

UNDERSTANDING SOLAR CELL TECHNOLOGY: PRINCIPLES, MATERIALS, PERFORMANCE AND FUTURE TRENDS

¹Neha Amol Shirsath, ²Jyoti Ashok Waje

Sandip Institute Of Engineering and Management, Nashik¹, Shatabdi Institute Of Engineering and Research, Nashik².

nehashiledar1991@gmail.com¹, jyotiwaje7114@gmail.com²

ABSTRACT

Solar cells transform sunlight directly into electricity through the photovoltaic effect. Due to rising global energy needs and environmental issues, photovoltaic technology has emerged as a key renewable energy solution. This overview describes how solar cells operate, key photovoltaic technologies, electrical properties, and strategies to enhance efficiency. It covers fundamental aspects of photovoltaic (PV) cells, including their operational principle, primary physical characteristics of PV cell materials, the importance of gallium arsenide (GaAs) thin films in solar technology, their potential, and some mathematical considerations related to p-n junction solar cells. The paper is composed in a straightforward way to ensure that undergraduate engineering students can easily grasp the physical principles behind the functioning of solar cells. Traditional crystalline silicon solar panels currently lead the market, yet thin film technologies and new materials like perovskites are quickly developing. The assessment also addresses reliability issues and potential advancements in photovoltaic systems.

Keywords: *Solar cell, photovoltaic effect, silicon solar cell, thin film solar cell, renewable energy, solar efficiency.*

INTRODUCTION

Energy demand across the world is increasing every year due to population growth, industrial development, and technological expansion. Traditionally, most electricity generation has depended on fossil fuels such as coal, oil, and natural gas. However, these energy sources produce greenhouse gases that contribute to climate change and environmental pollution. Renewable energy technologies are therefore gaining significant attention. Among them, solar energy is particularly attractive because sunlight is widely available and essentially inexhaustible. Solar cells, also called photovoltaic (PV) devices, convert sunlight directly into electrical energy without any moving parts.

Worldwide environmental issues and the rising demand for energy, alongside ongoing advancements in renewable energy technology are promoting the use of alternative power sources. Solar energy is the cheapest and most plentiful of all sustainable natural resources up to now [1]. Solar PV technology represents one of the most effective methods to employ solar energy to produce electricity by transforming sunlight into direct current in photovoltaic cells or solar cells [2,3].

PV energy transformation employs devices that rely on electronic semiconductors, especially but not solely, crystalline silicon (c-Si) or thin-film semiconductor substances. A (c-Si) A solar system based on solar energy is typically built using two fundamental types of crystalline substances, monocrystalline and polycrystalline solar panels. Single-crystal semiconductors possess enhanced electrical properties (20% efficiency) similar to polycrystalline materials. However, monocrystalline PV modules are not cost-effective compared to crystalline wafer-based alternatives technology costs too much [4,5].

The initial functional silicon solar cell was created at Bell Laboratories during the 1950s. Initial devices achieved efficiencies of approximately six percent. Ongoing enhancements in semiconductor materials, device design, and

manufacturing techniques have significantly boosted efficiencies. Currently, commercial crystalline silicon solar panels typically reach efficiencies exceeding twenty percent. Due to its dependability, scalability, and ecological advantages, solar energy is anticipated to be pivotal in the upcoming global energy landscape.

BASIC PRINCIPLE OF SOLAR CELL OPERATION

The functioning of a solar cell relies on the photovoltaic effect. When light hits a semiconductor material, photons can impart their energy to the electrons within the material. When the energy of the photon exceeds the semiconductor's bandgap, an electron is able to transition from the valence band to the conduction band. This procedure generates a pair of electron and hole. [6,7]

A PV cell is the fundamental component of a solar energy system that swiftly converts sunlight into electrical power. The solar cell functions as a p-n junction device. The n-type relates to the negatively charged electrons contributed by donor impurity atoms, while the p-type pertains to the positively charged holes generated by acceptor impurity atoms, as illustrated in Figure 1 of a PV framework [8,9,10].

