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# OVERVIEW AND PERFORMANCE ENHANCEMENT OF UNABRIDGED THIN FILM SOLAR CELL

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## Abstract

Solar cell designing and fabrication has always fascinated researchers, physicists, scientist and engineers of photovoltaic industry. Scientist seek solution to mend the efficiency and design of thin film solar cells. This paper illustrate the comprehensive overview of thin film solar cells and their structure. Furthermore various categories of thin film solar cells, strength and weakness of solar cells and techniques to enhance the efficiency of solar cells are also discussed in this paper. Thin film solar cell technology belongs to second generation of solar cells and fabricated by depositing layers of thin film of photovoltaic material on a substrate. Most prosaic substrate used to fabricate thin film solar cells are metal, plastic and glass. Thin film solar cells are much compendious as compared to their rival crystalline solar cell technology. The size of thin film solar cell diverges from few nanometres to ten micrometers. Review suggests that III-V semiconductor such as Gallium Nitride and Gallium Arsenide are endowed with many attractive properties for fabrication of thin film solar cell. Hetero-junction thin film solar cells hold much higher efficiency compared to homo-junction thin film solar cells owing to their high optical raptness.

**Keywords:** Hetero-junction, Solar cell, thin film, P-N junction

## 1. Introduction

Energy impasse is the most challenging dilemma of twenty first century. Photovoltaic cells are gaining attention due to their low cost solution to energy shortage. Solar cells are also beneficial for economy and environment of developing countries. Solar cells are the most promising candidate to overcome energy crisis as solar energy is available extensively. Global demand of energy is increasing due to fact that energy requirement is proportional to economic growth of a country. International Energy Agency(IEA) estimates that 2.6 % of world's energy is generated by renewable resources such as wind, solar and tidal energy [1]. Annual world growth of renewable energy trends shows that solar cells have 46.2% [1] growth as compared to other rival technology as revealed in the figure 1.

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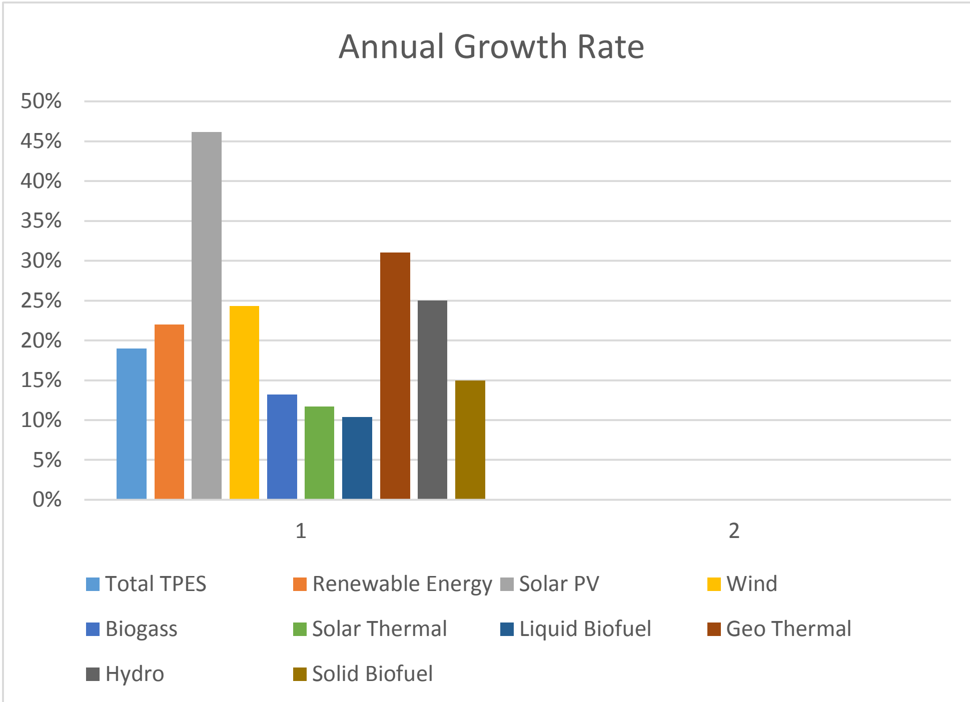


**Figure 1: Annual growth rate of world renewable resources from 1999 to 2014.**

World market energy consumption report estimates that consumption of energy will be increased by 44% [2] from 2006 to 2030 as shown in the figure 2.

