



Research Article

Advanced Semiconductor Materials for Renewable Energy Technologies

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DOI: <https://doi.org/10.5281/zenodo.20279519>

Abstract

The rapid increase in global energy demand and environmental pollution caused by fossil fuel consumption has accelerated the development of renewable energy technologies. Semiconductor materials are essential components in solar cells, optoelectronic systems, photocatalysis, hydrogen production, thermoelectric devices and energy storage technologies. Recent developments in nanotechnology, thin-film engineering and advanced material synthesis have significantly improved the efficiency and stability of semiconductor-based renewable energy devices. This review paper presents a comprehensive study of advanced semiconductor materials used in renewable energy technologies. The paper discusses the properties, fabrication methods, photovoltaic applications, nanostructures, performance enhancement techniques, challenges and future prospects of semiconductor materials. Special emphasis is given to selenium-based semiconductor systems, thin-film photovoltaic technologies, hybrid materials and next-generation renewable energy devices.

Manuscript Information

- ISSN No: 2583-7397
- Received: 01-04-2026
- Accepted: 13-05-2026
- Published: 17-05-2026
- IJCRM:5(3); 2026: 209-215
- ©2026, All Rights Reserved
- Plagiarism Checked: Yes
- Peer Review Process: Yes

How to Cite this Article

Zope D A, Bharambe N S, Bombatkar S U, Gopnarayan B B, Narkhede B A, Nimbolkar B M, Tarhale P. Smart study planner: AI-based academic stress reduction and student learning outcomes improvement. Int J Contemp Res Multidiscip. 2026;5(3):209-215.

Access this Article Online



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KEYWORDS: Semiconductor materials, Renewable energy, thin films, Solar cells, Photovoltaics, Nanotechnology, Selenium, Energy conversion.

1. INTRODUCTION

The increasing worldwide demand for electrical energy and the environmental impact of fossil fuel consumption have created a strong need for sustainable and renewable energy technologies. Conventional energy sources such as coal, petroleum and natural gas contribute significantly to greenhouse gas emissions, climate change and environmental degradation. Renewable energy systems, particularly solar photovoltaic technologies, are considered one of the most promising alternatives because of their abundance, cleanliness and sustainability. [1], [4], [5]

Photovoltaic (PV) systems directly convert sunlight into electrical energy using semiconductor materials. Semiconductor materials possess unique electrical and optical properties such as band gap energy, photoconductivity, carrier mobility and optical absorption, which make them suitable for renewable energy applications. Silicon has dominated the commercial solar cell industry for decades because of its stability and high efficiency. However, silicon-based technologies require expensive manufacturing processes, high-temperature fabrication and large material consumption. These limitations have encouraged researchers to explore alternative semiconductor materials for future renewable energy technologies. [6], [7], [8]

Thin-film semiconductor technologies have emerged as attractive alternatives to crystalline silicon solar cells because they require very small amounts of active material and can be fabricated on flexible substrates. Thin-film devices are lightweight, cost-effective and suitable for large-scale production. Materials such as cadmium telluride (CdTe), copper

indium gallium selenide (CIGS), selenium (Se), amorphous silicon and perovskites have attracted significant attention due to their high optical absorption coefficients and tunable electrical properties. [9], [10], [11]

Nanotechnology has further transformed renewable energy systems through the development of nanostructured semiconductor materials including nanoparticles, nanowires, quantum dots and hybrid heterojunction systems. Nanostructuring improves surface area, charge transport, light absorption and carrier collection efficiency. Modern semiconductor engineering techniques such as doping, interface engineering, surface passivation and heterojunction formation have significantly improved photovoltaic device performance. [12], [13], [14]

Selenium-based semiconductor materials have regained importance because of their favourable band gap, photoconductive behavior and compatibility with thin-film photovoltaic structures. Selenium exhibits excellent optical absorption and can exist in both amorphous and crystalline forms, providing flexibility for optoelectronic applications. Recent advancements in nanotechnology and deposition techniques have revived interest in selenium for next-generation renewable energy devices. [15], [16], [17]

This review paper presents a detailed overview of advanced semiconductor materials used in renewable energy technologies. The paper discusses material properties, classifications, fabrication techniques, photovoltaic structures, applications, performance enhancement strategies, challenges and future research opportunities. [18], [19]

