonly used in small-scale applications such as in pocket calculators as they produce low electrical power. These cells are manufactured by a process called stacking where several layers of amorphous silicon solar cells are combined, resulting good efficiency ranging between 6-8%. Generally very low silicon of the order 1% of the silicon used in crystalline silicon solar cells is used in amorphous silicon solar cell manufacturing.

Cadmium telluride solar cells

Cadmium telluride thin-film solar panel exhibits a very good efficiency in the range 9-11% which has crossed the cost-efficiency of crystalline silicon.

Copper indium gallium selenide solar cells

Among the thin-film technologies Copper Indium Gallium Selenide solar cells possess good potential in terms of energy and efficiency in the range 10-12%. The toxic nature of the material Cadmium Selenide presents a serious limitation on the technology.

Building-integrated photovoltaics

It is a new innovative way of integrating materials, methods with crystalline-based and thin-film solar cells to cover facades, roofs, windows, walls and many other things in a building seamlessly. Technology clearly looks costlier as the integration of solar photovoltaic materials with other conventional wall or roof materials is not simple.

Nano crystals in solar cell technology

Current solar cell technology (Figure 18) efficiencies range from 22% for first-generation solar cells to about 15% for second-generation solar cells. The Shockley–Queisser limit concerns the maximum theoretical limit for solar cells between 31% and 41%. Nano crystal solar cells are those in which substrate is coated with selected nano crystals like cadmium telluride (CdTe), copper indium gallium selenide (CIGS) or silicon.

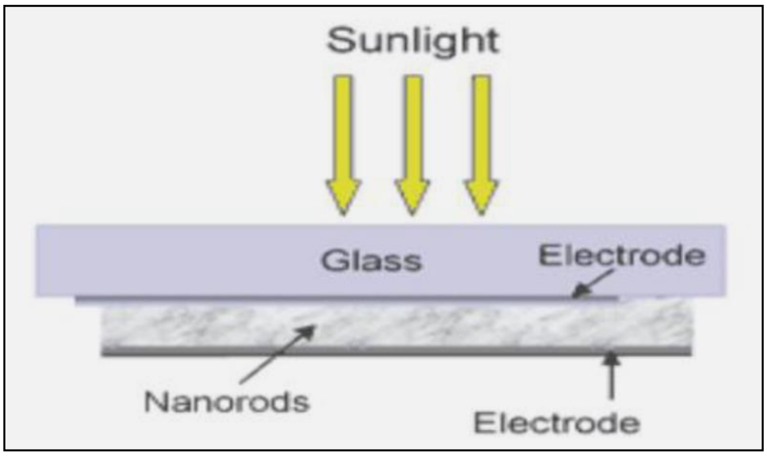

Figure 18: Nano crystal technology

Nano crystal solar cells are expected to overcome the theoretical limit. This innovative manufacturing is rapidly growing and promises lower costs and a higher efficiency. However, the electrical conductivity issue requires attention in order to reach expected potential.

Organic/polymer solar cells

The recent developments in molecular or organic semiconductors and conducting polymers have shown substantial advances in the conversion efficiencies of PV cells. The great promise of organic PV's is that they can be produced at low cost in large volumes using well-established polymer coating technologies.

The issues surrounding current solar cell technology

Solar cell and modules generate electricity from solar insolation by photovoltaic conversion and as the world continues on this shift to a clean energy future certainly great challenges are ahead to reduce the cost and improve the efficiency. Presently, solar energy devices are neither very efficient nor very cheap. The efficiency ranges from 2% to 20%. Before choosing the type of solar panel for typical application important factors to be taken into account are namely, climate conditions, influencing temperature on solar panel efficiency and the impact of solar insolation changes on the efficiency, available space, mounting and solar panel warranty conditions of its manufacturer, Cost and flexibility for the future expansion of the system [9,10].

Efficiency and design considerations

The choice of solar panel is based on the specific need is mainly affected by the efficiencies of solar panel apart from the basic factors. The Table 2 and Figures 19 and 20, shown below provide the similar information and the research level achievements studied at NREL Labs is also supported here with to the discussion [11,12].