Solar irradiance is the solar power per unit area received by the earth from sun [3]. Unit of solar irradiance is KWh/m2 .Pakistan has a lot of potential of solar irradiance. In Pakistan, average solar irradiation varies from 3.3 KWh/m2 to 7.2 KWh/$m^2$ [4] as compared to Germany which has solar irradiance of 2.5 KWh/m2 to 3.2 KWh/$m^2$. Solar irradiance are measured at 1.5 AM and 25 $^oC$.

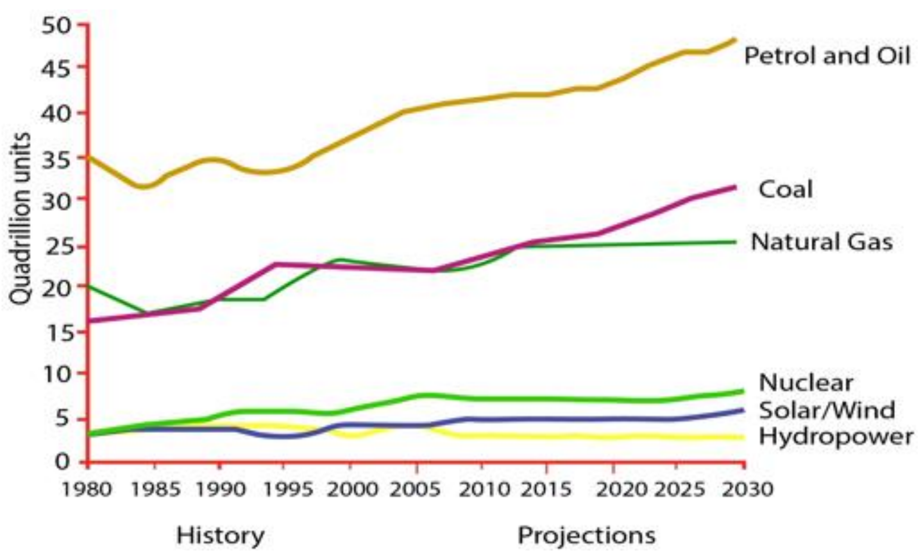


**Figure 2: Consumption energy from 1980 to 2030**

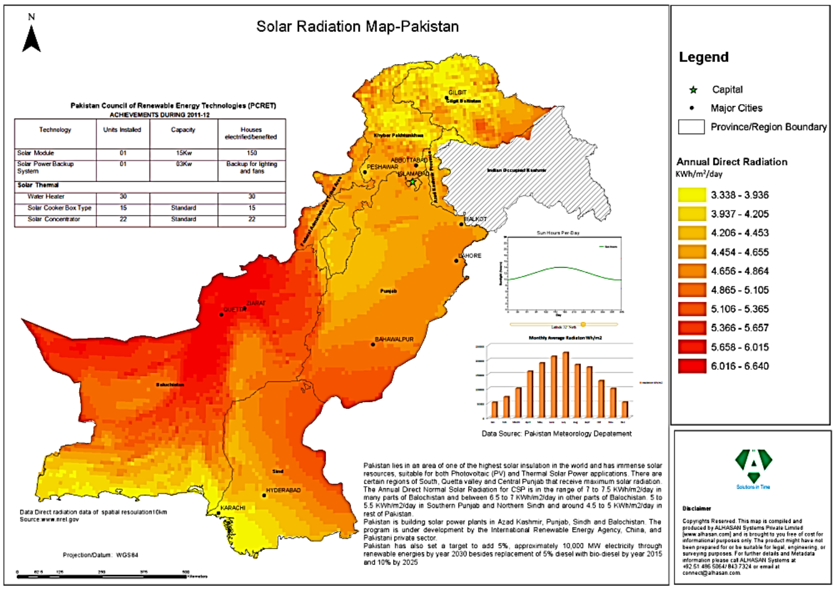


**Figure 3: Solar irradiance in various region of Pakistan**

## 2. Working and construction of solar cell

Typical solar cells are available in two common structures. A) p-n Junction B) p-i-n Junction

### *2.1.P-N Junction*

Basic interface of p-n junction is designed within same semiconductor crystal having p and n electrical conduction contiguously. If this junction is within one semiconductor then junction is called as homo-junction [5] and if junction is formed between two different semiconductor materials then the junction is called as hetero-junction [6]. The energy band diagram for homo-junction is shown in figure 4. Energy band diagram has slope [7] which is equal to

$$E = -\frac{dV}{dX} \qquad (1)$$

This slope represents innate electric field which is available in semiconductor devices. This region is commonly known as depletion region and it is the most crucial region of semiconductor devices [8].

