IAES Journal of Electrical and Electronics Engineering
Vol. 2, No. 2, December 2015, pp. 23~27
ISSN: 2338-7432, DOI: 10.11591/jeee.v2i2.pp23-27

Solar photovoltaic technologies: a review of materials, cell architectures, and performance evolution

Tole Sutikno[1], Auzani Jidin[2]
[1]Faculty of Industrial Technology, Universitas Ahmad Dahlan, Yogyakarta, Indonesia
[2]Faculty of Electrical Engineering, Universiti Teknikal Malaysia Melaka, Melaka, Malaysia

Article Info

Article history:

Received May 3, 2014
Revised Dec 18, 2014
Accepted Feb 27, 2015

Keywords:

Conversion efficiency
Crystalline silicon
Emerging photovoltaic technologies
Photovoltaic materials
Solar cell architecture
Solar photovoltaics
Thin-film solar cells

ABSTRACT

Solar photovoltaic (PV) technology has evolved substantially through advances in semiconductor materials, device architectures, and fabrication processes. This evolution has produced several technology families, including crystalline silicon, thin-film semiconductors, dye-sensitized solar cells (DSSCs), and organic PVs, each offering different combinations of conversion efficiency, manufacturing requirements, material availability, and stability. This review examines the development of solar PV technologies with emphasis on their material characteristics, cell architectures, and performance evolution. It discusses the operating principles and technological characteristics of major PV categories, including monocrystalline and multicrystalline silicon, amorphous silicon, cadmium telluride, copper indium gallium selenide (CIGS), and emerging organic and dye-sensitized devices. Particular attention is given to the relationship between absorber materials, device structures, charge-carrier collection, conversion efficiency, and long-term stability. The review also compares technological advantages and limitations while distinguishing laboratory cell records from commercial module performance. By connecting materials development with architectural innovation and independently confirmed efficiency records, this article provides a historical and comparative perspective on the progress of PV technology and identifies the principal engineering challenges.

This is an open access article under the CC BY-SA license.

1. INTRODUCTION

Solar photovoltaic (PV) technology is an important renewable energy technology because it converts sunlight directly into electricity without requiring mechanical energy conversion. Growing concerns about fossil fuel consumption, energy security, and environmental impacts have encouraged research into PV materials and devices with higher conversion efficiency and lower production costs. Since the development of the first practical silicon solar cell in the 1950s, PV research has progressed from conventional crystalline silicon devices toward a broader range of thin-film and emerging semiconductor technologies [1], [2].

The development of PV technology has primarily been driven by three interconnected objectives: improving conversion efficiency, reducing manufacturing costs, and enhancing device reliability. Crystalline silicon has maintained a dominant position because of its established manufacturing infrastructure, material availability, and relatively mature device technology. Meanwhile, thin-film and emerging PV technologies have attracted attention because they offer opportunities for reduced material consumption, flexible device configurations, and alternative manufacturing processes [3], [4].

This review examines the evolution of solar PV technologies by focusing on absorber materials, cell architectures, and reported conversion performance up to December 2013. It compares the principal technology families and discusses the engineering factors that influence their performance and practical limitations. The review also distinguishes laboratory cell efficiency from module-level performance to provide a more balanced assessment of technological progress.

2. FUNDAMENTALS OF SOLAR PHOTOVOLTAIC TECHNOLOGY

Solar PV conversion is based on the PV effect, in which incident photons generate charge carriers that can be separated and collected to produce electrical power. Semiconductor materials are central to this process because their optical and electronic properties determine photon absorption, carrier generation, transport, and recombination. The selection of absorber materials and the design of device structures therefore strongly influence the achievable conversion efficiency [1], [4].

A conventional solar cell generally consists of a light-absorbing semiconductor, charge-selective regions or junctions, electrical contacts, and protective or supporting layers. The absorber determines the spectral range of sunlight that can be utilized, while the junction and contact structures influence charge separation and collection. Consequently, improvements in PV performance require coordinated optimization of material properties, device architecture, and fabrication processes [1], [4].

The theoretical conversion limit of a conventional single-junction solar cell is constrained by fundamental processes, including incomplete photon absorption, thermalization of energetic carriers, and recombination. Shockley and Queisser established the detailed-balance framework for estimating the maximum efficiency of an ideal single-junction cell under specified assumptions [1]. This theoretical framework provides an important reference for understanding why material bandgap selection and device architecture are central to PV research [5].