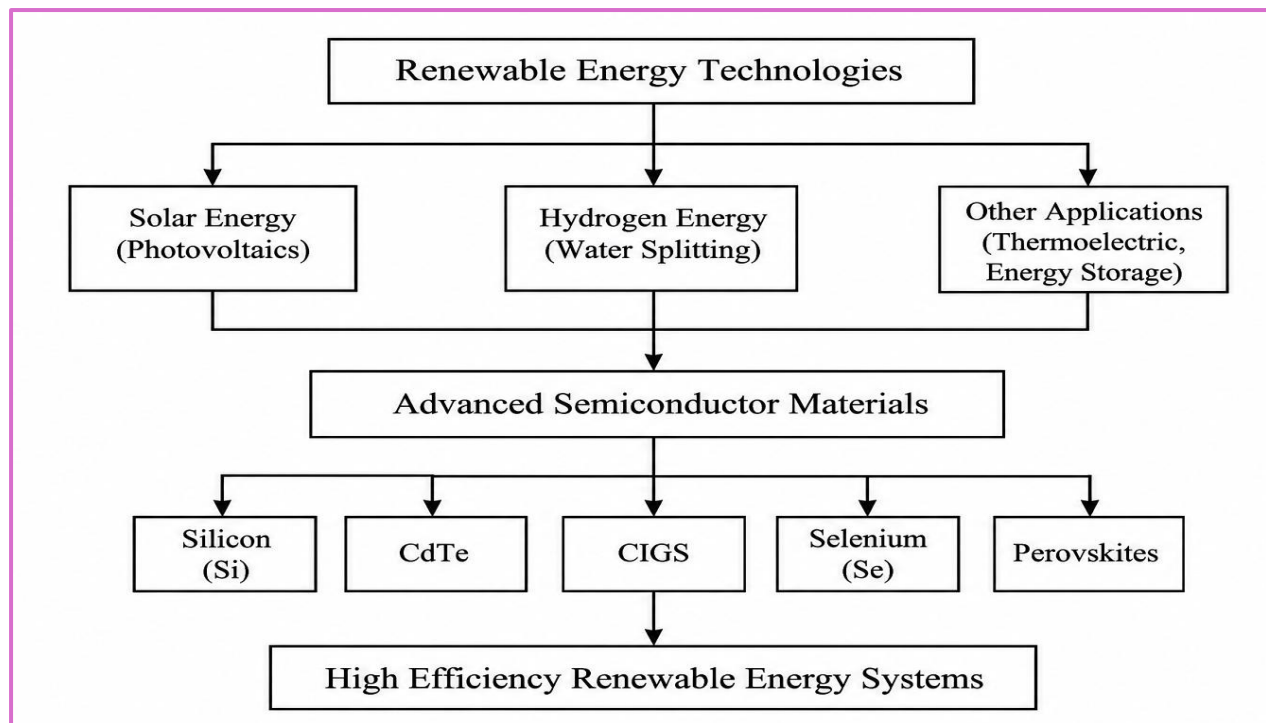


Fig. 1. Overview of advanced semiconductor materials for renewable energy technologies

2. Fundamental Properties of Semiconductor Materials

A. Band Gap Energy

Band gap energy is one of the most important parameters determining the suitability of semiconductor materials for photovoltaic and renewable energy applications. The band gap represents the energy difference between the valence band and the conduction band. Semiconductor materials with appropriate band gap values can efficiently absorb solar radiation and

generate electron-hole pairs for electrical power generation. [20], [21]

The ideal band gap for photovoltaic devices lies between 1.1 and 1.8 eV according to the Shockley–Queisser efficiency limit. Semiconductor materials with direct band gaps exhibit higher optical absorption coefficients compared to indirect band gap materials. Band gap engineering through alloying, doping and nanostructuring is widely used to optimize photovoltaic performance. [22], [23]