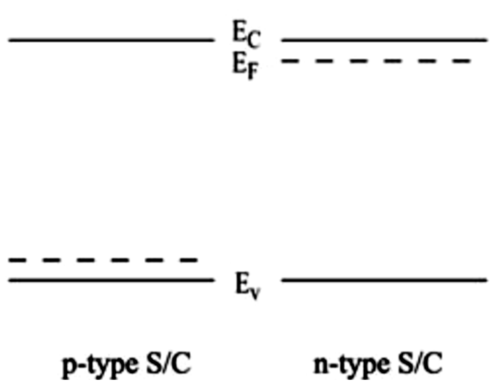


**Figure 4: Band gap diagram of p-n homo-junction**

When energy of photons incident on depletion region is greater than bandgap energy of semiconductor, incident photons are riveted by atoms and create electron hole pairs [9]. The built in electric field within semiconductor will keep separate opposite photo generated charges. Thus in order to improve photovoltaic phenomena a strong depletion region with loftier electric field should be used. Semiconductor material with high optical absorption properties should be used for maximum output [10].

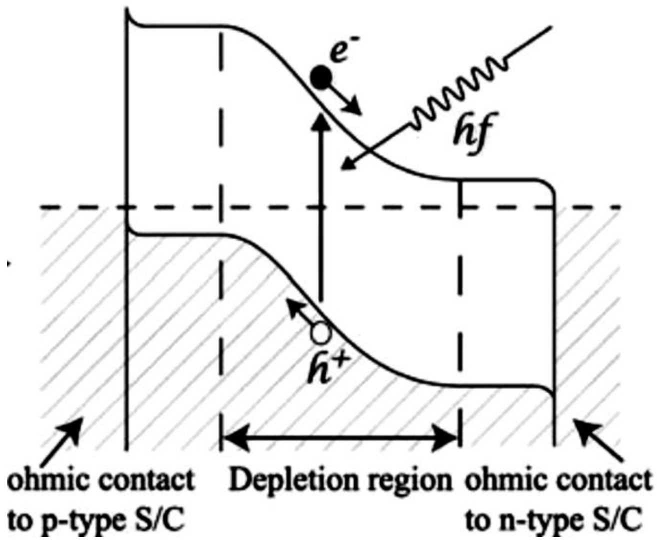


**Figure 5: Photovoltaic activity within p-n homo-junction**

## 3. Solar Cell Efficiency

Transformation efficacy of the solar cell is the most important parameter to appraise performance of every solar cell. Cell with high conversion efficiency and cheaper cost are desirable. The transformation efficiency of solar cell is given by equation 2.

$$\eta = (Voc.Jsc.FF)/Pin \qquad (2)$$

Where,

$\eta$= Efficiency of solar cell

Voc= Open circuit voltage

Jsc=Short circuit current density

Pin= Power input to solar cell

Solar cell efficiencies of various solar cells [5] are given in figure 6.

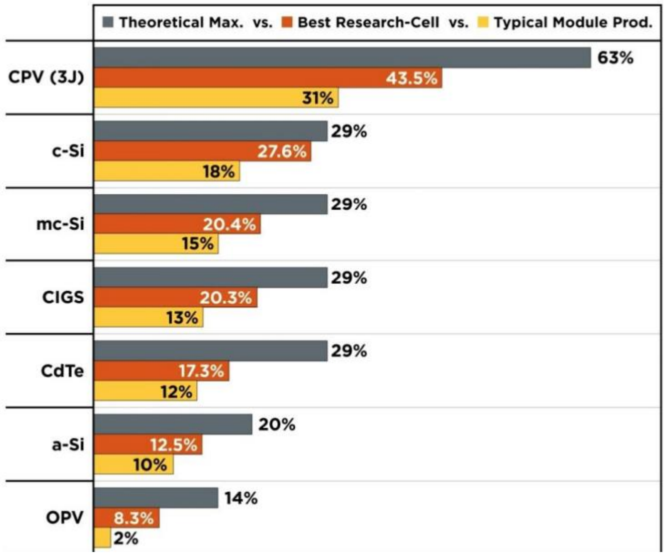


**Figure 6: Thin film solar cell efficiencies achieved from 1980-2015**

Different types of p-n structure solar structures are discussed as follows.

*3.1. Fabrication of Silicon P-N junction solar cell with zinc oxide layer with Al doping*Front contact layer of solar cells is the most imperative parameter to enrich the efficiency of solar cell. Vertically aligned Si arrays were designed to fabricate radial p-n junction [11]. Aluminium doped zinc oxide was deposited to improve light trapping mechanism. The technique used for deposition is atomic layer deposition technique (ALD). For this cell thickness of aluminum doped zinc oxide varied from 15 nano-meters to 80 nano-meters for optimum results. Best results were achieved at thickness less than 48 nano-meters. Optimum value of current density achieved is 22.2mA/cm$^2$ and sample had maximum efficiency of 5.6%.

