

Environmental and Material Considerations in Silicon-based solar cells

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Abstract:

The global transition toward clean and sustainable energy has propelled significant advancements in renewable energy technologies, with silicon-based solar cells emerging as a dominant force in the photovoltaic market. This article provides a comprehensive review of silicon-based solar cells, covering their historical development, working principles, types, advanced architectures, and material usage. The review highlights the evolution of technologies such as PERC, PERL, TOPCon, and emerging innovations like heterojunction (HJT) and perovskite-silicon tandem cells. Additionally, the article examines the environmental and economic implications of material usage, particularly silver and aluminum, in solar cell fabrication. By addressing current challenges and exploring future opportunities, this review underscores the critical role of silicon-based solar cells in achieving a sustainable energy future.

Keywords: Photovoltaic technology, silicon solar cells, resource sustainability.

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Introduction:

The global demand for clean and sustainable energy has driven significant advancements in renewable energy technologies, with solar energy emerging as one of the most promising solutions. Among the various photovoltaic technologies, silicon-based solar cells have dominated the market due to their high efficiency, durability, and scalability. This article provides a comprehensive review of silicon-based solar cells, focusing on their historical development, working principles, types, advanced architectures, and material usage. By understanding these aspects, researchers and industry professionals can optimize the design and production of solar cells for enhanced performance and sustainability.

2. Historical Development

The development of silicon-based solar cells began in 1954, when researchers at Bell Laboratories created the first practical silicon solar cell with an efficiency of around 6%[1]. This breakthrough marked the beginning of the photovoltaic industry. Over the decades, advancements in material science, manufacturing techniques, and device engineering have significantly improved the efficiency and affordability of silicon solar cells. Today, silicon-based solar cells account for over 90% of the global photovoltaic market, making them the most commonly used technology for solar energy conversion[2].

3. Types of Silicon-Based Solar Cells

Silicon-based solar cells are primarily categorized based on the type of silicon used in their fabrication. The three main types are monocrystalline silicon (c-Si), polycrystalline silicon (poly-Si), and amorphous silicon (a-Si)[3], [4].

3.1 Monocrystalline Silicon (c-Si):

Monocrystalline silicon is made from a single crystal structure, offering high purity and efficiency, typically ranging from 18% to 24%[2]. Its high efficiency and long lifespan make it ideal for applications where space is limited, such as rooftop installations. However, the production process is energy-intensive and costly.

3.2 Polycrystalline Silicon (poly-Si):

Polycrystalline silicon is composed of multiple silicon crystals, resulting in lower purity and efficiency, typically ranging from 15% to 20%[2]. Despite its slightly lower efficiency, poly-Si is more cost-effective to produce, making it a popular choice for large-scale solar farms.

3.3 Amorphous Silicon (a-Si):

Amorphous silicon, a non-crystalline form of silicon, is used in thin-film solar cells. While its efficiency is relatively low, typically ranging from 6% to 10%[2], it offers advantages such as flexibility, lightweight, and cost-effectiveness. However, amorphous silicon solar cells are prone to degradation over time, limiting their long-term performance.

4. Working Principle of Silicon-Based Solar Cells

Silicon-based solar cells operate on the principle of the photovoltaic effect, which involves the conversion of light energy into electrical energy. When sunlight strikes the silicon material, photons with sufficient energy are absorbed, creating electron-hole pairs. The built-in electric field at the p-n junction separates the electrons and holes, driving them toward opposite electrodes. The separated charges are collected by the metal contacts, generating an electric current. This current can then be harnessed for external applications, such as powering electrical devices or feeding into the grid. The efficiency of a solar cell depends on its ability to absorb photons, separate charges, and minimize energy losses.

5. Advanced Silicon-Based Solar Cell Technologies

In recent years, significant advancements have been made in silicon-based solar cell technologies to improve their efficiency and reduce costs. Three notable architectures are Passivated Emitter and Rear Cell (PERC), Passivated Emitter, Rear Locally-diffused (PERL), and Tunnel Oxide Passivated Contact (TOPCon)[5], [6], [7].

5.1 PERC (Passivated Emitter and Rear Cell):

PERC technology enhances the efficiency of traditional silicon solar cells by adding a passivation layer at the rear surface. This layer reduces electron recombination and improves light absorption, leading to higher efficiencies. PERC cells have become increasingly popular in the industry, with efficiencies exceeding 22%[7].

5.2 PERL (Passivated Emitter, Rear Locally-diffused):

PERL cells are an advanced version of PERC cells, featuring localized doping at the rear surface to further reduce recombination losses. This technology achieves even higher efficiencies, often exceeding 23%[2], [7], making it suitable for high-performance applications.

