Victor Du John H, Jackuline Moni D*, Gracia D

Department of Electronics and Communication Engineering, Karunya Institute of Technology and Sciences, Coimbatore, India.
*Corresponding Author, moni@karunya.edu

doi:10.15199/48.2020.12.02

A detailed review on Si, GaAs, and CIGS/CdTe based solar cells and efficiency comparison

***Abstract**. A solar cell is technically known as a photovoltaic device which converts light energy into an electric energy by the phenomenon called photovoltaic effect. Solar cells produce renewable energy and serve as a great substitute for conventional sources of energy such as petroleum, coal and natural gas. Solar cell is suitable for powering satellites due to its light weight and durability for several years, having ability to operate even in the vacuum space. It is also used in solar warm air electric power plants and every other PV powered devices ranging from heating systems, lighting, automobile to solar updraft towers and etc. It is of utmost demand to support research and development of renewable energy resources that would successfully power the world in the future without destroying the environment as the planet earth needs reduction in greenhouse gas emission. Immense progress has been observed over the years on several photovoltaic materials and devices based on conversion efficiencies.. This survey primarily focusses on different techniques and technologies analysed from the other cited references to enhance the working of a solar cell like selection of the most suitable material for each layer, various processing techniques and modifying the layer thickness of buffer. This review paper summarizes solar cell materials like Gallium Arsenide (GaAs), Silicon (Si), Cu(In,Ga)(S,Se2) (CIGS) and Cadmium Telluride (CdTe) that provide higher efficiencies when compared to other materials. In summation, it is understood that Gallium Arsenide solar cell provides highest efficiency when compared to Si, CIGS and CdTe based one junction solar cell. Factors such as, efficiency (η), open circuit voltage (Voc), short circuit current density (Jsc) & fill factor (FF) have been analysed for the study of modeling, simulation and fabrication of solar cell. Detailed survey has been presented in this paper on different types of solar cells that would help the researchers to do more research on these solar cells.*

***Streszczenie.** W artykule dokonao przeglądu i porównania różnych technologgi ogniw fotowoltaicznych. Przedstawiono ogniwa krzemowe, ogniwa bazujące na CdTe i CIGS oraz ogniwa bazujące na Gallium Arsenide (GaAs). W każdej grupie przedstawiono I porównano osiągane obecnie parametry I właściwości. (**Przegląd ogniw fotowoltaicznych bazujących na Si, GaAs, i CIGS/CdT p porównanie skuteczności**)*

Keywords: Si, CIGS, CdTe, GaAs, Solar cells, Single junction
Słowa kluczowe: ogniwa fotowoltaiczne, , Si, CIGS, CdTe, GaAs

Introduction

An important goal of a solar cell industry is to achieve cost effective and self-sustainable production of electricity. Figure 1 projects the potential use of various renewable energy sources including solar energy reported by (Connolly, 2012). By the year 2050 solar and wind energy will play a crucial role in the energy sector. Consumption of power from renewable sources is likely to become the main stream through designing of making low cost and high performance systems compared to other energy sources. In order to meet the global clean energy demands, it is essential to harvest maximum amount of solar energy from the sun. This needs solar cell design with a higher efficiency. Solar cells produce renewable energy and are thus a great substitute for conventional sources of energy such as petroleum, coal and natural gas. Solar cell is ideal in powering satellites as it is light weight, it lasts for years and it also works in the vacuum of space. It is also used in solar warm air electric power plants and every other PV powered device from heating systems, lighting and cars to solar updraft tower, etc. It is of utmost requirement to support research and develop renewable energy resources that would power the future sufficiently without damaging the environment- caused mainly because of greenhouse gas emission and thereby achieving cost effective sustainable production of electricity. It is expected to take over the main stream when its cost and performance become comparable with other energy resources. In order to meet the clean energy global requirement, it is essential to harvest incident photon with higher efficiency.

Solar cells are proficient to yield maximum energy if exposed properly to the sun. It is noticed that the first solar cell in the name of photovoltaic cell was designed by (Fritts, 1883). This solar device is fabricated by creating a gold (Au) metal coated over selenium (Se). The device achieved around 2% of light to electric energy conversion. Since then tremendous amount of research has been carried out to develop cost effective and highly efficient solar cells. The work done on Selenium based solar cell leads to the path of finding other materials for photo sensors that become electrically conductive when it absorbs light. In the middle of the 20th century, a substantial amount of power had been successfully generated by photovoltaic cells using crystalline silicon substrate.

To achieve preeminent electrical parameters, the design of solar cell should be well engaged with proper absorbers or any metamaterial based absorbers and also the selection of materials plays a major role in boosting the solar cell efficiency. The forthcoming chapters shows more impact on these concepts.

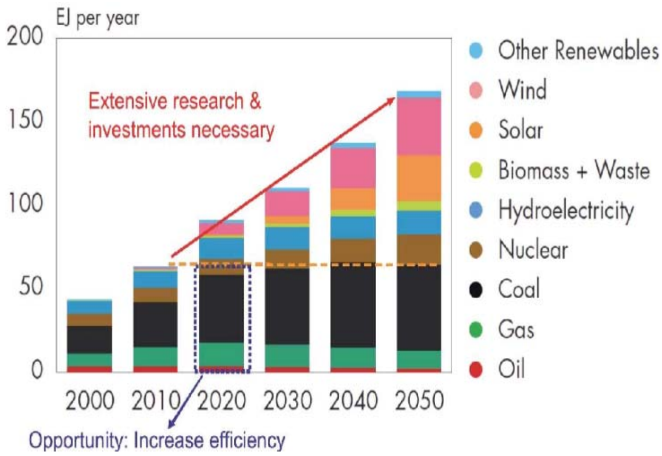

Fig.1 Potential of renewable energy sources (Mohamed, M.H. (2011). Design optimization of savonius and wells turbines.)

