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Enhancement of Photovoltaic Performance through Nano-Phased Materials and Thin Film Heterostructures in Solar Cells

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***Abstract*—** The purpose of this research is to investigate the possibility of enhancing the efficiency of photovoltaic (PV) systems by incorporating nano-phased materials and thin film heterostructures into existing solar cells. As a result of the incorporation of these cutting-edge components, solar cells will perform more effectively overall, ultimately satisfying the need for energy sources that are more dependable and efficient. In the context of this study, nano-phased materials are important due to the unique features they possess, which have the potential to significantly improve the efficiency with which solar energy is converted. The use of nanomaterials in solar cells makes it possible to achieve a number of benefits, including greater light absorption, reduced electron-hole recombination, and improved charge carrier mobility respectively. The increased functionality of the photovoltaic system leads to a more efficient use of the sunlight that is flowing in, which in turn increases the overall power conversion efficiency of the system. As an additional benefit, the incorporation of thin film heterostructures into solar cells improves the use of nano-phased materials by boosting the charge transport channels that are present inside the cells. Thin films, when precisely integrated into heterostructures, provide efficient charge separation and collection, hence minimizing the amount of energy that is lost during the conversion process. Through the synergistic interaction of thin film heterostructures with nano-phased materials, it is possible to construct a solar cell that has improved performance characteristics. In addition to the fabrication of thin film heterostructures by the use of advanced deposition techniques, the research includes the meticulous analysis of a wide variety of nanostructured materials, including nanowires, nanoparticles, and nanotubes. A thorough analysis and comparison of the performance of these unique solar cell designs with that of traditional solar cells will be carried out. The results of this comparison will provide valuable new information about the possibility of this much enhanced technology being widely used. By bringing forth a novel approach to enhancing photovoltaic performance, the purpose of this study is to make a significant contribution to the ongoing efforts that are being made to enhance the technology that is used for renewable energy sources. A combination of thin-film heterostructures and nano-phased materials might make it feasible for future generations of solar cells to be powered in a manner that is both environmentally friendly and efficient in terms of energy consumption.

Keywords : Photovoltaic, Nano-phased materials, thin film heterostructures, Solar cells.

I. INTRODUCTION

For the purpose of conducting a more in-depth investigation of solar technology, the introduction sets the basis. In the part that follows, the background material is discussed in comprehensive depth. This section also provides a summary of the research that has been done in the past and provides a contextual perspective on the greater field of study. This condition presents the research problem, which is the identification of a gap or constraint in the information that we already possess to begin with. In the next step, the objectives of the study are expressed in a manner that is comprehensible in connection to the research problem that has been identified.

The significance of the study is underlined, along with the manner in which it contributes to the existing body of knowledge and tackles topics that are relevant to everyday life. By meticulously describing the scope of the study as well as the limitations of the investigation, the criteria for the research are formed. For the purpose of providing conceptual guidance for the inquiry, a theoretical framework may be supplied if it is deemed essential. This provides the reader with a glimpse into the methodology that will be used in the research by providing a concise summary of the study's design and the methods that were used to collect data. The conclusion of the paragraph includes a synopsis of the structure of the paper, a guidance for the reader, and a seamless transition into the subsequent sections of the research being conducted. When everything is said and done, the introduction is methodically prepared with the intention of attracting the attention of the reader, providing background information, and making it clear why and how significant the research is.

Combining thin-film heterostructures with nanophase materials to enhance solar performance

In order to acquaint the reader with the primary concepts that are being investigated, the introduction, which serves as the entrance point for the paper, is intended to do this. This section provides an overview of the research challenge, which is cantered on the significant topic of enhancing photovoltaic performance by the use of thin film heterostructures and nano-phased materials in solar cells. As a means of providing light on the greater context of the rising need for sustainable energy sources, the introduction lays the groundwork for the research of cutting-edge solar technology. In addition to providing background information, the introduction delves into the underlying concepts that underlie the conversion of solar energy and examines the current state of solar cell technology.

This contextualization highlights how crucial it is to continue research in order to overcome the challenges that are now currently being faced and to enhance the efficiency with which solar energy is collected. The research objectives, which are articulated in a straightforward manner, provide an overview of the specific goals that this study intends to achieve.In order to achieve the ultimate objective of improving photovoltaic performance, these objectives will act as markers for additional study into the coupling of thin film heterostructures with nano-phased materials. In the next section, a concise analysis of the literature is offered, which offers a brief but critical evaluation of relevant scholarly articles. In addition to situating the current research within the context of the wider body of knowledge, this assessment highlights areas of uncertainty in the existing body of literature as well as areas in which the planned research will provide novel perspectives.