Table 2: Solar PV panel material and efficiency

Type of solar Panel	Conversion efficiency	PV cell material	Panel efficiency	Area needed for 1KWp
Copper Indium Gallium Selenide	10-13%	Monocrystalline silicon	13-16%	7m^2 (75 sq ft)
Cadmium Telluride	9-12%	Polycrystalline silicon	12-14%	8m^2 (86 sq ft)
Organic photovoltaic cell	7-12%	Amorphous silicon	6-7%	15m^2 (161 sq ft)

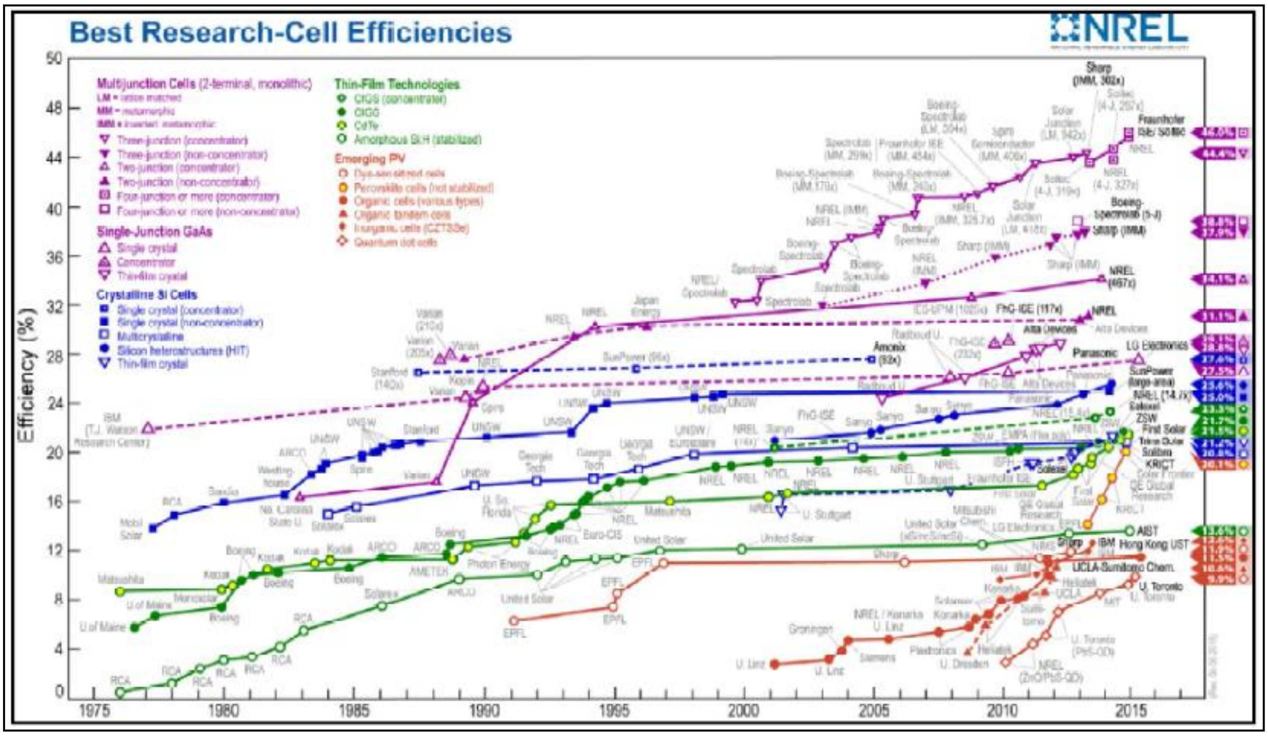

Figure 19: Comparison of solar cell efficiencies

Technical performance	Typical current international values and ranges					
Energy input/output	Sunlight/ Electricity					
Current PV technologies	Crystalline Si		Thin Film			CPV
	sc-Si	mc-Si	a-Si/m-Si (m-SiGe)	CdTe	CI(G)S	
Max. (record) cell efficiency, %	22 (24.7)	18 (20.3)	10 (13.2)	11.2 (16.5)	12.1(20.3)	(>40)
Max. module efficiency, %	19-20	15-16	9	na	na	na
Commercial modules effic., %	13-19	11-15	7-9	10-11	7-12	20-25
Land use, m^2/kW	6-8	7-9	11-15	9-10	9-15	na
Lifetime, yr	25 (30)		25			na
Energy payback time, yr	1-2		1-1.5			na
Material use, g/W	5-7		na			na
Wafer thickness, μm	<180-200		na			na
Market share, %	-85		-15			na
Typical size (capacity), kW	Residential < 10 kWp; Commercial < 100 kWp; Industry 100Kwp -1MWp; Utility > 1MWp					
Total cumulative capacity	1.4 GW (2001), 23 GW (2009), 40 GW (2010), 70 GW (2011)					
Annual installed capacity	2.8 GW (2007), 5.9 GW (2008), 7.2 GW (2009); 15 GW (2010); 30 GW (2011)					
Capacity factor, %	From 9-16% (in most favourable locations), based on annual electricity production					
CO2 emissions, gCO_{2eq}/kWh	Occurring during manufacturing only - between 12-25 gCO_{2eq}/kWh					
Avoided CO_2 emissions	- 600 gCO_{2eq}/kWh (based on electricity mix in developed countries); up to 900 gCO_{2eq}/ kWh in countries with coal-based power generation.					