Evolution of Solar Cells

The evolution of technology used in solar cells is defined in terms of the type of materials used in the device. The evolution of solar cell technology can be summarized as three major generations. All three generations have undergone rigorous research at the same time in order to improve efficiency. In the year 2007, the silicon based first generation solar cells were accounted for 89.7% of commercial power production reported by (González & Antonio, 2013). Figure 2 depicts the detailed classification of solar cells with three generations named first, second and third generations of solar cells.

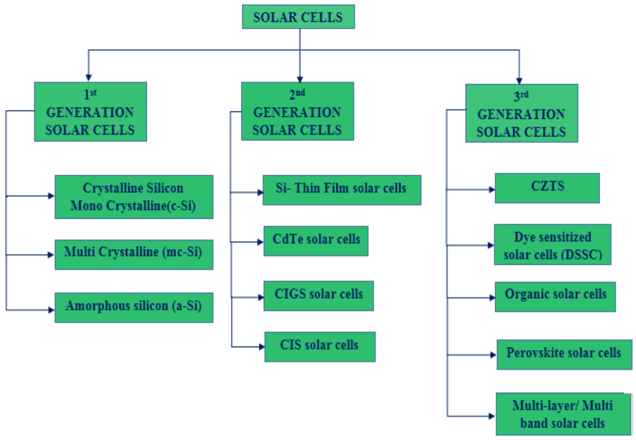

Fig.2 Classification of solar cells

First generation solar cells

First generation solar cell uses crystalline silicon (c-Si) which are classified as poly crystalline silicon (poly c-Si) and or mono crystalline silicon (mono c-Si). Poly crystalline (Poly c-Si) consists of random distribution of lattice structure in the crystal and (mono crystalline silicon) which is of continuous lattice distribution of the silicon crystal. Sometimes a non-crystalline silicon (amorphous silicon / a-Si) is also used in solar cells to boost the device performance.

Second generation solar cells

Second generation solar cells uses thin-film semiconductor substrates by doping one or more thin layers of silicon, gallium arsenide or metal. Today the commercial thin film solar cells are used in several technologies including CdTe, CIGS, and TF-Si. Thin film solar cells does not need silicon wafers to fabricate, however it distinctly uses 1μm to 4μm sized thin layers deposited on a huge economical substrates namely glass, polymer, or any metal (C. H. Huang et al., 2002).

Third generation solar cells

Third generation solar cell uses sensitized structures named as dye sensitized solar cells (DSSC), quantum dot materials and perovskite based polymer solar cells. These types of materials are used in solar cells as an absorber layer which is one of the most important layer used to absorb the light for energy harvesting (Mingsukang & Arof, 2017).

Silicon Solar Cells

About 95% of Solar cells around the world are composed of Silicon. The utmost common bulk material for photovoltaic cells is crystalline silicon also referred to as "Solar grade silicon". Bulk silicon is divided into various groupings depending on their crystallinity and size of the wafer. The concept behind these cells is pn- junction. C-si solar cells wafer thickness range between 160 and 240 micrometers.

Solar cells composed of mono-Si is one of the most efficient and high expensive material than the other types of cells. The edges of the PV cells are in the shape of an octagon, since the wafer material is obtained from cylindrical ingots, these are grownup by Czochralski process. Solar PVs made of mono-si cells have characteristic pattern of tiny white diamonds.

This is also known as multi-crystalline silicon (multi-Si) huge sets of melted silicon cautiously chilled and hardened. These types of materials are composed of tiny crystals which gives the material a characteristic metal fragment effect. Poly silicon solar cells are the most commonly used cells in PV cells and these type of cells are less expensive, but less efficient than mono-crystalline silicon.

Review on Silicon Solar Cells

Silicon (Si) thin-film cells are mainly from silane gas and hydrogen gas deposited by CVD process. On the basis of deposition constraints, this can able to produce Amorphous silicon which can be called as (a-Si), proto-crystalline silicon or nano-crystalline silicon (nc-Si or nc-Si:H), also known as micro-crystalline silicon. An amorphous silicon (a-Si) having a band gap of 1.7eV which is higher than crystalline silicon (c-Si) (1.1eV), which indicates that it imbibes the observable part of the solar spectrum has more deeply than the higher power density IR portion of the solar spectrum. The manufacturing of a-Si thin film solar cells is done by (PECVD) in which the glass is used as a substrate and a very thin layer of silicon can deposited.

(Aissat, Benyettou, Nacer, & Vilcot, 2017) describes the PiN solar cell based on silicon exhibits a Jsc of 23.55 mA/cm2 and Voc of 0.53V. It is understood that Jsc increases with increase in the number of quantum well layers since the majority of electron hole pairs are absorbed by quantum wells of Silicon and germanium (SiGe) whereas, the Voc residues almost constant. It is also understood that the power and conversion efficiency of the device increases with the increase in the quantum well layers.

(Zhou, Chung, Wang, & Bermel, 2016) found the potential efficiencies of up to 46% were obtained by a photovoltaic system which conglomerates the tools of cadmium telluride and silicon into a single platform. The highest efficiencies obtained by these tandem cells so far are 16.8%. A detailed model of CZT and CZT/c-Si are developed and verified using experimental data.

(Masuko et al., 2014) discussed an approach for exceeding the conversion efficiency of 25% the crystalline silicon heterojunction cells adopted the structure of an inter digitated back contact to lower optical loss from a front grid electrode, a transparent conducting oxide (TCO) layer and a a-Si:H layer. Hence, this resulted in an improved short-circuit current (Jsc) the crystalline silicon achieved world's largest efficiency of 25.6% under 1-sun illumination. After defining the structure of the solar cell the current–voltage (I–V) characteristics were evaluated by the National Institute of Advanced Industrial Science and Technology (AIST). Later, the characteristic parameters of solar cell were also obtained.