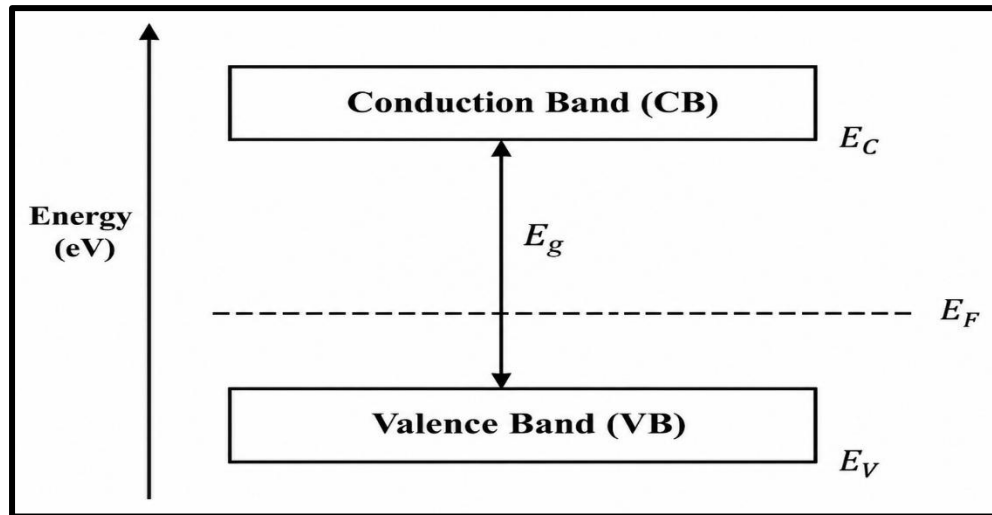


Fig. 2. Energy band diagram of semiconductor material

B. Electrical Properties

Electrical conductivity, carrier concentration, carrier mobility and resistivity are important parameters influencing semiconductor device performance. Intrinsic semiconductors possess equal electron and hole concentrations, while extrinsic semiconductors contain impurity atoms that increase conductivity through doping. [24], [25]

Carrier mobility determines the movement of photogenerated carriers inside semiconductor materials. High mobility materials exhibit lower recombination losses and improved photovoltaic efficiency. Crystalline semiconductor structures generally provide better carrier transport compared to amorphous structures. [26], [27]

C. Optical Properties

Optical absorption coefficient, photoconductivity, reflectivity and transparency are important optical characteristics of semiconductor materials. Thin-film semiconductor materials exhibit very high optical absorption coefficients, enabling efficient solar energy absorption with very thin active layers. [28], [29]

Photoconductivity is another important property where conductivity increases under light illumination. Selenium-based materials exhibit strong photoconductive behavior, making them suitable for photovoltaic and optoelectronic applications. [30]

Table 1: Properties of Important Semiconductor Materials

Material	Band Gap (eV)	Type	Application
Silicon	1.1	Indirect	Commercial Solar Cells
CdTe	1.5	Direct	Thin-Film PV
CIGS	1.0–1.7	Direct	Flexible PV
Selenium	1.8–2.0	Direct	Thin-Film Devices
Perovskite	1.5	Direct	High-Efficiency Solar Cells

3. Fabrication Techniques

A. Thermal Evaporation

Thermal evaporation is a simple and cost-effective vacuum deposition method widely used for semiconductor thin-film fabrication. In this technique, the source material is heated under vacuum conditions until evaporation occurs and the thin film is deposited onto the substrate surface. Selenium thin films fabricated using thermal evaporation exhibit good uniformity and optical characteristics. [31]

B. Sputtering

Sputtering is a physical vapor deposition technique where energetic ions bombard a target material, causing ejection and deposition onto the substrate surface. Sputtering provides better thickness control, adhesion and film uniformity compared to conventional deposition methods. [32]

C. Chemical Bath Deposition

Chemical bath deposition (CBD) is a low-cost solution-based technique suitable for large-area semiconductor thin-film deposition. The technique is widely used for CdS, ZnO and selenium-based semiconductor coatings. [33]

D. Advanced Techniques

Advanced deposition methods such as pulsed laser deposition (PLD) and atomic layer deposition (ALD) provide nanoscale thickness control and high-quality film growth for advanced photovoltaic structures. [34], [35]

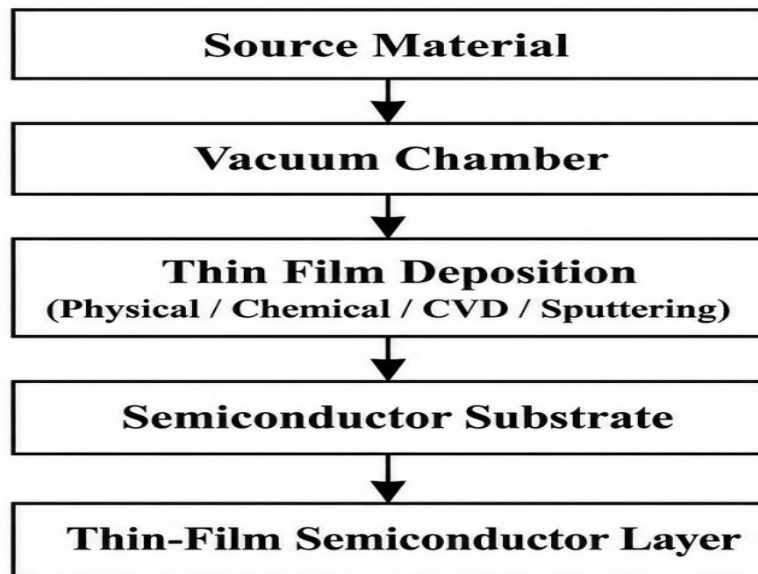


Fig. 3: Thin-film semiconductor fabrication process

4. Applications in Renewable Energy Technologies

A. Solar Cells

Solar cells are the most important application of semiconductor materials in renewable energy systems. Semiconductor photovoltaic devices convert sunlight directly into electricity using the photovoltaic effect. Thin-film solar cells, heterojunction structures, tandem cells and hybrid systems have

significantly improved solar energy conversion efficiency. [36], [37]

