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A Review of Current Trends in Thin Film Solar Cell Technologies

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Abstract**—**Growing energy demand and the world's dependence on fossil fuel-based energy systems causing greenhouse gas emissions and climate change have intensified the need for utilizing renewable energy sources. Solar energy can be converted directly into electricity via photovoltaic solar cells. Thin-film solar cells are preferred due to their cost effectiveness, less material consumption, flexibility, and rising trend in efficiency. In this paper, Gallium arsenide (GaAs), Amorphous silicon (a-Si), Copper Indium Gallium Selenide (CIGS), and Cadmium Telluride (CdTe) thin film solar cells are reviewed. The evolution, structures, fabrication methods, stability and degradation methods, and trend in the efficiency of the thin-film solar cells over the years are discussed in detail. Also, a comparison of the thin-film solar cells reviewed with crystalline silicon in terms of physical properties and performance is made.

Keywords**—**Climate change, conversion efficiency, solar energy, thin-film solar cell.

I. INTRODUCTION

HIGH population growth rates and industrialization have led to an increase in energy consumption, and the best response to meet the accelerating energy needs of the world is renewable energy. However, 80.2% of global energy consumption is dependent on fossil fuels which are associated with ozone depletion, greenhouse gas emissions, and climate change [1]. The dramatic climate change of the earth has led to the formulation of the Paris Agreement in 2015 by almost every country on earth, aiming to keep the global temperature within the 1.5 ºC threshold [2]. The transition from non-renewable to renewable energy is a change toward achieving sustainable economic development while aiming at the 2050 net zero emission goal [3]. In 2021, renewable energy sources accounted for about 12.2% of total U.S. energy consumption [4], as shown in Fig. 1.

Achieving 100% renewable energy in the U.S. by 2050 is a goal that is gaining traction in every sector of the economy. Jacobson et al. [5] presented a consistent set of roadmaps to achieving 100% clean and renewable energy within the U.S. They predicted that by 2050, 50% onshore and offshore wind, 37.9% utility-scale and rooftop photovoltaics, 7.3% concentrated solar power, 3.01% hydroelectric power, 1.25% geothermal power, 0.37% wave power and 0.14% tidal power would all be used to meet end-use load in the U.S.

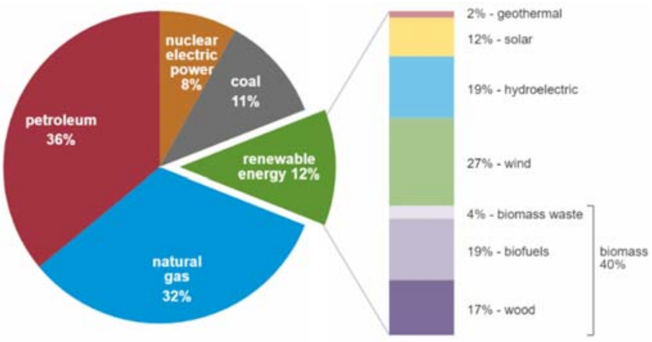

Fig. 1 U.S. primary energy consumption by sources [6]

Russia's invasion of Ukraine has exacerbated the energy crisis, driving gas prices up to their highest levels and forcing many countries to seek alternative energy sources [6]. Different countries are now considering transitioning to photovoltaic (PV) systems and other renewable energy sources. PV is a very promising technology to produce electricity from sunlight [7]. The sun provides the earth with an abundant and inexpensive source of energy, which makes the existence of life possible on earth. Sunlight consists of electromagnetic radiation in the regions of ultraviolet (UV), visible light, and infrared (IR) radiation. The solar spectrum reaching the earth's surface undergoes various absorptions in the air atmosphere, and the average solar energy falling on the earth's surface is generally known as air-mass 1.5 (AM1.5) irradiation [8]. Plants and animals need solar energy because it is an important ingredient in the photosynthetic reaction of plants to manufacture their food while animals, including humans, depend on plants for food and the oxygen they produce. The generated energy from solar does not produce any harmful emissions, thus reducing carbon dioxide (CO_2) generation. Solar energy can be utilized in its raw form for heating, drying, water purification, solar thermal, or converted form to generate electricity [9]. The most common ways of converting solar energy to generate power are PV (solar cells) and concentrating solar power (CSP).

Solar cells convert sunlight directly into electricity. Each cell generates low power [10]. In order to produce adequate electricity, several cells must be connected together to form a module, much like the rooftop panels. Unlike solar cells, which produce energy using sunlight, CSP use mirrors or lenses to focus sunlight into a narrow beam that warms a fluid to produce

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steam, which drives a turbine to produce energy [11]. Although solar energy is a free, clean, and sustainable energy source, solar power has some challenges. The cost of converting and storing solar power is high. This has motivated a lot of research and development toward reducing the cost. Secondly, the sun does not supply continuous energy, especially at night and during harsh weather conditions such as snow, fog, and hail. Also, installing solar panels and CSP requires much space, which can negatively impact the ecosystem by displacing plants and wildlife. Hence it is important to consider the improvement of the efficiency of solar P.V. in commercial and industrial applications.

The present paper reviews the literature on the principle of operation, ideal material properties, and efficiency of solar cells. Special attention was paid to thin film solar cells, their uniqueness, and their challenges. The trend in efficiency, stability, and degradation mechanism of thin film solar cells are presented. Finally, a comparison of material properties, structural properties, electrical properties, and efficiency of CdTe, a-Si:H, GaAs, and CIGS are highlighted.