(Nakamura, 2017) used a back contact and an amorphous silicon thin film technology in heterojunction back contact (HBC) structure silicon solar cell an energy conversion efficiency of 25.1% was obtained. The fabrication of HBC cell was done by a new patterning process. The unique technology of the super mount technology concept additionally added up to the superior performance of the HBC cell. The values obtained for short circuit current density (Jsc) and open circuit voltage (Voc) were 41.7 mA/cm2 and 736 mV respectively. The strength of HBC structure is determined by the high Jsc as well as high Voc.

(Meillaud, Shah, Droz, Vallat-Sauvain, & Miazza, 2006) developed a thermo-dynamical considerations and semi-empirical considerations on radiative recombination and classical diode equations respectively established certain limitations of single-junction and tandem p-n and p-i-n diodes with an optimum combination of tandem solar cells with an efficiency limit of 35%.

(Needleman, Wagner, Altermatt, & Buonassisi, 2016) developed a 3D based model on the polycrystalline materials the grain boundaries degrade the performance of the solar cells; yet, device modeling occasionally accurately is responsible for all their effects or their spatially localized nature. To determine the effect of grain boundaries on the performance of the silicon solar cells we use 3-D technology computer-aided design (TCAD).

(Chavali, Johlin, Gray, Buonassisi, & Alam, 2016) developed a challenge to broad adoption of this technology is the cell-to-module efficiency gap analyzed in a-Si/c-Si heterojunction solar cells. (Rahman & Boden, 2017) experimented to improve solar cell efficiency to model black silicon is a favorable approach by texturing the surface with both micro and nanoscale features. (Arefinia & Asgari, 2018a) developed a physics based device model imbibed with optical characteristics of FLG and SiQDs here the output parameter short-circuit current density increases when the band gap improvement in open-circuit voltage for FLG/SiQDs/Si structure. Here the mono-layer and 6-layer grapheme produced the highest efficiency of FLG/SiQDs/p-Si and FLG/SiQDs/n-Si, respectively. Further, by decreasing the size of SiQDs due to the quantum confinement effects the efficiency of FLG/SiQDs/Si solar cells could be improved.

(Čampa et al., 2018) examined an optical and electrical simulations of a back-contact silicon heterojunction solar cells were reported and the sensitivity of the same design was studied. The silicon heterojunction solar cell consisting of metal fingers at the front and back simulated in a 3-D optical simulation method. Specular illumination and Lambertian diffuse illumination were applied. And combined the 3-D optical simulations with 2-D electrical simulations with a multi scale technique.

(Fell et al., 2018) developed a modeling edge recombination in silicon using a new approach is demonstrated. The model is responsible for recombination both at the edge of the quasi-neutral bulk as well as at an exposed space-charge-region (SCR), the latter through an edge-length-specific diode property with an ideality factor of 2: a localized J02, edge. The J02, edge is applied to the edges of the three-dimensional geometry due to model implementation Quokka3; it imposes less simplified predictions compared to the usual way of applying it as an external diode. By fitting to entire detailed device simulations which determines a "worst-case" value for J02, edge assuming very high surface recombination which can resolve the SCR recombination.

(Mohammadnoor Imamzai et al., 2012) reviewed several materials and technologies are developed to create photovoltaic cells less expensively and with greater conversion efficiency. Silicon was the first material used to manufacture solar cell but has few disadvantages, high cost and low efficiency. Second generation of solar cell fabrication technologies is thin-film solar cells used to produce power electrical energy. Thin-film solar cells consists of various layers that help to reduce current losses because thin-film solar cells are produced based on higher efficiency as compare with traditional silicon solar cells. Here, comparison between thin film CdTe solar cells and traditional silicon solar cells is carried out.

(Hussain, Mehmood, & Ali, 2014) proposed a design of crystalline silicon based multi junction solar cells using thin film technology. In general, silicon has very low absorption rate and a low efficiency of 8%. But in the proposed work, nano crystalline silicon is used instead of amorphous silicon to form multi junction layers in the solar cell. This leads to a dual junction device improving the efficiency up to 10.2%. The absorber thickness was considered as an important factor to determine efficiency improvement.

(Meillaud et al., 2006) simulated a tandem solar cell using crystalline silicon to enhance the efficiency. The proposed structure reduces thermal loss associated with the cell. The proposed four layers solar cells arranged serially to achieve conversion efficiency up to 16% with thickness constraints on layers, Anti Reflection Coating (ARC), and etc. The authors preferred optimization techniques to improve the efficiency up to 19.29%. (Mingsukang & Arof, 2017) presented a review on efficiency losses in silicon based single junction and tandem solar cells. Normally efficiency is based on the amount of light absorbed in the surface of solar cell. As the absorption of light increases at the cell surface it increases the short circuit current density. It is known that in silicon solar cells efficiency drop occurs due to recombination effect in the intrinsic layer. The efficiency can be improved if the above factors are undertaken properly.

The solar cell obtained by (Masuko et al., 2014) consists of crystalline silicon hetrojunction structure results in greater conversion efficiency due to incomparably reduced recombination loss. An approach for exceeding the conversion efficiency of 25%, includes the crystalline silicon hetrojunction cells which adopts the structure of an inter digitized back contact to lower optical loss from a front grid electrode, a transparent conducting oxide (TCO) layer and a-Si:H layer. This improves the short-circuit current (Jsc) with a better efficiency of 25.6% under 1-sun illumination.

