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FIRST GENERATION SOLAR CELL: HISTORY AND DEVELOPMENT OF SILICON-BASED PHOTOVOLTAICS

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Abstract. The global transition toward new and renewable energy sources to address environmental issues and the limitations of conventional energy reserves remains a priority. Solar energy, through photovoltaic technology, emerges as a promising option for mitigating the environmental impact of traditional energy. The fact that solar energy is a sustainable resource and a viable means to reduce reliance on fossil fuels supports this. Solar cells are devices made from semiconductor materials capable of converting solar energy into electrical energy. We categorize first-generation solar cells into silicon monocrystalline, silicon polycrystalline, and III-V single junctions based on GaAs. This article reviews the characteristics of first-generation silicon-based solar panels, including efficiency, light absorption, and transmission, which dominate the global market. This review aims to provide an in-depth understanding of the factors influencing the performance of silicon-based solar cells, which will contribute to the development and application of solar cell technology in the future.

Keywords: solar energy, solar cell, silicon, monocrystalline, polycrystalline

Abstrak. *Transisi global menuju sumber energi baru dan terbarukan untuk mengatasi permasalahan lingkungan dan keterbatasan cadangan energi konvensional tetap menjadi prioritas. Energi surya, melalui teknologi fotovoltaik, muncul sebagai pilihan yang menjanjikan untuk mengurangi dampak energi tradisional terhadap lingkungan. Fakta bahwa energi surya merupakan sumber daya berkelanjutan dan cara yang tepat untuk mengurangi ketergantungan pada bahan bakar fosil mendukung hal ini. Sel surya merupakan perangkat yang terbuat dari bahan semikonduktor yang mampu mengubah energi matahari menjadi energi listrik. Kami mengkategorikan sel surya generasi pertama menjadi silikon monokristalin, silikon polikristalin, dan sambungan tunggal III-V berbasis GaAs. Artikel ini mengulas karakteristik panel surya berbasis silikon generasi pertama, termasuk efisiensi, penyerapan cahaya, dan transmisi yang mendominasi pasar global. Kajian ini bertujuan untuk memberikan pemahaman mendalam mengenai faktor-faktor yang mempengaruhi kinerja sel surya berbasis silikon, yang akan berkontribusi terhadap pengembangan dan penerapan teknologi sel surya di masa depan.*

Kata kunci: *energi surya, sel surya, silikon, monokristalin, polikristalin*

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1. Introduction

For an extended period, humans have depended on a variety of conventional energy sources, including coal, natural gas, fossil fuels, and others, to satisfy their daily electricity requirements. Numerous environmental hazards have resulted from the utilization of these traditional energy sources. Water pollution, air pollution, global warming, carbon emissions, acid rain, and soil erosion have been persistent issues that humans and the environment have dealt with for many years [1]. In addition to the numerous hazards that conventional energy sources present, their reserves are also restricted, rendering their continuous large-scale use unsustainable. Consequently, a transition to clean and sustainable energy sources has been implemented. Renewable energy sources, including hydropower, wind energy, solar energy, and biomass energy, are collectively referred to as clean energy sources.

Solar energy is one of the clean energy sources that is developing at a rapid pace. Photovoltaic technology is regarded as an effective method of mitigating harmful environmental impacts through the use of solar energy. Suitable for the expansion of the electrical grid at a reduced cost, photovoltaic cells, also referred to as solar cells, can directly convert light into electricity [2]. The development of solar cells is examined from a variety of perspectives, such as their efficiency, light absorption capability, transmission, and materials. Currently, crystalline silicon serves as the primary component of solar cells, accounting for 90% of the global solar cell market. Crystalline silicon-based solar cells are a component of the initial generation of solar cells [3]. Monocrystalline silicon (m-Si), polycrystalline silicon (p-Si), and III-V single junctions based on gallium arsenide (GaAs) are the three types of solar cells in the first generation.