II. PRINCIPLE OF OPERATION OF A SOLAR CELL

The working principle of solar cells is based on the formation of electron-hole pairs in two different layers of silicon that have been doped [12]. The doping process in manufacturing solar cells is to form a p-n junction by injecting impurity materials into a silicon wafer. The elements of III or V group are used in the doping process, during which the dopant materials are diffused thermally into the doping layer [13]. The p-type silicon is produced by adding atoms with one less electron in their outer energy level than silicon, such as boron and gallium, thereby creating an electron vacancy or hole. The n-type silicon is made by adding atoms that have one more electron in their outer level than silicon, such as phosphorus. In this case, one electron is not involved in bonding and is free to move inside the silicon structure.

The most basic solar cell interface consists of a layer of p-type silicon placed next to a layer of n-type silicon forming a junction, as shown in Fig. 2. In the n-type layer, there is an excess of electrons and an excess of positively charged holes in the p-type layer. A depletion zone is created around the junction of the two layers, where the electrons from one side fill the holes on the other side.

The design of solar cells functions for the conversion of photons coming from the sun into electricity. The sunlight, consisting of photons, has sufficient energy to stimulate the electrons from ground state to excited state thereby creating electron-hole pairs [14]. As electron flows from one layer to another through PV effect, this creates a voltage difference and provides energy to the external circuit [15]. In the process, the following steps must be done simultaneously to achieve effective P.V. energy conversion. These are:

- Absorption of photons from the sun
- Formation of electron-hole (charge carriers) pair
- Separation of oppositely charged free carriers before their recombination
- Collection of photo-generated charge carriers through electrical contacts and their passage through an external circuit to create useful electric current.

The amount of electricity created in a cell depends on some factors, such as the size of the cell, the quality of the light source, and the materials used for creating the device.

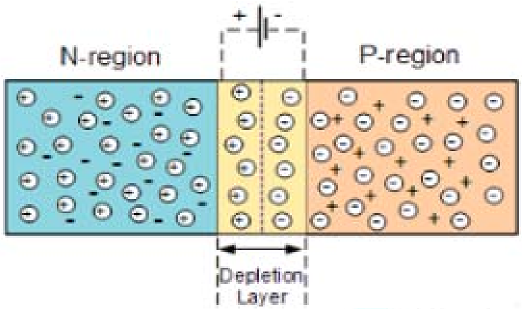

Fig. 2 Schematic representation of a solar cell

a. Properties of An Ideal Solar Cell Material

The key requirement of an ideal solar cell material includes [16]-[18]:

- it should have the bandgap between 1.1 and 1.7 eV,
- it should possess a direct band structure,
- it should be non-toxic in nature,
- it should obey the reproducible deposition techniques and be suitable for large area PV applications, and
- it should give good PV conversion efficiency and long-term stability.

b. Solar Cell Parameters

Solar cell efficiency is measured by using various parameters. There are four important parameters to consider for a solar cell device.

- Open circuit voltage (V_{oc}): This is the voltage measured when the external circuit is in open condition or when there is no current flow in the external circuit. The open circuit voltage of a Schottky barrier solar cell is given as:

$$V_{OC} = n\left[\Phi_b + \frac{kT}{e}.In\left(\frac{J_{sc}}{AT^2}\right)\right] \tag{1}$$

where n is the ideality factor of the diode, Φ_b is the flux, J_{sc} is the current density, and T is temperature.

The open circuit voltage that can be generated from a particular junction depends on the interface's electronic properties. The V_{OC} is also impacted by the cell's temperature. Due to the minimization of thermal agitation of charge carriers, the V_{OC} value rises as the temperature drops.

- Short circuit current density (J_{sc}): This is the current density produced when the two contacts are short-circuited or when there is zero voltage across the two contacts. The short circuit current density is given as:

$$J_{sc} = \frac{I_{sc}}{A} \tag{2}$$

However, the short circuit current density depends on the quantity of photo-generated charge carriers and their separation and collection rates in the external circuit. In order to maximize the value of the current density, the series resistance of the entire device must be kept to a minimum. Fig. 3 shows the I-V characteristics of a solar cell in the dark and under illumination.

- Fill factor or the curve factor (F.F.): This is a fraction defined to indicate the shape of the curve or the fraction of electric power that can be extracted from the solar cell.

$$FF = \frac{V_m I_m}{V_{oc} I_{sc}} = \frac{P_m}{V_{oc} J_{sc}} \tag{3}$$

where V_m and I_m represent the parameters at the maximum power extraction point (V_m, I_m).

- Conversion efficiency (η): The conversion efficiency of a solar cell is defined as the percentage of the maximum output of electrical power to the incident light power. It can be represented by using the following formula:

$$\eta = \frac{P_m}{P_{in}} = \frac{V_{oc} \times J_{sc} \times FF}{P_{in}} \tag{4}$$

where; P_m: Maximum power point; V_{oc}: Open-circuit voltage; J_{sc}: Short circuit current density; FF: Fill factor; P_{in}: Power input.