(Müller, Rech, Springer, & Vanecek, 2004), experimented different methods to lower the cost of photovoltaic cells. One of such method is to reduce the thickness of the solar cell. Thin-film solar cells improve efficiency incrementing the length of incoming light path which determines the device performance. The methodology focuses to trap maximum amount of light. A better scheme to trap the incoming light is implemented using Transparent Conductive Oxides (TCO) as a transparent front contact in solar cells such as silicon P-i-N.

(Meillaud et al., 2006) deals with the thermo-dynamical considerations and semi-empirical considerations on radiative recombination and classical diode equations respectively thereby establishing certain limitations of single-junction and tandem p-n and p-i-n diodes. The substantial values of Jsc, Voc, FF and η were compared with these limits for amorphous (a-Si:H) and micro-crystalline (μc-Si:H) silicon solar cells. Major efficiency gain for single junction solar cells is achieved by increasing short circuit current density (Jsc) through better light absorption. According to the work of (Rohatgi et al., 2017) a maximum of 23.8% efficiency is reported.

(Landis & Bailey, 1995) discussed the solar technologies used to enhance the efficiency of solar cell. Here the author found that, by including the solar concentrators in the design one can improve the efficiency of silicon solar cell up to 14% with gridded back contact. (Carlson, 1990) also discussed many techniques like solar concentrator, grid connections of cells, adding more junctions, etc. to improve the efficiency to the next level.

Table 1 Comparison of electrical parameters and efficiency of Silicon based solar cells.

References	Cell type	No of Layers	No of Junctions	Type	Jsc (mA/cm^2)	Voc (V)	FF (%)	η (%)	Advantages	Disadvantages
(Aissat, Benyettou, Nacer, & Vilcot, 2017)	P-i-N	80	Hetero junction	Si- Quantum well	37.48	0.62	76.82	18.14	Good efficiency Since it has more layers	More number of layers will costs high in all aspects
(Jankovec, Topič, & Herman, 2013)	PN	2	Hetero junction	diode model	7.2	0.59	69	12.5	Simple model	Less efficiency and complicated structure
(Arefinia & Asgari, 2018)	PN	3	1	Si-QD	54.24	0.30	62.87	10.3	Usage of QD	Less efficiency
(Davidson, Haque, & Toor, 2017)	PN	8	1	Multi band series type	12.69	1.466	91.25	16.98	Better efficiency	Using series of PN junctions to get better efficiency
(Masuko et al., 2014)	PN	Multi	Hetero junction	a-Si:H layer	41.8	0.75	83.2	25.6	Multi junction cell	More junctions will costs high in all aspects
(Zhou, Chung, Wang, & Bermel, 2016)	PN	Multi	1	Tandem cell	16	1.75	60	16.8	Multi junction cell	More junctions will costs high in all aspects
(Ali, Khan, & MatJafri, 2016)	PN	4	1	ARC & bsf	22.5	0.5	67	8.45	Simple model with some layer modifications	Less efficiency performance

Review on CdTe and CIGS Solar Cells

Copper Indium Gallium Selenide (CIGS) solar cell, also at times known as CI(G)S or CIS cell is a categorized thin film photovoltaic cell which is utilized to transform ultravioletlight into electrical energy. CIGS has a chalcopyrite crystal structure and is tetrahedrally bonded. It possesses notably an improved absorption coefficient of about 105 cm-1 for 1.5eV and higher energy photons. It exhibits high proficiency. The current efficacy of CIGS photovoltaic cell on a small area device is recorded as 21.7% (Mansfield et al., 2015). CIGS is advantageous than other conventional PV technologies because it yields a greater measured energy level, significantly displays a reduced temperature coefficient for power loss, decreased detectability to shadowing and short energy settlement time (Feurer et al., 2017). CIGS is a favorable substitute for Silicon due to its commensurable efficiency and production cost, which can be lowered considerably by utilizing economical substrates and foils made of glass and plastic respectively. Apart from its high efficiency and reasonable manufacturing cost, another advantage of preferring CIGS material for photovoltaic cells is that the material responsible for absorption wastage is minimized when contrasted to that of 1G solar cells (i.e. C-Si) because fabricating a solar cell requires only around 2mm thick CIGS absorber film. However, the cost of Indium used creates a setback in CIGS. The required amount of Indium to produce 1GW CIGS PV comes to around 31 tons by (Ramanujam & Singh, 2017).

Recently, an amended photocurrent in CIGS photovoltaic cells with a proficiency of 21.7% was reported. It records promising results with Voc of 717mV, Jsc of 37.2mA/cm2, and FF of 78.6%. Its key novelty includes alkaline Post-Deposition Treatment (PDT) of CIGS solar film, which was produced by the process of thermal co-evaporation of Copper, Indium, Gallium and Selenium. In the PDT procedure followed, the alkaline composition of CIGS cell was altered by the addition of alkaline essentials from the superficial adjacent of the film. The multi-junction was concluded with a fine buffer layer. The high photocurrent in CIGS solar cell was obtained by decreasing CdS buffer width and by including an enhanced steeper GGI parameters (Friedlmeier et al., 2015) and (Jackson et al., 2015).

Another approach of obtaining high photocurrent is making use of Zn(O, S) buffer. In this study, standard I-V analysis and External Quantum Efficiency (EQE) has been obtained. Microscopic film morphology was propertied by using high-resolution SEM (HR-SEM). To replicate photovoltaic cells with a model employing electrical contacts amidst CIGD/Mo and ZnO:Al-grid, SCAPS program was used. Ultimately, the model parameters were altered to suit the calculated I-V curve, C-V curve & EQE curve is a précised one for every possible actual devices. Another alternative for CdS as buffer material is ZnO. Post annealing and electro deposition is hypothetically a less cost industrial progress route for CIGS solar cells developed by (Malaquias et al., 2015).

