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Original Article

Thin Film Technology Advancements for Solar Photovoltaics

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ABSTRACT

Thin film photovoltaic (TFPV) technology has been approached as an attractive alternative to traditional crystalline silicon solar cells because it requires less material, cost of production is less, mechanical flexibility and could be applied on large areas. Thin film solar cells have had important enhancements in the last 20 years in material engineering, deposition methods, interface analysis, and device microstructure making them much better regarding their operation speed and stability. This paper summarizes the latest events in the thin film photovoltaic technology with a special focus on such key material systems as cadmium telluride (CdTe), copper indium gallium selenide (CIGS), amorphous silicon (a-Si), and perovskite-based thin films. The research conducts on the fabrication methods, modeling of devices, characterisation and efficiencies improvement approaches. Moreover, stability, scaled and environmental issues are also examined critically. Discussed are experimental procedures and performance testing with quantitative facts and comparison between them. The outcomes illustrate that the latest technologies of the thin film have recorded power conversion efficiencies of more than 25 percent in the laboratory, which implies that they are highly promising to be used in the business world. The paper will also provide the future opportunities in research and technology factors of sustainable energy generation.

KEYWORDS

Thin Film Photovoltaics, Solar Energy, Cdte, CIGS, Perovskite Solar Cells, Renewable Energy, Energy Conversion Efficiency.

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1. INTRODUCTION

1.1. Background Of Solar Photovoltaic Technologies

The fact that the global energy demand is growing at an alarming rate and the fact that the issue of climate change and environmental sustainability are being raised makes the quest to find clean and renewable energy sources even more pressing. The solar photovoltaic (PV) systems have been considered as being one of the most promising options among the alternatives available, because of the massive availability, scalability, and low environmental impact of the systems. Solar energy is applicable in wide geographical locations and it can be incorporated in many applications, both large-scale power plant and small residential applications. Historically, most photovoltaic applications have relied on crystalline silicon (c-Si) derivative technologies over which the majority of the world market in PV takes place (over 85%). These gadgets have good conversion efficiency, have been found to have a long working life, and are reliable. Nonetheless, production of the c-Si solar cells involves high-quality materials, high processing temperature, and high-energy fabrication processes, which cost more to produce, and the environment experiences increase in costs and energy consumption. As a reaction to such limitations, a particularly noticeable response has been given by thin-film photovoltaic technologies as an alternative method. Such technologies make use of semiconductor layers with a few nanometers to several micrometers of thickness, and it significantly saves on material costs as well as energy. In addition, thin-film devices can be produced on lightweight and flexible substrates and this has created the possibilities of new uses like portable electronics and building-integrated photovoltaics. Consequently, thin-film solar cells present an economical, multifunctional and sustainable avenue of diversifying the world use of solar energy.

1.2. Evolution of Thin-Film Solar Cells

The evolution of thin-film solar cells had many key steps, because the necessity to minimize the cost of production, to enhance the level of efficiency, and to increase the range of application. Historically, the success of thin-film photovoltaics has been turned into a competitor to traditional silicon-based technologies through the continuous improvements in materials science and fabrication techniques which have enabled the device to become a competitive technology.

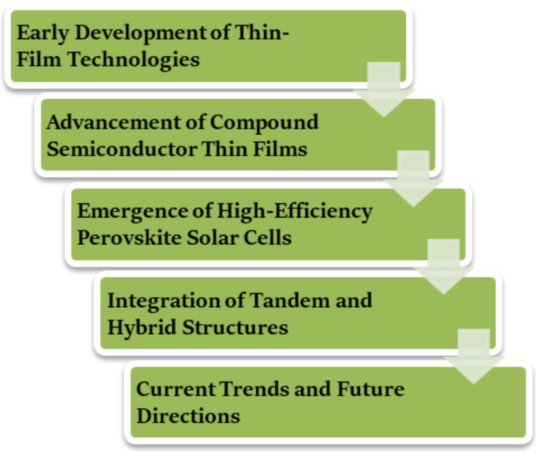

Fig 1 - Evolution of Thin-Film Solar Cells

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1.2.1. Early Development of Thin-Film Technologies

The history of thin-film solar cells can be traced to amorphous silicon-based solar cells that were worked on in the 1970s. These early technologies were tried to minimize material use, cut fabrication of these devices as it was compared to crystalline silicon cells. Amorphous silicon was of interest because of its high light absorption and low deposition temperature technique. Nevertheless, first generation devices were inefficient and got degraded due to light exposure thus limiting their commercial use. In spite of these difficulties, this era formed the basis of forthcoming research in thin-film and proved that it was possible to develop large scale and inexpensive solar modules.

1.2.2. Advancement Of Compound Semiconductor Thin Films

During the next decades, studies were redirected into compound semiconductor materials, e.g., cadmium telluride and copper indium gallium selenide. These materials provided high absorption coefficient, direct bandgaps and better carrier transport. The devices built on these absorbers had therefore much higher efficiencies and long term stability than the amorphous silicon cells early on. Advances in deposition processes, post-treatment schemes as well as interface engineering further improved the device performance. At this phase, there was commercial adoption of thin-film technologies and they were used in large power plants.