Selenium-based photovoltaic devices have attracted attention because of their low cost and favorable optical properties. Hybrid heterojunction structures combining selenium with ZnO, CdTe and perovskites improve charge separation and carrier transport efficiency. [38], [39]

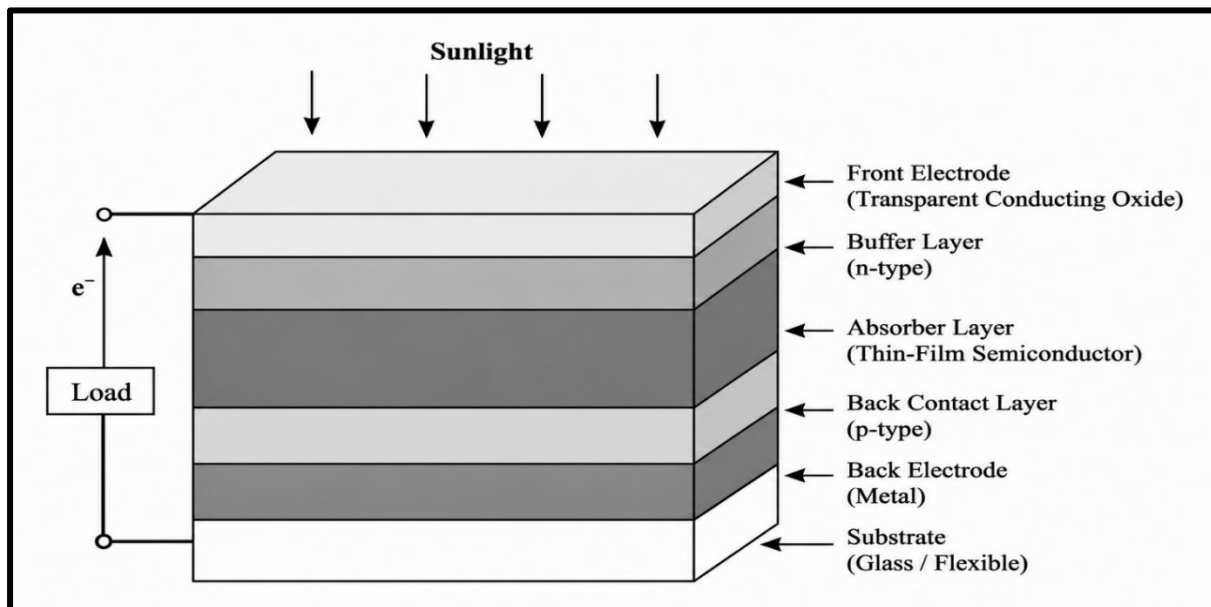


Fig. 4: Structure of thin-film photovoltaic device

5. Performance Enhancement Techniques

The performance of semiconductor-based renewable energy devices can be significantly improved using various material engineering and nanotechnology approaches. Researchers have focused on enhancing charge transport, optical absorption, carrier lifetime and device stability using advanced modification techniques. [40], [41]

A. Doping

Doping is one of the most effective techniques used to improve semiconductor properties. It involves introducing impurity atoms into semiconductor materials to modify electrical conductivity and carrier concentration. Dopants such as arsenic (As), boron (B), phosphorus (P), tellurium (Te) and aluminum (Al) are widely used in photovoltaic devices. [42], [43]

Doping enhances charge carrier mobility and reduces recombination losses, resulting in improved photovoltaic efficiency. Selenium thin films doped with tellurium and arsenic exhibit enhanced electrical conductivity and optical absorption. [44]

B. Surface Passivation

Surface defects and dangling bonds act as recombination centers in semiconductor devices, reducing carrier lifetime and device performance. Surface passivation techniques minimize defect density and improve charge transport efficiency. Thin dielectric coatings such as SiO_2 and Al_2O_3 are commonly used for passivation. [45], [46]

Surface passivation significantly improves open-circuit voltage, fill factor and overall solar cell efficiency. Nanostructured semiconductor devices particularly benefit from effective surface passivation techniques. [47]