The mandatory requirements to find a right and stretchy substrate to deposit thin film solar cells are its stability and compatibility through the total creation procedure and operative life-time of PV modules. Factors like vacuum compatibility, appropriate coefficient of thermal expansion, thermal stability, humidity barrier function, surface smoothness and chemical inertness also have to be considered for selection of a suitable flexible substrate and device. The pros and cons of using metals like Cu, Mo, Ti, Al, polymers and alloys like stainless steel are discussed in detailed by (Reinhard et al., 2013).

(Hosen, Bahar, Ali, & Asaduzzaman, 2017) describes the input conditions, connection layer information and working conditions for CIGS photovoltaic cell replication with ZnS memory layer.

Performance parameters were analyzed and the simulation results were obtained with values of Jsc as 34.87mA/cm2, Voc as 826.03mV, FF as 85.48% and η as 24.62%. The graphic diagram of CIGS PV solar cell is given in Fig. 1. The assembly forms a heap of materials Mo/CIGS/ZnS/i-ZnO/ZnO:Al/Al grid for modelling of CIGS solar cell. Soda lime and Molybdenum is used as back contact. To analyse the electrical and optical parameters and the performance of CIGS solar cell, a one dimensional online simulator, ADEPT 2.1 is used.

Table 2 CIGS/CdTe solar cell Comparison

References	No of Layers	No of Junctions	Type	Jsc (mA/cm^2)	Voc (V)	FF (%)	η (%)	Advantages	Disadvantages
(Sobayel et al., 2020)	5	1	CIGS	29.5	1.026	86.96	23.4	It has WS_2 as a window layer	More complex layer materials
(Morales-Acevedo, 2014)	6	1	CIGS	25.88	0.845	75.51	16.5	Good efficiency for single junction structure	More layers
(Matin, Mannir Aliyu, Quadery, & Amin, 2010)	7	1	Oxide contact	26.35	0.900	78.3	16.9	Good efficiency for single junction structure	More layers
(Fardi & Buny, 2013)	6	1	CdS/CdTe	28.45	0.917	75.99	19.83	Good efficiency for single junction structure	Combination of Cds/CdTe
(Safa Sultana, Bahar, Asaduzzaman, & Ahmed, 2017)	6	1	CdS/CdTe	34.40	0.946	75.72	24.66	Good efficiency for single junction structure	Combination of Cds/CdTe
(Nanayakkara, Horowitz, Kanevce, Woodhouse, & Basore, 2017)	12	Multi junction	CdTe/CIS CIGS/CIS	24.5	0.85	-	16.4	Good efficiency	More junctions will costs high in all aspects. Also it has CdTe/CIS CIGS/CIS combination of layers
(Song, Kanevce, & Sites, 2015)	5	1	CIGS/ InSb substrate	26.3	0.96	74.0	18.8	Good efficiency	CIGS/ InSb combination of layers
(Demtsu & Sites, 2005)	5	1	CdS/CdTe	27.0	0.9	79.5	19.0	Good efficiency	Combination of Cds/CdTe
(Xu, Wang, Gu, Quan, & Zhang, 2017)	6	1	CdZnS	25.468	0.922	75.4	17.71	Good efficiency	Using CdZnS material as absorber
(Kobayashi, Jehl Li Kao, Kato, Sugimoto, & Nakada, 2016)	5	1	Cd, Zn buffers	35	0.7	73	18	Good efficiency	Using Cd, Zn buffers
(Romeo et al., 2004)	5	1	CdTe/CIS	-	-	-	16.5	Good efficiency	Combination of Cds/CIS
(Gloeckler, Sankin, & Zhao, 2013)	4	1	CdTe	-	0.85	-	16	Good efficiency	CdTe absorber
(Nishio et al., 1996)	5	1	Cds/CdTe	25	0.84	74	15.8	Good efficiency	Combination of Cds/CdTe
(Ohyama et al., 1997)	5	1	CdS/CdTe	26	0.84	73	16	Good efficiency	Combination of Cds/CdTe
(Bachmann, Buehler, Shay, & Wagner, 1976)	-	1	InP /CdS	26	0.84	75	16.7	Good efficiency	Combination of Cds/InP

(C. H. Huang, Li, & Anderson, 2002) found CdTe is a polycrystalline semiconductor with very good light absorptivity. It is an outstanding material for thin films under low cost conditions compared to the conventional solar cell materials. In fact, CdTe material is a promising one to produce solar cells at low cost with a low efficiency of 13%.

(Tamboli et al., 2017) identified that it is very hard to achieve a better best efficiency rate in case of a single junction solar cell generic structure. The work looks for an alternative technology to improve the efficiency. The author proposes new structure called the tandem solar cells using CdTe and silicon materials together to reduce the cost incurred compared to that of CdTe alone. Here the CdTe material acts like an absorber layer. This layer is designed in TCAD software to improve solar cell efficiency. The individual efficiency of each cell is observed as 16% and the entire cell efficiency lies between 10% and 16%. This structure offers higher efficiency than the silicon solar cells but at the cost of material price and design complexity.

(Nanayakkara et al., 2017) evaluated the cost effectiveness and efficiency across CdTe/CIS and CIGS/CIS tandem solar cell models. Simulation results of the complex structure of these two tandem models provide an efficiency of 16.5% and 19.5% respectively. Here the CIGS/CIS combination produces better efficiency than other model comparatively. It is due to the high band gap in CIGS which is used for the absorption of solar energy. Though the efficiency is 19.5% is the performance improvement demands an increase in the cost upto 4% in case of CIGS/CIS material.