	1980	2007	2010	2015-20	2030+
Module effic., %					
Mono-c-Si	≤8	13-18	13-19	16-23	25-40
Mult-c-Si			11-15	19	21
TF	na	4-11	4-12	8-16	na
c-Si material use, g/Wp			7	3	<3
c-Si wafer thick, mm			180-200	<100	na
Lifetime, yr	na	20-25	25-30	30-35	35-40
En. payback, yr	>10	3	1-2	1-0.5	0.5

Figure 20: Historical view and solar cell efficiencies

Various losses affecting the solar cell efficiency

The performance of solar PV cell mechanism is greatly affected by various factors and tremendous work is in progress to reduce the effects in steps. Following are the few points listed:

- Loss due to non-absorption of long wavelengths
- Loss due to thermalization of the excess energy of photons
- Loss due to the total reflection
- Loss by incomplete absorption due to the finite thickness
- Loss due to recombination
- Loss by metal electrode coverage, shading losses
- Loss due to voltage factor
- Loss due to fill factor

Methods to improve solar flux collection

- Anti-reflective (AR) coatings are used in all solar panels to improve efficiency and lifetime of the solar cells. The sol-gel dip coating technology is a widely used for producing AR layers on large areas and surface treatment for improving hydrophobicity of anti-reflective coatings. The hydrophobic hexamethyl disiloxane (HMDS) coating is used to prevent the contamination of the AR layer. Porous structure of the film is needed to achieve a refractive index of the film to 1.23 which is required for zero reflection on a glass surface (Figure 21).

- Latest method is to use Perovskite layer of coating to improve solar flux collection and transfer ability of the solar materials (Figure 22).