C. Nanostructuring

Nanostructured semiconductor materials including nanowires, nanoparticles, nanotubes and quantum dots provide enhanced surface area and improved optical absorption. Nanostructured materials also improve carrier transport and reduce recombination losses because of shorter carrier diffusion pathways. [48], [49]

Quantum dots exhibit tunable band gaps through size variation, making them suitable for advanced photovoltaic applications. Selenium nanowires and nanocrystalline thin films have demonstrated improved photoconductive behavior and enhanced light trapping capability. [50], [51]

D. Interface Engineering

Interface engineering is an important strategy for improving charge transfer between semiconductor layers. Heterojunction interfaces reduce recombination and facilitate efficient carrier separation in photovoltaic devices. Materials such as ZnO , TiO_2 , CdS and graphene are commonly used for interface optimization. [52], [53]

Proper interface engineering improves open-circuit voltage (V_{oc}), short-circuit current density (J_{sc}) and fill factor (FF) in solar cells. Advanced multilayer structures have shown remarkable improvement in device stability and efficiency. [54]

E. Light Trapping Techniques

Light trapping methods increase photon absorption within semiconductor devices by reducing optical reflection and increasing optical path length. Surface texturing, plasmonic nanoparticles, anti-reflection coatings and photonic crystal structures are widely used to improve optical absorption. [55], [56]

Metal nanoparticles such as silver and gold exhibit plasmonic effects that enhance electromagnetic field intensity near the semiconductor surface, leading to improved photovoltaic conversion efficiency. [57]

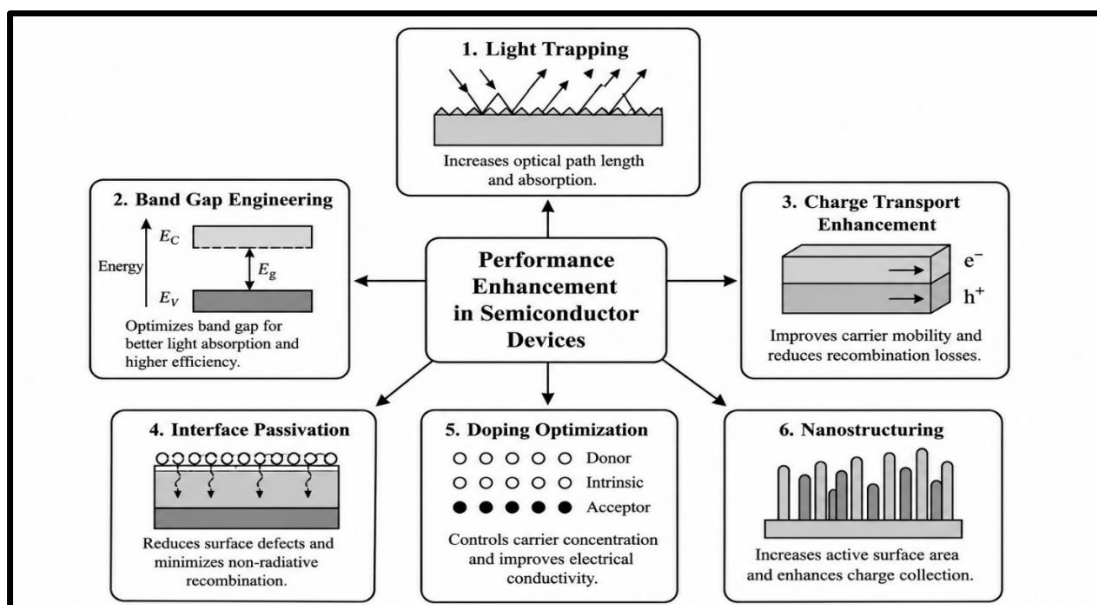


Fig. 5. Performance enhancement mechanisms in semiconductor devices

Table 2: Performance Improvement Techniques

Technique	Purpose	Improvement
Doping	Increase conductivity	Better carrier transport
Passivation	Reduce defects	Lower recombination
Nanostructuring	Increase surface area	Enhanced absorption
Interface Engineering	Improve charge separation	Higher efficiency
Light Trapping	Increase photon absorption	Better photocurrent

6. Challenges and Limitations

Despite significant advancements in semiconductor-based renewable energy technologies, several limitations continue to affect commercial applications. One of the major challenges is the relatively lower efficiency of some thin-film semiconductor materials compared to crystalline silicon solar cells. [58]

Many high-performance semiconductor materials contain toxic or rare elements such as cadmium, lead and indium, raising environmental and economic concerns. Toxicity issues create challenges related to disposal, recycling and environmental sustainability. [59], [60]