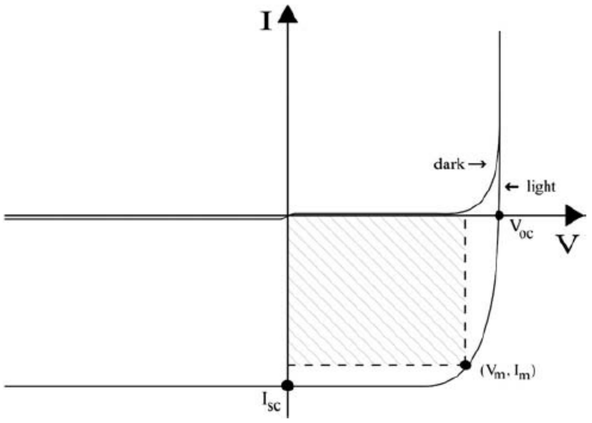

Fig. 3 I–V characteristic of a typical solar cell in the dark and under illumination [14]

c. *Types of PV Solar Cells*

PV cells are categorized into three main classes according to their modifications, and these classifications are called generations.

- *First-generation:* Monocrystalline or polycrystalline silicon crystals were used to make the first generation of solar cells, which were manufactured on silicon wafers [19]. According to Wilson et al. [20], the Silicon-based solar cell makes up about 90% of the world's solar cells. This is due to their relative abundance, stability, durability, and high conversion efficiency. However, they are expensive.
- *Second-generation:* These cells are often regarded as thin-film solar cells because relatively thin layers of semiconductor material are needed. The main drawback of first-generation PV solar cells is cost, and cost minimization can be achieved using thin-film technologies by reducing the material quantity, thereby lowering manufacturing costs. Some notable and commercially available thin film materials are cadmium-telluride (CdTe), CIGS, GaAs, and a-Si. Thin film solar cell has little market share because their conversion efficiency is low compared to the first-generation solar cell [21]. Also, they have a fast degradation phenomenon through induced light, which limits their outdoor applications.
- *Third-generation:* These cells combine the advantages of first- and second-generation solar cells targeted to achieve both high efficiency and low cost [22]. Emerging third-generation solar cells are copper zinc tin sulfide solar cell (CZTS), dye-sensitized solar cell (DSSC), organic solar cell, perovskite solar cell, quantum dot solar cell, and multi-junction cells [23]. The considerable advantages of third-generation PV solar cells may include solution-processable technologies, efficient technologies for commercial production, mechanical toughness, and high efficiencies at higher temperatures [24].

III. THIN FILM SOLAR CELLS

Thin-film chalcogenide PV technologies have remarkable prospects for high-performance, large-area module production, enabling the broad use and harnessing of solar energy [25]. In the last few decades, much effort has gone into developing a thin-film solar cell to take advantage of its lightweight and flexibility [10]. In a thin film solar cell, a layer that absorbs solar energy is sandwiched between two contact layers. The interfaces between the layers may need to be passivated with one or more additional layers to reduce interface recombination and consequently improving the conversion efficiency. Thin-film technologies are also being created in an effort to significantly lower the price of solar cells because they are more affordable to produce due to their lower capital, energy, handling, and material expenses [26]. The application of printed electronics (roll-to-roll) techniques is a particularly good example of this [27].

One of the most promising solar technologies, silicon solar cells, are based on naturally occurring silicon which is non-toxic and environmentally stable [28]. Materials readily available on earth that can be harvested, processed, and recycled at a low environmental cost are required to create thin-film solar cells. Several light-absorbing substances have been researched for use in thin-film solar cells, such as amorphous Si (a-Si), organic substances and compound semiconductors. Because of its unmatched high efficiency, GaAs-based thin-film solar cell may be the market's dominant product in the future. Presently, thin-film solar cells with absorber layers consisting of CIGS or CdTe are more popular commercially than those with a-Si. However, the toxicity of Indium (In) and cadmium (Cd) and their environmental impact are limiting factors for the development of CIGS and CdTe solar cells [29]. The advantages of thin film solar cells have been highlighted by several studies [14], [30], [31].

- Thin-film solar cells have high absorption coefficient than crystalline silicon solar cells.
- Solar thin-film costs less to manufacture than traditional

solar cells due to the nature of the manufacturing process and the use of less materials.
- Flexibility makes it easily adaptable to various applications.
- Shading effect has less impact on the performance of the solar cell.

However, thin film solar cells have some disadvantages that limit their solar market dominance. They are stated as follows:

- They tend to degrade faster than monocrystalline and poly solar panels, which is why they typically come with a shorter warranty.
- Higher space is required to achieve the same performance as the crystalline modules.
- Lower stability level causes a disparity between the laboratory efficiency and field efficiency of the solar cells.
- Some feedstock used for manufacturing solar thin films is scarce.

a. GaAs Solar Cell

GaAs belongs to III-V semiconductors and has a direct bandgap semiconductor of 1.42 eV. As a result of their wide bandgap, GaAs has become the standard for use in a high-temperature environment, such as in space applications. GaAs-based solar cells are preferred as absorber material to Si-based solar cells due to their high absorption coefficient. Compared with Si-based solar cells, GaAs solar cells have found useful applications in aerospace industry due to the following advantages [32]:

- high photoelectric conversion efficiency
- wide spectral coverage
- high radiation resistance
- direct bandgap semiconductor material

However, GaAs solar cell fabrication is complicated and expensive, thereby impeding the use of the device for terrestrial solar cells. The high cost is not only a result of the material cost but also the production equipment. In [33], the estimated cost of GaAs solar cells can be up to ten times higher than Si-based solar cells. Although, GaAs/Ge solar cells are more expensive than Si-based solar cells, their area and weight are reduced due to their increased performance. Another major problem is their higher recombination rate, which limits the performance of the device.