(Romeo et al., 2004) developed a CdTe heterojunction flexible solar cell where the absorber layer is made up of CdTe. CdTe has the highest absorption coefficient that leads to an efficiency of 16.5%. The work reports with CIGS material that the efficiency goes up around 16%. Here the CdTe is used at both substrate and superstrate levels nonetheless the highest efficiency is achieved at its superstrate level. Cells in superstrate level exhibit the highest efficiency of up to 16.5%. Initially the proposed design suffers from certain amount of non-linearity which causes initial performance difference between cell and module efficiency. The model incorporates sodium and molybdenum with CIGS as a combination and efficiency target for CdTe solar cell is increased from 16% upwards.

CIGS solar cell was reported by (Feurer et al., 2017) to have an efficiency of 22.6% for laboratory scale absorbers. It remarks the efficiencies of cell with CIGS absorber layer material achieved on rigid and flexible substrates by different research companies in detail. CIGS absorber layer can be produced by using co-evaporation technique, with selenization followed by sulfurization of precursors deposited by sputtering, electro-deposition or printing. The major challenge for these processes is that deposition and/or its consequent annealing temperature should not exceed -2000C in any step process. Both co-evaporation process and sputtering precursor with subsequent

selenization and sulfurization provide better performance of PV cell in terms of efficiency. Doping is one of the important factors of CIGS cell in achieving higher efficiency of the device. However at higher doping concentration levels, due to the reduction of minority carrier diffusion, the efficiency also decreases significantly was discussed by (Maragliano, Colace, Chiesa, Rampino, & Stefancich, 2013).

(Gloeckler et al., 2013) implemented a new solar cell design using CdTe materials with a target efficiency of 20% by increasing the junction current and fill factor using a numerical model. It is adapted to boost the efficiency up to 19%. The comparison of various CdTe/CIGS solar cell parameters across different solar cell designs is shown in Table 2

Copper Indium Gallium Selenide (CIGS) has a chalcopyrite crystal structure and is of tetrahedral bond. It possesses notably an improved absorption coefficient of about 105 cm-1 for 1.5eV and higher energy photons. (Mansfield et al., 2015) recorded a high efficiency of CIGS photovoltaic cell on a small area device of 21.7%.

Review on Gallium Arsenide (GaAs) Solar Cells

Gallium Arsenide is the compound of elements from Gallium and Arsenic. This material is a direct bandgap semiconductor from a combination of group III and V with a Zinc blende crystal structure. GaAs can be used for various transistors like MESFET, HEMT (a type of FET), JFET, HBT (Hetero-junction Bipolar Transistor) (www.waferworld.com). This material is prepared by three industrial processes: the Vertical Gradient Freeze (VGF), the Bridgman-Stockbarger technique and Liquid Encapsulated Czochralski (LEC) growth. The function of VGF technique is to grow the crystals evenly to a particular diameter and slicing the crystals finely, rounding the edges, polishing and packing the wafers. In Bridgman-Stockbarger technique, the crystals are developed in a horizontal zone furnace and it allows both Gallium and Arsenic vapors to react with furnace and then allow the free molecules to deposit on the seed crystal at the end of the furnace (en.wikipedia.org). The function of LEC growth method is producing high-quality single crystals that can be avoiding the semi-insulating materials.

The highest efficiency obtained so for GaAs based single junction solar cell is 32.196%. Single junction solar cells are very simple for realization, fabrication and optimization when compared to other junction solar cell (Attari, Amhaimar, El yaakoubi, Asselman, & Bassou, 2017).

Single junction solar cells are very simple for realization, fabrication and optimization when compared to other solar cells (Attari et al., 2017). The material GaAs is used for single crystalline thin film solar cells, multi-junction solar cells and it has a higher efficiency. The highest efficiency obtained so far by a generic GaAs based single junction solar cell is 21%.

In a model, authors used 2-D Atlas in Silvaco TCAD as simulator, here the multi-junction solar cell was improved the efficiency by 29-30% (AM0), 31-32% (AM1-5G) ("InGaP/GaAs-based Multijunction Solar Cells - Takamoto - 2005 - Progress in Photovoltaics: Research and Applications - Wiley Online Library," n.d.) and it is used for terrestrial applications. In this method, thin films are used and it is developed in metal film. Because thin film cells have high flexibility, light weight, high efficiency over 25% in AM0 and also have high radiation resistance.

The efficiency of GaAs-on-Si based solar cell is 21.3% and for GaAs homo epitaxial solar cell is 27.6% (Vernon, Tobin, Haven, Geoffroy, & Sanfacon, 1991). Material growth quality, cell design and device fabrication are used to increase the efficiency. This solar cell is based on the various process such as the variation of semiconductor structure, manufacturing process and encapsulation and its efficiency is about 26.2% at 1004suns (Ortiz, Algora, Rey-Stolle, Khvostikov, & Andreev, 2000). The aim is to improve the efficiency up to 25% at 1000 suns of the threshold value of GaAs photovoltaic concentrator technology. Low Temperature Liquid Phase Epitaxy (LT-LPE) is used because it gives high quality material.

GaAs is better than the silicon because of its direct band gap of 1.42eV and its mobility is six times greater than that of silicon (Li, Zhang, et al., 2015). The conversion efficiency of graphene/GaAs solar cell without anti-reflection layer is 10.4% and with anti-reflection layer is 15.5%. Monolayer graphene was grown by Chemical Vapor Deposition (CVD) technique by using the chemical reaction of CH4 and H2 deposited on the copper substrate. In research, heterostructure solar cell of graphene/GaAs is very well supported because of its great potential for practical applications. Graphene produces some optical and electrical properties like high carrier mobility, micro-scale ballistic transport, abnormal quantum effect and 2.3% constant absorption of visible light. And also it has some great thermal conductivity and high mechanical strength. When GaAs is comparing with si, GaAs is mostly used to fabricate the high efficient solar cells. Through Anti-Reflecting Coating (ARC), the conversion efficiency is improved up to 15.5%. By using a Keithley 4200 system, the current and voltage data were recorded.