The efficiency of solar cells is a critical factor for users in practical applications, as it directly influences the performance of solar panels. Solar cells that are more efficient are capable of absorbing solar energy and converting it into electrical energy. The performance of solar cells is also significantly influenced by light absorption and transmission properties, in addition to efficiency. The solar cells' capacity to absorb light energy is determined by their absorption properties, while the amount of light energy that passes through them to be converted into electrical energy is determined by their transmission properties. The performance of solar cells is enhanced by their superior absorption and transmission properties. Nevertheless, there is still a lack of comprehensive explanations of the characteristics of commercial solar panels. This review article will investigate the efficiency, light absorption, and transmission properties of a variety of first-generation silicon-based solar panels. The objective of this review is to offer a more comprehensive and detailed comprehension of the history and factors that influence the performance of silicon-based solar cells, thereby serving as a reference for the future development and application of solar cell technology.

2. Basic Working Principle of Solar Cells

Edmond Becquerel, a French physicist, was the first to discover the photovoltaic effect in 1839. He conducted experiments by subjecting electrodes coated with silver chloride (AgCl) and silver bromide (AgBr) to a variety of lights. It was discovered that the voltage produced by the electrode increases in proportion to the intensity of the incoming light [4,5]. The working principle of solar cells fundamentally relies on the photovoltaic effect, with silicon crystals serving as the primary component for energy conversion. The photovoltaic effect is the process by which solar cells convert absorbed sunlight into electricity. Sunlight is composed of photons, which are energy packets that fluctuate in energy according to the wavelength in the solar spectrum [5]. As shown in Figure 1, a solar cell basically consists of p-type and n-type silicon. The p-type silicon generally doped with trivalent elements such as Boron and Galium to create extra holes at the valence band of silicon. In contrast, the n-type silicon can be produced using pentavalent dopant like phosphor to have extra electron at the conduction band of silicon. The area of interface between the p-type and n-type is generally called depletion region. p-n junction is also a component of the solar cell's operating principle. Electrons from the n-type material diffuse into the p-type material at the p-n junction, while holes from the p-type material diffuse into the n-type material. This results in the formation of a depletion region by causing the boundary of the n-type junction to become positively charged and the p-type junction to become negatively charged. When two distinct charges are in close proximity, they generate an electric field in accordance with Coulomb's Law [6]. The energy of the photons can release electrons and holes from the depletion region when light strikes the p-n junction, resulting in its depletion. A current is formed as a result of the potential difference generated by the movement of free electrons and holes. The lamp will illuminate when both ends of the layer are connected to a load, such as a lamp, as also shown in Figure 1 [7]. By leveraging the distinct characteristics of p-type and n-type materials, solar cells can efficiently transform sunlight into usable electrical energy. This sophisticated process underpins solar energy systems globally.

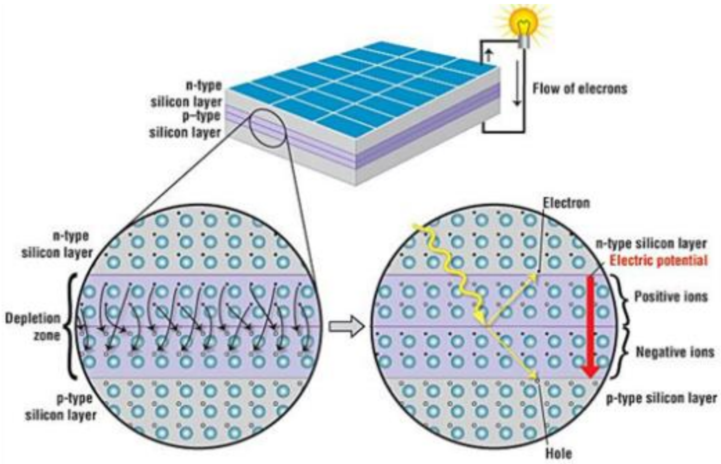

Figure 1. Working Principle of Solar Cells [7]. Copyright 2021: Springer

3. Theoretical Efficiency of Solar Cells

The efficiency of a solar cell is a measure of its ability to convert solar energy into electrical energy. The higher the efficiency value of a solar cell, the better its performance in generating electrical energy from solar energy. Mathematically, the efficiency of a solar cell is defined as the ratio of the maximum output power (P_m) to the input power generated from the solar light source (P_{in}) when it hits the surface of the solar cell. This efficiency is denoted by η and is expressed as a percentage (%) [8].

$$\eta = \frac{P_m}{P_{in}} \times 100\% \quad (1)$$

where

P_m = maximum output power (*Watt peak*/ Wp)

P_{in} = input power (*Watt peak*/ Wp)

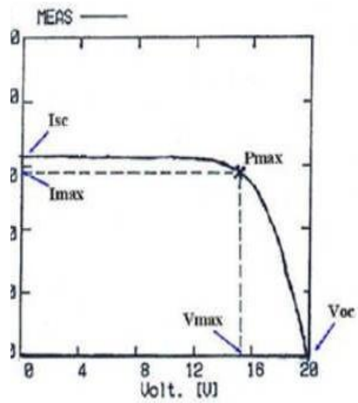

Figure 2. Characteristics curve of solar cells [9].