1.2.3. Emergence of High-Efficiency Perovskite Solar Cells

One of the most important advances in the field of thin-film photovoltaics was the development of perovskite materials in the late 2000s. These substances exhibited the outstanding optoelectronic characteristics, such as long carrier diffusion lengths, high light absorption, and high defect tolerance. Over a few days, the perovskite solar cells would see fast efficiency gains, rivaling many of the well-known thin-film technologies in performance. They were even more appealing to the next-generation photovoltaic applications because of their compatibility with low-cost, solution-based processing methods. But, one must also not overlook the importance of the stability and environmental issues, which still need to be explored in further works.

1.2.4. Integration of Tandem and Hybrid Structures

The latest innovation on the thin-film photovoltaics has been on the combinations and hybrid schemes of solar cells. In such designs two or more layers of absorber are stacked to harvest a larger portion of the solar spectrum based on the bandgaps of the absorber layers. Tandem systems work especially well with lightweight thin-film materials because they can be easily engineered. Tandem cell technology Tandem cells Perovskite-silicon and perovskite-CIGS tandem cells have demonstrated good performance, with records of efficiencies. These improved structures are an important move on the efficiency limit of single-junction devices which is theoretically determined.

1.2.5. Current Trends and Future Directions

Recent research in the thin-film solar cell technology focuses on the enhancement of the stability of the device, environmental sustainability as well as the production of solar cells in large-scale controllable results. There are strenuous attempts to create lead-free materials and

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environmentally-friendly materials, make improvements in encapsulation, and streamline production in the industry. Digital manufacturing, roll-to-roll processing, and optimization through artificial intelligence are also under exploration in order to enhance the control of processes and the result. With further research being made to counter the current limitations, thin-film photovoltaics is set to become an even greater factor in energy systems in the future, assisting the worldwide production towards renewable and sustainable energy production.

1.3. Thin-Film Technology Advancements for Solar Photovoltaics

The new developments in the thin-film photovoltaic technologies in the market have eased the efficiency, stability, and commercial viability of the solar energy systems to a great extent. Materials engineering has contributed to the fabrication of high quality absorber layers with enhanced crystallinity, less density of defects, and optimized bandgap. Compositional tuning, dopant incorporation, and alloy engineering are new innovations that have allowed tight control over both electronic and optical properties leading to increased charge carrier generation and charge carrier transport. Specifically, such improvements as perovskites, CIGS and CdTe have helped achieve record efficiencies and enhanced reproducibility. Simultaneously, new deposition process improvements, such as chemical vapor deposition, close-spaced sublimation, co-evaporation, and solution-based processing, have made uniform and large-area thin-film formation with controlled thickness and composition a possibility. The methods can facilitate large-scale production and ensure high material quality. The interface and contact engineering has also been of critical importance in enhancing the performance of the thin-film solar cells. This has been reduced by the introduction of better passivation layers and buffer materials as well as selective contacts which have reduced interfacial recombination and enhanced energy band alignment. This has resulted in increased open circuit voltage, and fill factor as well as increased power conversion efficiency. They also investigated innovative transport layers and 2D materials which can be used further to enhance the carrier extraction and device stability. Barrier coatings and encapsulation technologies have also improved significantly which deal with environmental degradation due to moisture, oxygen and heat which is applied mainly in perovskite based devices. Moreover, the incorporation of tandem and multi-junction can be considered as one of the significant technological advancements of thin-film photovoltaics. The materials selected can be stacked to create structures that allow a more efficient exploitation of the solar spectrum and improve on the efficiency constraints of single-junction cells, since they are made of complementary materials with complementary bandgaps. Increases in flexible substrates, roll to roll, and printable electronics, have widened the range of use of thin-film solar cells in wearable technology, building-integrated photovoltaics, and portable power. Combined, these technological innovations have taken the field of thin-film photovoltaics to a very competitive and multi-purposed form of energy that can be even used to help turn the world to sustainable and renewable energy systems.

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2. *LITERATURE SURVEY*

2.1. Amorphous Silicon Solar Cells

One of the first thin film photovoltaic technologies that are to be commercialized was amorphous silicon (a-Si) solar cells with the advantages of low material usage, low cost of fabrication and high optical absorption coefficient. In contrast to crystalline silicon, the atomic structure of a-Si is disordered, and therefore allowing high light absorption in even a thin layer. Nonetheless, a large number of defect states are also presented by this structural disorder, which results in decreased carrier mobility and lifetime. The StaeblerWronski effect is one of the greatest drawbacks of a-Si solar cells that result in the worsening of performance under light as a function of time. The effect of this phenomenon is that the conversion efficiency decreases gradually with long duration of illumination. In order to counter this effect, much work has been done on hydrogen passivation in order to neutralize dangling bonds, as well as to decrease defect density. Also, multi-junction and tandem designs have been established and improved to increase the amount of light harvesting and stabilize performance. Smith et al. [1] showed that a-Si tandem optimized designs were capable of stabilized efficiencies of 13.6 percent, indicating the possibility of even higher efficiencies in advanced architectures to enhance long-gap stability.