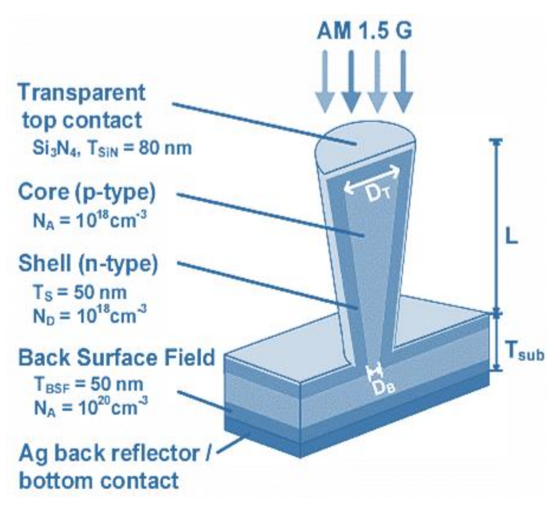


**Figure 7: Asymmetric p-n junction solar cell**

*3.2. Thin film silicon based solar cell with asymmetric p-n junction*

In order to improve solar cell electrical properties an asymmetric p-n junction[12] was proposed. Bottom core diameter is shrinkage to radial structure as shown in figure 6. Due to radial structure light trapping mechanism was improved. The asymmetric p-n junction has 10% more efficiency and current density as compared to symmetric p-n junction.

*3.3. Light trapping mechanism and solar energy harvesting using 3d photonic crystal*

Light ensnaring capabilities of solar cell can be enhanced by 3D photonic crystals [13]. No Metallic mirror is needed for absorption and silicon layer of 1 micron is needed for fabrication. Parallel-to-interface negative refraction (PIR) effect is used for light trapping. Features of photonic crystals are slow group velocity modes and enriched electromagnetic density of states. The structures provide supreme light absorption inclined at angle 0 to 80 degree. The structures have ability to absorb 75% of light incident on it. Photonic crystal solar cell is revealed in figure 8

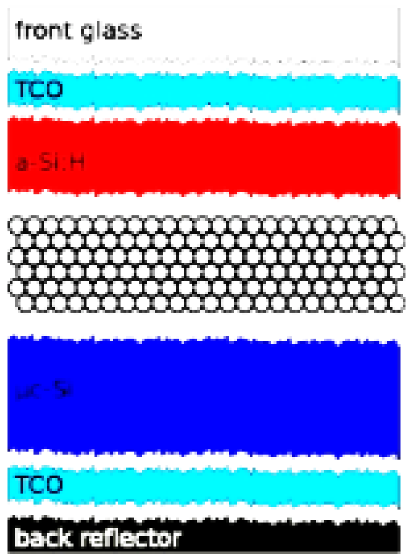


**Figure 8: 3D Photonic crystal solar cell and fill factor of the solar**

*3.4. Homo-junction CIGS solar cell*

Efficient solar cell based on Cu(In,Ga)Se2 (CIGS) was presented[14]. A homo-junction structure had an efficiency of nearly 17.2%. Thickness of n-CIGS was improved with doping concentration of 10-6 cm-2. Optimum value for n-CIGS achieved is 70 nano-meters. The structure of homo-junction CIGS solar cell [14] is shown in figure 9

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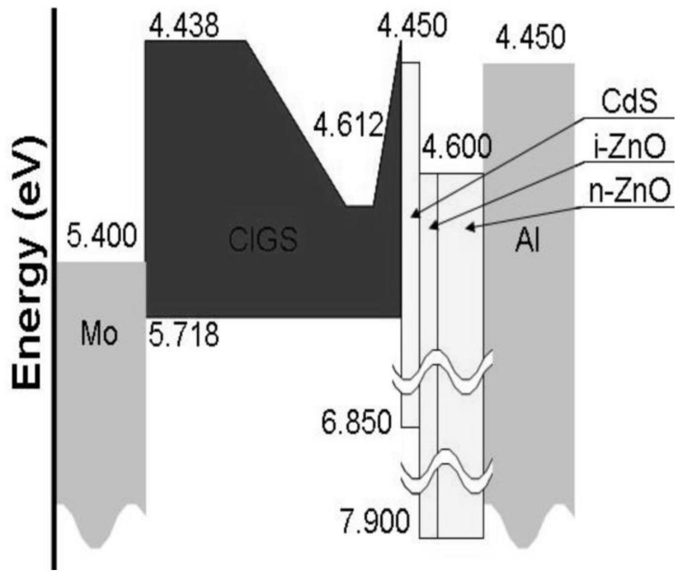



**Figure 9: CIGS homo-junction solar cell**

*3.5. BaSio2 based thin film solar cell*

An innovative solar cell was proposed with B-doped p type layer of BaSiO2 was grown with molecular beam epitexay. The structure was grown on Si(111) substrate. The average B-doping was achieved 4 x 1019 /cm3. The temperature for fabrication was 800ºC. The homo-junction solar cell structure [15] was shown in figure 10.