The GaAs solar cell was grown by low pressure metal organic chemical vapor deposition (K. Kim, Nguyen, Mho, & Lee, 2013). Inverted cone shaped nano holes are fabricated by Anodic Aluminium Oxide Masks. These masks are prepared by two step of anodization from an aluminum foil to improve the absorption of light and also the conversion efficiency. They are using metal nanoparticles or photonic crystals in nano patterning structures because of improving the light absorption due to the plasmonic and spontaneous effect. The conversion efficiency is improved from 10.53% to 11.57% by the conditions of 1-sun AM 1.5 G and increasing the short circuit current up to 11.63% by using nanohole arrays. Due to the light absorption, in the quantum efficiency of the solar cell is increased the wavelengths near the band gap energy of GaAs. From III and V compound semiconductor, triple junction solar cells have the highest solar electric conversion efficiencies (Dimroth et al., 2014). The efficiency of four junction solar cell is 44.7% at 297 suns concentration of the AM1.5d spectrum.

Table 3 GaAs solar cell Comparison

References	No of Layers	Type	No of Junctions	Jsc (mA/cm^2)	Voc (V)	FF (%)	Ƞ (%)	Advantages	Disadvantages
(Attari et al., 2017)	6	PN	1	34.79	1.0	85	22.08	Good efficiency since it has a full layer structure with GaAs absorber	--
(Dong, Bailey, Afanasev, & Zaghloul, 2014)	6	QD	1	22.53	0.983	83.9	14.1	Usage of QD layer	Less efficiency
(Hubbard et al., 2008)	4	P-i-N QD	1	23.9	0.83	77	10.8	Usage of QD layer with PiN structure	Not up to the expected performance
(Plá et al., 2007b)	6	-	1	26.4	1.039	88.1	24.1	Very good performance	--
Kazi Islam., et al. (2012)	4	PN	1	0.8	1.4	--	11.1	--	Less efficiency with less layers
Boqun Don., et al. (2014)	6	GaAs	1	22.53	0.983	83.9	14.1	Basic structure	Moderate efficiency
(S. Kim et al., 2015	6	GaAs fab	1	-	0.7	-	11.17	Basic structure fabrication	Less efficiency
(Al Wahshi & Nayfeh, 2014)	6	GaAs	1	-	22	0.98	14	Basic structure	Moderate efficiency

The thickness of the InGaP layer is dependent on the hole barrier height when direct tunneling currents are tuned on at the front surface (Plá, Barrera, & Rubinelli, 2007b). The obtained values were verified by electrical and optical modeling. The GaAs thin film solar cell is the top most thin film solar cell in the market because it has high Power Conversion Efficiency (PCE) when compared to other thin film solar cells (Moon, Kim, Kim, Heo, & Lee, 2016). The PCE of the single junction of GaAs solar cell is 22.08%. By optimizing the base region and the metal reflector on the back side of the thin film, the efficiency will be increased. By using realistic material parameters, it reaches 21.3% of power conversion efficiency which is 2.7 times greater than an optimized bare nano wire (N. Huang & Povinelli, 2014). The quantum well solar cell was first established by Branham ("(8) Numerical Simulation of Multi-Quantum Well Solar Cells GaAs / InAs Using Silvaco Atlas | Request PDF," n.d.).

Due to the quantum well solar cell increasing the absorption spectra into longer wavelengths, it increases the short circuit current and maintaining the open circuit voltage. When efficiency is exceeding up to 27%, the optimized solar cell is obtained. Back Surface Field (BSF) is the important element to increase the efficiency in a single junction or the multi junction device of GaAs concentrator solar cell (Galiana, Rey-Stolle, Baudrit, García, & Algora, 2006). By improving the heterostructure of c-GaN/GaAs solar cell using GaAs as a substrate, the simulated results of efficiency between 23% and 25% (Cruz et al., 2017). The quantum dot (QD) solar cell for short circuit current density was higher than that of non-quantum dot solar cell but for open circuit voltage of QD solar cell is smaller than that of non QD solar cell. The output characteristics of single junction GaAs based solar cell were Jsc = 16.10 mA/cm2, Voc = 2.392V, FF = 87.52% and Ƞ = 32.196% (Moon et al., 2016).

(Vernon et al., 1991) reported an efficiency of 21.3% with GaAs-on-Si based solar cell and 27.6% with GaAs homo-epitaxial solar cell. Here the material growth quality, cell design and device fabrication are the parameters that can considered to increase the efficiency. It is based on semiconductor structure, manufacturing process and encapsulation. The efficiency is about 26.2%.

(Ortiz et al., 2000) proposed methods to improve the efficiency up to 25% at 1000 suns of the threshold value of GaAs photovoltaic concentrator technology. This work uses Low Temperature Liquid Phase Epitaxy (LT-LPE) due to its high quality.

(Li, Chen, et al., 2015) suggested that GaAs is better than silicon because of its direct band gap of 1.42 eV, and mobility is six times greater than that of silicon. The conversion efficiency of graphene/GaAs solar cell without anti-reflection layer is 10.4% and with anti-reflection layer is 15.5% respectively.