The GaAs solar cell performance can be improved by layering resulting in multi-junction or cascade solar cells [34]. Single-junction and multi-junction GaAs solar cell technology has been developed to achieve the highest possible performance. The window layer changes the electrical and optical properties, thereby reducing the reflectance and generating a difference in refractive index across window and absorber layer [35]. Each layer has a unique composition and bandgap that absorbs light in a particular spectral range [36], as shown in Fig. 4. The topmost layer is usually made of material with large bandgap to absorbs light in the visible spectrum while the bottom layer has lower bandgap. Common and effective thin window layer materials are Aluminum Gallium Arsenide (AlGaAs), Indium Phosphide (InP), Indium Gallium Phosphide (InGaP), and Gallium Indium Arsenide (GaInAs). Moreover, GaAs and InGaP (III-V) semiconductors have a bandgap value close to optimum absorption value and have remarkable physical properties.

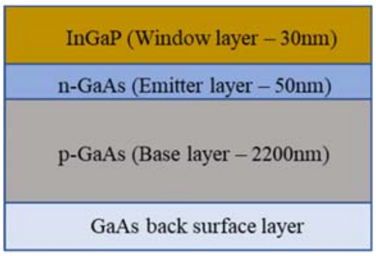

Fig. 4 Basic structure of GaAs

GaAs solar cells are used mainly in adverse environments such as space applications, so their working parameters should be stable even under extreme operating conditions. Papez et al. [37] observed the defects and impurities of GaAs after fabrication using electron beam induced current (EBIC) method. They discovered an electrically active impurity on a GaAs-based solar cell which caused electron tunneling. Using an EBIC method has revealed several undesirable defects and impurities that cannot be visible and detectable by scanning electron microscopy (SEM) and other analytical methods. Degradation due to thermal processing has been studied extensively by several researchers [38]-[40]. Sun et al. [38] conducted a study on the characteristics of GaAs solar cell after 200 hours of annealing at 400-450 ºC. Their result showed that the room temperature reflectivity and external quantum efficiency (EQE) are unchanged after annealing, and the peak EQE value of 90% was observed before and after such heat treatment, showing good thermal stability. After 300° C thermal processing, there is no significant change in the structure and I-V characteristics of the solar cell, indicating excellent stability of the material to thermal processing [40].

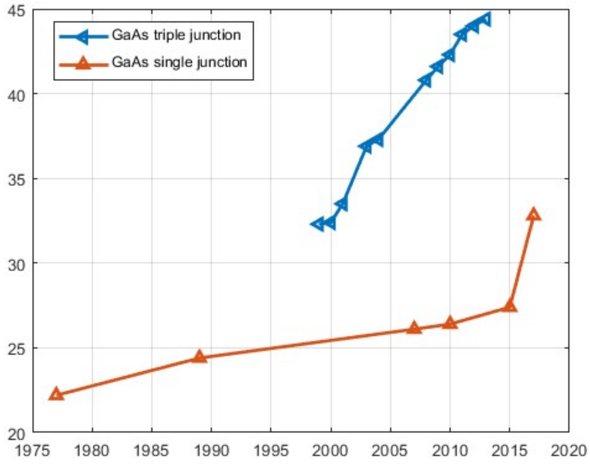

Fig. 5 Trend in the efficiency of GaAs solar cells [42]

Further study by Papez et al. [36] showed a decrease in the performance of solar cells when a sample is heat-treated at 350 ºC for 240 mins. However, the solar cell's performance loss is caused by different surface structures and internal degradation processes [41]. The trend in the efficiency of GaAs solar cells to date is shown in Fig. 5.

b. a-Si solar cell (a-Si)

a-Si is the non-crystalline allotrope of silicon and is the most developed thin-film solar cell. One of the attractive features of α-Si is its high absorption capacity, so a small layer of the material can be used to produce solar cells, thereby reducing costs. At low temperatures, it can be deposited on various structures, such as glass, metal, and plastic. Another interesting feature is the flexibility and ease of incorporating the modules into facades, roofs, and other structures. However, compared to crystalline silicon, the conversion efficiency of a-Si is still low (as shown in Table I). a-Si has short orders, and the dangling bond in their structure results in poor photoconductivity [30]. Therefore, unmodified a-Si is not very useful as a semiconductor. When silane gas (SiH_4) is used as a precursor during the fabrication of a-Si, hydrogen is added to the structure. By hydrogenating the material as it is formed, the dangling sites are bonded to hydrogen atoms. The product a-Si:H has low defect density. Hydrogenation of a-Si leads to the reduction of defects and consequently improves photoconductivity.

However, hydrogenation of a-Si comes with a cost. On exposure to light, the defect density of a-Si:H increases causing increased recombination losses. The recombination centers (where positive holes and negative electrons combine) arising from the defects shorten the carrier lifetime and make the transportation of charge carriers challenging, resulting in low conversion efficiency [43]. The conversion efficiency of a typical a-Si:H solar cell can be reduced by up to 30% in the first six months as a result of the Staebler-Wronski effect. This is a significant drawback of a-Si, and since hydrogenation was introduced to reduce defect density, Staebler-Wronski Effect could hardly be reduced without sacrificing material quality. While the exact mechanism is still unclear, it has been proposed that the effect can be minimized by using nanocrystalline silicon, stacking more layers of a-Si together with other materials, and operating at a high temperature.