The introduction addresses previous research in order to provide a conceptual foundation for the investigation that is now being conducted. The purpose of the introduction is to serve as a comprehensive prelude, directing the reader from the general context of the global energy landscape to the specific research issue, its objectives, and the existing body of knowledge. It is assured that the readers of the research paper will comprehend the significance of the study and will be prepared for the in-depth analysis that will be presented in subsequent sections if this planned technique is used.

PV Cell Design Materials

Throughout the process of designing solar cells, the selection of materials for the active films, buffer layers, and electrodes becomes an increasingly important factor. When it comes to determining how well photovoltaic cells operate, the design of the device is also a very important factor. Depending on whether the transport material, which may be an electron or a hole, came into touch with the incident light first, the device design can be characterized as either normal (or conventional) or inverted. As a consequence of this, indium tin oxide (ITO), which is a transparent conductive oxide (TCO) that has a high work function, enhanced transparency, and decreased electrical resistance, is often used as the anode in traditional device designs. Aluminium, which has a low work function, is often employed as the cathode in lithium batteries.

In recent years, a number of TCOs, such as FTOs or AZOs, have also been used in the production of devices that include an organic: inorganic composite layer. These devices include OPVs and HPVs. The procedure for collecting charges in a device design that is inverted is different from the one used in a conventional arrangement. It may be deduced from this that the transparent electrode functions as the cathode, while the anode is comprised of a metal that has a high work function, such as gold or silver. After the holes have been filled by the metal back contact, the electrons are collected by the TCO front electrode, which is composed of n-type materials such as ITO, FTO, and TiO_2.

Electrodeposition improves solar cell absorber film coating

In addition to enhancing the coating quality of the absorber film that is intended for use in solar cells, electrodeposition makes it possible to completely fill any physical gaps that may exist between the nanostructures. The fabrication of nanostructured, planar p-Cu_2O/n-ZnO films has been the subject of a significant number of experimental electrochemical investigations. The maximum efficiency that has been produced with this method to this point is less than 1.5%, despite the fact that electrodeposited p-Cu_2O/n-ZnO heterojunction solar cells have the potential to yield up to 18% conversion efficiency. A low intrinsic potential, a restricted open-circuit voltage that is the consequence of interface defects formed during sequential electrodeposition, and accelerated recombination via interfacial traps are all possible causes for this phenomenon.

There are various components that are necessary for solar cells, and one of them is the buffer transport layer. They may be able to increase the performance of the device by increasing the recombination for one charge type while decreasing it for another charge type. The electron blocking layer (ETL), the cathode buffer layer (CBL), and the anode buffer layer (ABL) are all designations that are sometimes used to refer to these layers. Styrene sulfonate and 3,4-ethylenedioxythiophene are the two components that work together to form PEDOT:PSS, the most common conducting polymer. In compared to ITO, it has a high work function, exceptional optical transparency in the visible region, and a high hole conductivity. Additionally, it is chemically stable in air and has outstanding chemical stability.

The literature review portion of the study report provides a comprehensive analysis of the body of research that has been conducted on the topic of enhancing photovoltaic performance in solar cells via the use of thin film heterostructures and nano-phased materials. This part of the report not only provides a justification for the inquiry, but it also provides a summary of the relevant literature and highlights areas that need more research.

A detailed analysis of prior research on thin film heterostructures, nano-phased materials, and solar cell technologies is presented in this work. An in-depth comprehension of the present state of affairs in the region may be attained by doing an analysis of the methodologies, results, and conclusions of these research. The suggested study builds upon previous, more important studies that laid the groundwork for it. This is done in order to show continuity between the two eras.

It is becoming more apparent that the nuances and limitations of prior studies are revealing gaps in the existing body of literature. These voids are indicative of areas that need further investigation or areas in which the incorporation of thin film heterostructures and nano-phased materials in solar cells has not been adequately examined. The current study is positioned as a beneficial contribution to bridge these gaps and promote the discipline by conducting this thorough evaluation for the purpose of advancing the field. One of the most essential aspects of the literature review is ensuring that the need of the present investigation is well defended.