Figure 2 shows the characteristic curve of a solar cell, linking current and voltage. Based on the figure (a), P_{max} or P_m is obtained by multiplying Imax with V_{max}, or the maximum power is obtained when the maximum current and maximum voltage are reached:

$$P_m = I_m V_m \tag{2}$$

When examining Figure (b) in more detail, there is a dark blue area (A) and a light blue area (B). The ratio between area B to area A is called the Fill Factor (FF). The fill factor is a parameter that influences the performance evaluation of a solar cell. A lower fill factor indicates that the solar panel produces less electrical power at its maximum power point [9]. Mathematically, it is expressed as follows:

$$FF = \frac{V_m I_m}{V_{oc} I_{sc}} \tag{3}$$

Substituting equations (1), (2), and (3) yields the equation for determining efficiency:

$$\eta = \frac{P_m}{P_{in}} = \frac{I_m V_m}{P_{in}} = \frac{FF\ V_{oc} I_{sc}}{P_{in}} \times 100\% \tag{4}$$

where:
I_m = Maximum current to produce maximum power (A)
V_m = Maximum voltage to produce maximum power (V)
V_{oc} = Voltage when the current is zero or open-circuit voltage (V)
I_{sc} = Current when the voltage is zero or short-circuit current (A)

V_{oc} and I_{sc} are the theoretical maximum values that a solar cell can produce. According to equation (4), several parameters affect the efficiency of a solar cell: fill factor, V_{oc}, and I_{sc}. To improve solar cell efficiency, these parameters can be adjusted and optimized. The standard values for measuring the efficiency of solar cells are:

- *Solar irradiance* = 1000W/m^2
- *Temperature* = 25ºC
- *Spectral irradiance* = AM1.5
- *Fill factor* = value between 0 and 1.

However, in practical applications, solar cell performance is influenced by both internal and external factors, which ultimately affect its efficiency. External factors that can affect solar cell performance include temperature and intensity. Temperature changes directly impact how electrons move within the solar cell, making the semiconductor sensitive to temperature. With increasing temperature, the band gap of the semiconductor will decrease, leading to higher resistance and reduced electron mobility. This results in a significant voltage drop, as clearly demonstrated in Figure 3. Additionally, light intensity affects solar cell performance, particularly the current.

The intensity of sunlight directly affects the current produced by the solar cell. Figure 4 demonstrates that the higher the intensity of solar light received by the solar cell, the more photon energy is absorbed by the semiconductor material. This causes more electrons to be released from the atoms in the semiconductor material, generating a larger electrical current [12].

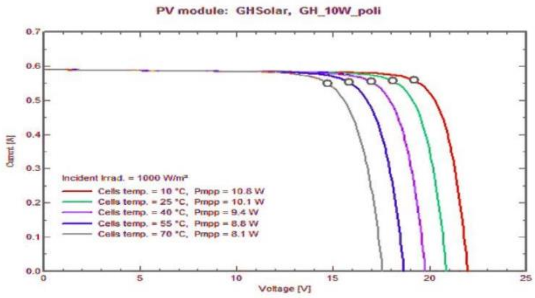

Figure 3. Graph of temperature effect on voltage [10]. copyright 2018: Jurusan Teknik Elektro dan Komputer, Fakultas Teknik, Universitas Syiah Kuala

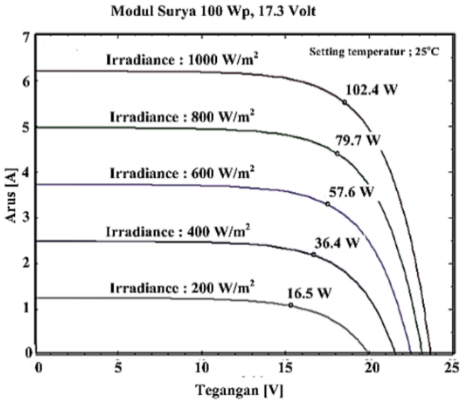

Figure 4. Graph of intensity effect on current [10].
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4. Swanson's Law

