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Scientific and Technical Aspects of Developments in Silicon Solar Cells

[1]Fatimah Mohammed Alwaer and [2]*Maher Mohamed Abed El Aziz
[1]Physics Department, Faculty of science Zawia, University of Zawia, Libya
[2]Chemistry Department, Faculty of Education Qaser Ben Ghasher, University of Tripoli, Libya
f.alwaer@zu.edu.ly[1] *Corresponding author: mah.mohamed@uot.edu.ly[2]

Abstract:

The present work provides a comprehensive review of recent advances in physics and technology of inorganic silicon solar cells, with a focus on operational principles, structural design, classification, and efficiency enhancement. It highlights the growing importance of solar energy in daily life, emphasizing its role in reducing dependance on fossil fuels, lowering electricity costs, enhancing energy security, and mitigating environmental impacts. The study categorizes solar cells into three generations based on materials and technological evolution: first generation (crystalline inorganic silicon), second generation (thin film technologies such as amorphous silicon, CdTe, and CIGS), and third generation (emerging technologies including perovskits, organic photovoltaics, quantum dots, and dye sensitized cells). Special attention is given to silicon solar cells due to their market value, reliability, and continuous efficiency improvements. The fundamental characteristics of silicon solar cells is discussed, including photon absorption, electron hole pair generation, and charge carrier separation at the p-n junction. Key equations such as the Planck-Einstein, Poisson's, and continuity equations are presented to describe the behavior and efficiency limits of these devices. The standard structure of a silicon solar cell is described including the n-type emitter, p-type base, anti-reflective coating, metallic contacts, and encapsulation materials. The paper also presents innovations in silicate-based materials such as rare earth doped yttrium disilicate ($Y_2Si_2O_7$) for down conversion of high energy photons, and silica (SiO_2) based nano coatings that have been shown to enhance cell efficiency by up to 9.32%. Ultrathin silica layers applied to TiO_2 surfaces in dye sensitized solar cells have demonstrated a 36% relative efficiency increase by reducing electron recombination. Finally, the paper outlines the fundamental efficiency equation for solar cells defining key parameters such as short circuit current (I_{SC}), open circuit voltage (V_{OC}), fill factor (FF), and overall power conversion efficiency (η). The study concludes that ongoing advancements in materials science, particularly in silicate chemistry/physics and surface engineering, hold great promise for overcoming current efficiency limitations and accelerating the global transition to sustainable solar energy.

Keywords: Photovoltaics, Silicon solar cells, Solar cell efficiency, Silicate materials Down conversion, Anti reflective coating, p-n junction, Renewable energy.

الملخص العربي

تقدم هذه الورقة البحثية مراجعة شاملة للتطورات الحديثة في فيزياء وتكنولوجيا خلايا السيليكون الشمسية، مع التركيز على مبادئ عملها، وتصميمها الهيكلي، وتصنيفها، واستراتيجيات تحسين كفاءتها. يبدأ البحث بتسليط الضوء على الأهمية المتزايدة للطاقة الشمسية في الحياة اليومية، ودورها في تقليل الاعتماد على الوقود الأحفوري، وخفض تكاليف الكهرباء، وتعزيز أمن الطاقة، والتخفيف من الآثار البيئية مثل تلوث الهواء والماء. تصنف الدراسة الخلايا الشمسية إلى ثلاثة أجيال بناءً على المواد والتطور التكنولوجي: الجيل الأول (السيليكون البلوري)، والجيل الثاني (تقنيات الأغشية الرقيقة مثل السيليكون غير المتبلور، وتيلوريد الكادميوم، وسيلينيد الإنديوم والنحاس والجاليوم)، والجيل الثالث (التقنيات الناشئة مثل البيروفسكايت، والخلايا العضوية الضوئية، والنقاط الكمومية، والخلايا الصبغية الحساسة للضوء). ويُولى اهتمام خاص لخلايا السيليكون الشمسية بسبب هيمنتها على السوق، وموثوقيتها، وتحسين كفاءتها المستمر. يناقش البحث الفيزياء الأساسية لخلايا السيليكون الشمسية، بما في ذلك امتصاص الفوتونات، وتوليد أزواج الإلكترون–ثقب، وفصل حاملات الشحنة عند الوصلة الثنائية (p–n junction). كما يُقدم المعادلات الأساسية مثل علاقة بلانك–أينشتاين، ومعادلة بواسون، ومعادلات الاستمرارية لوصف سلوك وحدود كفاءة هذه الأجهزة. ويُوصف الهيكل القياسي لخلية السيليكون الشمسية، بما في ذلك الطبقة السالبة(n–type) ، والطبقة الموجبة(p–type) ، والطبقة المضادة للانعكاس(ARC) ، والملامسات المعدنية، ومواد التغليف. يسلط البحث الضوء –أيضًا– على الابتكارات الحديثة في المواد القائمة على السيليكات، مثل سيليكات الإيتريوم ($Y_2Si_2O_7$) المطعمة بأيونات العناصر الأرضية النادرة لتحويل الفوتونات عالية الطاقة إلى فوتونات أقل طاقة(Down–conversion) ، والطلاءات النانوية القائمة على السيليكا (SiO_2) مثل (POSS) والتي ثبت أنها تعزز كفاءة الخلية بنسبة تصل إلى 9.32%. بالإضافة إلى ذلك، أظهرت طبقات السيليكا فائقة الرقة المطبقة على سطح أكسيد