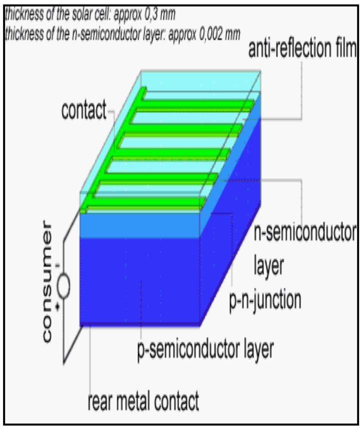

Figure 21: Anti-reflective light coating

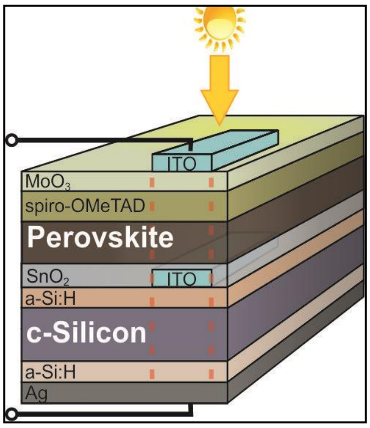

Figure 22: Pervoskite layer

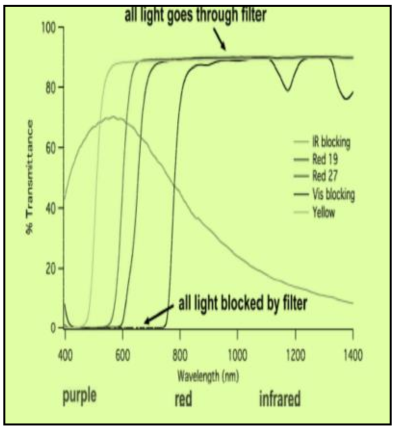

Figure 23: Effect of color filtering of light

- Reduction of shading losses by exposing the PV panel to the sun to a very good extent by proper mounting.
- Not all charge carries that are generated in a solar cell are collected at the electrodes. The photo-generated carries are the excess carriers with respect to the thermal equilibrium results in losses like incomplete absorption and recombination reducing the Solar cell collection.
- The electronic and optical properties of the solar cell are taken into account for the calculation of photovoltaic performance, the thickness, the saturation current and the photo-generated current. The saturation current density depends on the recombination in the solar cell that cannot be avoided.
- Use of Photonic crystal structures for light trapping in solar cells. Making use of the diffraction properties of the photonic crystal surface, light may be coupled into diffraction orders that will increase the path length of light inside the absorbing material. Photonic crystals applied to the back side of solar cells.
- The effect of use of colour filter (Figure 23) shows the following performance based on material and flux.
- Improving the performance of solar panels by the use of phase-change materials to maintain the temperature of the panels close to the ambient. High operating temperatures induce a loss of efficiency in solar photovoltaic and thermal panels.
- Practice of passive cooling to improve the performance.
- An aluminum heat sink was used in order to dissipate waste heat from a photovoltaic (PV) cell.
- Light trapping mechanism to cause total reflection of incident solar flux in the device (Figure 24).
- Use of prism based diffraction of light into a spectrum of different wave lengths (Figure 25).
- Mirror boosters to increase the solar flux incidence on the PV panel (Figure 26).

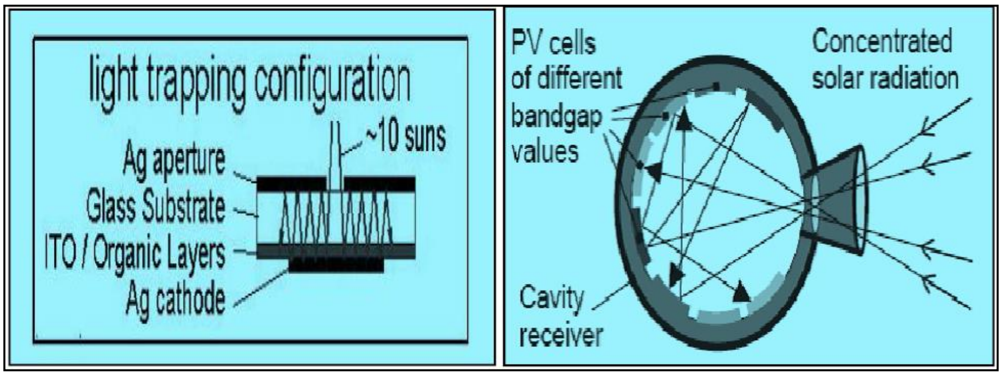

Figure 24: Light trapping methods to improve solar flux collection

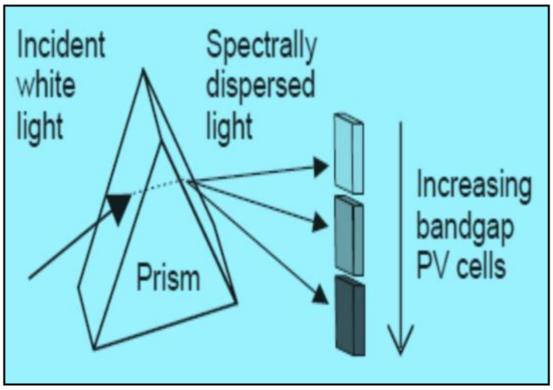

Figure 25: Prism based method to improve solar flux collection flux collection

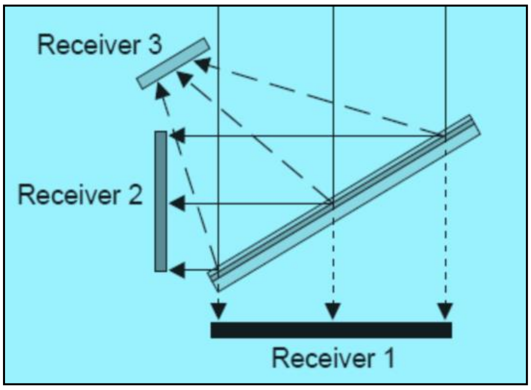

Figure 26: Mirror booster method to improve solar

CONCLUSION

Solar energy's contribution to the total global energy is very low but the potential is enormous and this provides security against conventional fuel supply disruptions and their prices. Theoretically Shockley-Queisser limit puts the constraint on the maximum efficiency of a single junction. The current developments in the solar energy systems are in the direction to find out the best substitute materials and technology to improve the performance of solar cells. Similarly study of response to the light spectrum, effects of different absorption levels in semiconductor material, anti-reflective coating materials, Nano technology and organic polymers have contributed to the greater saving in the cost and rapid production. Various factors influencing the performance of the solar energy system were discussed and few of the experimental measures to improve the performance were presented and compared. The practical mass production with such implements needs the greater support and finance. Solar cell efficiencies of devices using Perovskite structured compound materials is the new practice and noticed an increase from 3.8% in 2009 to 22.1% in early 2016. The potential of achieving even higher efficiencies at a very low production costs from the Perovskite solar cells has become commercially attractive for the start-up companies early in the market by 2017.

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