The cost of solar power generation has decreased exponentially over the decades, and this trend appears to be unstoppable. Swanson's law explains this price drop. Swanson's law states that the price of solar photovoltaic power (solar cells) tends to decrease by about 20% every time the volume of solar panel production doubles. This law is similar to Moore's law in the semiconductor industry, which states that the number of transistors on integrated circuits (ICs) will double approximately every two years, thereby reducing the cost per transistor [13], [14]. Swanson's Law illustrates how increasing production scale and technological innovations in the solar cell industry result in lower production costs, making solar panels more affordable. Swanson's method is a learning or experience curve analysis . This method was first developed by Theodore Paul Wright in 1975 in the aviation industry [15] and was widely applied in the photovoltaic industry in the 1990s [16]. Since 1977, the price of solar panels has dropped from $77 per watt to only $0.36 per watt in 2016, a drastic price drop that demonstrates the law's accuracy. Swanson's law can be illustrated through the following graph:

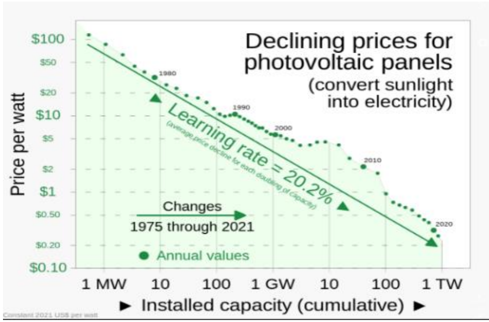

Figure 5. Swanson's Law Graph 1975 - 2021. Adapted from Global data change lab, under the terms of the Creative Commons Attribution 4.0 International License (CC BY 4.0). Available at: https://ourworldindata.org/grapher/solar-pv-prices-vs-cumulative-capacity

5. Trends in Silicon Solar Cell Prices

Figure 6 shows the price comparison of silicon, wafers, and cells with the average spot market prices for polycrystalline (mc-Si) and monocrystalline (mono-Si) modules in January 2017, 2018, and 2019, which were 0.390 USD/Wp, 0.354 USD/Wp, and 0.244 USD/Wp, respectively. This indicates a significant decline during that period.

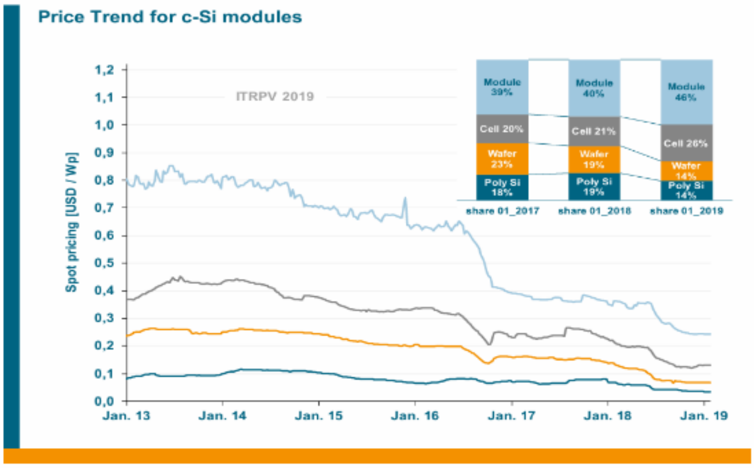

Figure 6. Price development of multicrystalline silicon modules, poly-Si, and multicrystalline wafers from January 2011 to January 2018 [17].
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The production costs of non-silicon modules, particularly consumable materials, and other components, greatly influence prices. With an estimated global solar module production capacity of around 150 GWp in 2018 and a global demand of about 120 GWp, there is no expected supply shortage [18]. Therefore, increasing production efficiency and managing consumable material costs are challenges that need to be addressed. Strategies to tackle these include reducing production costs per unit by improving production tool efficiency and optimizing material use, as well as introducing specialized module products for different market needs.