The basic structure of a-Si:H solar cells is the p-i-n structure, consisting of a thin p-type and n-type doped layer and a central intrinsic i-type layer, as shown in Fig. 6. The layer is usually a hydrogenated amorphous-silicon carbon alloy doped with boron, and the n-layer is either phosphorus-doped a-Si:H or phosphorus doped microcrystalline a-Si:H and is about 20–30 nm thick. The electrical transport in the i-type layer is assisted by an electric field typically between 250 and 500 nm in thickness. Carlson & Wronski [44] developed the first a-Si solar cell with a conversion efficiency of 2.4%. The a-Si has a p-i-n structure deposited on a substrate of indium tin oxide (ITO) coated glass at a temperature of 250-400 °C.

The degradation of a-Si modules is prone to defects that start within the first few hours of outdoor deployment and propagate over time. This is unhealthy for the performance and reliability of PV modules. Osayemwenre & Meye [45] studied the degradation of single junction amorphous silicon (a-Si:H) solar cells. They observed a significant decrease in efficiency during the monitoring period. The power of a-Si solar cell decreases by approximately 0.2% with every 1 ^{o}C increase in temperature. This shows that a-Si are insensitive to temperature compared to c-Si. The trend in the efficiency of a-Si solar cells to date is shown in Fig. 7.

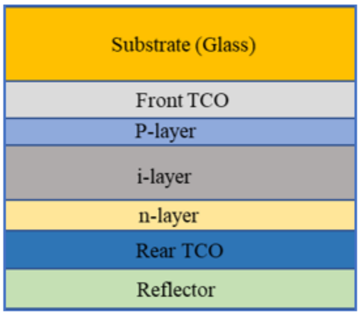

Fig. 6 Structure of a-Si:H

c. Copper Indium Gallium Selenide Solar Cell

The CIGS thin film solar cell is used to convert sunlight into electrical energy. CIGS is a flexible material that may be produced using various techniques and used in various form factors. For instance, substrates, including glass, metal foils, and polymers, can be used to deposit CIGS [46]. Applications that call for lighter-weight or more flexible modules are made possible by metal foils and polymers. $CuInSe_2$ (Copper indium selenide) is a ternary compound p-type absorber material that crystallizes as tetragonal chalcopyrite. CIGS is produced when Gallium (Ga) and Copper Indium Selenide are alloyed. The outstanding efficiency, cheap cost, and ease of integration of chalcopyrite $Cu(InGa)Se_2$ (CIGS)-based solar cells make them promising and popular solar cells. This is related to their tunable bandgap of approximately 1.0-1.48 eV and high absorption coefficient up to 10^5 cm^{-1} [47].

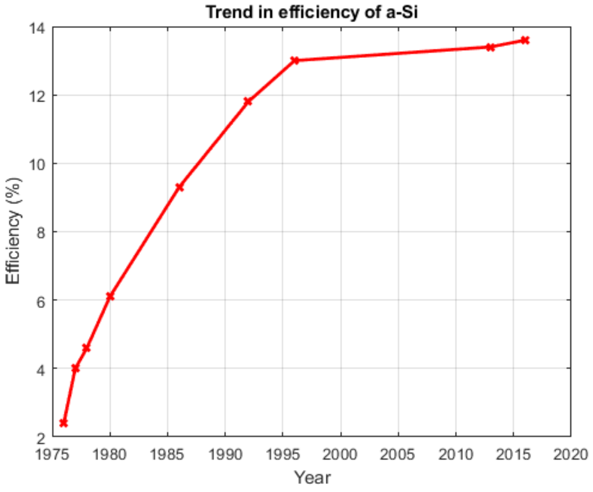

Fig. 7 Trend in the efficiency of a-Si solar cells [42]

The advantages of CIGS solar cells are given as [47]-[49]:

- CIGS layers are thin enough to be flexible, allowing them to be deposited on flexible substrates.
- CIGS-based solar cells are promising and widely used

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because of their remarkable efficiency, low cost, and easy integration.

- Comparatively simple to manufacture, CIGS-based solar cells can be grown on a variety of rigid and flexible substrates using vacuum and non-vacuum processes.
- Due to its direct band, high absorption coefficient, and minimal material waste, CIGS has attracted significant interest as a promising absorber material.
- CIGS solar cells have a high radiation tolerance, making them suitable for use in space applications.

However, the commercialization of CIGS-based solar cells is less widespread than that of c-Si solar cells due to the difficulty of obtaining high-quality and large-scale CIGS-based solar cells. The disadvantages are given below [50], [51]:

- The efficiency of the commercial CIGS module is much lower than the obtained lab-scale. A large difference in efficiency exists between small area cells (> 22.8%) and commercially available modules (16.1%).
- The efficiency of CIGS is constrained by the presence of electronic inhomogeneity.
- Another drawback is the compositional homogeneity from run to run, and in situ diagnostic instruments are essential for process management.
- Indium supply issues during mass production could result in a sharp price increase. For example, a 1 GW PV module requires 31 tons of Indium.
- Since Cadmium is toxic, disposal of the Cadmium-containing product causes adverse effects on the environment and produces toxic effects on humans.

The CIGS PV cell-based consists of a stack of several thin layers of different materials deposited on a substrate. The layers consist of the back contact, the absorber, the buffer layer, and the window layer, as shown in Fig. 8.