A solar cell contains a p-n junction formed by joining p-type and n-type semiconductor materials. The junction region contains an internal electric field created by diffusion of charge carriers. When light generates electron-hole pairs near the junction, this built-in electric field separates the carriers.

Electrons are pushed toward the n-type region while holes move toward the p-type region. When an external circuit is connected, electrons flow through the circuit and produce electrical current. The electrical current generated by a solar cell can be described using the diode equation:

$$I = I_{ph} - I_0 (\exp(qV/kT) - 1)$$

where I_{ph} is the photocurrent produced by light, I_0 is the diode saturation current, q is the electronic charge, k is Boltzmann's constant, T is temperature, and V is voltage. [11,12]

STRUCTURE OF A TYPICAL SILICON SOLAR CELL

Solar cells function through the photovoltaic effect, in which photons from sunlight are captured by a semiconductor, energizing electrons and generating electron-hole pairs. These energized electrons are divided by an electric field, producing an electrical current. The overall efficiency of a solar cell relies on its ability to convert solar energy into electricity, which is affected by the material's bandgap, electron mobility, and light absorption properties [13]. Photovoltaic Effect and Material Choice the photovoltaic effect is fundamental to the operation of every solar cell. A semiconductor material needs a suitable bandgap that enables it to capture light in the solar spectrum and produce electron-hole pairs effectively. The primary materials utilized for solar cells are silicon, thin-film substances like CdTe and CIGS, along with new materials like organic semiconductors and perovskites. The optimal material should harmonize effective light absorption with efficient electron conduction, and its characteristics are essential in influencing the efficiency and durability of the solar cell [14].

The majority of solar cells in commerce are composed of crystalline silicon. A standard silicon solar cell comprises multiple layers aimed at enhancing light absorption and electrical efficiency. The upper surface typically has an anti-reflective coating. This thin coating minimizes reflection losses, allowing more sunlight to penetrate the cell. Below this layer lies a thin n-type emitter region established on a p-type silicon substrate. Metal contacts are positioned on both the front and back surfaces to gather electrical current. The front contact typically features a grid design to ensure that it obstructs only a minor portion of incoming light. When light penetrates the cell, photons create charge carriers in the silicon substance. The electric field at the p-n junction separates these carriers and gathers them through the metal contacts, generating usable electrical energy.

MAJOR TYPES OF SOLAR CELLS

Solar cells can be classified based on the materials and technologies used to manufacture them. The most common categories include crystalline silicon solar cells, thin-film solar cells, and emerging technologies like organic and perovskite solar cells.

Crystalline Silicon Solar Cells

Crystalline silicon (c-Si) solar cells have been the leading technology in the solar sector for many years because of their comparatively high efficiency and well-established production methods. These cells can be classified into two types: monocrystalline and polycrystalline silicon cells. Monocrystalline cells consist of a single, unbroken crystal lattice, resulting in enhanced electron mobility and, as a result, increased efficiency, generally ranging from 18% to 22% [15]. Polycrystalline cells, composed of various silicon crystals, exhibit lower efficiency (15%-18%) but are cheaper to manufacture [16]. Recent innovations in silicon solar cell technology, including passivated emitter and rear contact (PERC) cells and bifacial solar cells, have enhanced efficiency and boosted energy production. PERC technology minimizes recombination losses and boosts the cell's overall efficiency by enhancing surface passivation and amplifying light absorption [17]. Bifacial solar cells, which absorb light on both sides of the panel, provide an added benefit, as they can boost energy production by 10%–30% in comparison to nonofficial cells [18].