Efforts to enhance power efficiency and cell modules without significantly increasing production costs are also crucial. However, the introduction of new technologies that are not clearly defined and do not reduce unit costs from the outset remains a current challenge.

6. Development of Silicon-Based Solar Panels

Silicon solar cells were first introduced for telecommunications devices by Bell Laboratories in Murray Hill, NJ in 1954 [19]. Subsequently, in 1966, based on Bell Laboratories' devices, Sharp produced solar modules and played a key role in developing photovoltaic cells [20].

The Institute for Essential Service Reform released the Indonesia Energy Outlook report, which explains that solar cells play a significant role in the decarbonization of Indonesia by 2060, or possibly even before 2050. However, it is regrettable that solar power usage in Indonesia only reached 0.2 GWp of the total installed capacity, contributing less than 1% of the total electricity generation by the end of 2021 [21]. Despite this, we can observe progress in Indonesia's solar power sector through reduced electricity costs under power purchase agreements implemented by PT PLN with private power developers.

Since the 1950s, the efficiency of commercial solar cells has significantly increased from less than 1% to over 23% [22]. Since then, silicon has become a pioneer material in the photovoltaic industry. The evolution of silicon solar cells is schematically shown in Figure 7.

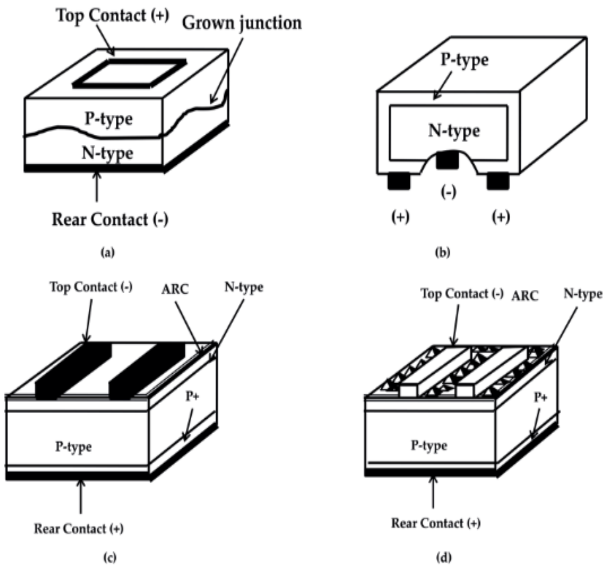

Figure 7. Evolution of silicon-based solar cells. (a) 1941: Reported solar cell with grown-in junction, (b) 1954: Solar cell p-n junction formed by dopant diffusion process, (c) 1970: Violet cell with Aluminum back surface plane, (d) 1974: Black cell with chemically textured surface [23]. Copyright 1998: Wiley

Silicon solar cells were first introduced by Russell Ohl of Bell Laboratories in the 1940s. These cells had efficiency levels of less than 1% due to inadequate control over junction location and the quality of silicon material used. The nomenclature for naming the p-type region (illuminated side) and n-type region (other side) was provided by Ohl and has since been used for solar cell naming conventions.

In the 1950s, significant advancements occurred in diffusion techniques using high temperatures to inject dopants into silicon. Pearson, Fuller, and Chapin of Bell

Laboratories developed solar cells with an initial efficiency of 4.5% using lithium-based doping, which increased to 6% after switching the dopant from lithium to boron through the diffusion process. These solar cells had a 'wrap-around' structure that encased the entire area (Figure 7b) with both contacts on the backside to avoid shading losses. However, this design resulted in higher resistive losses. The cell structure then evolved as shown in Figure 7c. For space exploration applications, high resistivity substrates of 10 Ω cm were used to achieve maximum radiation resistance. Vacuum-evaporated contacts were used on both sides, while silicon monoxide was coated on the front as an anti-reflective layer [23].

In recent day, silicon-based solar cells continue to be developed to produce high-efficiency solar cells to support the transition from fossil energy to cleaner renewable energy. Table 1 lists several studies on the development of methods, materials, and efficiencies of silicon-based solar cells.

