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Research on Strategies to Enhance Semiconductor Thin-film Solar Cells Efficiency

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Abstract. Recently, advanced solar cells are becoming growing essentially in the world due to their environmentally friendly and renewable, and new semiconductor thin film solar cells are gradually entering lives of people. Therefore, this paper mainly focuses on methods to enhance the performance of semiconductor thin-film solar cells. Elemental doping and modification techniques can change the properties of a semiconductor by doping the intrinsic semiconductor with specific elements and realizes the conductivity modulation of semiconductor thin film cells. Internal structure optimization can optimize the internal structure of the cell, through the optimization of the cell buffer layer or absorption layer to ameliorate battery performance. It is possible to insert insulating layers between internal structures or to optimize film absorbing and buffer layers. Solar cell transfer efficiency can be improved by these methods. Most importantly, these methods can significantly alleviate the environmental and energy pressures.

Keywords: Semiconductor Thin-film Solar Cells, Elemental Doping, Structural Optimization.

1. Introduction

Environmental and energy issues have become one of the most important challenges in the world today. The utilization of traditional fossil fuels results in the excessive emission of pollutants such as carbon dioxide, sulfur dioxide, and particulate matter, thereby impacting the quality of the atmospheric environment and contributing to air pollution and haze. Conversely, solar cells harness photovoltaic power generation, which directly converts solar radiant energy into electrical energy. Fossil fuel extraction and processing usually have a large amount of energy wasted. However, the use of solar cells can avoid this waste and reduce air pollution, etc. With huge environmental benefits, it is an valid measure to solve the environmental and energy problems.

Traditionally, solar cells are the use of semiconductor PN junction photovoltaic effect characteristics. On the contrary, being exposed to light, the distribution of electric charges inside an object changes, making for an electromotive force and voltage. Solar cells can be broadly divided into silicon-based photovoltaic cells, thin film photovoltaic cells and new photovoltaic cells according to their material structure. Thin film photovoltaic cells include gallium arsenide, cadmium telluride, and copper indium gallium selenide thin film photovoltaic cells, etc. Compared with traditional cells ,new solar cells have higher efficiency and stability advantages. For example, the comprehensive performance of chalcogenide solar cells is equal to silicon-based solar cells, and their manufacturing cost is relatively low. Moreover, the latest solar cells possess distinctive properties, such as weather resistance and flexibility. While traditional solar cells generate pollution during the manufacturing process, newer variants are more environmentally friendly, incorporating biodegradable materials and cutting down energy consumption. Therefore, it is particularly vital to modify these traditional solar cells to improve their performance.

For semiconductor thin-film solar cells, cell efficiency can be increased in two approaches. One is the elemental doping modification of the material of battery, aiming to change carrier transport capacity, hence improving the cell efficiency. The first approach is simple, easy to implement, and cost-effective, making it suitable for widespread use in solar cell production. The second involves structural adjustments to enhance sunlight utilization and improve cell efficiency.

These two methods offer fresh insights for advancing solar cell research. Leveraging solar energy and developing efficient, stable solar cells have the potential to significantly mitigate the global energy crisis. In the future development of science and technology and production life, solar cells could assume an increasingly important role. Therefore, it is necessary to study these two respects.

Therefore, this paper mainly explores the following two means to advance the productivity of thin-film solar cells. The intrinsic semiconductor doped with specific elements and optimize the internal structure to change the semiconductor properties, for achieving the semiconductor thin-film battery conductivity regulation and modify the performance of solar cells. Semiconductor thin-film solar cells occupy a dominant position in the future development of new energy sources, doping specific elements into an intrinsic semiconductor to change the properties of the semiconductor and optimizing internal structures such as using metal mesh as an alternative to ITO electrodes.

In this paper, from the angle of element doping and structure optimization, the performance improvement ways of solar thin film cells are systematically studied, and a variety of specific ways are discussed to provide possibilities for improving battery efficiency.

2. Research contents

2.1. Elemental doping

Traditionally, silicon is widely used for fuel cell materials. However, the energy band structure of silicon limits the absorption and transmission efficiency. Elemental doping is an effective modification to improve the efficiency of fuel cells. It dopes specific elements into intrinsic semiconductors to alter the properties of semiconductors and realize the conductivity modulation of semiconductor thin film cells.