3. MAJOR SOLAR PHOTOVOLTAIC MATERIALS AND CELL ARCHITECTURES

Solar PV technologies can broadly be classified into crystalline silicon, thin-film inorganic semiconductors, and emerging organic or sensitized devices. These categories differ in their absorber materials, device structures, manufacturing processes, and technological maturity. Table 1 summarizes their principal characteristics and engineering considerations. The characteristics in Table 1 reflect the technological status and literature available by the end of 2013 [4], [6]–[9].

Table 1. Major solar PV technologies and their characteristics

Technology	Main absorber materials	Typical cell architecture	Main advantages	Major limitations
Monocrystalline silicon	Single-crystal Si	p–n junction; wafer-based	High efficiency, mature technology, established reliability	Energy-intensive wafer production and material processing
Multicrystalline silicon	Multicrystalline Si	p–n junction; wafer-based	Established manufacturing, lower material processing cost than monocrystalline Si	Grain boundaries and associated recombination losses
Amorphous silicon	a-Si:H	Thin-film p–i–n	Low material consumption, suitable for large-area deposition	Light-induced degradation and relatively lower efficiency
Cadmium telluride (CdTe)	CdTe	Thin-film heterojunction	Strong optical absorption and relatively simple thin-film structure	Cadmium toxicity and material availability considerations
CIGS	$Cu(In,Ga)Se_2$	Thin-film heterojunction	High thin-film efficiency and potential for flexible substrates	Complex composition control and manufacturing processes
DSSCs	Dye-sensitized TiO_2	Photoelectrochemical architecture	Potentially low-cost fabrication and good light-harvesting properties	Electrolyte stability and long-term sealing challenges
Organic PVs	Conjugated polymers and organic semiconductors	Bilayer or bulk heterojunction	Lightweight, potentially flexible, and solution-processable	Stability, morphology control, and relatively limited operational lifetime

3.1. Crystalline silicon solar cells

Crystalline silicon has historically been the most established PV technology because of its semiconductor properties and compatibility with large-scale industrial manufacturing. Monocrystalline silicon cells use highly ordered single-crystal wafers, whereas multicrystalline cells use silicon containing multiple crystal grains. Both technologies generally employ junction-based architectures, although improvements in surface passivation, contact design, and cell structures have progressively enhanced their performance [3], [4].

Monocrystalline silicon devices can achieve relatively high conversion efficiencies because their crystal quality supports effective carrier transport and reduced grain-boundary recombination. Multicrystalline silicon provides an alternative manufacturing route that can reduce production costs,

although grain boundaries and defects may introduce additional recombination losses. Research on silicon heterojunctions, improved passivation, and advanced contact structures had further expanded the performance potential of crystalline silicon by 2013 [3], [10].

3.2. Thin-film inorganic solar cells

Thin-film PV technologies reduce the amount of semiconductor material required by depositing relatively thin absorber layers onto supporting substrates. Important examples include hydrogenated amorphous silicon, cadmium telluride, and copper indium gallium selenide (CIGS). Their strong optical absorption allows thin active layers to capture a substantial fraction of incident sunlight, making them attractive alternatives to conventional wafer-based devices [4].

Amorphous silicon uses a disordered silicon structure and is commonly fabricated in p–i–n configurations. CdTe and CIGS generally employ heterojunction architectures in which the absorber is combined with additional semiconductor and contact layers to facilitate charge separation and collection. Although these technologies offer material and manufacturing advantages, their development is influenced by stability, material availability, composition control, and environmental considerations [4], [10].

3.3. Dye-sensitized solar cells

Dye-sensitized solar cells (DSSCs) use a photosensitive dye attached to a porous semiconductor, commonly titanium dioxide, to absorb incident light and initiate charge transfer. Unlike conventional p–n junction cells, light absorption and electron transport occur through different components of the device. This architecture offers opportunities for relatively simple fabrication and alternative approaches to PV conversion [6], [7].

DSSC performance depends on the dye's light-absorption characteristics, electron injection into the semiconductor, charge transport, and the regeneration of the dye by the electrolyte. Research before 2013 explored improved sensitizers, solid-state electrolytes, and alternative device configurations to enhance efficiency and stability. Nevertheless, liquid electrolyte leakage, long-term material stability, and sealing requirements remained important engineering challenges [6], [7].

