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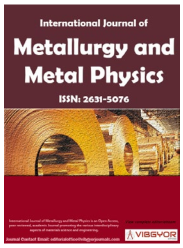

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Functional Materials for Solar Thermophotovoltaic Devices in Energy Conversion Applications: A Mini-Review

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Abstract

In recent years, the demand for energy that caters for the socio-economic needs on Earth has led to the use of fossil fuels which currently satisfy over 80% of this demand, however, the drawback of this source of energy includes; lack of economical sustainability and environmental pollution. Consequently, renewable energy sources such as wind, biomass, hydro, geothermal, tidal and solar energy were introduced as alternative consumable fuels to mitigate detrimental climate changes caused by fossil fuels. Furthermore, the abundance of direct sunshine amongst these renewable sources has made solar energy one of the most preferred alternative sources of renewable energy. Solar energy can supply the Earth with the energy it needs because radiant solar energy moves at 186,000 miles per second hence, the energy produced comprising helium and hydrogen gas that touches the Earth in an hour is enough to supply the Earth for an entire year. However, only less than 1% of this energy is extracted and converted to generate electricity, attributed to the challenges of the solar cells. Notably, the conventional conversion of solar energy to electricity is through solar thermal systems and photovoltaics. Nonetheless, there are difficulties in converting the solar energy extracted from these systems to electricity. This study reviews solar thermophotovoltaic devices and the high-tech material used in solar thermophotovoltaic systems as a solution to the conversion challenge by converting the solar energy to heat first, before converting the heat to electricity.

Keywords

Energy conversion, Solar Energy, Thermophotovoltaic device

Introduction

In 2019, the global energy consumption growth rate slowed down by +0.6% compared to its ever-increasing trend, contributing to slow economic growth. Consumption in Algeria and Indonesia was dynamic; however, South Africa, Saudi Arabia and Nigeria continued to increase [1,2]. Generally, energy consumption is a socio-economic human need, and the energy demand was met by fossil fuels such as carbon and hydrogen compounds where petroleum, natural gas and coal are derived. Coal was one of the first fossil fuels, used for steam engines, transportation and the production

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of steel, while petroleum was used for fuel in combustion engines and lighting paraffin lamps, natural gas was used for cooking and to generate electricity. Nonetheless, the adverse effects of these fossil fuels include but not limited to; the emission of nitrous oxides (N_2O) and carbon monoxide (CO). Inhalation of CO causes dizziness and headaches that may lead to death. N_2O, on the other hand, generates ground-level ozone, harmful to crops and the respiratory systems. More so, oil and coal contain Sulphur, and, in contact with moisture, forms Sulphur acid, a very damaging acid rain. Greenhouse gases are also one of the most destructive emissions of fossil fuels, causing global warming and disrupting the surface temperature of the earth from sustaining life, consequently, alternative energy sources have been developed [3]. This study reviews the innovation in renewable energy sources that are cleaner, more accessible and derived from natural sources. These sources include wind, geothermal, hydrogen, hydroelectric, biomass, ocean and solar energy.

Solar Energy

The primary source of solar energy which travels at 3.0×10^8 meters per second is the sun. The sun, made up of helium gas and hydrogen, makes this energy in its core through fusion [4]. Fusion consists of hydrogen isotopes, and with the transformation of matter, it comes together to form helium atoms, and this transformed matter is given off as radiant energy by the sun. Radiant energy emitted from the sun gets to the Earth surface in tiny portions approximately 1.7×10^{18} W, and these rations are enough to supply the energy needed on Earth. The sun supplies energy to different parts of the Earth in small fractions per time, making it necessary to capture the solar energy through solar collectors before transforming it to electricity [5].

Conversion of solar energy to electricity

A solar cell built from semiconductor materials is one device that is electronically a collector to convert solar energy to electricity. The material used for solar cells must absorb sunlight which raises electrons in the light to higher energy states and then the high energy electron moves from the cell to an external circuit [6]. Urbanization is constantly increasing global electricity consumption and like other types of energy, the need to reduce the price increases its supply, performance and storage of electricity makes solar cell devices a fundamental solution. Solar thermal systems and photovoltaics are two methods of converting solar energy into electricity. Solar thermal systems comprise concentrated solar power, which uses solar energy to generate electricity. The process involves using a solar collector, having a mirrored surface to direct sunlight into a standby receiver that in turn heats a liquid. The heated liquid makes steam, which produces electricity [7]. While the photovoltaic process of generating electricity involves the use of solar cells made up of silicon which supplies electricity when the radiant energy from the sunlight strikes the cell triggering the electrons in the cell to move and this movement of electrons jerks an electric current, switching from solar energy to electricity [8].