B. Mouhib [1] et al. doped $ATiO_3$ (A = Ca, Ba, and Sr) with S, Se, or Te, and the structure of the product is an ideal crystalline cubic structure. This study is carried out by using the MDJLDA by functionality to achieve accurate bandgap values as a means of investigating the electronic and optical properties of $ATiO_3$ at different concentrations of the changes. It is demonstrated that the optical properties of the doped system are promoted in the photovoltaic range. L.Zhang [2] et al. selected the dopant system for the photovoltaic devices by using Ta doped TiO_x to prepare TTO solar thin film cells, TTO had a chalcogenide structure and shows a uniform granular structure on the surface by electron microscope scanning. In Figure 1(a), the electrical and passivation properties of titanium oxide (TiO_x) were improved by adding titanium (Ti) as dopant. In Figure 1(b), the enhancement of electrical properties was verified by density functional theory simulations. An efficiency enhancement of 21.58% was achieved by using ultra-thin ALD-TTO films as a solar cell composition. In Figure 1(c) and Figure 1(d)，They show both the average τ_{eff} of TTO films fuel cells and the distributed τ_{eff} of TTO films by 130 °C annealing.

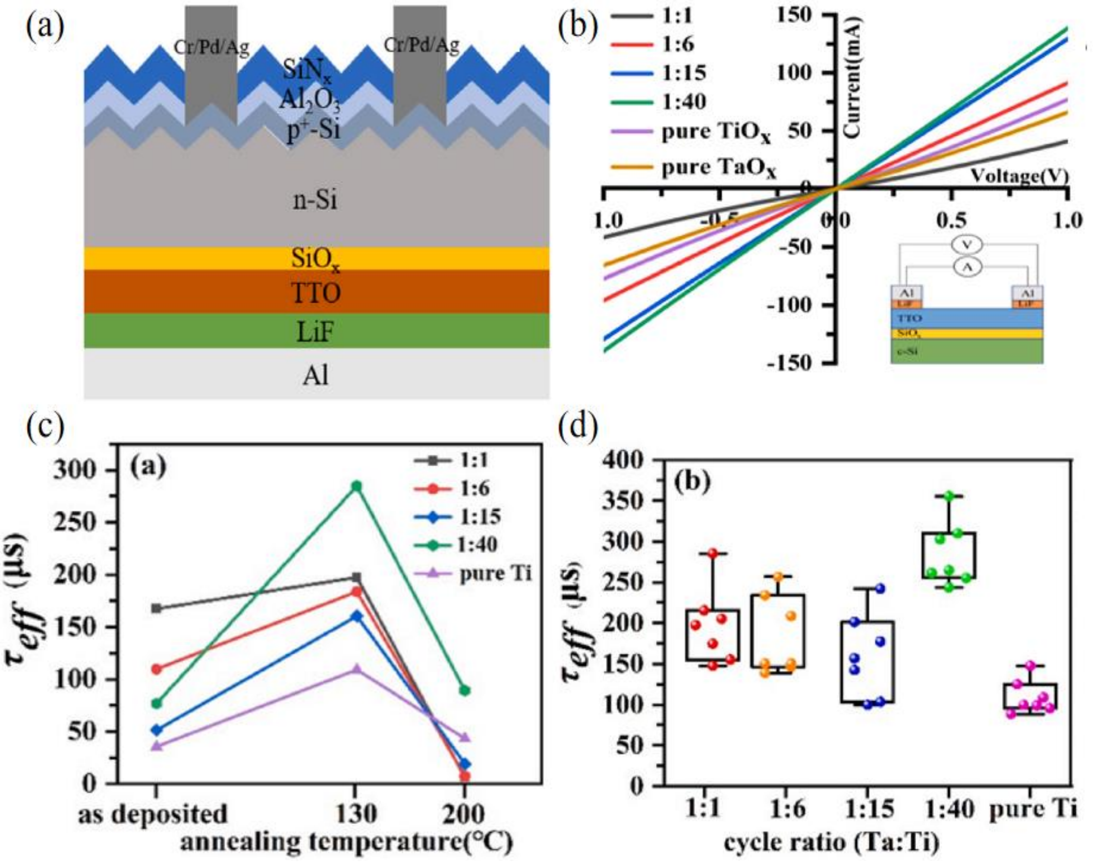

Figure 1. (a) The cross-section structure of the electron-selective contact solar cells; (b) I-V measurement for TTO films; (c) Average τ_{eff} of TTO films fuel cells; (d) Distributed τ_{eff} of TTO films by 130 ℃ annealing [2]