5.3 TOPCon (Tunnel Oxide Passivated Contact):

TOPCon technology utilizes a thin tunnel oxide layer and a doped polysilicon layer to create a passivated contact at the rear surface. This design minimizes recombination losses and improves carrier transport, resulting in efficiencies of up to 25%. TOPCon cells are considered a promising candidate for next-generation silicon solar cells due to their high efficiency and compatibility with existing manufacturing processes[2], [7].

5.4 Heterojunction Technology (HJT) Bifacial Solar Cells (Emerging Technology)

HJT cells combine crystalline and amorphous silicon layers, achieving efficiencies of 25% or higher. Companies like REC Group and Panasonic [8] have commercialized HJT modules with bifacial designs to maximize energy output. HJT fabrication involves depositing thin intrinsic amorphous silicon layers on both sides of a crystalline silicon wafer using Plasma-enhanced chemical vapor deposition (PECVD) technique, followed by sputtering transparent conductive oxide (TCO) layers. These steps improve electrical conductivity and minimize optical losses.

5.5 Perovskite-Silicon Tandem Cells (Emerging Technology)

Perovskite-silicon tandem cells demonstrate the potential to achieve efficiencies exceeding 30%. Oxford PV [9] is a leader in commercializing these technologies, targeting utility-scale applications. The elaboration process includes solution-based or vapor deposition techniques for the perovskite

layer. This is coupled with silicon cells, requiring precise control of layer thickness, uniformity, and interface engineering to enhance charge transfer.

6. Market Share Trends of Silicon-Based Solar Cell Technologies

Figure 1 illustrates the market share trends of silicon-based solar cell technologies. It is evident that TOPCon technology is gradually overtaking PERC, which is expected to be phased out by 2031, potentially remaining only in limited residual projects. According to the latest ITRPV (International Technology Roadmap for Photovoltaic) report, the solar cell market is undergoing a significant shift. In 2023, PERC dominated with a 63% market share, but this is projected to decline to 40% in 2024 as TOPCon gains momentum, reaching a 49% market share in the same year. Meanwhile, HJT (Silicon Heterojunction) technology is anticipated to account for nearly 8% of the market in 2024, growing to 15% by 2034. Additionally, Si-Tandem technology is expected to enter the market in 2026 with a modest 0.1% share, gradually increasing to 10% by 2034. This roadmap highlights the dynamic evolution of photovoltaic technologies in the coming decade.