Limitations to the conversion methods

There is an absolute theoretical Shockley-Queisser SQ limitation to the efficiency of conventional solar cells [9]. The conversion of solar energy to electricity by solar cells is established on the photoelectric effect, which is an interaction between the transformed matter and the electromagnetic wave. During their study, Shockley and Queisser [9] realized there was a mismatch between the emission angles and the absorption, therefore, they proposed that the sun and solar cells act as black bodies and to this effect, a single layer of solar cells consisting of silicon was detailed through emission angle restrictions, photon recycling and optical concentration to having an upper limit of a little above thirty-two percent for a 1.1 eV gap. The SQ limit defines 32-33.6% as the maximum solar energy conversion efficiency achievable for any solar cell material. This limitation, which was developed in 1961, is applicable on the principle of detailed balancing which equates the photon flux that goes into the solar cell device with the electron or photon flux that goes out of it at different open-circuits conditions [10].

Exploring solutions to the theoretical limitations

In recent times, possible ways of increasing the efficiency of solar cells above the absolute limit have been made namely; adding multiple layers of solar cell which increases the incident intensity, the current density and the voltage. Angle restriction filters can also be used to reduce the existing recombination current; multiple semiconductors with several band gaps can also be used to decrease the thermal losses and increase efficiency. Axelevitch [11] reviewed the ways of improving the efficiency of single-junction solar cells with specific attention given to solar cells enhanced with Plasmon. The author described using multi-junction solar cells, down-conversion solar cells, up-conversion solar cells, and multiple exciton generation solar cells, solar cells with intermediate bands and hot carrier solar cells as enhancement mechanisms of solar cells from the SQ limitations. The possibility of using nano-dimensional structures made up of gold or silver nanoparticles were also discussed, concluding that the combination of an up-converter and a Plasmon is a promising solution to the SQ limitation. The Plasmon with extreme energy photons will generate multiple charged carriers under the absorption of one photon while the up-converter uses the wavelength photons to increase the efficiency of solar cells. Nonetheless, a preferred alternative in exceeding the SQ limitations is the conversion of solar energy to heat first before generating the electrical power through solar thermophotovoltaic devices.

High-Tech Materials for Solar Thermophotovoltaic Devices

Conventional photovoltaic materials convert solar energy directly to electricity hence, they undergo theoretical limitations, however, ways of increasing the overall efficiency is to convert solar energy first to heat, then use the heat to generate electrical energy. Devices used for this application are referred to as solar thermophotovoltaic (STPV). STPV pairs low-efficiency conventional solar cells with an added layer of high-tech material that helps in multiplying the Shockley-Queisser limitation, making it possible for the cells to generate more power. The device works on the principle of dispersing waste solar energy as heat inside the solar cell; a by-product of the nuclear, chemical reactions or mechanical work. The heat is then absorbed by the transitional component in temperatures that will allow this component to produce thermal radiation. The configurations of the cell and the high-tech materials used in the devices are fine-tuned to the right wavelengths for the cell to capture light, which improves its efficiency.

According to Jayawardena, et al. [12], perovskite cells mixed with lead-tin as an absorber can achieve a fill factor above 80% by post treating the absorber with guanidinium bromide. The authors showed that the post-treatments were favourable in aligning the cathode and anode interfaces thus, enabling a bipolar extraction which resulted in the device having an area of 0.43 cm^2, a fill factor above 80% with 14.4% power conversion efficiency. Rau, et al. [13] proposed using fluorescent collectors with photonic structures which acts as an omnidirectional spectral band stop-filter to enhance the efficiency of photovoltaic solar cells and they concluded that the combination of fluorescent collectors with photonic structure can close the theoretical SQ limitation while saving about 99% of the solar cell material. Thus, the authors recommended more research should be focused on the potential of 2-3 dimensional photonic structures used with fluorescent collectors. Briggs, et al. [14] developed an up-converter solar cell using thermodynamics to exceed the SQ limitation. The results showed that the efficiency of the solar cell increased from 28 to 34% with an increase in the up-converter quantum yield and capacity. Jia, et al. [15] reported the use of silicon nanocrystals built into the dielectric matrix as a promising high-tech material for solar cells. Conversely, the material did not exceed the SQ limitation, therefore; the authors investigated the maximum efficiency of the material, and they stated that the practical limit of the solar cell's efficiency was 32%. Based on these results, they made suggestions for further studies to figure out the reason for the limitation and the proposed solution to improving the performance of the cell.