H.Xu [3] et al. prepared Na-K co-doped $Cu_2ZnSn(S, Se)_4$ (CZTSSe) thin films using a solution-based method. Each CZTSSe film featured a bilayer structure, with a large particle layer on top and fine particle layer underneath. The SnZn defects in the CZTSSe films can be suppressed by adopting a suitable k-doping strategy. The findings indicate that the back-contact barrier continues to be a significant limiting factor for CZTSSe solar cells, even following localized K-doping reduction. K. Muska [4] et al. investigated the effect on the absorber material properties of CZTS powders grown as monolayer (MGL) solar cells in the liquid phase with different li - ki ratios of fluxes, by employing a synthesis-growth approach; the products were all structured as The structure of the products are all tetrahedral crystals; the photovoltaic properties show that the addition of Li to the CZTS absorber has the greatest effect on the VOC value, and finally the optimum solar conversion cell is derived by controlling the Li-K molar ratio: VOC is 718 mV, JSC is 20.9 mA/cm^2, FF is 62.5%, and the power conversion efficiency is 9.4%.

S. Jang [5] et al. enhanced the photovoltaic effect of thin-film solar cells (TFSCs) by co-doping Al and F into zinc oxide thin films (FAZO) in order to increase the transmittance with controlled carrier concentration. The structure of the product was a tetrahedron with sp^3 hybridization. The mobility was about 27.6 cm^2/V higher than that of the reference AZO film. The monolayered $FAZO_2$ film had the highest transmittance of 89.3% with a bandgap of 3.67 eV. In summary, the study showed that the incorporation of F by double doping with another metal ion can effectively improve the performance of ZnO thin films. Luo. Y. [6] et al. improved the heterojunction interface of Sb_2Se_3 solar cells by introducing effective aluminium (Al^{3+}) cations into the CdS buffer layer, and then modified the energy band arrangement of the heterojunction from a "cliff-like" structure to a "spike-like" structure to suppress compound losses. The "spike-like" structure suppresses compound loss, enhances the carrier transport mechanism, and opens up avenues for further research. Z.Yan [7] et al. prepared gallium-doped zinc oxide (GZO) thin films by using a low-damage reactive plasma deposition (RPD) technique at different oxygen flow rates. In Figure 2. (a)and Figure 2. (b), they show both schematic diagram of SHJ solar cell with Front GZO and with Rear GZO. The structure of the products matched the structure of typical hexagonal fibrillated zinc ore zinc oxide (JCPDS File36-1451); the experimental results showed that at 60 sccm oxygen flow condition, the GZO films had high average transmittance, and the SHJ solar cells synthesised based on GZO films under this condition had high optimized efficiencies. Figure 2. (c) shows the EQE curve and Figure 2. (d) displays the series resistance of the front GZO solar cell and two side IWO solar cell. Y. Wang [8] et al. investigated the first principles of the electronic and optical properties of the formic acid-doped organic-inorganic chalcogenides $MAPbI_3$ by doping them with formic acid, which in turn revealed that the $HCOO^-$ doped HOIP system to reveal the microscopic mechanism of high PCE; the structure of the product was a 2×2×2 super monomer structure, which fully optimized the octahedral distortion, etc. for theoretical study, the optical characteristics and parameters pertinent to solar cells of four unique structures within the cubic phase of MAPbI3 were meticulously determined through density-functional theory calculations. This involved systematically substituting a single I-ion with HCOO- in each structure. The findings revealed that in the HCOO- doped $MAPbI_3$ system, the spin-orbit coupling (SOC) effect induced a significant Rashba splitting in the energy band structure of both the conduction band minimum (CBM) and valence band maximum (VBM). Furthermore, the absorption coefficients of these structures all exceeded 105 cm^{-1} after doping. Moreover, the power conversion efficiencies (PCEs) of all four structures surpassed 30%, with the maximum potentially reaching 32.5%. Calculations indicated that PCE can be enhanced through doping with $HCOO^-$.