Table 1. Development of Silicon-based Solar Cells with its efficiency in the last few years

Material	Performance	Year	Reference
Interdigitated back contacts/heterojunction silicon crystalline	12.14% (*efficiency*)	2017	[24]
m-Si	22.7% (*efficiency*)	2018	[25]
Silicon heterojunction	>18.6% (*efficiency*)	2018	[24]
mc-Si Al-BSF solar cells	18.99% (*efficiency*)	2020	[26]
HPM (High-Performance Multicrystalline) with composite nucleant	19.51 % (*max efficiency*) 80.20% (*Fill factor)*	2020	[27]
mc-Si (additive-assisted Ag-MACE for multi-crystalline)	23,5% (*efficiency*), 81.8% (*Fill factor)*	2020	[28]
Silicon Heterojunction Solar Cells using MoOx as hole-selective contact(a-Si dan c- Si)	25% (*efficiency*)	2020	[29]
Silicon IBC solar cells	18.25% (*efficiency*)	2020	[30]
m-Si (deposited with nanoscale TiO_2 and Ta_2O_5 ARClayers)	18.73% (*efficiency*) 80.3% (*Fill Factor)*	2021	[31]
mc-Si solar cells with improved Al-BSF	24% (*efficiency*)	2021	[32]
TPC for c-Si	25.7% (*Efficiency perovskite/silicon tandems*)	2021	[33]
Silicon-based tandem solar cells	47.2 *watts/day (PV total power)*	2021	[34]
Monocrystalline coated with Graphene	14.23% (*efficiencbsorption at the tip of the sample)y*)	2022	[35]
Monocrystalline (Solar Roof Slates)	10.06% (*efficiency*)	2022	[36]
Polycrystalline (Solar Roof Shingles)	≈5–10% cm^{-1} (*absorptionin the bulk)*	2022	[36]

Quasi-monocrystalline silicon	12.14% (*efficiency*)	2022	[37]
Polycrystalline Silicon (Synthesized FeS2)	19.6% (efficiency)	2022	[38]
mono-crystalline silicon PERC solar cells	22.69% (efficiency)	2022	[39]
Monocrystalline (Front-Surface Cooling with 96% Alcohol)	18.8% (efficiency increased 3,2%)	2023	[40]
Metal-Assisted Chemical Etching/MACE Monocrystalline	3.0% (effective reflectivity)	2023	[41]
Silicon heterojunction solar cells	26.81% (efficiency)	2023	[42]
Polycrystalline (COCG)	17.89% (efficiency)	2024	[43]

In 2017, Yoshikawa et al. researched silicon heterojunction, integrating it with back contact to achieve a high efficiency of 26% [24]. In 2018, Gupta et al. studied the application of pyramid-shaped surface texture on silicon solar cells, achieving a maximum efficiency of 12.14%, which is 25.45% higher than normal silicon solar cells without texture [25]. In the same year, silicon heterojunction was used to achieve an efficiency of 22.7% [44]. In 2020, Lei et al. used composite nucleators on High-Performance Multicrystalline (HPM) and achieved an efficiency of 18.99% [27]. Shortly after, Li et al. developed additive-assisted Ag-MACE on multicrystalline, resulting in an efficiency of 19.51% and a fill factor of 80.20% [28]. Dreon et al. also developed silicon-based heterojunction solar cells with MoOx as a hole-selective contact, achieving a high efficiency of 23.5% and a fill factor of 81.8% [45]**.** In 2023, research by Pera et al. using Metal-Assisted Chemical Etching (MACE) on monocrystalline silicon wafers (mono c-Si) successfully achieved an effective reflectance (Reff) of 3.0% for $\rho = 0.916$, thus improving its light capture efficiency [41]. The latest research in 2024 by Gunasekaran and Kaliyanann focused on designing polycrystalline silicon solar cells covered with transparent sheets made of cyclic olefin copolymer with gahnite (COCG). Gahnite (ZnAl2O4) mixed with various weight percentages (wt. %) of COC aimed to enhance anti-reflective properties. This resulted in a Power Conversion Efficiency (PCE) of 16% and 17.89% [46].