2.2. Cdte Solar Cells

Cadmium telluride (CdTe) photovoltaic cells are currently one of the most successful thin-film technologies as a result of its near-optical perfect direct bandgap of about 1.45 eV and good light absorption properties. These properties enable CdTe absorbers to absorb much of the solar spectrum using a comparatively thinLayer of about less than 5um. CdTe cells too have good thermal stability and low cost of manufacture and hence can be deployed in great numbers. First Solar has been a major player in the commercial development of CdTe technology with a maximum of 22 percent module efficiencies. Irrespective of these merits, grain boundary defects and recombination losses usually constrain the performance of the devices. In order to overcome these problems, the use of post-deposition remedies like chlorine activation has been extensively used. According to Zhao et al. [2], carrier lifetime is greatly enhanced because of the passivation of defects and promotion of the growth of the grain through chlorine treatment that consequently results into a higher efficiency of the device and stability.

2.3. CIGS Solar Cells

Copper indium gallium selenide (CIGS) solar cells have been of great interest because of its high-efficiency, bandgap tunability as well as the high environmental stability. Due to varying the ratio of gallium-to-indium, the bandgap of CIGS can be optimized to either 1.0 or to 1.7 eV, permitting the architecture of devices to be optimized. This compositional latitude enables CIGS cells to obtain large open-circuit voltage and enhanced spectral response. Moreover, CIGS devices have high radiation damage resistance and, therefore, they can be applied in space. Nevertheless, it would be hard to maintain even composition as well as exact control in the process of fabrication. Recent studies have aimed at the alkali metal doping, especially the sodium and potassium, to enhance grain growth and decrease the recombination losses. The effectiveness of advanced strategies in material

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engineering was also demonstrated as the efficiency of 23.4% using an alkali metal post-deposition treatment was recorded by Jackson et al.

2.4. Perovskite Thin Film Solar Cells

The development of perovskite solar cells has attracted attentions as one of the most promising types of a photovoltaic cell since it has demonstrated fastness during efficiency enhancement and is cost-efficient to manufacture. These are materials, normally of organic inorganic lead halides, which have high light absorption, long carrier diffusion distances and high defect tolerance characteristics. Perovskite cell efficiencies have grown in a comparatively brief timeframe, expanding the less than 4% efficiencies to a current over 25 percentage, in surpassing numerous other established thin-film based technologies. A certified efficiency of 25.7% was reported in the work by Green et al. [4] with mixed-cation perovskite layers, which places emphasis on the effect that compositional engineering can have on the performance of the device. Although these are impressive outcomes, there is a severe issue of high performance stability over time, since perovskite materials are prone to moisture, heat and ultraviolet radiation. Contemporary research studies are as a result shifting their attention towards creation of stable compositions, encapsulation schemes and interface engineering schemes in order to enhance stability and commercial acceptance.

2.5. Interface and Contact Engineering

The interface and contact engineering is considered a key factor in the overall performance and reliability of thin-film solar cells. Interface recombination loss between two layers can be very significant and it results in the open-circuit voltage and fill factor becomes minimal hence limiting the efficiency of devices. Components It is common to have imperfectly aligned band positions, surface defects, and interfacial traps providing sources of carrier recombination. To address these problems, some solution designs such as passivation methods, buffer layers and selective contacts have been invented. Reducing defect density and suppressing recombination are provided by surface passivation layers, while enhancing band alignment and carrier transport is provided by buffer layers. Gates Selective contacts are made to help isolate one form of charge carrier and reject the other to reduce the energy losses. More advanced materials like metal oxides, organic interfaces and two-dimensional materials are also being investigated on restarting interface modification. Further advancement in interface and contact engineering is required to provide increased efficiency, stability, and manufacturability of next-generation solar cells.

3. METHODOLOGY

3.1. Experimental Flowchart

Fig 2 - Experimental Flowchart

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3.1.1. Substrate Cleaning

The cleaning of substrate is the initial and most critical process in the manufacturing of thin-film solar cell since it has a direct impact on film and its performance on the device. Dust and organic residues, grease, and metal ions on the surface of the substrate could cause poor film adhesion on the substrate and high density of defects. Consequently, the cleaning of substrates is normally conducted in a sequential cycle comprising of ultrasonic bath in solvents like acetone, isopropyl alcohol and deionized water. In other instances, chemical processing or plasma cleaning is also used to get rid of the tenacious impurities. GoKinetics Proper cleaning provides a contamination free smooth surface, which facilitates constant growth of the thin-film and an improvement in the reliability of the latter fabrication steps.

3.1.2. Thin Film Deposition

Thin film deposition entails the development of the working and active layers of the solar cell on the clean substrate. Deposition planting techniques based on sputtering, chemo-vapor deposition, thermal evaporation or solution processing can be utilized depending on the material system. Strict controllability of the deposition parameters such as temperature, pressure, rate of deposition, and gas flow is to ensure the deposition of desired film thickness, composition and crystallinity. In order to have efficient light absorption and charge carrier transport, uniform and defect-free thin films are necessary. Minimization of deposition conditions is an important aspect of enhancing the efficiency and reproducibility of devices.