Long-term stability is another major concern in advanced photovoltaic devices. Exposure to moisture, oxygen, heat and ultraviolet radiation can degrade semiconductor materials and reduce device performance over time. Perovskite-based solar cells particularly suffer from moisture instability and thermal degradation. [61], [62]

Large-scale fabrication of high-quality thin films remains technically challenging. Uniform deposition over large substrate areas and reproducibility of nanostructured materials require sophisticated fabrication systems and process optimization. [63]

Selenium-based semiconductor devices also face challenges such as lower conversion efficiency, charge recombination losses and stability issues under prolonged illumination. Optimization of film thickness, crystallinity and heterojunction structures is necessary to improve device performance. [64], [65]

Table 3: Challenges in Semiconductor Renewable Energy Devices

Challenge	Effect
Low efficiency	Reduced power output
Toxic materials	Environmental concerns
Stability degradation	Reduced device lifetime
Large-scale fabrication difficulty	High production cost
Recombination losses	Lower photovoltaic efficiency

7. Future Scope

Future research in semiconductor renewable energy technologies is expected to focus on high-efficiency, low-cost, environmentally friendly and flexible energy devices. Artificial intelligence (AI) and machine learning techniques are increasingly being used for semiconductor material discovery and device optimization. AI-based computational models can accelerate material screening and predict photovoltaic performance with high accuracy. [66], [67]

Flexible and wearable photovoltaic devices represent another important research direction. Lightweight and bendable semiconductor materials can enable integration into portable

electronics, smart textiles and building-integrated photovoltaic systems. [68]

Hybrid semiconductor structures combining organic, inorganic and nanostructured materials are expected to improve charge transport and device stability. Tandem solar cells integrating multiple semiconductor layers with complementary band gaps can achieve significantly higher conversion efficiencies than single-junction devices. [69], [70]

Quantum semiconductor devices, plasmonic nanostructures and advanced heterojunction architectures are also expected to play a major role in next-generation renewable energy systems. Research on recyclable and eco-friendly semiconductor materials will become increasingly important for sustainable development. [71]

8. CONCLUSION

Advanced semiconductor materials have become fundamental components in modern renewable energy technologies. Significant advancements have been achieved in photovoltaic systems, photocatalysis, thermoelectric devices, hydrogen production and energy storage applications through the development of thin-film semiconductors, nanostructured materials and hybrid heterojunction systems. Semiconductor materials such as silicon, CdTe, CIGS, selenium and perovskites exhibit unique electrical and optical properties suitable for efficient renewable energy conversion. [72], [73]

Recent developments in nanotechnology, fabrication techniques and material engineering have significantly improved device efficiency, charge transport and operational stability. Selenium-based semiconductor materials have shown promising potential because of their favourable band gap, strong photoconductivity and compatibility with thin-film photovoltaic structures. Advanced techniques such as doping, surface passivation, interface engineering and nanostructuring have further enhanced photovoltaic performance. [74]

Despite these advancements, several challenges remain, including long-term stability, toxicity concerns, large-scale fabrication difficulties and recombination losses. Continued research on environmentally friendly materials, flexible devices, tandem structures and AI-assisted semiconductor optimization is expected to overcome these limitations. [75]

Future renewable energy systems will increasingly rely on advanced semiconductor technologies integrated with sustainable manufacturing methods, intelligent material design and next-generation nanostructures. These developments are expected to contribute significantly toward global energy sustainability and clean energy production.

Acknowledgment

The author would like to thank the Department of Engineering Physics and supporting faculty members for their valuable guidance and encouragement during the preparation of this review paper.

REFERENCES

- Green MA. *Solar Cells: Operating Principles, Technology and System Applications*. Englewood Cliffs (NJ): Prentice-Hall; 1982.