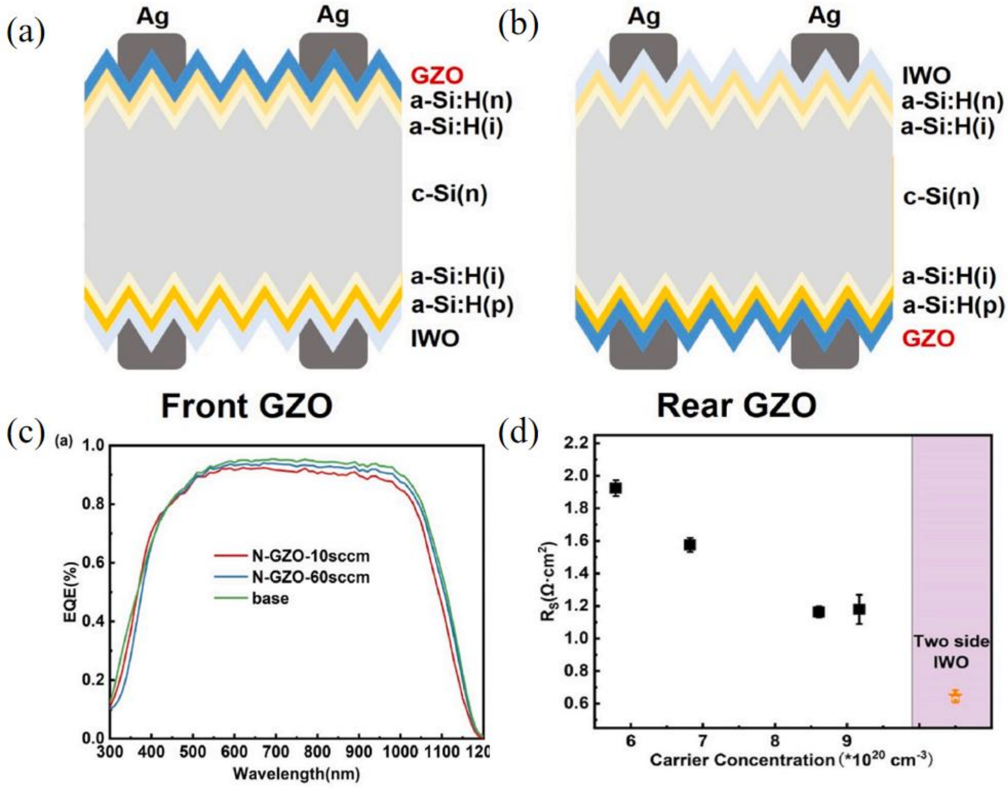

Figure 2. (a) Schematic diagram of SHJ solar cell with Front GZO; (b) Schematic diagram of SHJ solar cell with Rear GZO; (c) The EQE curve; (d) The series resistance of the front GZO solar cell and two side IWO solar cell [9]

In summary, metal elements such as S, Se and other types of elements, with special structure and properties, can be improved in terms of photovoltaic effect and conversion efficiency of solar cell. Ag and other types of elements can be formed on the surface of the cell in a dense metal grid and they provide an effective pathway for electron transmission. Strong acid ions, such as HCOO-, can be associated with related oxide thin film chemical reaction, and then boost the optical properties of the battery. Therefore, it is imperative to conduct further in-depth investigations into the doping processes of solar thin-film batteries. This method can significantly upgrade the execution of solar batteries and effectively alleviate the environmental and energy pressures.

At present, the method for amplifying the capability of solar cells by element doping still has the instability of material structure, and the doping of specific elements may increase the cost and complexity of the preparation process, limiting the commercial application of the battery. Therefore, in view of the above problems, we believe that we can reduce the preparation cost and improve the control performance by optimizing the doping type, adjusting the doping concentration, and exploring new doping technologies, such as ion implantation or magnetic doping.