التيتانيوم TiO_2 في الخلايا الشمسية الصبغية زيادة في الكفاءة النسبية بنسبة 36% عن طريق تقليل إعادة اتحاد الإلكترونات. أخيرًا، توضح الورقة المعادلة الأساسية لكفاءة الخلايا الشمسية، وتحدد المعايير الرئيسية مثل تيار القصر (I_{SC})، وجهد الدائرة المفتوحة (V_{OC})، وعامل التعبئة (FF)، وكفاءة تحويل الطاقة الكلية (η). وتخلص الدراسة إلى أن التقدم المستمر في علم المواد، وخاصة في كيمياء وفيزياء السيليكات وهندسة الأسطح، يحمل وعدًا كبيرًا للتغلب على قيود الكفاءة الحالية وتسريع الانتقال العالمي إلى الطاقة الشمسية المستدامة.

الكلمات المفتاحية: الخلايا الكهروضوئية، خلايا السيليكون الشمسية، كفاءة الخلايا الشمسية، مواد السيليكات، التحويل النزولي(Down conversion)، الطلاء المضاد للانعكاس، الوصلة الثنائية (p–n junction)، الطاقة المتجددة.

Introduction

Photovoltaics is the branch of technology that deals with using solar cells to convert sunlight into electricity. It plays a vital role in today's economy and enables cleaner and renewable energy production, reduces the dependence on fossil fuels and contributes to global efforts to combat climate change. Photovoltaics also makes an important contribution to energy security, lowers electricity costs in the long term and creates jobs in manufacturing, installation and maintenance [**1**]. Solar energy has moved beyond being an alternative power source to become a practical, everyday solution for homes, businesses, and entire communities. Its importance in daily life can be seen in everything from lower utility bills to a cleaner local environment. Home electricity, water heating, ventilation, cooling, outdoor lighting, personal electronics, agriculture and transportation are considered a daily life applications of solar energy [**2**]. Sunlight is free and hence solar energy has many benefits including shields households and businesses from volatile fossil fuel prices. Many solar owners see payback within 5-10 years, with panels lasting 25-30 years. Pairing solar with battery storage means critical appliances (refrigerators, medical devices, lights) can run during blackouts. This is especially valuable in areas prone to extreme weather or unstable grids. The solar industry employs millions of people in manufacturing, installation, maintenance, and sales. These local jobs contribute to community economic health. Every kilowatt-hour of solar electricity avoids the CO_2, SO_2, and N_xO_y emissions that would otherwise come from coal or natural gas [**3**]. This leads to cleaner air, fewer respiratory illnesses, and a direct contribution to fighting

