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Crystalline silicon photovoltaic technology: performance characteristics, limitations, and development perspectives

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ABSTRACT

Crystalline silicon (c-Si) photovoltaic technology is one of the most established and widely deployed approaches for direct solar-to-electricity conversion. Its development has been supported by the abundance of silicon, mature semiconductor-processing knowledge, reliable device performance, and continuous improvements in cell and module manufacturing. This review discusses the principal characteristics of monocrystalline and multicrystalline silicon solar cells, including their material properties, device structures, performance parameters, and manufacturing processes. It also examines major limitations associated with material defects, wafer production, recombination losses, temperature sensitivity, and module degradation. By 2014, advances in surface passivation, selective emitters, rear-contact designs, and silicon heterojunction structures had enabled substantial improvements in laboratory cell efficiency. Further progress will depend on balancing conversion efficiency with manufacturing cost, material utilization, module reliability, and environmental considerations.

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1. INTRODUCTION

Crystalline silicon (c-Si) photovoltaic technology has played a central role in the development of the modern solar energy industry. Its widespread adoption is supported by the availability of silicon, established semiconductor manufacturing infrastructure, and the demonstrated durability of silicon-based modules. Continuous improvements in wafer quality, cell architecture, and manufacturing processes have also enabled higher conversion efficiencies and lower production costs [1], [2]. c-Si solar cells are generally classified into monocrystalline and multicrystalline technologies according to the structure of their silicon wafers. Monocrystalline silicon consists of a single continuous crystal, whereas multicrystalline silicon contains multiple grains separated by grain boundaries. These structural differences influence material quality, carrier recombination, manufacturing requirements, and ultimately cell performance [1], [3].

This review examines the performance characteristics, limitations, and development perspectives of c-Si photovoltaic technology using literature published no later than 2014. Particular attention is given to material properties, conventional and advanced cell structures, efficiency records, and engineering challenges. The central argument is that future improvements require coordinated optimization of silicon quality, device design, manufacturing processes, and long-term module reliability.

2. MATERIALS AND DEVICE STRUCTURES

2.1. Monocrystalline and multicrystalline silicon

Monocrystalline silicon is widely used in high-performance photovoltaic cells because its relatively uniform crystal structure supports efficient charge-carrier transport. It is commonly produced using the Czochralski process, which involves growing a single-crystal ingot from molten silicon. Although this method provides high-quality material, crystal growth and wafer preparation require substantial energy, specialized equipment, and careful control of impurities [3], [4].

Multicrystalline silicon is produced by solidifying molten silicon in a controlled casting process, resulting in ingots containing multiple crystal grains. Its manufacturing route can be less demanding than single-crystal growth and has historically supported lower-cost wafer production. However, grain boundaries, dislocations, and impurity-related defects can increase carrier recombination and reduce the electrical performance of multicrystalline solar cells [3], [4].

2.2. Conventional cell architecture

The conventional c-Si solar cell typically consists of a silicon wafer with a p–n junction, front and rear electrical contacts, and surface coatings for optical and electrical optimization. The front surface is commonly textured and coated with an antireflection layer to reduce reflection losses and improve light absorption. Metallic grid fingers collect photogenerated current while allowing sunlight to reach the active semiconductor region [1], [2].

In a conventional p-type wafer cell, a phosphorus-diffused n-type emitter is formed near the front surface to create the p–n junction. The rear surface is generally equipped with an aluminum contact, often forming a back-surface field that helps reduce recombination at the rear of the wafer. This architecture has been widely adopted because it combines relatively straightforward processing with reliable electrical performance and compatibility with high-volume manufacturing [1], [2].

2.3. Advanced cell architectures

Advanced c-Si cell designs have been developed to reduce optical and electrical losses beyond the capabilities of conventional structures. Passivated emitter and rear cell (PERC) technology improves rear-surface passivation and incorporates local rear contacts, reducing recombination while enhancing light reflection within the wafer. Selective-emitter designs, meanwhile, optimize the doping profile beneath metal contacts to reduce contact resistance while maintaining good surface passivation elsewhere [5].

Other high-efficiency architectures include interdigitated back-contact (IBC) cells and silicon heterojunction (SHJ) cells. IBC devices position both electrical polarities on the rear surface, reducing front-side shading and improving optical collection. SHJ cells combine c-Si wafers with thin amorphous silicon layers to provide effective passivation and carrier-selective contacts, enabling high open-circuit voltage and improved efficiency [6], [7].