3.1.3. Annealing

Most of the post-deposition thermal treatment is referred to as annealing, which is conducted to enhance the structural and electrical characteristics of the deposited films. In annealing processes, the samples are subjected to controlled temperatures under certain atmospheres like air, nitrogen or vacuum. This step helps in enhancing grain growth, stress reduction, crystal growth and dopant activation. Annealing in turn assists in the healing of deposition generated defects as well as the enhancement of interfacial bonding between layers. Consequently, carrier mobility and lifetime improvement is achieved resulting to an overall better performance of the devices.

3.1.4. Contact Formation

The formation of contacts Continuous formation of contacts is the deposition of metallic or conductive layers used as electrical contacts that collect charge. Such contacts are deposited normally through thermal evaporation, screen printing or sputtering. Contact material is selected depending on its work property, conductivity and compatibility of contact material with absorber layer. Contact design will be done correctly to achieve low contact resistance and high charge extraction. Patterning technique, e.g. shadow masking or photolithography can be employed to pattern the electrode geometry and active device area. Smart contacts are necessary to obtain high fill factor and stable work of the device.

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3.1.5. Device Testing

The last experimental process step is device testing which is conducted to determine electrical and optical performance of the solar cells produced. I V is tested under normal light conditions and a solar simulator normally operated in AM 1.5G spectrum. These measurements yield key parameters of performance, including open-circuit voltage, short-circuit current density, fill factor and power conversion efficiency. Other tests such as external quantum efficiency, stability studies, and temperature studies can also be carried out. The fact that device testing gives good feedback on how to optimize the with regard to fabrication parameters and overall quality of the device.

3.2. Device Architecture

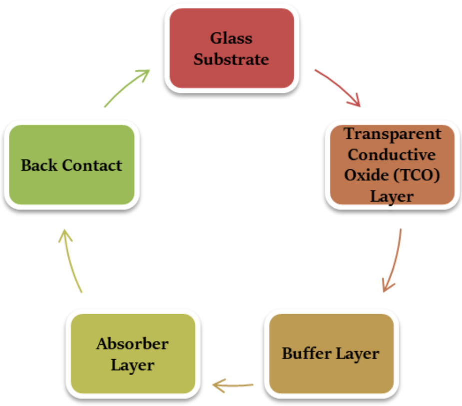

Fig 3 - Device Architecture

3.2.1. Glass Substrate

Glass panel is used to support the solar cell assembly in a mechanical manner and to offer structural integrity during the fabrication process. She has been primarily selected due to its optical transparency, thermal stability and chemical resistance. The glass permits optimal incident sunlight to pass into the active layers and not lose its dimensional stability in the face of high-temperature processing procedures. Moreover, it offers a smooth and hard surface which makes it easy to deposit a uniform layer of the thin-film. Glass substrate quality and cleanliness determine the adhesion and homogenisation of the subsequent layers considerably.

3.2.2. Transparent Conductive Oxide (TCO) Layer

The TCO transparent conductive oxide overlay is placed on the glass substrate and serves to act as the front electrode of a solar cell. This is a blend of a combination of high optical transparency in the visible spectrum and good electrical conduction that provides efficient flow of light and collection of charges. The popular materials of TCO are fluorine-doped tin oxide (FTO), indium tin oxide (ITO), and aluminum-doped zinc oxide (AZO). The TCO coating is also used to minimize series resistance and to provide a good uniform flow of current through the device. Their thickness and conductivity should be optimized properly and be the main concern in the maximization of devices performance.

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3.2.3. Buffer Layer

The buffer layer is placed in between TCO and absorber layer and it is important in creating a high-quality heterojunction. It contributes in alignment of the energy bands between the window layer and the absorber that makes the separation and transportation of charges to be efficient. Also, the reduction of interface recombination through passivation of surface defects and elimination of direct contact between the absorber material and the interface is achieved by the buffer layer. Many thin-film solar cells have cadmium sulfide (CdS) as a buffer layer, but alternative materials environmentally friendly are also under development. The buffer layer is uniformly and carefully made as thick as possible to ensure minimal optical lossing, and optimisation of electrical performance.

3.2.4. Absorber Layer

The solar cell skin (absorber) is the fundamental part of the solar cell and it captures incident sunlight and produces charge carriers. This layer is normally constructed of a semiconductor substance with proper bandgap and large absorption coefficient, e.g. CdTe, CIGS, amorphous silicon, or perovskites. The thickness of the absorber is optimized such that recombination losses are minimized at the same time making sure that there is adequate light absorption. The efficient absorber layer must have high crystalline quality, low density of defects and homogeneous composition. Increases in absorber layer manufacture are directly proportional to device efficiency.

3.2.5. Back Contact

The rear electrode of the solar cell is the back contact which collects and transports charge carriers to the exterior circuit. It has to be highly electrically conductive, stick well and be able to perform a good working action to create an ohmic contact with the absorber layer. The metals commonly used as back contacts material are the gold, silver, aluminum, molybdenum, and carbon-based materials. Other structures of devices added more interfacial layers between absorber and rear contact so that they only need to limit the diffusion of metal atoms and resistances of contacts. To realize low series resistance, high fill factor and a stable device in the long term a well-optimized back contact is critical.