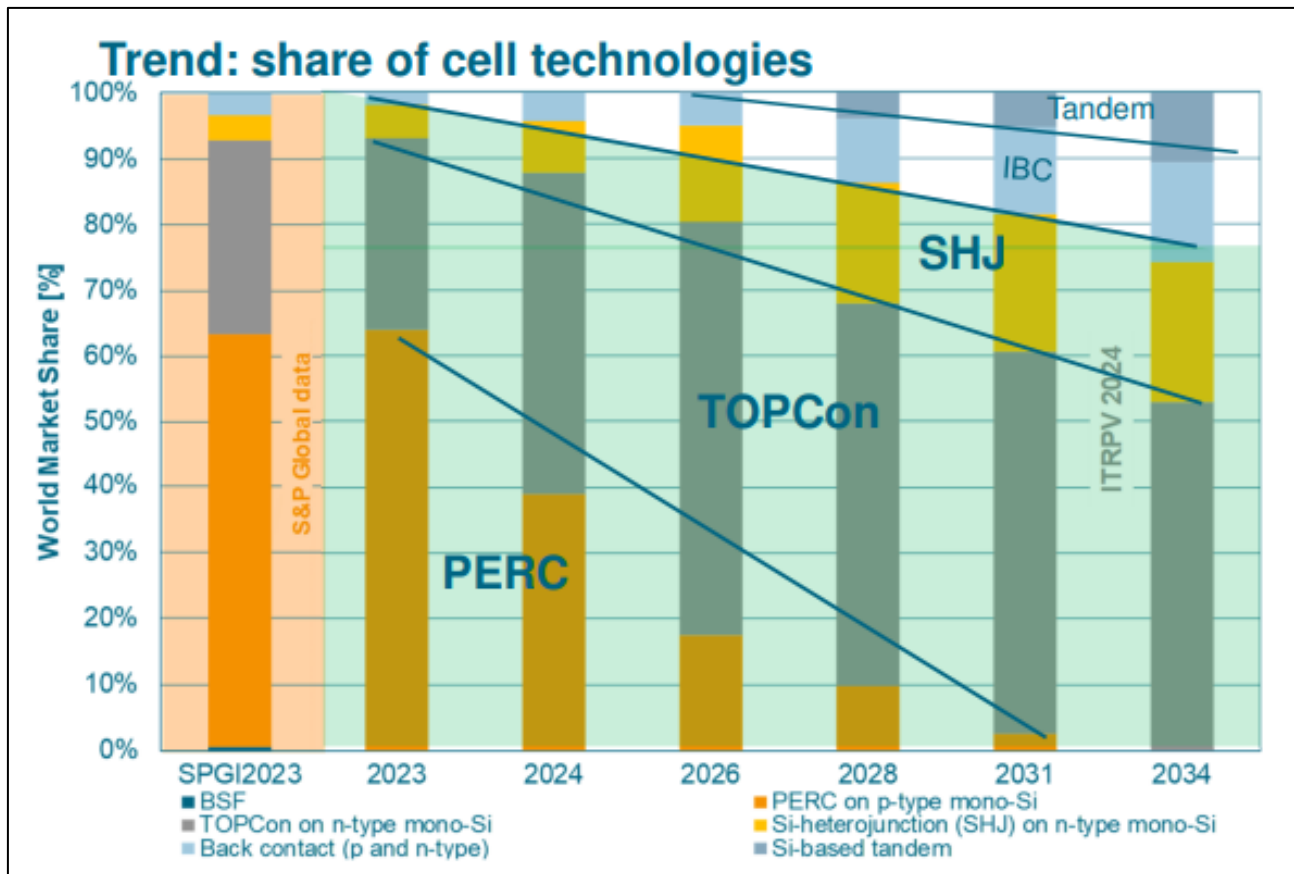


Figure 1: Projected Market Share Trends of Silicon-Based Solar Cell Technologies [10].

7. Material Usage in Silicon-Based Solar Cells

The fabrication of silicon-based solar cells involves the use of various materials, including: silver, and aluminum, which play critical roles in ensuring efficient charge collection and conductivity.

7.1 Traditional Silicon Solar Cells (BSF):

Traditional silicon solar cells rely heavily on silver for front-side contacts and aluminum for rear-side contacts. A typical cell uses approximately 100-150 mg of silver and 1-2 g of aluminum per cell.

7.2 PERC Solar Cells:

PERC cells incorporate a passivation layer at the rear surface, reducing aluminum usage to 0.8-1.5 g per cell. Silver usage remains significant, averaging 80-120 mg per cell.

7.3 PERL Solar Cells:

PERL cells feature localized doping at the rear surface, reducing silver usage to 70-110 mg per cell and aluminum usage to 0.7-1.3 g per cell.

7.4 TOPCon Solar Cells:

TOPCon cells minimize aluminum usage to 0.5-1 g per cell and reduce silver usage to 60-100 mg per cell through advanced screen-printing techniques.

The table 1 summarizing the material usage (silver and aluminum) in different types of silicon-based solar cells:

Table .1 Overview of silver and aluminum material usage in different Si based solar cell technologies:

Solar Cell Type	Silver (Usage /cell)	Aluminum (Usage /cell)	References
BSF	100-150 mg	1-2 g	[10]
PERC	80-120 mg	0.8-1.5 g	[10]
PERL	70-110 mg	0.7-1.3 g	[5], [11], [12]
TOPCon	60-100 mg	0.5-1 g	[10]

8. Environmental and Economic Implications

The use of silver and aluminium in silicon-based solar cells has significant environmental and economic implications. Silver, in particular, is a costly and finite resource, and its extensive use in solar cells contributes to the overall cost of photovoltaic systems. Reducing silver usage through advanced technologies like copper plating designs can lower production costs and enhance the sustainability of solar energy. Optimizing and exploring alternative materials are critical for achieving a sustainable and cost-effective photovoltaic industry.

9. Conclusion

Silicon-based solar cells have been instrumental in the growth of the photovoltaic industry, offering a combination of high efficiency, durability, and scalability. This article has provided an in-depth review of the technology, from its historical roots to the latest advancements in PERC, PERL, TOPCon, and emerging architectures like HJT and perovskite-silicon tandem cells. The analysis of

material usage, particularly the reliance on silver and aluminum, highlights the need for innovative approaches to reduce costs and enhance sustainability. As the world continues to prioritize renewable energy, ongoing research and development in silicon-based solar cells will be essential to meet global energy demands. By addressing material constraints and optimizing manufacturing processes, silicon-based solar cells will remain a cornerstone of the renewable energy landscape.

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