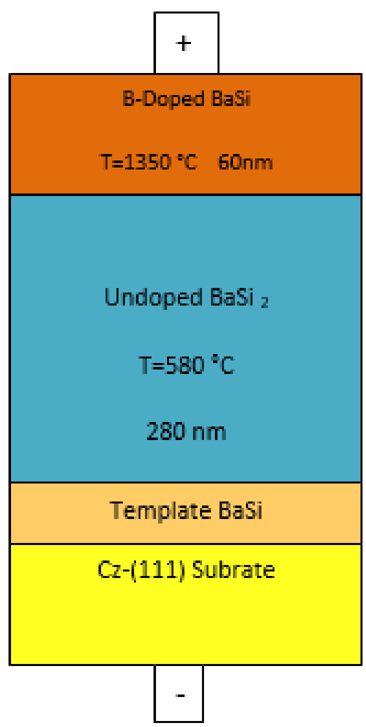



**Figure 10: B-doped BaSiO2 based p-n junction solar cell**

*3.6. Atom-probe tomography for CIGS based solar cell*

In CIGS based solar cell Cd and impurity distribution was improved by using atom-probe tomography [16]. Advantage of atom-probe tomography was that it operates at low annealing temperature of 250 to 300 $^{o}$C. Segregation of p-n junction was enhanced by this technique.

## 4. P-I-N Junction

Doping concentration determine the properties of depletion region. Low doping concentration will create a wide depletion region and high doping concentration produces a shrill depletion region. Physicists and material scientist are working to find optimum value of concentration to achieve prime thickness of depletion region[9]. The quest of optimum thickness of depletion region led to discovery of p-i-n structure. In p-i-n structure intrinsic semiconductor is sandwiched between n and p type semiconductor material. Energy band diagram of structure is shown in figure 11.

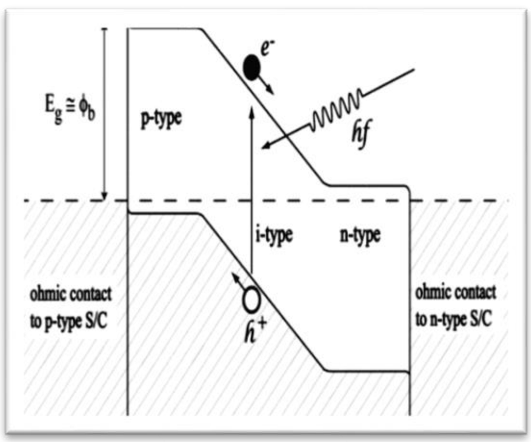



**Figure 11: Photovoltaic mechanism in p-i-n structure**

The purpose of this arrangement is to align the Fermi level of semiconductor material. The thickness of intrinsic layer will control the size of depletion region. These p-i-n structures are used to produce high barrier potential. Different p-i-n solar cells are discussed as follow.

*4.1. InGaN solar cell with P-I-N and N-I-P structure*

We know that acceptor layer was easy to activate so p-i-n structure was more superior as compared to n-i-p structure. Electric field create barrier for photocurrent which impedes the performance of device. Ga faced n-i-p structure of solar cell was proposed. The electric field was managed in such way that it will help photocurrent. The p typing doping of cell is 5 x 1017 cm-3 and n type doping is 1 x 1018 cm-3. The intrinsic layer has thickness of 126 nanometer. The simulated result proved that n-i-p layer have superior results as equaled to p-i-n structure [17].

*4.2. Amorphous silicon carbide p-i-n solar cell*

Due to amorphous nature of SiC defects are induced in solar cell fabrication [18]. The defects are removed by hydrogenation. Further defects in intrinsic layer of p-i-n solar cell were removed by photo-thermal deflexion spectroscopy technique. The structure of p-i-n SiC solar cell was shown in figure 12. Intrinsic layer was optimized at 500 nano-meters. Optimum value of band gap is 2eV.