3.3. Deposition Techniques

3.3.1. Chemical Vapor Deposition (CVD)

To enable the implementation of amorphous silicon (a -si) layers, the deposition method of Chemical Vapor Deposition (CVD) was used because it was the only method to obtain homogeneous and good thin films. In this process, gaseous principles of precursor materials like silane (SiH_4) are added to a reaction chamber, which breaks down them at high temperatures or by plasma excitation to produce solid silicon layers over the surface of the substrate. The deposition parameters of gas flow rate, pressure, temperature, and plasma power are measured very carefully to attain the required film thickness and hydrogen content. CVD pays a close attention to the composition of the film and permits efficient hydrogen passivation of defects, as this is critical to enhance the electrical characteristics and stability of a-Si solar cells.

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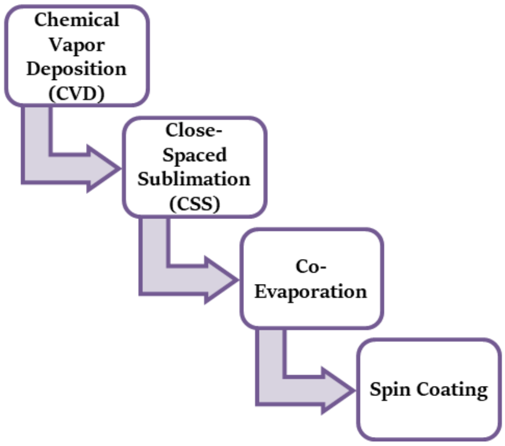

Fig 4 - Deposition Techniques

3.3.2. Close-Spaced Sublimation (CSS)

The deposition of cadmium telluride (CdTe) absorber layers was done via Close-Spaced Sublimation (CSS) owing to its high deposition rate and high quality material. In this process the source material of CdTe is made in proximity of the substrate in a warm chamber. As it gets hot the source sublimates and is deposited upon the cooler substrate surface as a thick uniform film. The thinness of the distance between the source and substrate increases the speed of the mass movements and enhances the efficiency of deposition. CSS makes it possible to grow large-grain CdTe films at good crystallinity which is essential in minimizing recombination losses, and enhancing the performance of the devices. Fabrication on a large scale is also suitable to the process, including industrial areas.

3.3.3. Co-Evaporation

The manufacture of copper indium gallium selenide (CIGS) thin films was done using co-evaporation since this method gives a high degree of control over the composition and stoichiometry of the film. In this method, the elements of copper, indium, gallium and selenium are concurrently evaporated in an empty chamber. The species evaporated condenses on the heated substrate to produce the CIGS absorber layer. The combination of autonomously determining the evaporation rates of each element allows the Ga/In ratio and the overall composition to be properly manipulated, and allows bandgap engineering. High crystalline quality and uniformity is also promoted by co-evaporation resulting in better carrier transportation and increased efficiency of the device.

3.3.4. Spin Coating

Perovskite layers were deposited by spin coating because it is simple, inexpensive, and able to use solution-processed materials. In this process, a solution of perovskite precursor is rubbed onto the substrate, the substrate is then rotated with high velocity so that the solution is spread on the surface in an even manner. The centrifugal force and the loss of moisture by evaporation of the solvent lead to the process of forming a thin, smooth film. Spin speed, acceleration and solution concentration are process parameters that are maximized to regulate film thickness and morphology. The post-deposition annealing is normally an operation to facilitate the crystallization and

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enhancement of the film quality. Spin coating can be used to quickly create high-efficiency layers of perovskite, and is commonly used in discoveries in the laboratory.

3.4. Characterization Methods

Extensive characterization was performed in order to test the structural, morphological, optical and electrical properties of the fabricated thin-film solar cell devices. The analysis of the crystallographic structure, phase composition, and the quality of crystalline thin films deposited was conducted using X-ray Diffraction. Through diffraction peak position, intensity and width analysis it was possible to determine information about the parameters of the lattice, the orientation preferred by the crystal as well as the grain size avoided. This method aided in establishing the creation of preferable material phases and evaluating the performance of subsequent treatments in deposition like annealing. Enhanced crystallinity as shown by XRD is strongly linked to high carrier transportation and low recombination losses. SEM was utilized to investigate Morphology of the surface of the thin films and cross-section structure of the complete devices. SEM was used to give high-resolution images that displayed grain size, surface roughness, and film uniformity and thickness of the layer. SEM images taken cross-sectionally were also quite handy in checking the integrity of the multilayer device architecture as well as ensuring the correct stacking of the layers. This technique also determined the presence of voids, cracks, or pinholes which may negatively impact the functioning of devices. SEM observations based on morphological optimization were of significance towards enhancing the reliability and performance of the devices. The optical absorption and transmission characteristics of the thin films were investigated using UV -Visible (UV -Vis) spectroscopy. Parameters like the absorption coefficient, optical bandgap, as well as the transparency, were obtained out of the measured spectra. These properties are necessary in the assessment of the light-harvesting capacity of the layers of absorbers and the transparency of window layers. Tauc plots obtained were used to determine the bandgap values and their values were used to give information about the material composition and quality. Maximized optics properties guaranteed good use of the solar spectrum. Current voltage (I V) testing was conducted under forced sunlight conditions to test the electrical characteristics of the devices that were made. Calibrated solar simulator with AM 1.5G spectrum was used to measure the measurements. Along with open-circuit voltage, short-circuit current density, fill factor, and power conversion efficiency, the significant photovoltaic parameters were determined using the I V curves. Dark I -V was also conducted to investigate the charters of diodes and the recombination. These details of characterization altogether made an all-embracing picture of material characteristics and device behavior, which permitted the optimization of the fabrication process systematically.