3.4. Organic photovoltaic cells

Organic PV cells use conjugated polymers or small-molecule organic semiconductors as light-absorbing materials. Early bilayer devices evolved toward bulk heterojunction architectures, in which donor and acceptor materials are blended to create distributed interfaces for exciton dissociation. This architectural development was important because the short exciton diffusion length in organic materials requires charge-generating interfaces to be located close to the regions where photons are absorbed [8], [9].

Organic PV research demonstrated substantial efficiency improvements through new donor–acceptor materials, morphology control, interfacial layers, and processing techniques. Their potential advantages include lightweight structures, mechanical flexibility, and compatibility with solution-based manufacturing. However, operational stability, environmental sensitivity, and reproducibility of active-layer morphology remained significant barriers to widespread deployment by 2013 [8], [9].

4. PERFORMANCE EVOLUTION OF PHOTOVOLTAIC TECHNOLOGIES

The development of PV performance has been characterized by improvements in absorber materials, carrier collection, surface passivation, and device architecture. Crystalline silicon benefited from advances in wafer quality and junction engineering, while thin-film technologies progressed through improved absorber composition and interface control. Emerging technologies also demonstrated rapid laboratory efficiency gains, although their maturity and long-term reliability differed substantially [3], [4], [8]–[10].

By 2013, independently confirmed research-cell results demonstrated that several PV technologies had reached efficiencies previously associated primarily with more mature semiconductor systems. Green et al. reported a crystalline silicon cell efficiency of 24.7% for a large-area device, while CIGS, CdTe, and organic devices also demonstrated significant laboratory achievements. These results should not be interpreted as representative commercial module efficiencies because the reported records involve different device areas, measurement conditions, and levels of technological maturity [10], [11].

The comparison in Table 2 illustrates that high laboratory efficiency alone does not establish the overall technological superiority of a PV material. Device area, stability, manufacturing scalability, material availability, and module integration must also be considered when assessing practical performance. In particular, emerging technologies such as organic and perovskite PVs had demonstrated promising research results by 2013, but their long-term operational reliability and commercial maturity remained less established than those of crystalline silicon [8]–[11].

Table 2. Selected independently confirmed PV cell efficiency records [10], [11]

PV technology	Reported cell efficiency (%)	Interpretation
Crystalline silicon	24.7	Large-area research cell
Multicrystalline silicon	19.5	Large-area research cell
CIGS	20.4	Small-area thin-film cell
CdTe	19.6	1 cm² research cell
Organic PV	11.1	Small-area research cell
Perovskite PV	14.1	Emerging small-area research cell

Source: Adapted from the independently confirmed efficiency records reported by Green *et al.* [10], [11]. Values are research-cell results, not typical commercial module efficiencies.

5. ENGINEERING FACTORS AFFECTING PV PERFORMANCE

PV performance is determined by the combined influence of material properties, cell architecture, fabrication quality, and operating conditions. Absorber bandgap and optical absorption affect the amount of sunlight converted into charge carriers, while defects and recombination reduce the fraction of carriers that can be collected. Surface passivation, interface engineering, and contact optimization are therefore important strategies for improving device performance [1], [3], [4].

Cell architecture also determines how effectively photogenerated carriers are separated and transported toward electrical contacts. Conventional silicon cells rely on junctions and selective contacts, whereas thin-film heterojunctions and organic bulk heterojunctions use different mechanisms and material interfaces. These differences explain why a fabrication or architectural improvement that benefits one PV technology may not produce equivalent gains in another [4], [7]–[9].

Environmental and operational stability represent additional considerations when translating laboratory performance into practical electricity generation. Temperature, moisture, ultraviolet exposure, and material degradation can influence device output and lifetime, while encapsulation and module construction provide protection against external stresses. Therefore, long-term performance evaluation should complement initial conversion-efficiency measurements when comparing PV technologies [4], [10].

6. CRITICAL DISCUSSION AND FUTURE PERSPECTIVES

The evolution of solar PV technology demonstrates that no single material or architecture simultaneously provides the highest efficiency, lowest manufacturing cost, greatest stability, and simplest production process. Crystalline silicon had achieved a strong position through manufacturing maturity and high performance, while thin-film technologies offered alternative approaches to material utilization and device fabrication. Organic and sensitized solar cells introduced additional architectural possibilities, but faced more substantial challenges in stability and large-scale implementation [3], [4], [6]–[10].