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climate change. Conventional power plants consume huge amounts of water for cooling. Solar energy systems generate electricity without water consumption, helping to preserve freshwater resources for drinking and agriculture [**4**]. Over the past two decades, the solar market has evolved from a niche industry into one of the world's primary sources of electricity generation, driven by technological advancements, massive economies of scale, and urgent climate policies. The Asia-Pacific region (APR) is the center of gravity for solar energy; it has shifted from Europe to Asia-Pacific region. By 2026, APR is estimated to account for a massive 68% of global solar deployment. This is driven by the sheer scale of installations in China which alone added more than 279 GW of new capacity in 2025 and India, which is projected to add over 50 GW in 2026, surpassing the U.S. to become the world's second largest market [**5**]. The last 20 years have been defined by the dramatic reduction in the cost of solar modules. This has been achieved through manufacturing innovations, economies of scale, and technological advancements (from traditional cells to more efficient). The market today is characterized by record-low module prices, making new solar projects among the cheapest sources of new electricity globally. The market's size is now measured in hundreds of billions of dollars. The global rooftop solar system market alone is projected to grow from 128 billion in 2025 to 161 billion in 2026. The total market for all solar photovoltaics is forecast to reach $333.7 billion in 2026, under scoring solar's role as the central pillar of the global energy transition [**6**]. Due to the above-mentioned benefits, importance, applications, and global market effectiveness of solar energy, our present work aims to highlight the recent advances trends in physics and chemistry of solar cells materials, especially silicon type including the principal operation, classifications, architecture, and efficiency enhancement technology.

Importance and study objectives

This study is important because it provides a comprehensive, up-to-date, and scientifically rigorous review of silicon solar cell technology, bridging fundamental physics with cutting-edge materials science and real-world applications. It serves as a valuable resource for researchers, engineers, and policy makers working toward a sustainable energy future.

The primary research objectives of this study are to review the scientific and technical foundations of silicon solar cells, classify them by generation, present key physical equations, explore recent advances in silicate-based materials for efficiency enhancement, highlight the global importance of solar energy, and identify pathways to surpass current efficiency limits through tandem architectures and surface engineering.

Methodology

The methodology of this study is based on a systematic review and synthesis of published scientific literature, textbooks, industry reports, and official standards. It employs a structured analytical frame work that covers fundamental physics/chemistry, material classification, structural design, performance equations, recent innovations in silicate-based materials, and global market trends. The study rather integrates existing knowledge to provide a comprehensive overview of silicon solar cell technology and its future directions.

Previous studies

The reviewed studies demonstrate a clear different approaches to advancing solar cell technology. The first is a drive towards new device architectures that overcome fundamental physical limits, while the second focuses on material science innovations that significantly boost the performance of existing technologies. There are two main trends:

1. Breaking efficiency limits with tandem architecture. These cells work by stacking a perovskite cell which absorbs high energy photons on top of a silicon cell which absorbs lower energy photons. This configuration captures a much broader range of the solar spectrum. A 2025 review in Materials Chemistry Frontiers confirms that these tandem cells have achieved a certified power conversion efficiency (PCE) of 34.85%, representing a significant breakthrough in the field.
2. Enhancing silicon cells via silicate-Based Materials Separately, a significant body of research is dedicated to improving the efficiency of standard silicon cells using novel silicate materials. This approach offers a potentially cost-effective pathway to boost performance without completely redesigning the cell architecture. Down conversion with rare earth doped silicates and antireflective coatings with POSS Nanocages are two practical examples for this approach.

Types and generations of solar cells

Solar cells are classified according to the original chemical nature into three main categories [**7-10**]:

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1. Inorganic solar cells including silicon cells, copper oxides cells, dichalcogenides, group III-V semiconductors, group II-VI semiconductors, inorganic perovskites, and kesterites.
2. Organic solar cells including materials for dye-sensitized solar cells (DSSC).
3. Mixed solar cells including inorganic/organic hybrid Perovskites, quantum dot-based materials, and inorganic/organic hetero-junctions' solar cells.

The development of solar cells is generally divided into three main generations as shown in table (1), each representing a significant shift in materials, manufacturing processes, and overall performance. This classification helps to illustrate the technology's journey from the first practical silicon cells to today's advanced experimental designs.