7. Commercial Silicon Solar Cell Technology

Silicon (Si) is one of the most abundant elements on earth and widely used in the semiconductor industry. 98% purity of metallurgical-grade silicon is obtained by heating quartz sand (SiO_2) combined with carbon at high temperatures between 1,500-2,000°C [47]. Then, Mg-Si is further refined to obtain solar-grade silicon with 99.99% purity. Solar-grade silicon with 99.99% purity then undergoes further processing to produce monocrystalline and multicrystalline silicon ingots, which are large masses of silicon. In monocrystalline silicon, purified silicon chunks are processed into a large, homogeneous single crystal. Monocrystalline silicon has atomic arrangements with the same crystal orientation throughout its material. Solar cells with (100) crystal orientation are often chosen because they are easy to texture to minimize surface reflection [48]. Multicrystalline silicon has many grains with different orientations, unlike monocrystalline, which is uniform. Monocrystalline material has a longer minority carrier lifetime compared to multi-crystalline, resulting in higher solar cell efficiency.

The Czochralski (Cz) method is used to make monocrystalline silicon ingots, where high-purity molten silicon doped with dopants is slowly pulled to obtain ingots up to 300 mm in diameter and 2 m in length [49]. To obtain specific types of monocrystalline silicon ingots weighing up to 200 kg, the molten silicon can be doped with either p-type or n-type dopants [17]. Wafers cut from these ingots are called 'pseudo square' due to their rounded edges. Multicrystalline silicon ingots are produced by melting high-quality silicon, then undergoing crystallization in a large vessel using directional solidification methods, ultimately forming silicon material with different orientations [50]. Multicrystalline ingots can now weigh over 800 kg and are then cut into blocks and wafers [17].

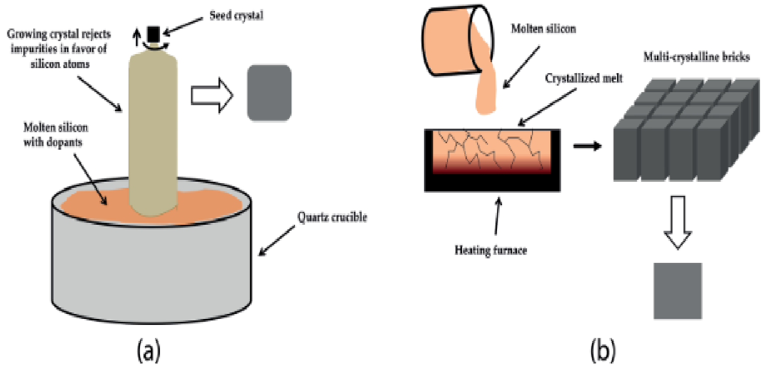

Figure 8. Czochralski method for manufacturing mono-crystalline ingots (a) multi-crystalline ingot directed melting and solidification process (b) [26]. Adapted from Mehul C. Raval and Sukumar Madugula Reddy, Industrial Silicon Solar Cells, under the terms of the Creative Commons Attribution 4.0 International License (CC BY 4.0). Available at: https://www.intechopen.com/chapters/67140

Monocrystalline and polycrystalline wafers used for solar cells are sized 6 inches x 6 inches. Monocrystalline wafers are slightly smaller than polycrystalline wafers due to their rounded edges. Boron-doped p-type silicon substrates are the most dominant material used for making solar cells. N-type silicon substrates can also be used as the base material for high-efficiency solar cells, but there are technical challenges in achieving uniformly distributed doping along the silicon ingot.

The general classification of various types of solar cells and their efficiency ranges are shown in Figure 9. Standard Aluminum Back-Surface Field (Al-BSF) solar cells are one of the most widely available technologies due to their relatively simple manufacturing process. The standard Al-BSF technology is based on the deposition of aluminum across the entire rear side (RS) through a screen-printing process and the formation of a p^+ BSF to repel electrons from the backside of the p-type substrate and increase cell efficiency. Figure 10 demonstrates the Al-BSF fabrication process for solar cells. The standard design for commercial solar cells features a grid-patterned FS contact and a full-area RS contact.