2. Luque A, Hegedus S. *Handbook of Photovoltaic Science and Engineering*. 2nd ed. Chichester (UK): Wiley; 2011.
3. Nelson J. *The Physics of Solar Cells*. London (UK): Imperial College Press; 2003.
4. Sze SM, Ng KK. *Physics of Semiconductor Devices*. 3rd ed. Hoboken (NJ): Wiley; 2007.
5. Grätzel M. Photoelectrochemical cells. *Nature*. 2001;414(6861):338-344.
6. Shah A, Torres P, Tscharnner R, Wyrsh N, Keppner H. Photovoltaic technology: The case for thin-film solar cells. *Science*. 1999;285(5428):692-698.
7. Chopra KL, Paulson PD, Dutta V. Thin-film solar cells: An overview. *Prog Photovolt*. 2004;12(2-3):69-92.
8. Ginley DS, Bright C. Transparent conducting oxides. *MRS Bull*. 2000;25(8):15-18.
9. Kamat PV. Quantum dot solar cells: Semiconductor nanocrystals as light harvesters. *J Phys Chem C*. 2008;112(48):18737-18753.
10. Nozik AJ. Nanoscience and nanostructures for photovoltaics and solar fuels. *Nano Lett*. 2010;10(8):2735-2741.
11. Hodes G. *Thin Film Materials for Photovoltaics*. Amsterdam (Netherlands): Elsevier; 2005.
12. Bube RH. *Photoconductivity of Solids*. New York (NY): Wiley; 1960.
13. Konagai M. *Thin Film Solar Cells*. Amsterdam (Netherlands): Elsevier; 2012.
14. Parida B, Iniyan S, Goic R. A review of solar photovoltaic technologies. *Renew Sustain Energy Rev*. 2011;15(3):1625-1636.
15. Shockley W, Queisser HJ. Detailed balance limit of efficiency of p-n junction solar cells. *J Appl Phys*. 1961;32(3):510-519.
16. Kittel C. *Introduction to Solid State Physics*. 8th ed. Hoboken (NJ): Wiley; 2005.
17. Neamen DA. *Semiconductor Physics and Devices*. 4th ed. New York (NY): McGraw-Hill; 2012.
18. Singh J. *Semiconductor Devices: Basic Principles*. New York (NY): Wiley; 2001.
19. Streetman BG, Banerjee S. *Solid State Electronic Devices*. 6th ed. Upper Saddle River (NJ): Pearson; 2006.
20. Grundmann M. *The Physics of Semiconductors*. Berlin (Germany): Springer; 2010.
21. Tributsch H. Photoelectrochemistry and photovoltaics. *Electrochim Acta*. 2000;45(15-16):2571-2580.
22. Swanepoel R. Determination of the thickness and optical constants of amorphous silicon. *J Phys E*. 1983;16(12):1214-1222.
23. Ellmer K. Resistivity of polycrystalline zinc oxide films. *J Phys D*. 2001;34(21):3097-3108.
24. Chu TL, Chu SS. Thin film II-VI photovoltaics. *Solid State Electron*. 1995;38(3):533-549.
25. Poortmans J, Arkhipov V. *Thin Film Solar Cells: Fabrication, Characterization and Applications*. Chichester (UK): Wiley; 2006.
26. Green MA. Third generation photovoltaics. *Prog Photovolt*. 2001;9(2):123-135.
27. Rühle S. Tabulated values of the Shockley-Queisser limit. *Solar Energy*. 2016;130:139-147.
28. Schock HW, Noufi R. CIGS-based solar cells. *Prog Photovolt*. 2000;8(1):151-160.
29. Powalla M, Dimmler B. Scaling up issues of thin film solar cells. *Thin Solid Films*. 2000;361-362:540-546.
30. Hamakawa Y. *Thin-Film Solar Cells: Next Generation Photovoltaics and Its Applications*. Berlin (Germany): Springer; 2004.
31. Ditttrich T. *Materials Concepts for Solar Cells*. London (UK): Imperial College Press; 2014.
32. Fonash S. *Solar Cell Device Physics*. 2nd ed. Amsterdam (Netherlands): Elsevier; 2010.
33. Rockett A. *The Materials Science of Semiconductors*. New York (NY): Springer; 2008.
34. Sites JR, Mauk PH. Diode quality factor determination for thin-film solar cells. *Solar Cells*. 1989;27(1-4):411-417.
35. Ohring M. *Materials Science of Thin Films*. 2nd ed. San Diego (CA): Academic Press; 2002.
36. Granqvist CG. *Handbook of Inorganic Electrochromic Materials*. Amsterdam (Netherlands): Elsevier; 1995.
37. Cahen D, Hodes G. Chemical solution deposition. *MRS Bull*. 2000;25(8):27-31.
38. Goetzberger A, Hebling C, Schock HW. Photovoltaic materials. *Mater Sci Eng R*. 2003;40(1):1-46.
39. Snaith HJ. Perovskites: The emergence of a new era. *J Phys Chem Lett*. 2013;4(21):3623-3630.
40. Wolf S, Tauber RN. *Silicon Processing for the VLSI Era*. Sunset Beach (CA): Lattice Press; 2000.
41. Würfel P, Würfel U. *Physics of Solar Cells*. 2nd ed. Weinheim (Germany): Wiley; 2016.
42. Singh J. *Electronic and Optoelectronic Properties of Semiconductor Structures*. Cambridge (UK): Cambridge University Press; 2003.
43. Schroder DK. *Semiconductor Material and Device Characterization*. 3rd ed. Hoboken (NJ): Wiley; 2006.
44. Swanepoel R. Optical properties of selenium thin films. *J Non-Cryst Solids*. 1983;59-60:1231-1234.
45. Schmidt J, Cuevas A. Electronic properties of silicon surface passivation. *J Appl Phys*. 1999;86(6):3175-3180.
46. Atwater HA, Polman A. Plasmonics for improved photovoltaic devices. *Nature Materials*. 2010;9(3):205-213.
47. Yablonoitch E, Cody GD. Intensity enhancement in textured optical sheets for solar cells. *IEEE Trans Electron Devices*. 1982;29(2):300-305.
48. Wang ZL. *Nanostructures and Nanomaterials: Synthesis, Properties and Applications*. 2nd ed. Singapore: World Scientific; 2003.
49. Klimov VI. *Nanocrystal Quantum Dots*. Boca Raton (FL): CRC Press; 2010.
50. Xia Y, Yang P, Sun Y, Wu Y, Mayers B, Gates B. One-dimensional nanostructures: Synthesis, characterization and applications. *Adv Mater*. 2003;15(5):353-389.
51. Lieber CM, Wang ZL. Functional nanowires. *MRS Bull*. 2007;32(2):99-108.
52. Basol BM. Thin film heterojunction solar cells. *J Appl Phys*. 1984;55(2):601-607.