First generation marks the birth of modern solar technology. In 1954, scientists at Bell Labs developed the first practical silicon solar cell with 6% efficiency, and by 1958 they were already powering space satellites [**11**]. The push for lower costs led to the development of thin film solar cells. Instead of thick, rigid silicon wafers, these technologies use layers of semiconductor material only a few micrometers thick, deposited directly onto glass, plastic, or metal. This significantly reduces material usage and opens the door to flexible panels. Amorphous Silicon (a-Si) often used in small electronics like calculators [**12**]. Cadmium Telluride (CdTe) is a leading thin film technology for large, utility scale power plants due to its low manufacturing cost while copper Indium Gallium Selenide (CIGS) was known for achieving the highest efficiencies among thin films and being very flexible. Third generation represents the current cutting edge of solar research, aiming to overcome the fundamental efficiency limits of single junction silicon cells or drastically lower costs. Perovskite Solar Cells have taken the research world by storm due to their rapid efficiency gains, low material cost, and ease of processing. When combined with silicon in a tandem cell, they have achieved laboratory efficiencies exceeding that of silicon alone. Organic Photovoltaics (OPV) cells use organic semiconductors and can be made into ultra-light weight, flexible, and even semi-transparent films. While their efficiency is currently lower, they are ideal for niche applications like portable chargers or building-integrated windows. Quantum Dot and Dye-Sensitized Cells (DSSC) technologies use novel mechanisms to absorb light and generate charge, offering potential for low-cost and colorful solar panels for architectural integration [**13**].

Table (1): Materials, characteristics, and applications of solar cell generations

Generation	Basic Materials	Characteristics & Efficiency	Applications
1st Generation	**Monocrystalline Silicon (c-Si), Polycrystalline Silicon (p-Si)**	**High efficiency (15-22%), reliable, high manufacturing cost, rigid panels.**	**Large scale solar farms, residential and commercial rooftops, satellite power.**
2nd Generation	**Amorphous Silicon (a-Si), Cadmium Telluride (CdTe), Copper Indium Gallium Selenide (CIGS)**	**Lower efficiency (7-13% for a-Si; up to 22% for CIGS), lower cost, flexible and light weight, requires less material.**	**Building-integrated photovoltaics (BIPV), portable electronics, large-scale utility plants (especially CdTe).**
3rd Generation	**Perovskites, Organic Polymers, Dye-Sensitized Cells, Quantum Dots**	**Lab efficiency up to >29% (perovskite/silicon tandem), solution processable potential for very low cost, still in development, focus on stability.**	**Emerging applications include transparent solar windows, lightweight flexible panels, and tandem cells for ultra-high efficiency.**

Silicon solar cells

Silicon (Si) makes up 25.7% of the earth's crust, by weight, and is the second most abundant element, being exceeded only by oxygen. Silicon is not found free in nature, but occurs chiefly as the oxide and as silicates. Sand, quartz, rock crystal, amethyst, agate, flint, jasper, and opal are some of the forms in which the oxide appears. Granite, hornblende, asbestos, feldspar, clay, mica are but a few of the numerous silicate minerals. Silicon is prepared commercially by heating silica and carbon in an electric furnace, using carbon electrodes. Several other methods can be used for preparing the element. Amorphous silicon can be prepared as a brown powder, which can be easily melted or vaporized [**14**]. The Czochralski process is commonly used to produce single crystals of silicon used for solid state or semiconductor devices. Hyper pure silicon can be prepared by the thermal decomposition of ultra-pure trichlorosilane in a hydrogen atmosphere, and by a vacuum float zone process. Hyper pure silicon can be doped with boron (B), gallium (Ga), phosphorus (P), or arsenic (As) to produce silicon for use in transistors, solar cells, rectifiers, and other solid-state devices which are used extensively in the electronics and space age industries. Hydrogenated amorphous silicon has shown promise in producing economical cells for converting solar energy into electricity. At the heart of every silicon solar cell is a semiconductor p-n junction. This structure is the physical foundation that allows for the conversion of light into electricity. The operation relies on three key physical phenomena [**15**]:

1. Photon Absorption: When sunlight (composed of photons) strikes the silicon solar cell, photons with energy greater than the semiconductor's band gap can be absorbed. For crystalline silicon, this band gap is 1.12 eV, which corresponds to light in the near-infrared spectrum (approximately 1100 nm).
2. Electron-Hole Pair Generation: The absorbed photon transfers its energy to an electron in the silicon's crystal lattice, exciting it from the valence band (where electrons are bound) to the conduction band (where they can move freely). This process leaves behind a "hole" in the valence band, creating a mobile electron-hole pair, also known as an exciton.
3. Charge Carrier Separation: This is the most crucial step, the built-in electric field at the p-n junction immediately separates the newly created electron-hole pair. Electrons are swept toward the n-type (negative) side, and holes are swept toward the p-type (positive) side. If an external circuit is connected, these charges flow as an electric current, producing usable electricity.