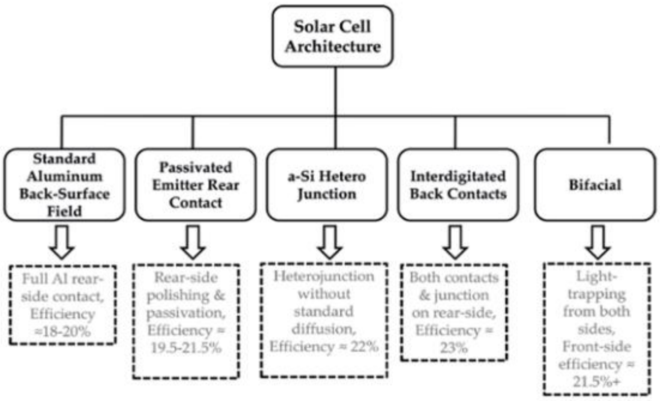

Figure 9. Classification of different types of solar cells [26]. Adapted from Mehul C. Raval and Sukumar Madugula Reddy, Industrial Silicon Solar Cells, under the terms of the Creative Commons Attribution 4.0 International License (CC BY 4.0). Available at: https://www.intechopen.com/chapters/67140

Passivated emitter rear contact (PERC) solar cells are an advancement of the Al-BSF solar cell architecture (Figure 10), with an added passivation layer on the rear side to enhance the internal reflection of the cell. Aluminum oxide is a suitable material for RS passivation, with average solar cell efficiencies reaching up to 21% [51]. Existing Al-BSF solar cells can be upgraded to PERC types using two additional tools (RS passivation layer deposition and laser for local contact opening on the RS).

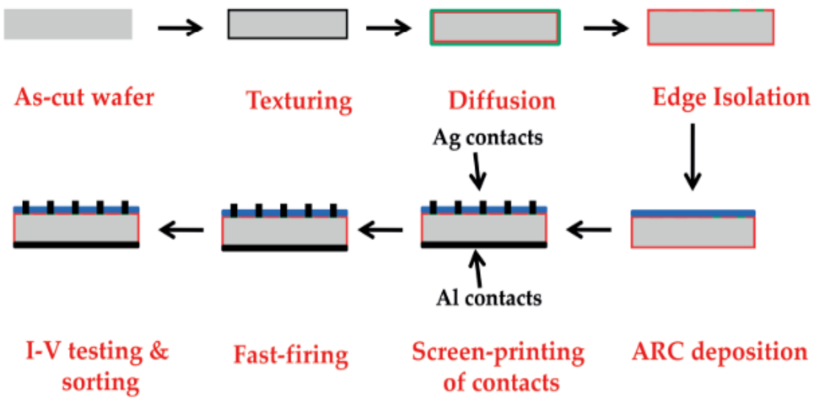

Figure 10. Manufacturing flow of Al-BSF solar cells [26]. Adapted from Mehul C. Raval and Sukumar Madugula Reddy, Industrial Silicon Solar Cells, under the terms of the Creative Commons Attribution 4.0 International License (CC BY 4.0). Available at: https://www.intechopen.com/chapters/67140

Three other solar cell architectures are high-efficiency solar technologies based on n-type Si substrates. Heterojunction solar cells based on a-Si have a-Si layers on the front (FS) and rear (RS) sides of the n-type Si substrate to form 'heterojunctions,' differing from the conventional high-temperature diffusion-based p-n junction. This technology can be implemented at lower temperatures but risks producing solar cells with high sensitivity to interface quality.

Commercial production of a-Si-based heterojunction solar cells was initially done by Sanyo Electric but has now been taken over by Panasonic [52]. In the design of interdigitated back contact (IBC) solar cells, both contacts are on the rear side, eliminating the contact shadow loss on the front side (FS). SunPower Corporation was one of the early manufacturers of high-efficiency n-type IBC solar cells [53]. Bifacial solar cells, as the name suggests, can capture light on both the front and rear sides. This is possible because the rear side of bifacial solar cells also has grid-patterned contacts that can collect light from reflector reflections. An example of bifacial technology is the BiSON solar cell developed and produced by ISC, Konstanz [54].

8. Conclusion

The development of silicon-based solar cells continues to progress, with advancements in materials such as monocrystalline silicon, polycrystalline silicon, IBC silicon solar cells, and silicon heterojunctions. These advancements are achieved through various methods, primarily focusing on increasing efficiency. The authors state that reducing production costs and increasing the efficiency of silicon solar cells are crucial for enhancing solar energy utilization. Although many silicon solar cell efficiencies have approached theoretical limits, there is still plenty of room for improvement. Given the abundance of silica materials around us, leveraging knowledge in physics, chemistry, and multidisciplinary sciences, as well as engineering, is expected to accelerate the discovery of the latest high-performance solar cells.

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