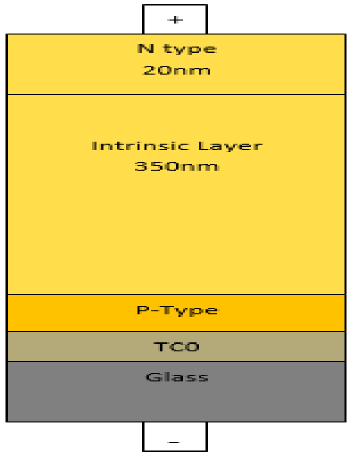



**Figure 12: SiC: H p-i-n solar cell**

*4.3. Silicon based p-i-n solar cell*

Modelling of p-i-n silicon based solar cell was performed [19]. The optimization was obtained by considering doping concentration, light trapping mechanism and temperature. Superior result was achieved with 25.84% efficiency and 90.13% fill factor. Lattice constant, permittivity and electron and hole density of states are considered for solar cell. The p-i-n structure silicon solar cell[19] was shown in figure 13.


**Figure 13 (a): p-i-n Silicon based solar cell**

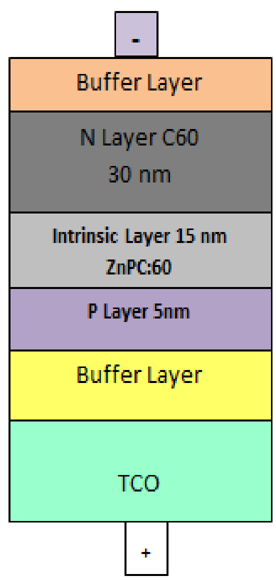



**Figure 13 (b): Germanium based p-i-n solar cell**

*4.4. Germanium based p-i-n solar cell*

Germanium based p-i-n structure was modeled and simulated [20]. P type material doping concentration was fixed and n type doping was change to get optimized results. Superior result was achieved with 26.04% efficiency and 89.63% fill factor. The structure was shown in figure 13(b)

*4.5. p-i-n amorphous silicon solar cell with combination of silver and gold plasmonic nano-particles*

Gold and silver nano-particles was used to improve the enactment of amorphous silicon solar cell [21]. On top of solar cell 80 nano-meters of gold and silver nano-particles was fabricated. These particles had improved the current density of the solar cell from 4.53 to 4.59mA/cm$^2$. Nano-particles also improved efficient of the conventional amorphous silicon solar cell from 2.37 to 2.41%.The plasmonic nano-particles [21] was helpful in light trapping mechanism as shown in figure 15.

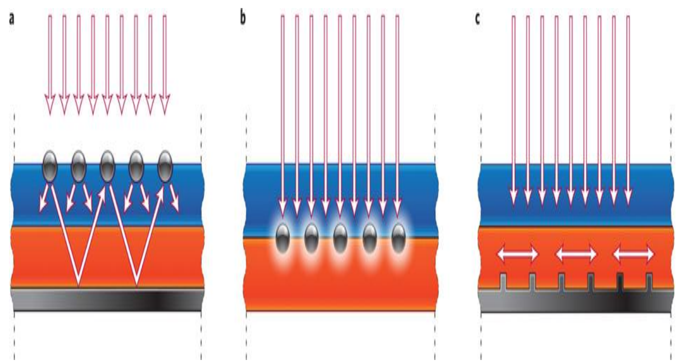



**Figure 15: Scattering of light within cell due to nano-particles**

## 5. Hetero-Junction Solar Cell

A hetero-junction has two different semiconductor material at the interface of p-n junction. Using two different semiconductors of different optical properties will allow large spectrum to be absorbed by the solar cell [22]. III-V compound such as gallium nitride and cadmium telluride are frequently used for hetero-junction cell fabrication. The energy band diagram of hetero-junction structure is delineating in figure 16. Various types of hetero-junction solar cells are discussed as follow.

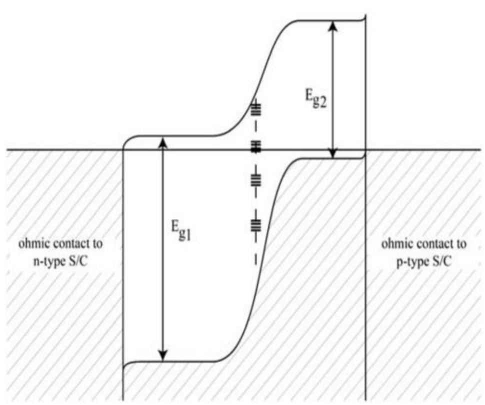



**Figure 16: Band diagram of p-n hetero-junction**

*5.1. Novel high efficiency hetero-junction silicon solar cell*

Nano composite plasma deposited amorphous silicon sub oxide for surface passivation combined with high quality micro crystalline silicon [23]. A p+/n+ structure was proposed. Superior quality hetero-junction solar cell was fabricated by passivation properties of amorphous silicon sub oxide which prevent recombination at hetero-interface. Doped high transparent layer had improved the open circuit voltage to 0.702 volts. Structure of solar cell is delineating in figure 17.