In general, the innovation of the element doping method includes two points. First, the optimization of doping for specific materials: The selection and concentration of doping elements are optimized for the characteristics and needs of specific solar cell materials. For example, enhancing the photovoltaic effect of thin-film solar cells (TFSCs) by co-doping Al and F into zinc oxide thin films (FAZO) in order to increase enhance transmittance while maintaining regulated carrier concentration. Second, the use of composite doping strategy: combining different types of doping technology to achieve the effect of composite doping to further intensify the photoelectric performance of the material. For example, the paper combines metal doping and non-metal doping to improve the electrical conductivity and light absorption performance of semiconductor materials.

2.2. Structural optimization

Traditionally, optimizing the thickness of the absorber layer and enhancing the intrinsic toughness of the primary components were effective methods for enhancing solar cell efficiency. However, this approach could also introduce certain issues. For instance, employing a metal mesh instead of ITO electrodes significantly enhanced the mechanical robustness of flexible chalcogenide solar cells (FPSCs). Nonetheless, they exhibited a relatively low power conversion efficiency (PCE) of 13.62%. To enhance both the PCE and mechanical robustness of FPSCs, novel design strategies were necessary.

Mustapha Beraich et al. synthesized Cu_2O thin films on copper substrate by the electrodeposition method using citric acid as an absorber layer for solar cells. The Cu_2O thin films are in the form of small pyramidal nano-structures, with uniform, dense and adherent layers, and the use of copper substrate reduces the bandgap value to close to 1.8 eV. It has the advantage of high photosensitivity and low cost production, because of its high visible spectrum absorption coefficient [9]. In Figure 3 (b), Xuan Chang et al. improved the performance of tunnel junction (TJ) solar cells through inserting a TiO_2 insulating layer between the CIGS/CdS interfaces deposited by atomic layer deposition (ALD). The TiO_2 insulating layer effectively reduces the interfacial composite of the CIGS/TiO_2/CdS structure, and decreases the energy band bending on the p-CIGS surface in Figure 3 (a). The 1.5 nm TiO_2 insulating layer significantly enhances the built-in potential and reduces the saturation current density in Figure 3 (c) [10]. Hussein Sabbah et al. chose ZnO as the electron transport layer (ETL) and Spiro-OmeTAD as the hole transport layer (HTL). Its structure followed an inverted (p-i-n) arrangement, and used $Cs_2AgBiBr_6$ as the absorber material to prepare chalcogenide solar cells. In Figure 3 (d), Spiro-OMeTAD was chosen as HTL because it has a bandgap of 2.9 eV, this significantly improves the transparency and thus minimizes the light loss before light penetrates through the active bicinchonite layer. The optimized absorbing layer structure improved more than four times over the original structure, with a power conversion efficiency of 26.3% [11].