53. Wolf M, Rauschenbach H. Series resistance effects on solar cell measurements. *Adv Energy Convers.* 1963;3(2):455-479.
54. Goetzberger A, Knobloch J, Voss B. *Crystalline Silicon Solar Cells*. Chichester (UK): Wiley; 1998.
55. Atwater HA. The promise of plasmonics for solar cells. *Sci Am.* 2007;296(4):56-63.
56. Campbell P, Green MA. Light trapping properties of pyramidally textured surfaces. *J Appl Phys.* 1987;62(1):243-249.
57. Pillai S, Catchpole KR, Trupke T, Green MA. Surface plasmon enhanced silicon solar cells. *J Appl Phys.* 2007;101(9):093105-1-093105-8.
58. Powalla M, Paetel S, Ahlswede E, Wuerz R. Thin-film solar cells exceeding 20% efficiency. *IEEE J Photovolt.* 2017;7(3):845-854.
59. Teale FW. Environmental effects associated with photovoltaic materials. *Energy Policy.* 2003;31(9):839-848.
60. Leijtens T, Eperon GE, Snaith HJ. Stability of metal halide perovskite solar cells. *Adv Energy Mater.* 2015;5(20):1500963-1500963.
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61. Powalla M, Dimmler B. Large-area deposition techniques for solar modules. *Thin Solid Films.* 2000;361-362:540-546.
62. Butler K, Davies DW, Cartwright H. Machine learning for molecular and materials science. *Nature.* 2018;559(7715):547-555.
63. Forrest SR. The path to ubiquitous and low-cost organic electronic appliances. *Nature.* 2004;428(6986):911-918.
64. Yamaguchi M, Takamoto T, Araki K. Multi-junction III-V solar cells. *Solar Energy.* 2005;79(1):78-85.
65. Turner JA. Sustainable hydrogen production. *Science.* 2004;305(5686):972-974.
66. Armaroli N, Balzani V. *Energy for a Sustainable World*. Weinheim (Germany): Wiley-VCH; 2011.
67. Jäger-Waldau A. *PV Status Report 2020*. Luxembourg: European Commission; 2020.
68. REN21. *Renewables 2023 Global Status Report*. Paris (France): REN21 Secretariat; 2023.
69. Green MA. Solar cell efficiency tables. *Prog Photovolt.* 2021;29(1):3-15.
70. Hosono H, Paine DC, Ginley D. *Handbook of Transparent Conductors*. New York (NY): Springer; 2011.
71. Kojima A, Teshima K, Shirai Y. Organometal halide perovskites as visible-light sensitizers. *J Am Chem Soc.* 2009;131(17):6050-6051.
72. Law M, Greene L, Johnson JC. Nanowire dye-sensitized solar cells. *Nature Materials.* 2005;4(6):455-459.
73. Bisquert J. *Nanostructured Energy Devices*. Boca Raton (FL): CRC Press; 2014.
74. O'Regan B, Grätzel M. A low-cost high-efficiency solar cell based on dye-sensitized colloidal TiO₂ films. *Nature.* 1991;353(6346):737-740.
75. Green MA, Bremner SP. Energy conversion approaches and materials. *Nature Materials.* 2017;16(1):23-34.

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