The review highlights the significance of the proposed investigation by bringing to light the deficiencies, unresolved issues, and unexplored avenues that are present in the body of existing research. The combination of thin film heterostructures with nano-phased materials is a promising method that may be used to fill these gaps and improve solar performance. In a systematic manner, the literature review brings together the many threads of past research, therefore shining light on the benefits and drawbacks of the existing body of information. Not only does this in-depth analysis give background for the ongoing investigation, but it also makes a compelling argument for the significance of the planned research and the urgency with which it should be conducted in the process of creating solar cell technology.

2. OBJECTIVES OF THE STUDY

1. To study on Combining thin film heterostructures with nano phased materials to enhance solar performance
2. To study on electrodeposition enhances the absorber film's coating quality for use in solar cells.

3. RESEARCH METHOD

Within the methodology section of the research paper on enhancing photovoltaic performance via the utilization of nano-phased materials and thin film heterostructures in solar cells, a comprehensive explanation of the study idea, methods used, as well as materials, processes, and techniques utilized, can be found. It is of the utmost importance to ensure that the procedure can be repeated in order to allow other researchers to replicate the study and get confirmation of the findings. An explanation of the research design is provided, along with an outline of the overall methodology that was used in order to accomplish the objectives of the study. In this study, an organized and systematic strategy that involves experimental methodologies is used in order to investigate the incorporation of thin film heterostructures and nano-phased materials into solar cells.

This section provides an explanation for the design that was chosen, with a particular emphasis on how well it satisfies the goals of the research. The materials that were employed in the inquiry are discussed in great depth. These materials include nano-phased materials, thin-film components, and any other substances that were necessary for the experimental setup. In order to guarantee transparency throughout the study process, it is necessary to provide explicit facts about the characteristics and origins of these materials. Explanations of the methodologies and tactics that were used during the course of the experimental phase give a comprehensive road map for carrying out the study effectively.

This includes the processes that are involved in the creation of nano-phased materials and thin film heterostructures, as well as the assembly and testing of solar cells. Providing other researchers with detailed information on the apparatus and methods of measurement helps them to accurately replicate the study. A significant amount of focus is placed on repeatability in the techniques section, with particular care paid to the manner in which processes are described. Both the robustness and credibility of the research are improved when the measurements, parameters, and variables are defined in a manner that makes it simpler to replicate the study in a consistent manner.

The methodology part offers a comprehensive review of the idea, design, and execution of the research, to summarize the information presented in the section. Through the inclusion of complete information about the research design, materials, methods, and techniques, with a particular emphasis on replicability, this section ensures that the scientific community will be able to properly evaluate, duplicate, and build upon the findings of the study.

Substratum n-Si sterilization

For this experiment, a SiO2-covered n-Si (100) substrate with a thickness of 500 nm and an aperture of φ=2 mm (active area of 3.14 mm2) was used. The substrate had a thickness of 1–5 Ã cm and was doped with P. The oxide layer that had naturally evolved on the aperture was removed by washing it in a solution of isopropanol (IPA) and clean water. This was done after it was immersed in hydrofluoric acid (HF) at a concentration of 4.7 weight percent for a period of thirty seconds. After placing the n-Si substrate within a vacuum chamber, a turbo molecular pump was used to support it. The base pressure of the chamber was set at 5à10−4 Pa.

The process of annealing the n-Si substrate involved gradually heating it to a temperature that ranged from 400 to 800 degrees Celsius, maintaining it at that temperature for a predetermined amount of time, t, which could be anywhere from 0 to 10 minutes, and then bringing it down to a temperature that was lower than 400 degrees Celsius at a rate of approximately 400 degrees Celsius per minute (Supplementary Information, Figure S1). During the course of the annealing process, the temperature saw a steady ascent, while the pressure reached a peak of 2×10^{-2} Pa.

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PEDOT fabrication: PSS/n-Si photovoltaic cell

The mixture consisted of two components: twenty milliliters of PEDOT: PSS aqueous dispersion (500 S/cm, Heraeus Deutschland GmbH & Co. KG, Leverkusen, Germany) and fifty volume percent IPA. Both of these components were blended. The mixture was spin-coated onto the passivated n-Si substrate for a period of sixty seconds at a speed of two thousand revolutions per minute. The temperature was then raised to 130 degrees Celsius, and it was left to anneal at room temperature for ten minutes. We used a mask to spin-coat the edges of the n-Si substrate in order to lessen the edge effect and prevent short circuits from occurring with the substrate. A bottom indium (In) cathode was welded onto the backside of the n-Si in order to finish the solar cell. Additionally, a top gold (Au) anode was formed by sputter-deposited a 2.2 mm square or round aperture onto the PEDOT: PSS. Both of these steps were necessary in order to finish the solar cell.