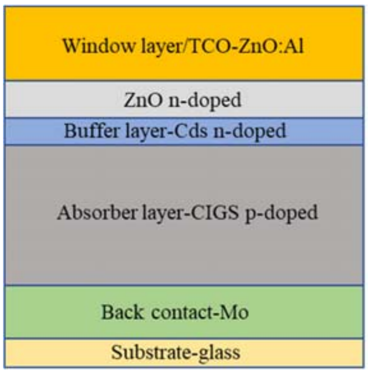

Fig. 8 Schematic of CIGS Thin film layers

The substrate is generally made of soda–lime glass (SLG), insulating and stable to resist successive deposits. The creation of thermal stresses during the manufacturing of films is constrained by its coefficient of thermal expansion, which is comparable to that of CIGS. The excellent performance of the cell is due to sodium which is naturally supplied by glass [31], [52]. Sputtering is used to deposit the molybdenum on the glass substrate with a thickness of around 500 nm [53].

The cell's absorber is made up of CIGS, a p-type semiconductor material, and inherent doping is ensured by the development of imperfections, such as copper gaps, and the substitution of indium and gallium. Also, its chemical composition and properties range from $CuInSe_2$ to $CuGaSe_2$ depending on the amount of indium and gallium substitution [54]. Cadmium sulfide (CdS), the n-type semiconductor in the p-n heterojunction formed between the CIGS and the CdS, serves as the buffer layer. This junction permits the separation of charge carriers, and the CdS layer also has the property of passivating the surface defects of the absorber [55].

The methods of deposition are classified majorly into two: the vacuum methods and non-vacuum methods. The vacuum methods include [56]-[59]:

- Co-evaporation
- Chemical vapor deposition
- Molecular beam epitaxy
- Pulsed laser deposition
- Physical vapor deposition
- Metalorganic chemical vapor deposition
- Sputtering
- Electron beam deposition

However, researchers are forced to create inexpensive and straightforward non-vacuum technologies due to the high cost of production and complicated vacuum processes [60]. The non-vacuum method essentially consists of a two-step procedure that starts with low-temperature precursor deposition and is followed by high-temperature annealing in a chalcogen environment [58]. The major advantages of this method include low energy requirement, low capital investment, high compatible processing, lower material costs, and higher material utilization [49], [61], [62].

The long-term stability of CIGS PV technology is becoming more crucial as it reaches industrial production levels. The key to the market success of CIGS is to increase this long-term stability by comprehending and reducing the deterioration of this PV technology. However, performance predictability is also crucial since to assess their risks, financiers, homeowners, utilities, planners, and particularly PV manufacturers need to forecast when their PV modules would stop working. Product reliability is crucial to achieving the lowest and most predictable electricity bills.

CIGS thin-film cells have shown good performance for the majority of the visible spectrum under terrestrial conditions at a high operating temperature [63]. Also, due to its strong radiation resistance, CIGS solar cells can be employed for space applications. Since modules are susceptible to water intrusion, humidity is the primary threat to the stability of nonencapsulated CIGS solar cells. They have also been discovered to be sensitive to temperature (shocks), electrical bias, and illumination. However, these loads do not always have a negative effect [64]. The trend in efficiencies of CIGS solar cells to date is shown in Fig. 9.

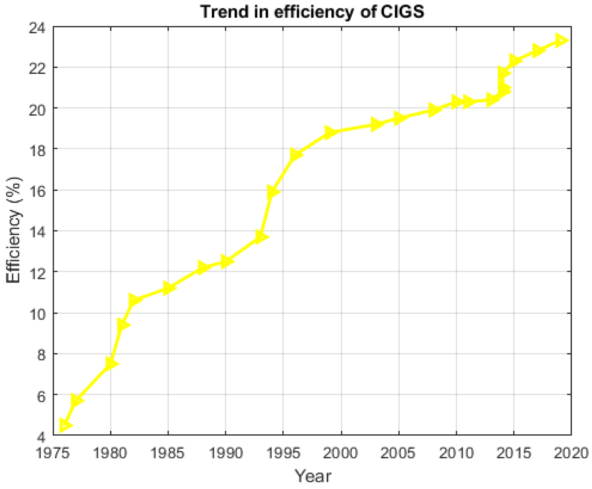

Fig. 9 Trend in the efficiency of CIGS solar cells [42]

d. Cadmium Telluride (CdTe)

CdTe solar cell thin film PV technology was developed in the early 1970s and is currently the leading thin film technology in the top ten global manufacturers. This is because CdTe is a very durable and chemically stable material that can also be deposited using a wide range of techniques, making it perfect for production over a vast area [65]. In 1972, Bonnet and Rabenhorst made the first CdTe solar cell, which had a CdS/ CdTe heterojunction with a 6% efficiency [66]. Since that time, thin film CdTe-based solar cells have been produced using this sort of heterojunction until recently, when it underwent a significant change. In the last decade, CdTe solar cell devices have experienced remarkable improvement considering new characteristics, including band gap grading, copper embedding, and transparent n-layer [20], culminating in higher efficiency. ZnO-based transparent conduction oxide (TCO) can be used to enhance the CdTe cell performance by reducing surface roughness, thereby improving the transparency of the device [67]. With these adjustments, First Solar produced a device with an efficiency of 21.5%, which was later enhanced to 22.1% [66].

Thin-Film CdTe-based PV cells are known for their low-cost PV energy conversion because of the chances of higher efficiency with reduced materials, reliable and stable cell operation. CdTe solar cells have some advantages listed as:

- CdTe technology is currently leading the thin-film PV industry due to its low-cost fabrication process [67].
- CdTe can be deposited on a variety of substrates, such as glass and polycrystalline materials [68].
- CdTe is known to have high efficiency and a great advantage of large production due to cost-effective production processes [69].
- CdTe has a direct optimum band gap (1.54eV) with a high absorption coefficient. This means all the potential photons with energy more significant than the band gap can be absorbed within a few micrometers of the CdTe absorber layer [68].