Trupke, et al. [16] tried generating a multiple electron-hole pair, down-conversion high-energy photon in enhancing the efficiency of solar cells. The authors detailed that there was an increment in the efficiency of the solar cell from 30.9% to 39. 63%. In another study, Trupke, et al. [17] showed how an up-conversion of a sub-band gap light can be used to enhance solar cell efficiencies by 47.6% for non-concentrated sunlight and 63.2% for concentrated sunlight. Pusch, et al. [16] investigated the reason why intermediate band solar cells could not exceed the SQ limitation and they realized that the restriction was attributed to the radiative recombination through the intermediate band yet, they stated that suppressing the radiative recombination by introducing a quantum ratchet to the intermediate band can enhance the solar cell efficiency, therefore, the authors recommended using quantum ratchets as a more effective alternative to single-gap solar cells. On the other hand, Wang, et al. [18] used carrier transport and photon recycling simulation to figure out the reasons why thin-film GaAs solar cells did not exceed the SQ limitation by studying a single-junction thin film solar cell and the influence of the design parameters. The authors concluded that increment of the efficiency will occur via enhancements on the backside mirror reflectivity above 95%, thus, naming the series resistance and the back mirror reflectivity as the two important factors to focus on when creating high-efficiency thin-film solar cells. While Schaller, et al. [19] showed that charge carriers in large portions can enhance the performance of solar cells by increasing the photon to exciton conversion by 700%.

Xu, et al. [20] used nanostructured solar cells as photovoltaic devices which under a 1.5 solar illumination showed a maximum efficiency of about 42%. However, they reported that the device did not exceed the theoretical limit for planar devices with optical concentrations even though it exceeded the SQ limitations for non-planar devices. The authors attributed the failure to reach the SQ limitations to the principle of detailed balance with good knowledge of the absorption in the device structure. They recommended that nanostructured devices should be developed with limited absorption for wavelengths and angles very different from the incident illumination. More so, the improvement of the devices should come from the open-circuit voltage with non-radiative recombination and good quality surface passivation. Mann, et al. [21] showed that large absorption of the cross-sections is not responsible for the enhancements of solar cells using Nanophotonic materials for photovoltaics, however increasing the directivity bounds which consists of the nanoscale concentrations in macroscopic solar cells and the maintenance of high short-circuit currents are the significant voltage enhancement factors. Bierman, et al. [22] developed a high tech nanophotonic crystal that was used to emit the desired wavelengths of light when heated while integrated into a system vertically aligned with carbon nanotubes which serve as absorbers while operating at about 1000 °C. When the crystal was heated it continued to give out light that matches the band of wavelengths that the solar cell uses to convert to electric current. The carbon nanotube enables all the energy of the photons to get converted to heat which in turn re-emits light that matches the solar cell's peak efficiency through the nanophotonic crystal. The authors using an absorber, solar stimulator photovoltaic receiver and filter all in one device argue that the device coupled with a thermal storage system could provide a continuous on-demand of electrical power. They recommended further studies in increasing the current laboratory size of the device for commercial purposes [23,24].

Future Recommendations

Literature has shown that converting solar energy to heat and then from heat to electricity is an efficient way of exceeding the SQ limitation. This knowledge has sparked up significant interest in using solar thermophotovoltaic devices where photons from a hot emitter are used to transverse a vacuum gap that is absorbed by the solar cell and used to generate electricity. Nonetheless, recent reports have shown that the temperature of the emitter is still very low to give off a photon flux sufficient for the photovoltaic cell, thus limiting the service life of these devices. New approaches use thermophotovoltaic energy conversion mechanisms like photon-assisted tunnelling called a bipolar grating-coupled complimentary metal-oxide-silicon tunnel diode or a micro-thermophotovoltaic generator, and these are recommended solutions to increase efficiency. Solar thermophotovoltaic devices lack suitable structural designs that overcome the thermal losses experienced with current fabrication techniques which can be improved. Thus, further studies need to be made to enhance current designs. Furthermore, innovative materials that can be used as absorbers and emitters should be explored for long-term thermal stability. Ways to reduce the cost of setting up the existing thermophotovoltaic systems is high and cheaper alternatives should also be investigated.

Conclusion

In this paper, we discussed how the world's demand for energy consumption led to the development of fossil fuels, however; economical sustainability and environmental pollution have created a need for cleaner energy sources. Solar energy was outlined as a preferred alternative source of renewable energy attributed to its availability and sustainability however, the efficiency of this source of energy in its conversion mechanism to electrical power is limited. Therefore, we presented a literature review on different solar thermophotovoltaic devices, materials and methods researchers have used in exceeding the theoretical limitations and future recommendations and solutions were shown. Surveying the studies presented, it is clear that nanomaterials as an advanced functional material can enhance the efficiency of solar thermophotovoltaic devices. In general, solar energy is a significant source of fulfilling the required energy demands.