The efficiency of a solar cell is linked to the quality of its silicon crystal. Crystalline silicon (c-Si) has a highly ordered, repeating atomic lattice. This order is essential for efficient electron mobility and predictable electronic properties, making it the dominant technology in the market due to its proven long-term reliability. Amorphous silicon (a-Si), where the atoms are arranged randomly, is used in thin film solar cells but generally has lower efficiencies. For high energy photons, any energy above the 1.12 eV band gap is lost as heat. Researchers are exploring ways to modify silicon's properties to better match the solar spectrum. For instance, creating nanostructures like a "silicon nano-sponge" causes quantum confinement. This phenomenon widens the material's effective band gap, allowing it to be tuned to absorb different parts of the solar spectrum more efficiently. Several fundamental equations describe the behavior and efficiency limits of silicon solar cells. Planck-Einstein equation links the energy of a photon to its wavelength and is used to determine the minimum energy required to generate an electron-hole pair [**16**].

$$E = \frac{hc}{\lambda} \dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots . (1)$$

Where:

E is the energy of a photon (Joules or eV)
h is Planck's constant (6.626×10^{-34} J · s)
c is the speed of light in a vacuum (3.00×10^{8} m/s)
λ is the wavelength of light (meters)

For a silicon band gap of 107 kJ/mol, the maximum wavelength of light that can be absorbed is approximately ~ 1117 nm. Photons with a longer wavelength (e.g., infrared) have less energy and simply pass through the cell without generating electricity. The detailed operation of a solar cell is described by a system of partial differential equations that govern the flow of electrons and holes. These equations derived from fundamental laws of physics, account for the generation, recombination, drift, and diffusion of charge carriers within the device. Poisson's Equation relates the electric field within the device to the distribution of charge. Continuity Equations for electrons and holes describe how the concentration of these carriers changes over time due to generation, recombination, and current flow. Sophisticated numerical models solve these coupled equations to accurately predict cell performance and identify limiting factors. Through such analysis, researchers have identified bandgap narrowing and surface recombination as the most significant barriers to achieving higher efficiencies in silicon solar cells.

Basic structure of silicon solar cell

The basic structure of a silicon solar cell, as shown in figure (1) is a sandwich-like shape of different layers, each with a specific function. The entire design is optimized to absorb as much light as possible and to efficiently collect the generated electrical charge. At the heart of every silicon solar cell is a p-n junction. This is created within a single silicon crystal by introducing different impurities (a process called doping) into two adjacent regions.

- n-type Layer (Emitter): The top, very thin layer is doped with an element like phosphorus (P), which has one more valence electron than silicon. This creates an excess of mobile, negatively charged electrons.
- p-type Layer (Base): The much thicker bottom layer is doped with an element like boron (B), which has one less valence electron. This creates a deficit of electrons, equivalent to having mobile, positively charged holes.
- Depletion Region (Electric Field): Where the n-type and p-type layers meet, electrons and holes recombine, creating a region depleted of free charge carriers. This region

naturally possesses a built-in electric field that acts as a one-way street for charge. When a photon of sufficient energy is absorbed in or near this depletion region, it creates an electron-hole pair. The built-in electric field then immediately separates them, sending the electron toward the n-side and the hole toward the p-side creating the electrical current. An individual solar cell is fragile and produces a relatively low voltage (around 0.5-0.7 V). For practical use, many individual cells are wired together and encapsulated to form a solar module (or panel). Tempered glass is the top layer providing strength and weather protection. Ethylene vinyl acetate (EVA) sheets sandwich the cells, providing adhesion, electrical insulation, and UV protection. Polymer back sheet is the bottom layer that blocks moisture and provides electrical isolation. Aluminum frame provides structural rigidity and mounting points.

Mechanism of solar cell operation

Light strikes the cell's surface which is often textured with microscopic pyramids to reduce reflection and trap more light inside the silicon. An anti-reflective coating (ARC) typically a thin layer of silicon nitride (Si_3N_4) or titanium dioxide (TiO_2), helps more light enter the cell rather than bouncing off. Photons with the right energy penetrate the silicon and are absorbed by its atoms creating electron-hole pairs. The built-in electric field of the p-n junction immediately separates the electron and the hole forcing them to move in opposite directions. Metallic contacts (fingers and busbars) printed on the cell's surface collect the flowing electrons directing them out of the cell and into an external circuit to provide power into a load. The electrons reenter the cell on the back contact and recombine with holes completing the electrical circuit.