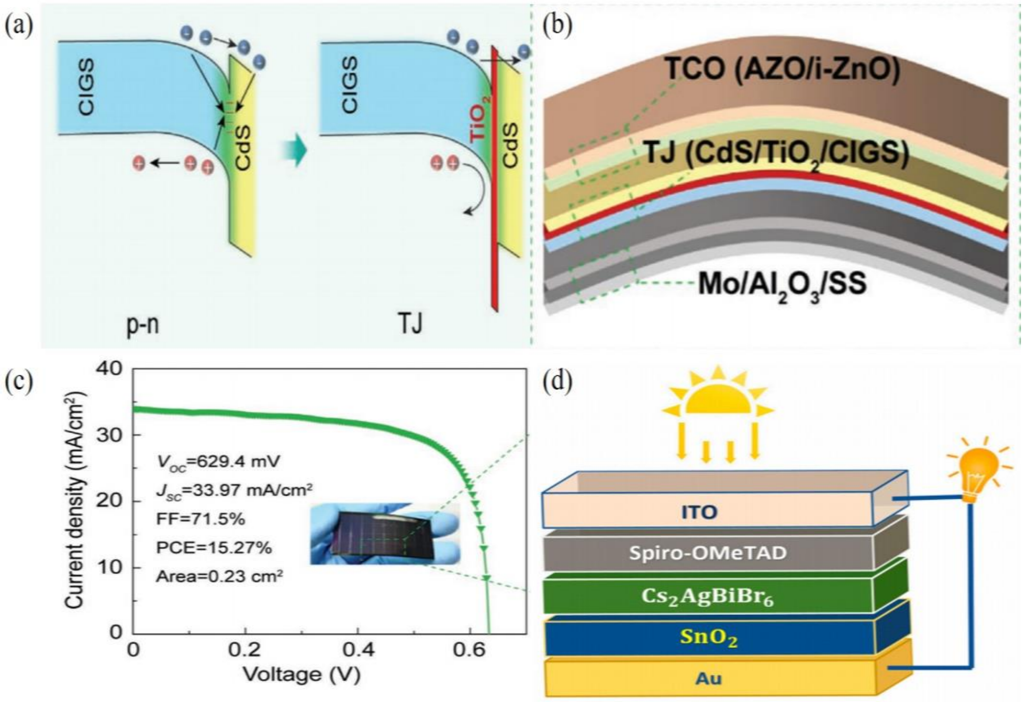

Figure 3. (a) Energy level diagrams of CIGS/CdS and CIGS/TiO$_2$/CdS structures, respectively; (b) Photo and structure drawing of the CIGS solar cell; (c) J-V curve of champion efficiency CIGS solar cell; (d) Schematic diagram of Cs$_2$AgBiBr$_6$-based PSC[12]

Meihe Zhang et al. found that the internal structure of FPSCs can be optimized by introducing buffer layers (BLs) with suitable energy band structure and excellent mechanical properties. The BLs includes PEDOT:EVA, sulfonated graphene oxide (s-GO), etc. The principle of using PEDOT:EVA is derived from the way of the vertebrae and soft tissues work together, and this bionic structure can improve the efficiency and mechanical robustness of FPSCs at the same time in Figure 4 (a). The use of s-GO is based on the toughness and hydrophobicity of graphene oxide. It effectively blunts the defects of null iodine by interacting with [PbI6]$^{4-}$, preserving more than 80% of the original PCE [12]. In Figure 4 (b), Marija Tkalčević et al. prepared thin films of Ge QWs in alumina substrates via magnetron sputtering in a nitrogen environment to improve the performance of solar cells. The germanium quantum dots in silica prepared by magnetron sputtering have an interfacial shell layer containing germanium oxide states. It produces moderate bandgap tuning, and the oxide-enriched region greatly affects the light absorption of the germanium quantum dots. In Figure 4 (c), currents from films with quantum wells are much stronger than those from films with quantum dots. The interconnection of the three-dimensional lattice of Ge quantum wells ensures efficient transport of charge carriers [13]. In Figure 4 (d), Khalil ElKhamisy et al. used a three-dimensional multiphysics field simulator to study the effect of temperature variations of triangular gratings on the surface of surface plasmonic excitations (SPP) on the efficiency of the whole silicon thin film solar cell array. The path of reflected light is elongated due to the diffraction ability of the grating surface. The absorbing layer also affects the energy of the surface plasma generated in the notch. The surface plasmon resonance effect and this effective light trapping improves the efficiency of the solar cell. Plasma gratings can be added to the surface of solar cells to help increase cell efficiency [14].