Production of n-Si/CNT photovoltaic cell

In order to manufacture CNT/n-Si solar cells, the procedure that was provided in the earlier report16 was used. After using bath sonication for a duration of three minutes, 100 microliters of the dispersion were combined with water to produce an aqueous solution of sodium dodecylbenzene sulfonate (0.5 weight percent, 10 millilitres). Subsequently, the carbon nanotube (CNT) film was produced. The SDBS was removed from the film by first filtering it, then washing it with 100 mL of filtered water, allowing it to drop to the bottom, and then heating it in a water bath at 95 degrees Celsius for seventy minutes. Immediately after the transfer of the carbon nanotube (CNT) film from the hot water to the n-si substrate, a little amount of ethanol was added and allowed to dry on top. This was done in order to ensure that the two materials would form a substantial bond. An aperture of 2.2 millimetres was produced as a consequence of the sputtering of the top gold anode onto the carbon nanotube (CNT) film using a mask. Welding was then used to form the bottom in cathode, which was located on the opposite side of the n-Si.

Descriptive analysis and quantitative evaluation

Forming PEDOT: The optical transmittance and sheet resistance tests were made feasible by PSS films on quartz glass and CNT films on polyethylene terephthalate (PET) substrates, respectively. Both of these films were used to form PEDOT. In order to determine the optical transmittance, UV-visible spectrophotometry was used, and the four-point probe technique was utilized in order to conduct the sheet resistance measurement. Spectroscopic ellipsometry and X-ray photoelectron spectroscopy were used in order to conduct an in-depth investigation of the passivation layers that were generated on the n-Si substrates.

The spectroscopic ellipsometry analysis for each condition had three points for each sample, and it was based on three samples that were automatically created. For the purpose of determining the performance of photovoltaic cells, a solar simulator and a solar cell assessment system were used to conduct an analysis on four cells for each scenario. The intensity of the radiation was adjusted with the help of a conventional silicon photodiode. A CEP-2000 integrated system was used in order to evaluate the external quantum efficiency (EQE) of a few cells.

The monochromator and xenon light were utilized in the measurement process. A light blocking mask made of nickel foil, with a hole of 2 millimetres in diameter and 10 square millimetres in area, was put on the solar cell in order to ensure that it was exposed to light in an equal manner during the assessment process.

4. DATA ANALYSIS

PEDOT: Passivation-free and passivated PSS/n-Si solar cells

We investigated the impact that passivation had on the photovoltaic performance of heterojunction solar cells composed of PEDOT: PSS/n-Si. PEDOT: PSS is considered to be one of the most effective and widely used conductive materials because to its high conductivity, suitable work function, and remarkable film forming properties25, 26. Through the process of spin-coating a mixture of PEDOT: PSS and IPA onto the passivated n-Si, a PEDOT:PSS film was successfully produced. Through the manipulation of the spin-coating duration and speed, it was feasible to exert control over the thickness. Figure S2 illustrates the inverse relationship between the transmittance and resistance of the films in respect to one another. As seen in Figure 1a, the experiment employed PEDOT: PSS films that had a sheet resistance of 150 Ω/sq and an optical transmittance of 92% at 550 nm. These films were utilized in the experiment. An example of the replication of the oxide-layered PEDOT: PSS/n-Si heterojunction solar cell design can be shown in Figure 1b.

Experiments were conducted to establish the optimal passivation condition for PEDOT: PSS/n-Si heterojunction solar cells. These experiments included testing with various combinations of annealing temperature and duration in order to get the highest possible photovoltaic (PV) performance. For solar cells that were manufactured using n-Si passivated at 500 degrees Celsius for 0, 1, 3, and 10 minutes, the J-V curves are shown in Figure 1c. The percentages of efficiency (PCEs) that were acquired were as follows: 12.22%, 10.96%, and 11.31%. These percentages were obtained at varied annealing temperatures. During the time when the Voc was falling from 0.56 to 0.52V, the FF was increasing from 0.65 to 0.71.