Future development, as understood from the literature available by 2013, required a stronger balance between efficiency improvement and practical engineering requirements. Research priorities included improved material quality, reduced recombination, stable interfaces, scalable manufacturing, and more reliable module packaging. The comparison of PV technologies should consequently consider not only laboratory conversion records but also manufacturability, resource constraints, environmental implications, and long-term field performance [4], [10], [11].

7. CONCLUSION

Solar PV technology has developed from conventional silicon junction devices into a diverse field encompassing crystalline silicon, thin-film inorganic semiconductors, dye-sensitized cells, and organic PVs. Advances in absorber materials and cell architectures have contributed to substantial improvements in independently confirmed research-cell efficiencies by the end of 2013. However, these improvements have not eliminated differences in manufacturing maturity, stability, material requirements, and module-level performance across technology families. The main conclusion of this review is that PV technology development should be assessed through an integrated perspective combining materials, device architecture, conversion performance, and operational reliability. Crystalline silicon remained a mature and high-performing technology, while thin-film and emerging PV devices offered alternative pathways for future development. Continued progress therefore depended on translating laboratory advances into reliable, scalable, and economically practical PV modules.

REFERENCES

[1] W. Shockley and H. J. Queisser, "Detailed balance limit of efficiency of p-n junction solar cells," *Journal of Applied Physics*, vol. 32, no. 3, pp. 510–519, Mar. 1961, doi: 10.1063/1.1736034.

[2] D. M. Chapin, C. S. Fuller, and G. L. Pearson, "A new silicon p-n junction photocell for converting solar radiation into electrical power [3]," *Journal of Applied Physics*, vol. 25, no. 5, pp. 676–677, May 1954, doi: 10.1063/1.1721711.

[3] A. Goetzberger and C. Hebling, "Photovoltaic materials, past, present, future," *Solar Energy Materials and Solar Cells*, vol. 62, no. 1, pp. 1–19, Apr. 2000, doi: 10.1016/S0927-0248(99)00131-2.

[4] B. Parida, S. Iniyan, and R. Goic, "A review of solar photovoltaic technologies," *Renewable and Sustainable Energy Reviews*, vol. 15, no. 3, pp. 1625–1636, Apr. 2011, doi: 10.1016/j.rser.2010.11.032.

[5] A. Goetzberger, J. Luther, and G. Willeke, "Solar cells: Past, present, future," *Solar Energy Materials and Solar Cells*, vol. 74, no. 1–4, pp. 1–11, Oct. 2002, doi: 10.1016/S0927-0248(02)00042-9.

[6] M. Grätzel, "Dye-sensitized solar cells," *Journal of Photochemistry and Photobiology C: Photochemistry Reviews*, vol. 4, no. 2, pp. 145–153, Oct. 2003, doi: 10.1016/S1389-5567(03)00026-1.

[7] L. M. Peter, "Dye-sensitized nanocrystalline solar cells," *Physical Chemistry Chemical Physics*, vol. 9, no. 21, pp. 2630–2642, 2007, doi: 10.1039/b617073k.

[8] Z. X. Wang *et al.*, "Organic photovoltaic cells: Novel organic semiconducting materials and molecular arrangement engineering," *Chinese Science Bulletin*, vol. 57, no. 32, pp. 4143–4152, Nov. 2012, doi: 10.1007/s11434-012-5202-3.

[9] Y. W. Su, S. C. Lan, and K. H. Wei, "Organic photovoltaics," *Materials Today*, vol. 15, no. 12, pp. 554–562, Dec. 2012, doi: 10.1016/S1369-7021(13)70013-0.

[10] M. A. Green, K. Emery, Y. Hishikawa, W. Warta, and E. D. Dunlop, "Solar cell efficiency tables (version 42)," *Progress in Photovoltaics: Research and Applications*, vol. 21, no. 5, pp. 827–837, Aug. 2013, doi: 10.1002/pip.2404.

[11] M. A. Green, K. Emery, Y. Hishikawa, W. Warta, and E. D. Dunlop, "Solar cell efficiency tables (version 43)," *Progress in Photovoltaics: Research and Applications*, vol. 22, no. 1, pp. 1–9, Jan. 2014, doi: 10.1002/pip.2452.