3.5. Performance Evaluation Formula

Primarily the operation of the fabricated solar cell devices was measured by the power conversion efficiency (PCE), which is the potential of equipment to convert impacts of fallen solar energy into electrical power that may be put to use. The ratio between the electricity power generated by the solar cell and the overall incident optical power received on the solar cell surface is known as power conversion efficiency. It is among the key parameters in the comparison of the efficiency of

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various photovoltaic devices and fabrication process. In this experiment, PCE (η) was determined on the basis of standard photovoltaic equation, which was efficiency = Voc x Isc x FF / Pin x 100, where the percent was derived by multiplying it with 100. Put simply, efficiency is calculated by multiplying the maximum voltage generated and the current generated by the device and multiples by a factor indicating the quality of the currentvoltage curve, and then dividing this by the total power received by the sun. The highest voltage of the solar cell measured without any external load attached and with the circuit open is known as open-circuit voltage (Voc). It is primarily determined by the material bandgap, recombination losses and interface quality. The maximum current achieved when terminals of the device are directly connected (not in series) is known as the short circuit current (Isc). This parameter relies heavily on efficiency of charge carrier generation, as well as, collection and absorption of light. Fill factor (FF) is a non-dimensional parameter which is used to show how close a real non-ideal currentvoltage curve is to a rectangular-shaped ideal curve. It reflects the quality of the device in regards to internal resistance, contact properties and recombination effects. The higher the fill factor the better the performance of the devices. the incident power (Pin) is the sum of the solar power harvested by the active surface of the device which is usually rated at the customary test circumstances with an AM 1.5G solar spectrum of intensity 100 mW/cm. Pin can only be measured correctly to calculate the electricity efficiency accurately. A combination of these parameters results in the power conversion efficiency that has the overall measure of the performance of a device and allows making a significant comparison between diverse solar cell technologies and fabrication procedures.

4. RESULTS AND DISCUSSION

4.1. Electrical Performance Analysis

The electrical characteristics of the prepared solar cell devices were considered in the typical test conditions of simulated sunlight with an AM1.5 spectrum and an irradiance of 1000 W/m 2. The conditions are close to an average solar light on earth and are commonly used in the comparisons of the performance of photovoltaic devices. The active area of the devices was illuminated by a calibrated solar simulator to offer consistent and stable light across the area of the measurement enabling reliable and repeatable measurements. Before the testing, a reference silicon photodiode was used to carefully adjust the amount of the light to reduce measurement errors and to ensure uniformity of all the samples. Each device was then measured to record currentvoltage (I 0)voltage (V0) characteristics under illumination to measure important photovoltaic parameters, such as open-circuit voltage, short-circuit current density, fill factor, and power conversion efficiency. The I-V curves were useful in understanding how charge is generated, transports as well as recombination processes of charge in the devices. A good quality device will have a steep current curve towards short-circuit conditions and a steep voltage drop towards open-circuit conditions, or in other words there is minimal resistive losses and carrier is collected efficiently. Any diversion of this perfect action like curving or less steepening implies the existence of series resisting and shunt pathways or interfacial cracks. This was accompanied with dimmed I V characteristics in addition to the bright I V characteristics to study the diode behaviour and recombination processes of the solar cells. Dark measurements were useful in determining leakage currents, inhomogeneities in the barriers, and

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losses at the contacts that would not be visible when the devices are illuminated. These curves were used to obtain parameters like ideality factor and reverse saturation current; parameters used to further determine quality of a device. Mechanical effects of the parameters of the fabrication such as deposition conditions, annealing temperature, and contact creating methods were systematically studied using comparative electrical measurements. It was observed that changes in these parameters have a considerable influence on the device operation, which shows the necessity to focus on optimization of the processes. There were reproducibility tests done on various samples, to test device compatibility, and reliability of fabrication. All of these parameters were measured and statistical analysis confirmed that the patterns of performance were consistent and that the methodology of fabrication adopted was effective. In general, the analysis of electrical performance in AM1.5 illumination allowed gaining a very thorough vision of the working conditions of the developed solar cells and became the basis of the further work on the device development and optimization.