The FF, on the other hand, stayed lower even when the annealing period was increased even more. The J-V curves of solar cells that were produced with n-Si passivated at temperatures of 400, 500, 550, 600, 700, and 800 degrees Celsius for one minute are shown in Figure 1d. It was decided that one minute would be the annealing time. While the material was being passivated at 550 degrees Celsius, FF produced a high PCE of 12.65% and a maximum value of 0.73.

As the temperature rose, the voltage characteristic curve (Voc) and the short circuit current density (Jsc) began to decline, which led to PCEs that were below average. Regardless of this, a passivation layer of superior quality was produced as a result of the fact that the FF remained relatively high (over 0.60). Table 1 provides a summary of the PV parameters of these solar cells, and Figure S3 illustrates the dark J-V characteristics of these cells. Per the results, a single minute of rapid annealing at temperatures ranging from 500 to 550 degrees Celsius was sufficient to generate passivation.

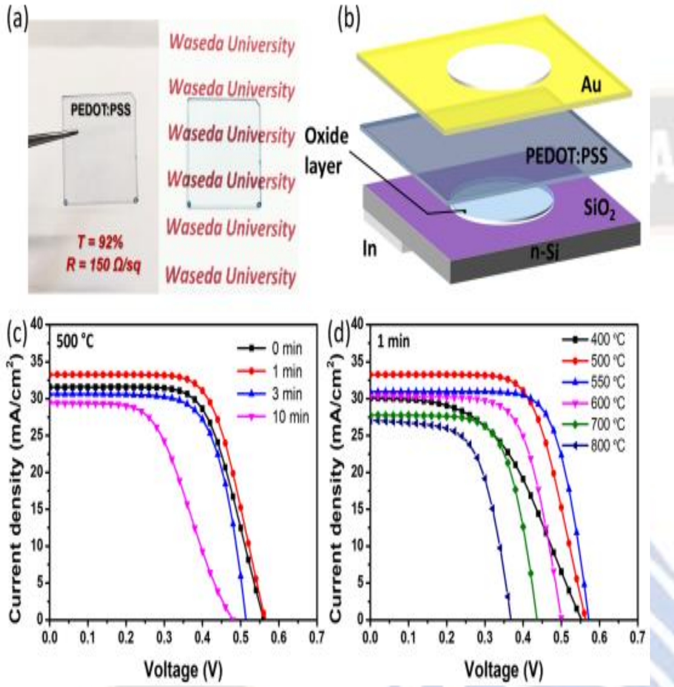

Figure 1. (a) A quartz glass substrate with a PEDOT: PSS film spin coating. (b) A schematic depicting the passivated oxide layer in a PEDOT: PSS/n-Si heterojunction solar cell. the junction potential (J-V) curves of PEDOT: PSS/n-Si heterojunction solar cells (c) subjected to 500 °C for 0-10 minutes and (d) subjected to 400-800 °C for 1 minute.

Table 1. The photovoltaic properties of PEDOT: PSS/n-Si heterojunction solar cells subjected to varying degrees of passivation. The findings of the four cells that were manufactured for each condition are used to calculate the average and standard deviation.

Celsius temp.	Duration	Jsc = mA/cm^2	Voc(V)	FF	PE(%)
500° C	0.0	31.26±0.31	0.560±0.001	0.652±0.004	11.31±0.14
500° C	1.0	32.64±0.43	0.562±0.007	0.676±0.008	12.22±0.24
500° C	3.0	30.41±0.25	0.520±0.006	0.707±0.007	10.96±0.11
500° C	10.0	29.67±0.26	0.470±0.011	0.513±0.006	7.16±0.17
400° C	1.0	29.90±0.62	0.543±0.005	0.503±0.014	8.20±0.05
550° C	1.0	30.84±0.17	0.564±0.004	0.725±0.015	12.65±0.16
600° C	1.0	30.13±0.46	0.506±0.012	0.675±0.008	10.27±0.13
700° C	1.0	27.62±0.31	0.432±0.004	0.674±0.006	8.05±0.07
800° C	1.0	27.07±0.17	0.370±0.006	0.625±0.013	6.26±0.16

Additionally, in order to passivate the n-Si substrates, they were heated to a temperature of 500 degrees Celsius for one minute. After that, XPS was employed in order to evaluate them in both directions. A very small peak at around 102 eV was seen in the Si 2p spectra shown in Figure S4b. This peak is most likely produced by SiOx. In addition, the O 1 s spectra displayed a peak at around 532.5 eV, which is in agreement with the Si-O group (Fig. S4c to be more specific). Following the annealing process, the intensities of the two peaks that were connected to SiOx rose, which indicated that SiOx growth had taken place.