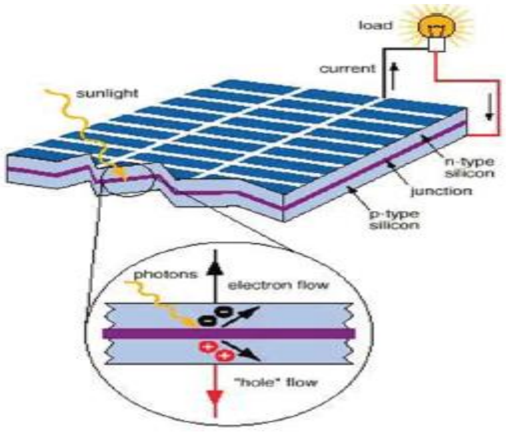

Fig. (1): The basic structure of silicon solar cell [17]

Advances in silicon/silicate cells

Silicon's role is expanding beyond being just the light absorbing semiconductor. Novel silicate materials are being actively researched to boost the performance of existing solar cells through optical manipulation and surface engineering. Standard silicon solar cells are inefficient at using high energy (blue UV) light and cannot use low energy (infrared, IR) light. Silicate host materials like yttrium disilicate ($Y_2Si_2O_7$) can be doped with rare earth ions (such as Pr^{3+} and Yb^{3+}) [**18**]. These ions absorb high energy photons and emit two or more lower energy photons that the silicon cell can efficiently convert to electricity. This process called down conversion (DC) has the potential to significantly increase overall efficiency by better utilizing the solar spectrum. Researchers have developed a silica (SiO_2) like nanocoating based on Polyhedral Oligomeric Silsesquioxane (POSS) nanocages. This thin transparent coating was found to enhance the efficiency of a silicon solar cell by 9.32%. This is a significant gain achieved simply by modifying the external surface of an existing cell. In dye-sensitized solar cells (DSSCs) a common loss mechanism is the recombination of electrons at the TiO_2 surface. A method has been developed to deposit an ultra-thin, conformal insulating layer of silica (SiO_2) precisely on the TiO_2 surface to block these recombination sites, resulting in a 36% increase in relative efficiency [**19**].

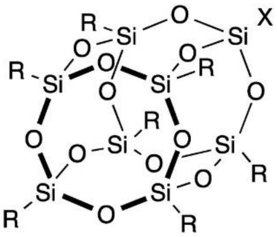

Fig. (2): Chemical structure of polyhedral oligomeric silsesquioxane (POSS) nanocages

Efficiency enhancement of solar cells

The efficiency of a silicon solar cell is a measure of its ability to convert sunlight into usable electrical power and it is the most important metric for comparing cell performance. Calculating the efficiency is straight forward and is based on the ratio of electrical power output to the light power input. The fundamental equation for calculating the efficiency (η) of any solar cell is [**20**]:

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$$\eta = \frac{P_{\max}}{P_{\text{in}}} = \frac{I_{\text{SC}} \times V_{\text{OC}} \times \text{FF}}{P_{\text{in}}} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots . (2)$$

Where:

η is the efficiency (often expressed as a percentage)

$P_{\max}$ is the cell's maximum power output (in Watts)

P_{in} is the total power of the incident light (in Watts)

I_{SC} is the short-circuit current (in Amperes)

V_{OC} is the open-circuit voltage (in Volts)

FF is the Fill Factor (a dimensionless number between 0 and 1)

The Short Circuit Current (I_{SC}) and Open Circuit Voltage (V_{OC}) are the two fundamental electrical parameters of a cell. The Fill Factor (FF) describes how "square" the I-V curve is. Short Circuit Current (I_{SC}) is the current when the cell's terminals are directly connected. It is directly proportional to the number of photons absorbed and converted into charge carriers (electrons and holes). To improve I_{SC}, engineers use textured surfaces to trap light and anti-reflective coatings to reduce light reflection. Open Circuit Voltage (V_{OC}) is the voltage when the circuit is broken (no current flows). It is determined by the cell's material properties and the level of recombination where electrons and holes recombine before being collected. The equation for V_{OC} is:

$$V_{\text{OC}} = \frac{nkT}{q} \ln\left(\frac{I_{\text{SC}}}{I_0} + 1\right) \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots . (3)$$

Where:

I_0 is the reverse saturation current, which is directly related to recombination. Minimizing

recombination (e.g., with surface passivation layers) is key to raising V_{OC}.

n = Ideality factor (or diode ideality factor), a dimensionless number (typically between 1 and 2) that indicates how closely the solar cell's behavior matches an ideal diode.