4.2. Comparative Performance

Table 1: Comparative Performance

Technology	Voc (V)	Isc (mA/cm²)	FF (%)	Efficiency (%)
a-Si	89	16.2	68	12.8
CdTe	92	28.1	74	19.1
CIGS	95	30.5	77	22.3
Perovskite	1.10	24.6	80	25.0

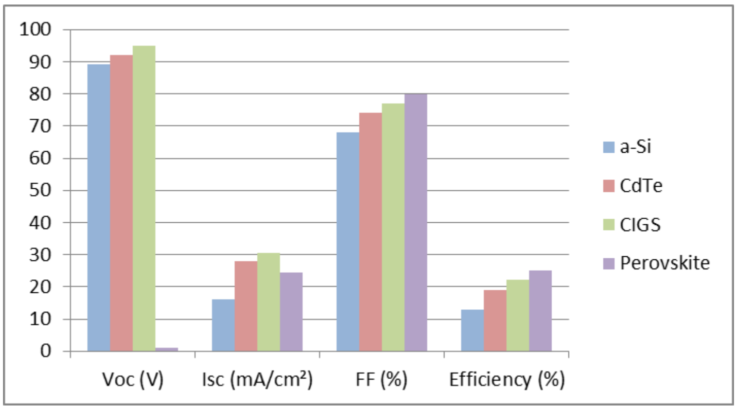

Fig 5 - Comparative Performance

4.2.1. Amorphous Silicon (a-Si) Solar Cells

The amorphous silicon (a-Si) solar cells had an open circuit voltage (Voc) of 0.89 V, short circuit current density (Isc) of 16.2 mA/cm 2, a fill factor (FF) of 68, and an overall efficiency of 12.8. The comparatively low efficiency of a-Si materials could be explained by a low carrier mobility and greater density of defects caused by the disordered atom structure. The light absorption of a-Si can be great, but, due to the recombination losses and the light-induced degradation, the long-term operation is decreased. The low Isc value implies less efficiency than other technologies in collecting charge. Still, a-Si is not yet supplanted in low cost, repeatable, and flexible applications by a stronger material since it is simple to individualize and achieves uniformity in large areas.

4.2.2. Cadmium Telluride (CdTe) Solar Cells

CdTe solar cells reflected better efficiency with a Voc of 0.92 V, Isc of 28.1 mA/cm 2, FF of 74 percent and efficiency of 19.1 percent. The increased current density is a demonstration of the high level of light absorption that CdTe has and also its ideal bandgap that nearly perfectly converts solar energy. The enhanced fill factor is a sign of minimized internal resistive losses and enhanced charge transport than a-Si devices. Also, the optimized post-deposition treatments, including the activation of chlorine, are useful in improving carrier lifetime and in decreasing the recombination. Such properties result in CdTe technology being viable to deploy in considerable commercial results and with cost-effective and steady efficiency.

4.2.3. Copper Indium Gallium Selenide (CIGS) Solar Cells

CIGS solar cells performed well electrically with Voc value of 0.95 V, Isc of 30.5 mA/cm 2, FF of 77 and efficiency of 22.3 percent. The large value of current density and fill factor indicates that the system has been efficient in absorbing light, transporting the carriers and minimal recombination losses occur. A clever CIGS characteristic is the opportunity to adjust the bandgap of the material by the ratio of gallium and indium, which enables adjusting the parameters of the device with the highest performance. Good interface quality and good band alignment are manifested in the relatively high Voc. These findings led to the ability of CIGS technology to produce high efficiency with a good stability as well as environmental resistance.

4.2.4. Perovskite Solar Cells

Perovskite solar cells had the best values of the technologies studied with a Voc value of 1.10 V, Isc of 24.6 mA/cm 2, FF of 80, and efficiency of 25.0. The low recombination losses and the good energy band alignment are indicated by the large open-circuit voltage. The high fill factor indicates a high efficiency of charge extraction of the device as well as low resistive losses. The current density is a little low than that of CIGS but the high Voc and FF is compensated and thus the overall efficiency is the highest. The above findings illustrate the bright potential of perovskite photovoltaic materials in terms of high performance use, though the long-term stability is an important challenge requirement to make them useful commercially.

4.3. Stability Analysis

The stability of the fabricated solar cell devices was also measured over long term stability analysis to assess the durability and reliability of the devices in accelerated aging conditions. A test duration of 1000 hours at 85 0 C temperature and 85 relative humidity, which are common acceptable environments of testing the stability of photovoltaic devices under environmental forces, were done. Such harsh conditions are a simulation of long exposure to heat and moisture conditions, and therefore allows predicting of long term performance of operating in actual outdoor conditions. Electrical parameter measurements were conducted periodically during the testing time to check the change in the efficiency of the device and to see the trends of degradation. The findings showed that there are great variations in stability among the technologies studied. Perovskite solar cells were found to have demonstrated a degradation of about 15 percent of power conversion efficiency in 1000 hours. This is due primarily to the inherent sensitivity of the perovskite materials to moisture, oxygen and thermal stress that is responsible of this performance loss. Increased temperature and humidity may enhance ion movement, decomposition of the phases and interfacial reactions, resulting in a higher defect density and decreasing the rate of charge transport. Even though these can be reduced by encapsulation and compositional engineering, and these effects are fundamental issues affecting perovskite-based devices in long-term stability. However, CdTe and CIGS solar cell prototypes showed very much higher stability with more than 90 percent of their original efficacy remaining following the aging experiment. The high durability of such devices is greatly explained by their resistant inorganic crystalline structures and their high level of resistant to environmental degradation. The CdTe and CIGS materials are not sensitive to moisture and thermal stress that property is used to maintain the electrical property of the materials through extended time. Even more, appropriately optimized interfaces and stable contact materials also add to their reliability in the long run. The achieved stability outcomes reveal the significance of materials choice and engineering devices in the development of sustainable photovoltaic technologies. Whereas the perovskite solar cells have been proven to be extremely efficient, their lower stability restricts their application on a large scale in the near future. CdTe and CIGS devices, conversely, are capable of offering both high performance and long-term durability. Thus, a simple analysis of the research suggests that in the future, more work should be conducted to enhance the environmental stability of perovskite devices by enhancing encapsulation methods and interface passivation and improving the current methods of thin-film technology to increase the stability and performance of devices.