The GaAs solar cell was grown by low pressure metal organic chemical vapor deposition in (S. Kim et al., 2015) Inverted cone shaped nano holes that are fabricated using Anodic Aluminium Oxide Masks. These masks are prepared by two step of anodization from an aluminum foil to improve the photonic absorption and conversion efficiency. It uses metal nanoparticles or photonic crystals in nano pattern structures to increase photonic absorption by plasmonic and spontaneous effect. The conversion efficiency is improved from 10.53% to 11.57%. By using nanohole arrays, it increases the short circuit current up to 11.63%. During the light absorption the quantum efficiency of the solar cell increases for the wavelengths which are near to the band gap energy of GaAs.

In (Plá et al., 2007a), it is reported that the thickness of the InGaP layer is dependent on the hole barrier height when direct tunneling currents are tuned ON at the front surface. The result is verified by electrical and optical modeling. The work prefers GaAs thin film solar cell as the top most layer of a solar cell because of its high Power Conversion Efficiency (PCE) when compared to other materials.

(Moon et al., 2016) reports a power conversion efficiency of a single junction GaAs solar cell as 22.08%. The proposed work comprises of optimized base region and modified metal reflector on the back side of the thin film which further increases the efficiency.

In another work reported by (N. Huang & Povinelli, 2014), using the realistic material parameters, the conversion efficiency reaches 21.3% which is 2.7 times greater than that of an optimized basic nano wire device.

(Al Wahshi & Nayfeh, 2014) investigates Si and GaAs based hetrojunction solar cells in TCAD platform. The work is a study on the effect of minority carriers and its life time and concludes that the thickness of GaAs layer has an impact on efficiency computing. The result has Voc of 0.8V and efficiency of 11.1% achieved by using the Transfer Matrix method in the solar spectrum range of AM1.5G. Since GaAs material has direct band gaps, simulation results show an absorption rate of 36% in a wide band. This concludes that GaAs is the best absorption material for solar cell working under wide wavelength range.

(Dong et al., 2014) simulated InAs and GaAs based single and multi-layered solar cell using TCAD tool with quantum dot inner layer. The design leads to higher efficiency comparably. In this work, authors used the same material for all layers. The final result shows an efficiency of 14.1% in a single junction cell. The inference is that the quantum dot inner layer is used as an absorber along with GaAs layer to increase the solar energy absorption.

(Al Wahshi & Nayfeh, 2014) investigated on obtaining optimum thickness by varying the layer thickness to improve solar cell efficiency. It is reported that at a thickness of 0.5μm the solar cell the efficiency starts to rise. Thus, when the optimum thickness is fixed as 0.5μm and it gives out an efficiency around 14%. In this work, Ge is heavily doped by P type semiconductor which in turn is used as a back contact but not to generate photons. The review work of (Asim et al., 2012)focuses on materials such as gallium arsenide, Silicon, CIGS and Cadmium Telluride. It concludes that GaAs exhibits higher efficiency than crystalline silicon due to its energy conversion efficiency of 25 to 35% due to its direct band gap nature and better absorptivity. Table 3 shows the parameter values from modeling and simulation of GaAs based solar cell.

Efficiency comparison of Si, CIGS/CdTe and GaAs

Figure 3 shows the year wise growth and variations of efficiency for various materials like silicon, gallium arsenide and CIGS/CdTe materials. Considering the different solar cell materials such as silicon, cadmium telluride, and gallium arsenide, it is observed that gallium arsenide is the optimum material for solar cell design as it possesses very good light absorption capability. This ensures that GaAs solar cell exhibits higher efficiency than the former two materials. In addition to material selection, there are other ways to increase the effective absorption rate of GaAs solar cells. One of the popular methods is addition of metamaterials.

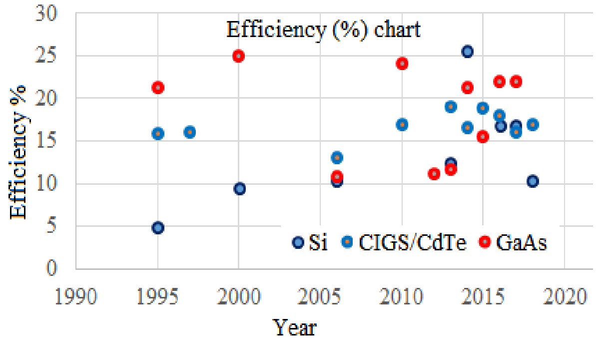

Fig. 3 Year wise efficiency comparison

Conclusion and future work

From the survey it is observed that the solar cells are simulated and fabricated by using various techniques which shall producing a different performance based on the technique used. There are several advantages and disadvantages of each and every techniques discussed. Also As discussed in the previous sections, a solar cell design has numerous challenges such as inefficient performance, low absorption rate, production cost, number of layers, durability and to name a few. Among all possible challenges, following points are the critical issues prevalent in the solar power industry and research is to improve the absorption rate, choice of the suitable materials for solar cell layers, number of junctions and layers, geometry of the unit cell, metamaterial absorber design and market price.

Also from the above comprehensive literature survey, some inferences were obtained shall be used for the future work. Solar energy which is an increasing demand for solar power across the globe with improper selection of material such as semiconductors, metals, and metamaterials leads to fall in performance of the device. Improving the efficiency of single junction solar cells by proper selection of absorber material. GaAs based solar cell design gives better performance than other types. Absorption coverage of wide range of solar spectrum by selection metamaterial, polymer based solar or plasmonic based absorbers. Also high absorption with low complexity using metamaterials.

Authors: Victor Du John H. e-mail: victoreee11@gmail.com; Jacquline Moni D., Professor, e-mail: moni@karunya.edu; Gracia D., e-mail: graciad@karunya.edu.in; Department of Electronics and Communication Engineering, Karunya Institute of Technology and Sciences, Coimbatore, India

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