The use of ellipsometry allowed for a more accurate description of the passivation layer that was generated under a variety of situations. There were three points that were examined for each and every tree sample that was created for each and every passivation condition (Fig. 2a,b). The n-Si substrate exhibited a surface layer that had a thickness of around 0.5-0.6 nm and a refractive index of 1.458 after being etched with HF for a duration of thirty seconds. When the annealing time and temperature were increased, the n-Si substrates displayed greater surface layers, and the thickness of these layers increased as well. From 0.9 to 1.5 nanometres, these strata were present.

The oxide layer that was generated by annealing on the surface of the Si material that had been treated with HF had a higher refractive index (1.465-1.470) compared to the native oxide layer from the layer that did not undergo annealing, which was about 1.458. This indicates that the oxide layer had a greater density. Annealing with low pressure and speed reduces the oxygen supply and produces a thinner oxide layer. On the other hand, annealing at high temperatures increases atomic diffusion and causes the structure of the oxide layer to become more pliable.

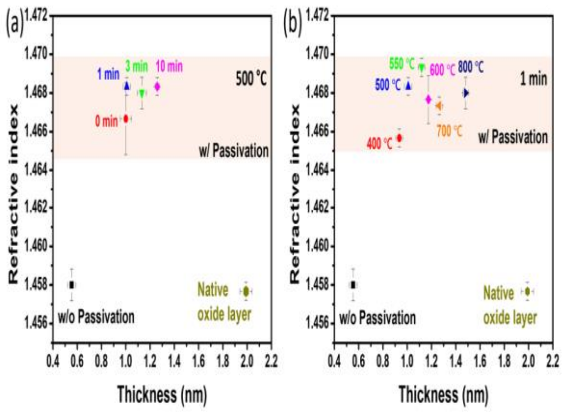

Figure 2. The surface oxide layer on Si that was created by annealing (a) at 500 °C for 0-10 minutes and (b) at 400-800 °C for 1 minute, as seen using spectroscopic ellipsometry. An n-Si substrate "w/o Passivation" has been etched in HF; an n-Si substrate "native oxide" has been air-treated for 10 days after HF-treatment; and an n-Si substrate "w/

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Passivation" has been annealed with passivation following HF-treatment. For every situation, we took a tree sample and measured it three times. You can see the standard deviation on the error bars.

Annealing at higher temperatures or for longer periods of time results in thicker oxide layers, which in turn leads to worse performance. Annealing may be continued for extended periods of time. Following that, we used the J-V curves of the solar cells in order to compute the series resistance (Rs) and the shunt resistance (Rash) of the cells. In contrast to Rs, which is associated with charge transfer and interface contacts, Rash is often associated with manufacturing and internal defects. This considerable improvement in FF was shown in the solar cells' decreased Rs and increased Rsh (Table 1, Figure S5).

Increasing Rsh was also observed. By analyzing the Rs and Rsh of the devices, it was possible to determine the technique that the passivation layer used. In solar cells that do not have passivation29, significant dark currents are produced as a consequence of carrier recombination that is not adequately reduced when the oxide layer is either too thin or too thick. The application of the appropriate amount of heat during the annealing process may result in the formation of a thin oxide layer on the surface of n-Si. The characteristics of the diode and Rsh are improved by this layer, which also serves as a passivate. Additionally, the tunnelling action is possible to transmit holes thanks to this layer. Increasing the thickness of the oxide layer even more stops holes from going through, which results in an exponential rise in the value of Rs. The thick and thin oxide layers perform the functions of a high-quality hole transport layer as well as a passivation layer, which results in an improvement in the FF and PCE of the solar cells.

CNT/n-Si photovoltaic cells with and without passivation

The CNT/n-Si heterojunction solar cells were constructed by employing passivated n-Si substrates and CNT films. The purpose of this experiment was to assess whether or not the addition of additional n-Si heterojunction solar cells may possibly increase PV performance. The work that we have done in the past has contributed to the development of a low-overhead method for creating high-quality CNT films while preserving CNT30. This method involves repeatedly distributing and extracting CNT powder.