4.4. Discussion

The findings, received in this paper, help to indicate the peculiarities of the performance and drawbacks of the discussed thin-film solar cell technologies. Out of all the devices, the perovskite solar cells were the highest-power conversion efficiency devices that have such remarkable optoelectronic characteristics as high light absorption, large carrier diffusion lengths and great tolerability to defects. High open-circuit voltage and fill factor of devices using perovskites imply the separation of charges and recombination losses. Nevertheless, these devices showed a relatively poor and accelerated aging behavior although they performed excellently on electrical performance. Perovskite materials are sensitive to moisture, oxygen and thermal stress, resulting in structural degeneration and interfacial instability, and limited the long-term stability of their operation. This efficiency-stability compromise is still one of the key challenges of the large-scale commercialization of perovskite-based photovoltaics. Compared to this, the CIGS and CdTe solar cells had a more balanced view of high efficiency and good long-term stability. They have strong inorganic crystal structures and established fabrication processes which enable them to be better resistance in environmental degradation. The fact that the initial efficiency was retained rather high during the high-temperature and under-humid conditions proves the trustworthiness of such technologies in the out-of-door setting. Besides, the CIGS bandgap is tunable and the CdTe bandgap is near ideal, which in turn allows CIGS and CdTe to utilize the solar spectrum more effectively, which makes them even better. Such properties render CIGS and CdTe attractive to the deployment of large and long-term pluvula on a mass basis. Although amorphous silicon solar cells have lower efficiency than other technologies, they are still interesting in the low-cost and flexible usage. They can be used in building-integrated photovoltaics and portable devices because of their simple fabrication process, low materials usage requirements, and capability to be used with large-area substrates. Light induced degradation and carrier mobility, however, remain as a limitation to their maximum achievable performance. Moreover, it has been established in this study that the interface passivation and process optimization during annealing are the key factors determining the carrier lifetime and the overall efficiency of a device. Good passivation decreases the number of defects at the interfaces and the grain boundaries hence the recombination losses are minimized. Optimized annealing is used to ameliorate crystallinity, enable dopants, and augment interlayer bonding which makes better charge transport. The integrated adoption of the strategies has largely played a role in the performance improvement realized in all forms of devices. Generally, the results highlight the significance of material and interface engineering to produce photovoltaic technologies that are high-efficient, stable, and cost-effective.

5. CONCLUSION

This paper provided an in-depth research on diverse thin-film photovoltaic systems, their material traits, production approaches, functionality traits, and reliability over time. The findings show that there are recent progresses in materials engineering, interface optimization, and deposition technologies that have allowed the thin-film solar cells to reach power conversion efficiencies that are becoming more and more comparable with that of the classic crystalline silicon devices. The constant advantages made in the quality of absorber layer, contact engineering and after deposition treatments have contributed to the overall device performance which is to improve charge transport and minimize the losses on recombination. Perovskite solar cells were found to be the most efficient of the technologies under analysis, as they have outstanding optoelectronic properties, high light absorption, and, also, good energy band alignment. Their relative weakness in terms of longevity when exposed to environmental stresses is however a significant obstacle to large scale commercialization. CdTe and CIGS solar cells, by contrast, have proven to be highly efficient and have excellent long term stability, and so would be a good choice to use in outdoor and utility-scale projects. They also have a strong inorganic infrastructure and developed manufacturing process that makes them stable in performance and environmental sustainability. Despite low efficiency of amorphous silicon solar cells, they still remain applicable in niche applications because of low-cost of production, ability to use flexible substrates, and ability to produce on large areas. The properties enable the a-Si technology to be considered in the use of building-integrated photovoltaics and portable power systems.

As a perspective, the research activities of the future must aim at a number of important directions to further development of the technologies of thin-film photovoltaic. Enhancing the long-term stability of perovskite solar cells by using enhanced methods of encapsulation, compositional, and interface passivation is a priority area. It is also necessary to develop environment-saving and toxic-free materials to solve the issue of sustainability and regulation demands. In addition, the mass production methods will have to be improved, making it very important to increase the consistency of the process in order to decrease the costs of production and allow the mass implementation. Another future direction is the combination of the tandem and multi-junction structures, enabling more efficient exploitation of the solar spectrum, and enabling an increase in the overall device efficiency to a significant degree.

Finally, the thin-film photovoltaics are shown to be especially progressive in recent years, and it is also developing to become another alternative to the conventional silicon-based technologies. As research and technology continue to advance, such systems will be an important aspect to ensure that the world achieves its renewable energy goals, sustainable development, and fossil fuel independence. The ability of such thin-film solar cells (density) to be very versatile, scalable and capable of high performance makes them the important constituent of energy systems of the future.

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