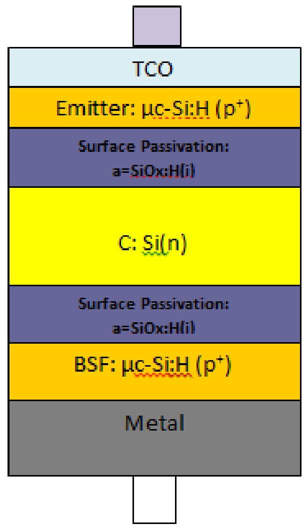
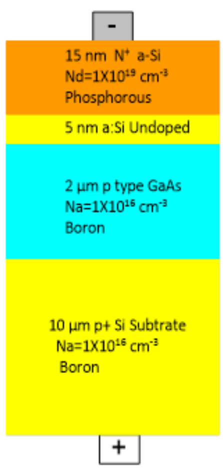



**Figure 17: Surface passivized hetero-junction silicon solar cell**

*5.2. Amorphous silicon/crystalline gallium arsenide/crystallin silicon heterojunction solar cell*

A hetero-junction thin film solar cell was presented. A-Si/c-GaAs/c-Si structure was proposed[24]. Minority carrier life time of gallium arsenide and its thickness was the main focus to rally the recital of solar cell. The solar cell was compared with silicon based solar cell. Results show that open circuit voltage was 0.8 V for gallium arsenide and 0.68 V for silicon solar cell. Current density of gallium arsenide was 1.4 mA/$cm^2$ more than silicon solar cell. The solar cell is delineating in figure 18.



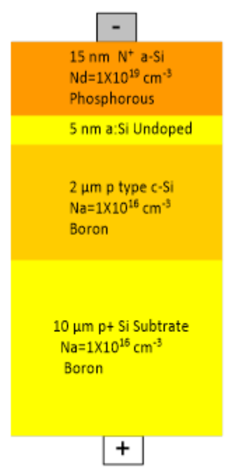




**Figure 18: a-Si/c-GaAs/c-Si** **b) a-Si/c-Si/c-Si**

*5.3. Efficient hetero-junction silicon solar cell in p and n type wafer*

Hetero-junction silicon solar on n and p type wafer was proposed [25]. This solar cell had high potential front and rear emitter. It was demonstrated that silicon solar cell on p type wafer have reduced minority carrier lifetime which caused decrease in fill factor. Passivation's of layer was performed to minimize the reduction of fill factor. Open circuit voltage for n type wafer was 0.732 V and for p type wafer was 0.693 V. Hetero-junction solar cell on p type wafer had an efficiency of 22.14% and on n type wafer have efficiency of 22.38%. Maximum efficiency can be achieved using p type wafer. The schematic of two solar cells are shown in figure 19(a) and 19(b).

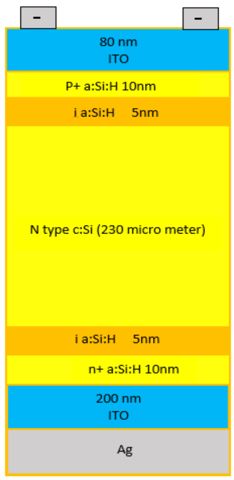



**Figure 19(a): Silicon solar cell on n type wafer**

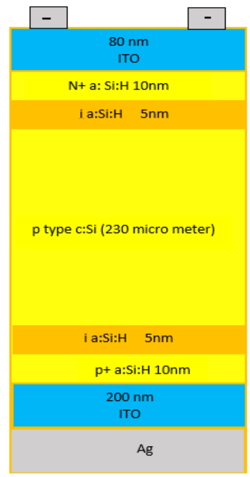



**Figure 19(b): Silicon Solar cell on p type wafer**

*5.4. Optically enhanced hetero-junction based silicon solar cell with silicon carbide as an emitter*

Silicon with p type hydrogenated amorphous silicon carbide was compared with p type hydrogenated amorphous silicon [26]. Amorphous silicon is extensively deployed as an emitter material for hetero-junction silicon solar cells. It was demonstrated that parasitic absorption loss and reflection losses are reduced by using hydrogenated amorphous silicon carbide. The use of amorphous hydrogenated silicon carbide increased the current density up to 1 mA/cm$^2$ as compared amorphous hydrogenated silicon. Short circuit current density of 40.3 mA/cm$^2$ and efficiency of 20.8% was achieved using amorphous hydrogenated silicon carbide.