The concentration of the CNT solution was changed in order to get a range of different optical transmittance values for the films. Doping-free carbon nanotube (CNT) films were employed to fabricate the CNT/n-Si cells that were used in this investigation. These films had a sheet resistance of 208 Ω/sq and an optical transmittance of 90%. For the purpose of passivating the n-Si substrate, it was promptly annealed in a vacuum at 550 degrees Celsius for one minute. After that, a sheet of carbon nanotubes (CNT) was applied to the passivated substrate in order to build the heterojunction junction machine. a schematic exhibiting the heterojunction solar cell composed of n-Si and oxide layers.

In Figure 4a, the J-V curves of both the passivated and non-passivated cells are shown, and an inset photograph of the passivated cell is included inside the figure. The passivated CNT/n-Si solar cells with similar values of 0.55 V, 0.58 FF, and PCE of 8.52% demonstrate superior photovoltaic (PV) performance in contrast to the non-passivated device (6.61% vs. 26.53 mA/cm2), with the passivated solar cells exhibiting a higher PCE of 8.52%.

During the passivation process, the dark J-V characteristics of the solar cells show that there is a reduction in the amount of interface carrier recombination (Figure 4b). It was observed that the increased EQE exhibited a wider range of wavelengths (400–1000 nm), and the estimated integrated current density was somewhat greater (26.20 mA/cm2) than it was in the solar cells that did not have passivation (24.71 mA/cm2). This was in conformity with the J-V characteristics. In the same way that the oxide layer functions as both a hole transport layer and a passivation layer in the PEDOT: PSS/n-Si solar cells, our findings demonstrate that the oxide layer significantly improves the photovoltaic (PV) efficiency of the CNT/n-Si heterojunction solar cells too.

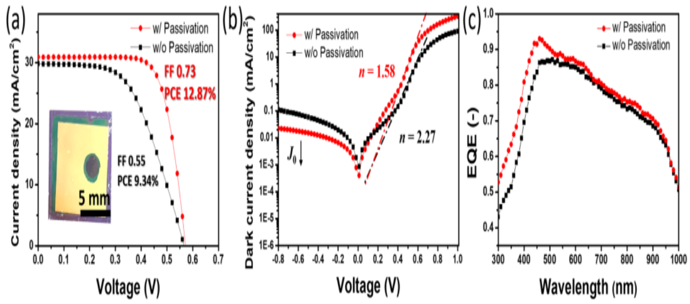

Figure 3. (a) PEDOT: PSS/n-Si heterojunction solar cells' J-V curves, with and without passivation of the Si surface in each case. In (a), you can see the digital picture of the passivated solar cells in the inset. (b) PEDOT, the leader in PSS/n-Si heterojunction solar cells, dark log J-V curves. (c) Under AM 1.5G irradiation, the excelling PEDOT: PSS/n-Si solar cells' EQE spectra both with and without passivation.

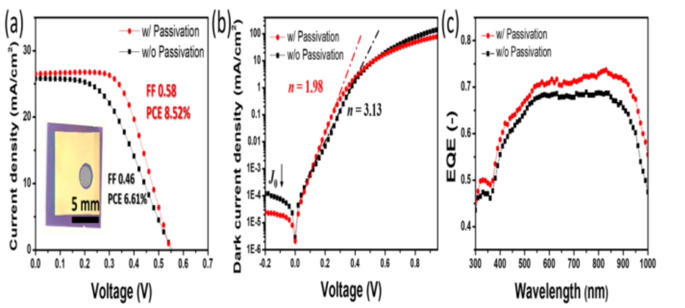

Figure 4. (a) J-V curves—passivated and non-passivated—of the best CNT/n-Si heterojunction solar cells. The digital picture of the passivated solar cell is shown in the inset of (a). (b) In the absence of light, our top-performing CNT/n-Si heterojunction solar cells display their log J-V curves. (b) Under AM 1.5G irradiation, the EQE spectra of the champion CNT/n-Si heterojunction solar cells either without passivation or with it.