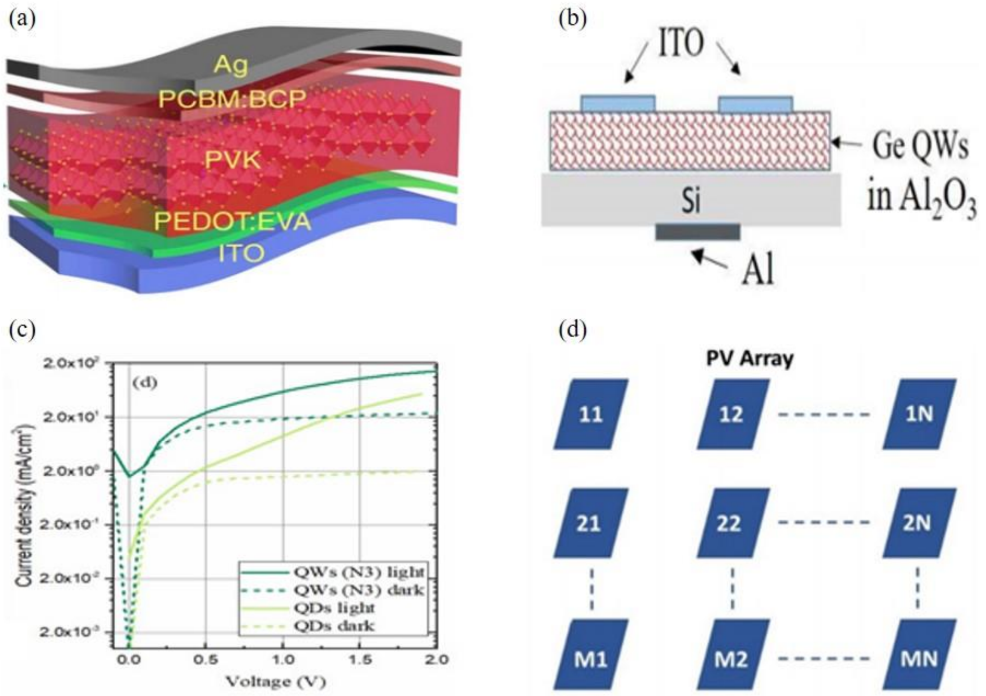

Figure 4. (a) Biomimetic mechanisms of the vertebrae and PSCs; (b) Scheme of the the I-V and QE measurements; (c) I-V measurements for the QWs and QDs; (d) PV array structure of the thin-film solar cell in SIMULINK/MATLAB

KISHORE KUMAR Y B et al. successfully prepared Cu_2ZnSnS_4 thin films by an optimized chemical spray pyrolysis process for Cu_2ZnSnS_4 solar cells by glass/Mo/Cu_2ZnSnS_4/CdS/Au layer sequences. The Cu_2ZnSnS_4 thin films have a p-type conductivity, a kesterite structure, and a direct energy bandgap between 1.45-1.60 eV with high optical absorption coefficient. The higher crystallinity leads to a narrower range of energy levels, and reduces the energy required to lift electrons from the valence band to the conduction band, bringing about a smaller energy band gap. The observed band gap value, which is near the ideal band gap, has the potential to boost photovoltaic conversion efficiency. The efficiency of Cu_2ZnSnS_4 thin-film heterojunction solar cells is about 0.5%, and continuous efforts are needed in the future to improve the efficiency of this cell [15].

In contemporary times, materials with suitable bandgaps are utilized as absorber layers in semiconductor thin-film solar cells, such as Cu2O thin films synthesized on Cu substrates. Additionally, inserting insulating layers between the internal structures, such as 1.5 nm TiO2 insulating layers, can optimize the structure and subsequently enhance its properties. However, improving the thin film absorber layer and buffer layer can enhance cell performance, for instance, by utilizing MoS2 as the buffer layer or increasing the thickness of the CZTS absorber layer to 2μm.

At present, the methods to improve the efficiency of solar cells by structural optimization still have the problems of complex preparation and poor material compatibility. Therefore, in view of the above problems, we believe that the efficiency and stability of the battery can be improved by simplifying the structure and selecting a combination of materials with good compatibility and high performance. In addition, through the development of new preparation technologies, such as nanofabrication, solution treatment, etc., there is also the possibility of achieving low-cost preparation of complex structures.

In general, the innovation of structural optimization method includes two points. The first is to design a solar cell structure with multiple functions, such as the integrated multilayer structure mentioned in the paper or the mixed structure of multiple materials, to achieve the optimization of light absorption, carrier separation and electron transport. Second, by using nanotechnology and nanostructure design to regulate the structure and morphology of materials, enhance light absorption and carrier separation efficiency, and improve the performance of the cell.

3. Conclusions

Nowadays, the extensive use of fossil fuels has aggravated the greenhouse effect and formed acid rain, and thus endanger the environment. This paper summarizes the efficiency improving methods of semiconductor thin-film solar cells. Elements, such as Ag, S, Se, can be doped in intrinsic semiconductors, and it can form a dense metal lattice structure and react chemically with the relevant oxide film to improve the fuel cell power conversion efficiency. Materials with a suitable bandgap can be used as the absorber layer, and the thickness of the absorber layer is increased to optimize the structure of the interlayer and improve the power conversion efficiency of the cells. Most importantly, this research can improve the properties of semiconductor thin-film solar cells and alleviate the energy tensions.

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