*5.5. Gallium nitride based hetero-junction thin film silicon solar cell*

N type gallium nitride and hetero interface of p type silicon was proposed [27]. This novel design had improved light reception as gallium nitride has high band gap energy. The gallium nitride and silicon based hetero-junction solar cell shown superior result of 17.5% and current density of 30.12 mA/cm$^2$. The solar cell has an area of just 4.54 micrometer square. The gallium nitride based silicon solar cell structure was shown in figure 21(a).

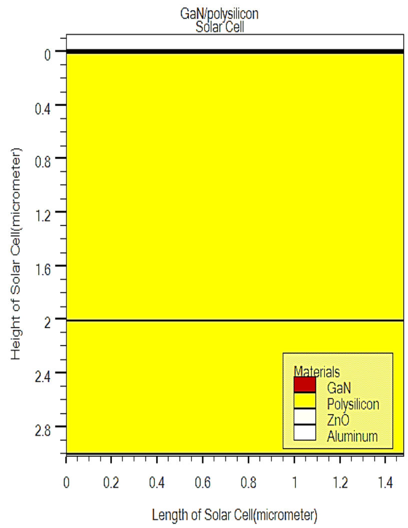



Figure 21(a): GaN based Si solar cell

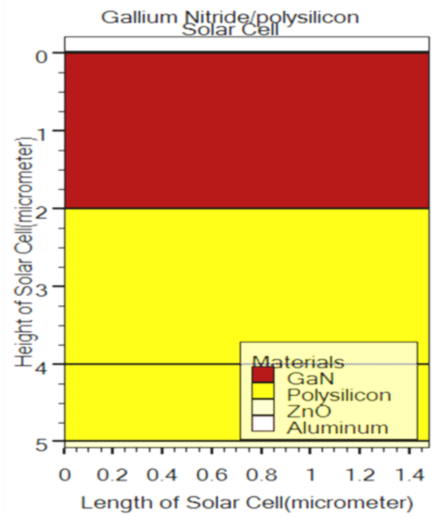



Figure 21(b): GaN based Si solar cell

The same cell was further optimized to improve the efficiency of solar cell to 26.67% [28].This efficiency was achieved by having optimum value of intrinsic layer at 7 micrometer. The cell structure was shown in figure 21(b).

## 6. Commercially available thin film solar

Alta device has fabricated the GaAs based thin film solar cell with efficiency equal to 27.6% under 1.5AM illumination [29]. This device has record efficiency under non concentrated sunlight. The device was fabricated on flexible substrate. The semiconductor device has open circuit voltage of 1.017 V, short circuit current density of 29.6 mA/cm$^2$.The fabricated solar cell has a fill factor of 84.1%.

### *6.1. Gallium Arsenide Based Thin Film Solar Cell*

Alta device has fabricated the GaAs based thin film solar cell with efficiency equal to 27.6% under 1.5AM illumination [29]. This device has record efficiency under non concentrated sunlight. The device was fabricated on flexible substrate. The semiconductor device has open circuit voltage of 1.017 V, short circuit current density of 29.6 mA/cm$^2$.The fabricated solar cell has a fill factor of 84.1%.

### *6.2. Cadmium Telluride Based Thin Film Solar Cell*

First solar has fabricated cadmium telluride thin film solar cell that has achieved 18.6% record efficiency. Fill factor has an efficiency of 74.2% [30]. The short current density achieved is 1.533 ampere.

### *6.3. Perovskite Thin Film Solar Cell*

Formamidinium lead iodide (FAPbI3) has high band gap energy and perovskite cell was proposed based on it has conversion efficiency of 20%[31]. Perovskite solar cells are distinctive type of thin film solar cells in which dense layer of (FAPbI3) was deposited.

## 7. Conclusion

Scientists and researchers has made considerable progress in eminent field of thin film solar cell. The cost of solar cell is dwindling and efficiencies of solar cells are enhanced by the efforts of scientists and researchers. Progress in thin film solar cells and fabrication technique drastically reduces the cost of thin film solar cells. New design technique such as radial p-n junction, plasmonic nanoparticles and perovskite solar cell are evolved to improve the efficiency beyond the theoretical limit of Shockley-Kaiser limit. GaAs thin film solar cell commercially fabricated by Alta Devices has highest conversion efficiency of 27.6%. In perovskite solar cells, Formamidinium lead iodide (FAPbI3) based solar cells have maximum efficiency of 20%.

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