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Additionally, the photovoltaic capabilities of these devices were significantly boosted. Following that, we carried out a preliminary stability test on the hybrid heterojunction solar cells by exposing them to air at ambient temperature, without any light or encapsulation. Both the PEDOT: PSS/n-Si and CNT/n-Si cells started with PCEs of 12.64% and 8.52%, respectively, as shown in Figure 5. This figure depicts the observed efficiency development for both of these cell formulations. Following about one thousand hours of operation, the power conversion efficiency (PCE) of the PEDOT: PSS/n-Si solar cell saw a considerable decline. The possible explanation for this decrease is that it is the result of an interaction between the airborne moisture and the PEDOT: PSS/n-Si junction.
When the PSS was exposed to PEDOT for 960 and 1500 hours, it would absorb water and produce dipoles at the interface, which would result in a J-V curve that had the shape of a S. Immediately after 1500 hours, there is a significant rise in Rs, which goes from 2.21 to 10.27 é cm2, and a fall in FF, which goes from 0.73 to 0.37. This results in a decrease in the PCE, which now stands at 5.21%.
The CNT/n-Si solar cell, on the other hand, was found to be more durable than the PEDOT: PSS/n-Si solar cell. This might be related to the fact that CNT is more stable than PSS. When exposed to air for 1200 hours, the PCE dropped to 7.01% from its previous level. It is expected that the incorporation of a chemical doping process or the inclusion of an encapsulating layer would result in solar cells that are substantially more stable. At the moment, research and investigations concerning the efficient doping of heterojunctions are carried out.

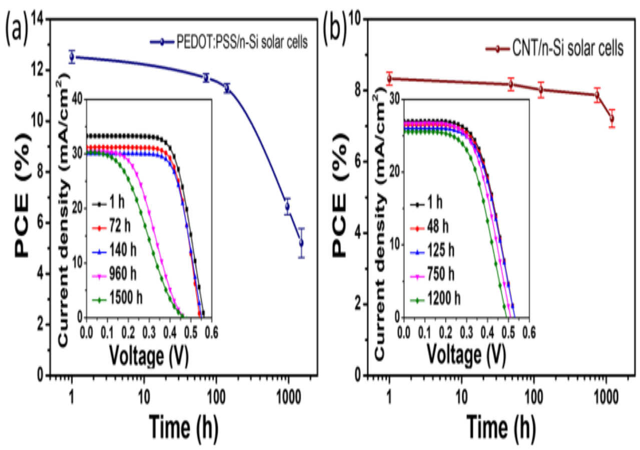

Figure 5. performance characteristics of (a) PEDOT: PSS/n-Si heterojunction solar cells and (b) CNT/n-Si heterojunction solar cells with respect to time spent in air without light and encapsulation. The n-Si substrates were annealed for 1 minute at 550 °C to passivate them. For each kind, we tested anywhere from three to five cells; the bars representing the standard deviation represent the errors. For each kind of cell, the insets show the temporal evolution of the J-V curves.

It is necessary to make advancements in both the production of crystalline Si substrates and the fabrication of connections in order to manufacture solar cells that are extremely readily available at low cost. By using a process that we had previously developed, which we referred to as "rapid vapor deposition of liquid Si and in situ melt crystallization", it is possible to create continuous polycrystalline Si films with lager grain sizes exceeding 100 µm in only one minute. In-situ surface passivation is expected due to the fact that the generated Si films cool down fast in vacuum from around 1400 degrees Celsius. The quick processes of printable heterojunction, Si surface passivation, and Si film fabrication will be combined in order to produce heterojunction solar cells that are extremely economical.

5. CONCLUSION

The main conclusions drawn from the study are summarized in the research paper's conclusion section, which focuses on improving photovoltaic performance in solar cells using thin film heterostructures and nanophased materials. It functions to summarize the key discoveries, highlight the importance of the study, and suggest possible directions for further investigation. The conclusion reviews the key findings and conclusions that were found during the research process after providing a brief synopsis of the major findings. This summary makes sure that readers comprehend the results and their consequences in a straightforward and comprehensive manner. The research's relevance is then emphasized once again, this time focusing on the study's contribution to the larger area of solar cell technology. The conclusion explains the significance of the study and how it adds to our understanding, whether it is via the creation of new materials, the optimization of thin film hetero-structures, or the increase of total solar efficiency. The conclusion makes recommendations for further inquiry and exploration in light of the future. This might include expanding on the results of the present study, resolving research constraints, or exploring relevant but uncharted territory in photovoltaic technology. The conclusion lays the groundwork for future developments in the subject by outlining these possible directions. The conclusion provides a thorough assessment on the relevance of the study, its influence on the field, and potential paths for future research endeavors. It functions as a summary of the research trip. It satisfies the reader's need for closure while arousing interest in the ever changing field of solar cell technology.

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