$n = 1$ for an ideal diode (diffusion-limited recombination)

$n = 2$ when recombination in the depletion region dominates

k = Boltzmann constant, $k = 1.38 \times 10^{-23}$ J/K (joules per kelvin)

T = Absolute temperature, $T = 298.15$ K (25°C).

q = Elementary charge (charge of an electron), $q = 1.602 \times 10^{-19}$ C (coulombs)

The term $\frac{nkT}{q}$ has units of volts and is often called the thermal voltage scaled by the ideality factor. The thermal voltage $V_T = \frac{kT}{q}$ is approximately:

$$V_T \approx \frac{1.38 \times 10^{-23} \times 298.15}{1.602 \times 10^{-19}} \approx 0.0257\ \text{V} = 25.7\ \text{mV at } 25°\text{C} \ldots\ldots\ldots\ldots\ldots (4)$$

With the ideality factor n, the term becomes $n \cdot V_T$. Thus, the equation can also be written as:

$$V_{oc} = nV_T \ln\left(\frac{I_{SC}}{I_0} + 1\right) \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (5)$$

Fill Factor (FF) is a measure of the cell's quality and is strongly affected by internal resistance. It is calculated as:

$$\text{FF} = \frac{P_{\max}}{I_{\text{SC}} \times V_{\text{OC}}} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (6)$$

A higher FF means the cell operates closer to its ideal conditions, delivering more power. Even for a perfect silicon cell with no electrical losses, there is an absolute maximum theoretical efficiency known as the Shockley-Queisser (S-Q) limit. This limit is a consequence of the fundamental physics of a single junction semiconductor. For crystalline silicon (c-Si) with a band gap of 1.12 eV, this limit is approximately ≈ 34%. The limit arises because a single band gap can't perfectly match the broad solar spectrum. Photons with energy below the band gap, their energy is too low to excite an electron and is simply lost as heat. Photons with energy above the band gap, the extra energy is not converted to electricity but is also lost as heat. These unavoidable loss of solar spectrum energy is the primary reason why the efficiency of a standard single junction silicon cell cap at around ~ 34%. The most promising way to surpass the 34% efficiency limit is to stack multiple solar cells creating a tandem cell. Each cell in the stack has a different band gap calibrated to absorb a specific part of the solar spectrum more efficiently. High energy photons (UV light) are absorbed by a top cell with a wide band gap. Lower energy photons (IR light) pass through the top cell and are absorbed by a bottom cell with a narrow band gap. By capturing more of the solar spectrum efficiently, tandem cells have achieved laboratory efficiencies over 34%. The most intensely researched tandem design combines a silicon bottom cell with a perovskite top cell [**21**].

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Conclusions

This review highlights that silicon solar cells remain the dominant photovoltaic technology due to their reliability, continuous efficiency improvements, and established manufacturing infrastructure. The fundamental physics of p-n junctions, photon absorption, and charge carrier separation governs their operation, while advanced materials such as rare earth doped silicates and silica based nanocoating materials have shown significant potential for enhancing spectral utilization and reducing recombination losses. Despite approaching the Shockley-Queisser limit (~34%) for single junction devices, tandem architectures particularly perovskite silicon combinations offer a viable pathway to surpass this threshold. Ongoing innovations in surface engineering, anti-reflective coatings, and down conversion layers are critical for achieving higher efficiencies and accelerating the global transition toward sustainable solar energy.

Recommendations

To accelerate the global transition toward sustainable and high-efficiency solar energy, this study recommends a multi-pronged approach:

(1) Continued research and developments (R&D) into tandem architectures and down-conversion materials.
(2) Industrial adoption of silicate-based nano-coatings.
(3) Cost reduction and recycling improvements.
(4) Supportive government policies and educational initiatives.
(5) Immediate priority should be given to scaling perovskite/silicon tandem cells and commercializing POSS-based anti-reflective coatings, as these technologies have demonstrated significant efficiency gains in laboratory settings and are ready for pilot production.

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