Although CdTe has shown some interesting advantages, its development has been hindered by the following disadvantages.

- They exhibit some inherent lateral non-uniformities in their structures in terms of grain size and thickness variation [70].
- The toxicity of Cadmium (Cd) and its environmental impact are limiting factors for the development of CdTe solar cells.
- Tellurium (Te), a feedstock of CdTe, is a scarce element.
- CdTe has a low open circuit voltage, close to 0.85V, while it would be expected, according to the band gap, to be at least around 1.2V [71].

CdTe-based solar cells are manufactured starting from glass, so the first layer is a Transparent Conducting Oxide (TCO) that acts as a front electrical contact [72]. The basic structure of CdTe has a glass superstrate and a layer of TCO as front contact, near-transparent n-type cadmium sulfide (CdS) window layer, p-type CdTe, and rear contact, as shown in Fig. 10.

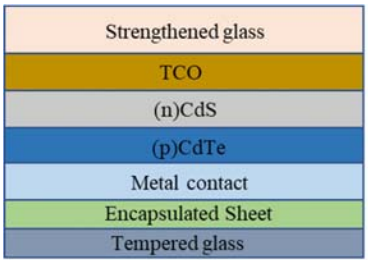

Fig. 10 The layout of a superstrate glass-glass CdTe/CdS solar cell [73]

The TCO performs the function of front contact and a window layer. The arrangement of p-type and n-type regions creates a heterojunction structure. This architecture takes advantage of the window layer to reduce the quantity of light-induced charges within the absorber layer. Sputtering and vacuum evaporation can be used to deposit the n-type CdS window layer, which is used as a buffer layer nowadays and is around 100 nm thick [74], while the p-type CdTe (~5 µm thick) absorber layer can also be deposited by physical vapor deposition (PVD), sintering or screen-print. The back contact can be made of Aluminium (Al), Gold (Au), Nickel (Ni), or Platinum (Pt) by employing the vacuum thermal evaporation (VTE) Technique.

Cu is a recognized factor in the degradation of CdTe solar cells. Cu is usually added to help increase the ohmic proximity to p-CdTe and, thus, the general cell PV performance [75]. Gretener et al. [76] devised a new method to investigate CdTe solar cell stability by drawing up CdTe solar cells in substrate configuration and putting in a small amount of Cu to CdTe after recrystallization. Their result showed that 90% of the initial power output after 1000 hours of operation at maximum power under one (1) sunlight intensity at 80 ºC substrate temperature, suggesting good performance stability. The trend in efficiencies of CIGS solar cells to date is shown in Fig. 11.

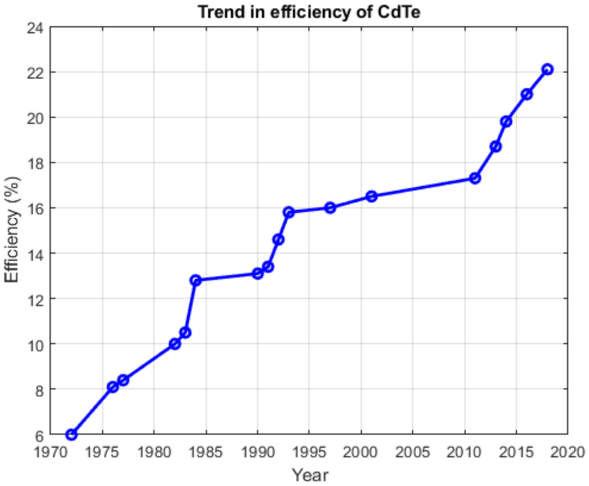

Fig. 11 Trend in efficiency of CdTe Solar Cells [42]

IV. COMPARISON OF THIN-FILM SOLAR CELLS

a. Trend in Efficiency

GaAs: Alferov's team in 1970 developed the first GaAs heterostructure solar cells [67]. GaAs solar cells gain market dominance in the 1990s as most preferred solar cell for space application. GaAs thin-film cells have a reported conversion efficiency of 29.1% for single-junction and 44.4% for triple-junction solar cells [32] based on GaAs with germanium and indium gallium phosphide layers and can also operate with light as concentrated as 2,000 suns.

a-Si:H: From the efficiency of 2.4% reported by Carlson & Wronski in 1976 using the p-i-n structure [42], researchers have used different methods to improve the conversion efficiency. The MIS or Schottky diode structure was used instead of the p-i-n structure to achieve an efficiency of 4.8% by Wilson & McGill [77]. Sai et al. used plasma-enhanced chemical vapor deposition (PECVD) and observed that reducing the deposition rate could lower the light-induced degradation of a-Si:H [78]. They reported a 14.0% efficiency for a triple-junction a-Si:H. A way to increase efficiency over the above limits would be to use multijunction cells by optically cascading two or more solar cells with different bandgaps. This concept exhibits less light-induced degradation effect, thereby improving efficiency.