Thin-Film Solar Cells

Thin-film solar panels are created by applying thin layers of photovoltaic substances onto a base. These substances consist of cadmium telluride (CdTe), copper indium gallium selenide (CIGS), and amorphous silicon (a-Si). Thin-film technology provides numerous benefits compared to crystalline silicon solar cells, such as reduced manufacturing expenses, flexibility, and decreased weight. This renders them appropriate for uses like adaptable and mobile solar equipment. Nonetheless, thin-film solar cells generally demonstrate reduced efficiency compared to crystalline silicon cells, with usual efficiencies falling between 10% and 22% [19]. Solar cells based on CdTe, especially, have demonstrated encouraging results regarding efficiency and cost-effectiveness. Firms such as First Solar have effectively brought CdTe cells to market, and their cost per watt has greatly decreased over the years [20]. CIGS-based thin-film cells, in contrast, provide greater efficiency but come with a higher production cost [21]. Though they have lower efficiency than silicon-based cells, thin-film solar cells are frequently viewed as a budget-friendly option, especially for large-scale utility projects.

Perovskite Solar Cells

Thin-film solar cells are created by applying thin coatings of photovoltaic materials onto a surface. Perovskite solar cells represent a developing technology that has attracted considerable interest because of their excellent efficiency and straightforward manufacturing process. Perovskites are a type of material that possesses the same crystalline structure as calcium titanium oxide, which can be designed to effectively absorb sunlight and transform it into electrical energy. Perovskite solar cells have made significant advancements in efficiency, with lab efficiencies exceeding 25% [22]. This resembles the efficiency of commercial silicon solar cells, yet offers the advantages of reduced manufacturing expenses and more straightforward production methods. Even with their encouraging performance, perovskite solar cells encounter issues concerning durability over time and harmfulness. Perovskite materials are vulnerable to humidity, changes in temperature, and UV light, potentially resulting in degradation over time, consequently shortening the operational life of the solar cells [23].

Additionally, the perovskites containing lead utilized in many of these cells present environmental and health hazards, although current studies on lead-free perovskites might address this issue [24]

Organic Photovoltaics (OPVs)

Organic photovoltaics (OPVs) utilize organic substances, like conjugated polymers or small molecules that can be employed to capture sunlight. OPVs provide multiple benefits, such as being lightweight, flexible, cost-effective to produce, and having the capability for large-scale manufacturing through roll-to-roll techniques [25]. Nonetheless, OPVs presently show reduced efficiency when compared to silicon-based or perovskite solar cells, with usual efficiencies between 10% and 15% [26]. Recent developments in OPVs have aimed at enhancing the efficiency and durability of organic materials. By creating innovative donor-acceptor materials and enhancing device structures, scientists have reached efficiency rates of up to 18% in controlled environments [27]. OPVs offer significant potential for use in portable electronics, building-integrated photovoltaics (BIPV), and various flexible solar applications [28].

Various photovoltaic technologies have been created based on the materials employed and production methods. Crystalline Silicon Solar Cells represent the most commonly utilized solar cells globally. They can be classified into monocrystalline and polycrystalline varieties. Monocrystalline cells consist of a single silicon crystal and typically offer greater efficiency. Polycrystalline cells are made from various silicon crystals and tend to be more affordable. Thin film solar cells are created by applying very thin layers of semiconductor material onto substrates like glass, metal, or plastic. Typical thin film substances consist of cadmium telluride (CdTe), copper indium gallium selenide (CIGS), and amorphous silicon. These technologies require less material and can be produced across extensive surfaces. New photovoltaic materials are being researched to enhance efficiency and reduce production expenses in solar cells. Perovskite solar cells represent one of the most promising new technologies due to their ability to be produced at lower temperatures and their demonstrated rapid advancements in efficiency in laboratory settings.

ELECTRICAL CHARACTERISTICS OF SOLAR CELLS

The efficiency of a solar cell is usually evaluated through the current–voltage (I–V) characteristic curve when exposed to light. This curve illustrates how the current shifts as the voltage across the device changes. Key factors for assessing solar cell performance comprise: Short Circuit Current (I_{sc}) – the peak current generated when the output terminals are connected directly. Open Circuit Voltage (V_{oc}) – the highest voltage achieved when current is not present.

Fill Factor (FF) – an indicator of the sureness of the I–V curve and the efficiency of the cell's power conversion.

Conversion Efficiency – the proportion of electrical output power to the incoming solar power.

Greater values of these parameters typically suggest improved performance of solar cells.