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References

1. Xu G, Schwarz P, Yang H (2020) Adjusting energy consumption structure to achieve China's CO2 emissions peak. Renewable and Sustainable Energy Reviews 122: 109737.
2. Zhou W, Chen Q, Luo D, Jiang R, Chen J (2020) Global Energy Consumption Analysis Based on the Three-Dimensional Network Model. IEEE Access 8: 76313-76332.
3. Malhotra R (2020) Fossil energy. Springer.
4. Kalogirou SA (2013) Solar energy engineering: Processes and systems. Academic Press.
5. Panwar N, Kaushik S, Kothari S (2011) Role of renewable energy sources in environmental protection: A review. Renewable and Sustainable Energy Reviews 15: 1513-1524.
6. Fonash S (2012) Solar cell device physics. Elsevier.
7. Peuser FA, Remmers KH, Schnauss M (2013) Solar thermal systems: Successful planning and construction. Routledge.
8. Grätzel M (2005) Solar energy conversion by dye-sensitized photovoltaic cells. Inorg Chem 44: 6841-6851.
9. Shockley W, Queisser HJ (1961) Detailed balance limit of efficiency of p-n junction solar cells. Journal of Applied Physics 32: 510-519.
10. Rühle S (2016) Tabulated values of the Shockley-Queisser limit for single junction solar cells. Solar Energy 130: 139-147.
11. Axelevitch A (2018) Photovoltaic Efficiency Improvement: Limits and Possibilities. Sci Revs Chem Commun 8: 115.
12. Jayawardena K, Bandara R, Monti M, Butler-Caddle E, Pichler T, et al. (2020) Approaching the Shockley-Queisser limit for fill factors in lead-tin mixed perovskite photovoltaics. Journal of Materials Chemistry A 8: 693-705.
13. Rau U, Einsele F, Glaeser GC (2005) Efficiency limits of photovoltaic fluorescent collectors. Applied Physics Letters 87: 171101.
14. Briggs JA, Atre AC, Dionne JA (2013) Narrow-bandwidth solar upconversion: Case studies of existing systems and generalized fundamental limits. Journal of Applied Physics 113: 124509.
15. Jia X, Puthen-Veettil B, Xia H, Yang TCJ, Lin Z, et al. (2016) All-silicon tandem solar cells: Practical limits for energy conversion and possible routes for improvement. Journal of Applied Physics 119: 233102.
16. Trupke T, Green M, Würfel P (2002) Improving solar cell efficiencies by down-conversion of high-energy photons. Journal of Applied Physics 92: 1668-1674.
17. Trupke T, Green M, Würfel P (2002) Improving solar cell efficiencies by up-conversion of sub-band-gap light. Journal of Applied Physics 92: 4117-4122.
18. Wang X, Khan MR, Gray JL, Alam MA, Lundstrom MS (2013) Design of GaAs solar cells operating close to the Shockley-Queisser limit. IEEE Journal of Photovoltaics 3: 737-744.
19. Schaller RD, Sykora M, Pietryga JM, Klimov VI (2006) Seven excitons at a cost of one: Redefining the limits for conversion efficiency of photons into charge carriers. Nano Lett 6: 424-429.
20. Xu Y, Gong T, Munday JN (2015) The generalized Shockley-Queisser limit for nanostructured solar cells. Scientific Reports 5: 13536.
21. Mann SA, Grote RR, Osgood RM Jr, Alù A, Garnett EC (2016) Opportunities and limitations for nanophotonic structures to exceed the Shockley-Queisser limit. ACS Nano 10: 8620-8631.
22. Bierman DM, Lenert A, Chan WR, Bhatia B, Celanović I, et al. (2016) Enhanced photovoltaic energy conversion using thermally based spectral shaping. Nature Energy 1: 1-7.
23. Davids PS, Kirsch J, Starbuck A, Jarecki R, Shank J, et al. (2020) Electrical power generation from moderate-temperature radiative thermal sources. Science 367: 1341-1345.
24. Chan WR, Bermel P, Pilawa-Podgurski RC, Marton CH, Jensen KF, et al. (2013) Toward high-energy-density, high-efficiency, and moderate-temperature chip-scale thermophotovoltaics. Proceedings of the National Academy of Sciences 110: 5309-5314.