CIGS: The first thin film CIGS solar cell was created by Kazmerski [79] in 1976 with a conversion efficiency of 4.5% using a substrate made up of SLG. Also, a 12.5% efficiency was attained by maximizing the V_{OC} and reducing the IR absorption losses in ZnO by using the quaternary $CuInGaSe_2$ layer's higher bandgap by Devaney et al. [80]. Researchers have also explored several other methods to improve the efficiency of CIGS solar cells. Among these are optimizing the ZnO window layer, extending the diffusion length of the minority carriers, lowering recombination in the space-charge area, and enhancing the interface between the CIGS absorber and CdS buffer layer, which yielded an efficiency of 18.8% in 1999 [81]. Recently, improvements in CIS absorber layer, junction formation process, and novel deposition procedures have been explored, which enabled the partial overcoming of the saturation of V_{OC} for higher gallium content and also increased CIGS deposition rates. These different methods have yielded efficiencies of 21% [82], 21.7% [83], and 22.3% [84] respectively.

CdTe: The first significant laboratory CdTe cell was reported in 1972 by Bonnet and Rabnehorst, who developed a thin film graded gap CdTe-CdS p-n heterojunction solar cell having a 6% efficiency [85]. Fig. 11 shows the evolution of the efficiency of CdTe thin-film solar cells over the years. Nakayama et al. (1976) investigated screen-printing techniques in CdTe solar cells and obtained an efficiency of 8.1% [86]. In 1982, Eastman Kodak Company reported a 10% efficiency by integrating a layer of tellurium between the metal contact and the layer of p-type CdTe [42]. Between 1995 to 2005, the change in the efficiency of CdTe solar cells was fairly constant. Acevedo [87] extended the research to obtain an efficiency of 16.5%. Their findings led to the hypothesis that a CdSTe alloy film exists because of the diffusion of sulfide into CdTe and Te into CdS. First Solar Research and Development have been at the forefront of the commercialization of CdTe [41]. They reported a record efficiency of 22.1% for a laboratory CdTe solar cell and an average commercial module efficiency of 18%.

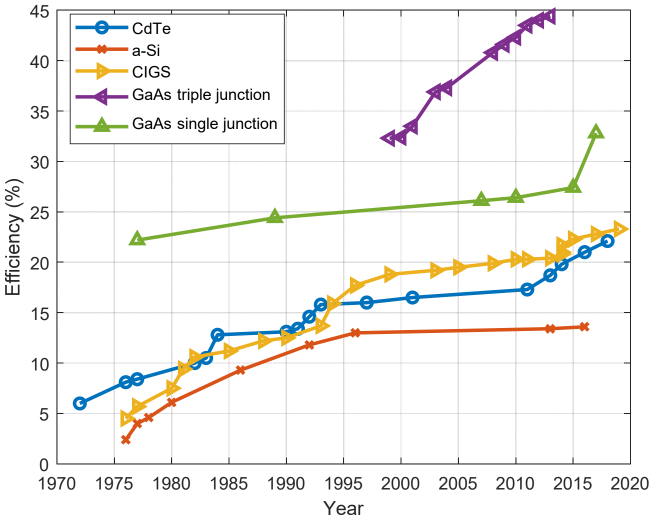

Fig. 12 Trend in efficiency of thin-film solar technologies [42]

b. Material and Electrical Properties

GaAs is a promising solar cell used in high-temperature environments such as space applications due to their high absorption coefficient, thermal stability, and high efficiency. However, GaAs fabrication is complicated and expensive, limiting its application as a terrestrial solar cell. CIGS and CdTe solar cells have comparable properties, but the scarcity of Indium and Tellurium impedes large-scale production. Yet, their thermal stability is superior to other thin film solar cells. Table I summarizes the material, structural and electrical properties of the thin-film solar cells reviewed.

V. CONCLUSION

In the last few decades, much effort has been put into developing thin-film solar cells to take advantage of their unique features, such as being lightweight and flexible. The trend in efficiency, stability, and degradation mechanism of thin film solar cells has been reviewed. Also, a comparison of material properties, structural properties, electrical properties, and efficiency of CdTe, a-Si:H, GaAs, and CIGS has been highlighted. Fig. 12 shows the evolution trend in the efficiency of thin-film solar cells over the years. The reported conversion efficiencies for a-Si, CIGS, CdTe, and GaAs are 14.0%, 23.4%, 22.1%, and 44.4%, respectively. However, regarding material availability, some of these technologies exhibit concerns that limit their future production. Particularly, CdTe and CIGS are manufactured with rare and toxic materials, and the reserve of tellurium is limited and is likely to limit the future production of CdTe solar cells. The market share of CdTe solar cells will likely decline soon, and Indium used in CIGS solar cells is limited and is likely to be the bottleneck to the future production of CIGS solar cells.

TABLE I
PHYSICAL PROPERTIES OF THIN FILM TECHNOLOGIES [14], [22], [34], [36], [42], [30], [63], [65], [41]

Physical Properties	c-Si	a-Si:H	CIGS	CdTe	GaAs
Conversion efficiency (%)	27.6	14.0	23.4	22.1	44.4
Bandgap (eV)	1.12	1.75	1.48	1.54	1.42
Temperature coefficient (%/°C)	-0.48	-0.20	-0.31	-0.25	-0.21
Sufficient thickness (μm)	100	1-2	1–2.5	2–8	5
Absorption coefficient (cm^{-1})	> 10^3	> 10^3	> 10^4	> 10^4	> 10^6
Material availability	available	available	In is limited	Te is limited	available
Stability	Less stable	Less stable	Stable	Very stable	Very stable
Toxicity level	Non-toxic	Non-toxic	Less toxic	Toxic	Non-toxic

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