METHODS FOR IMPROVING SOLAR CELL EFFICIENCY

Scientists are consistently creating techniques to enhance the efficiency of solar cells. An essential method is surface passivation. Surface flaws may lead to the recombination of electrons and holes, thereby decreasing current. Passivation layers assist in minimizing these recombination losses. An additional method includes anti-reflective coatings that reduce light reflection from the surface. Surface texturing is commonly employed to capture light within the semiconductor substance. Sophisticated cell designs like PERC (Passivated Emitter and Rear Cell), TOPCon (Tunnel Oxide Passivated Contact), and heterojunction cells integrate various materials and

passivation layers to enhance carrier collection and minimize losses. These advancements have enabled contemporary silicon solar cells to reach substantially greater efficiencies compared to previous models.

Crystalline Silicon Improvements

For crystalline silicon cells, advancements such as passivated emitter and rear contact (PERC) technology have greatly enhanced cell efficiency by minimizing recombination losses and increasing charge carrier mobility. Additionally, tandem solar cells, which integrate several layers of silicon along with other photovoltaic substances, represent another hopeful strategy to enhance efficiency. These tandem cells utilize the complementary absorption spectra of various materials, resulting in increased overall efficiencies [29].

Tandem Solar Cells and Multi-Junction Technology

Tandem solar cells, stacking various layers of distinct photovoltaic materials, have demonstrated considerable potential in enhancing efficiency. For instance, integrating perovskite solar cells with silicon or other efficient materials can create a tandem arrangement that captures a wider spectrum of solar energy. This method has already reached laboratory efficiencies exceeding 30%, indicating the possibility of even greater performance in the future [30]. Multi-junction solar cells, which incorporate several semiconductor layers with varying bandgaps, have reached efficiencies over 40% in controlled laboratory settings [31]. While these cells are mainly utilized in niche areas such as space missions, they offer significant promise for land-based uses too, provided that production methods can be expanded and expenses lowered.

RELIABILITY AND DEGRADATION

Solar panels need to function in outdoor environments for over twenty years. Throughout this period, they encounter environmental factors like temperature variations, humidity levels, ultraviolet rays, and physical stress. Multiple degradation processes can impact photovoltaic modules. Light-induced degradation happens in certain silicon materials after prolonged exposure to sunlight. Potential-induced degradation may happen when significant voltage disparities arise between modules and the ground. Producers utilize enhanced encapsulation substances, superior module design, and rigorous testing protocols to guarantee the durability of photovoltaic systems over time.

Merging various materials to develop tandem solar cells offers potential for reaching efficiencies greater than 30%, allowing for increased energy generation from identical solar panel areas [32]. Creating lightweight, flexible solar panels will allow them to be incorporated into diverse uses, including apparel, mobile gadgets, and building exteriors [33]. Effectively storing solar energy is essential for its extensive use, especially in off-grid and home-based applications. Improvements in battery technology will be crucial in boosting the dependability of solar energy [34]. Initiatives are being implemented to substitute the lead-containing components in perovskite solar cells with more eco-friendly options, enhancing their sustainability while minimizing possible health hazards [35].

FUTURE PROSPECTS

Upcoming studies in solar cell technology emphasize enhancing efficiency and lowering expenses. A promising approach involves tandem solar cells, which stack together two or more semiconductor materials with varying bandgaps to harness a broader range of the solar spectrum. Tandem cells made from perovskite and silicon have shown efficiencies exceeding thirty percent in laboratory trials. Flexible solar panels and building-integrated photovoltaics are likewise under development to broaden the scope of solar energy uses. Through ongoing research and extensive implementation, solar energy is anticipated to emerge as a key source of clean electricity in the future decades.

CONCLUSION

The technology of solar cells has advanced notably in the last few decades. Advancements in semiconductor materials, device physics, and production methods have enhanced the efficiency and affordability of photovoltaic systems. Crystalline silicon presently leads the commercial market, yet new materials and innovative device designs provide thrilling prospects for future advancements. Grasping the essential concepts of solar cells will enable engineering students and researchers to aid in the progress of sustainable energy solutions.

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