3. PERFORMANCE CHARACTERISTICS

The performance of c-Si solar cells is commonly evaluated using conversion efficiency, open-circuit voltage, short-circuit current density, and fill factor. Conversion efficiency indicates how effectively incident solar energy is converted into electrical power, while voltage and current reflect the electrical and optical properties of the device. Fill factor represents the quality of the current–voltage response and is influenced by recombination, series resistance, and shunt losses [1], [2].

c-Si has an indirect bandgap, which means that relatively thick absorber layers are needed to absorb a substantial fraction of incident sunlight. Despite this characteristic, silicon's well-understood electronic properties and the availability of effective surface-texturing and light-trapping techniques support high device performance. Its relatively stable material properties also make it suitable for long-term outdoor photovoltaic applications [1], [5].

By 2014, c-Si research cells had achieved efficiencies above 25%, demonstrating the potential of advanced passivation and contact architectures. Green *et al.* [8] reported a 25.6% independently confirmed efficiency for a large-area Panasonic heterojunction cell, while a large-area SunPower rear-junction cell achieved 25.0%. These values represent research-cell records rather than typical commercial module efficiencies, which are lower because of cell interconnection, inactive module areas, and additional optical and electrical losses.

Table 1 presents a comparison of monocrystalline and multicrystalline silicon photovoltaic technologies in terms of their structural characteristics, material quality, carrier recombination, manufacturing processes, typical performance, advantages, and limitations.

Table 2 summarizes selected c-Si research-cell efficiency records reported by 2014, highlighting the differences in efficiency and research context among the major cell technologies.

Table 1. Comparison of major c-Si photovoltaic technologies

Characteristic	Monocrystalline silicon	Multicrystalline silicon
Crystal structure	Single continuous crystal	Multiple crystal grains
Typical wafer appearance	Uniform, often dark	Grain-patterned, often blue
Material quality	Generally higher and more uniform	More variation due to grain boundaries and defects
Carrier recombination	Generally lower	Can be higher due to grain boundaries and impurities
Manufacturing route	Single-crystal ingot growth and wafering	Directional solidification and wafering
Typical performance	Generally higher cell efficiency	Generally lower cell efficiency
Main advantage	High electrical performance	Historically lower-cost wafer production
Main limitation	Crystal growth and wafering costs	Defect-related performance losses

Note: The table summarizes general technology characteristics; actual performance depends on wafer quality, cell design, and manufacturing processes.

Table 2. Selected c-Si research-cell efficiency records reported by 2014

Cell technology	Efficiency	Record context
Crystalline silicon heterojunction, rear-junction	25.6%	Panasonic; independently confirmed in 2014
Large-area crystalline silicon, rear-junction	25.0%	SunPower; independently confirmed in 2014
Conventional-contact crystalline silicon	25.0%	UNSW PERL research cell; earlier record
Multicrystalline silicon	20.4%	Independently confirmed research-cell record

Source: Green *et al.*, "Solar cell efficiency tables (version 44)," 2014 [8]. These are research-cell records, not representative commercial module efficiencies.

4. LIMITATIONS AND ENGINEERING CHALLENGES

4.1. Material quality and defects

Material quality remains a major factor governing c-Si cell performance. Impurities, dislocations, grain boundaries, and other crystallographic defects can act as recombination centers, reducing the lifetime of minority charge carriers. These effects are particularly important in multicrystalline silicon, where the distribution of defects can vary considerably within a single wafer [3], [4].

4.2. Wafer production and material consumption

Wafer manufacturing contributes significantly to the material and processing requirements of c-Si photovoltaics. Conventional wafering involves slicing silicon ingots with wire saws, which produces kerf losses and limits the amount of usable silicon obtained from each ingot. Reducing wafer thickness and minimizing material losses can lower manufacturing costs, but excessively thin wafers are more vulnerable to breakage and handling damage [2], [4].

4.3. Recombination and surface passivation

Electrical recombination at the front and rear surfaces can limit the voltage and efficiency of c-Si solar cells. Surface passivation reduces the number of electrically active defects and improves the collection of photogenerated carriers, making it essential for high-efficiency devices. However, effective passivation must be maintained during subsequent processing and throughout the module's operating lifetime [5].

4.4. Temperature and environmental effects

c-Si solar cell performance is affected by operating temperature and environmental exposure. Increasing temperature generally reduces cell voltage and conversion efficiency, although the actual effect depends on cell design and operating conditions. At module level, moisture, ultraviolet radiation, thermal cycling, and mechanical stress can contribute to corrosion, discoloration, delamination, and other degradation mechanisms [9].

4.5. Manufacturing cost and process integration

Advanced cell architectures can improve efficiency but often require additional process steps, tighter process control, or more sophisticated equipment. The economic benefit of higher efficiency therefore depends on whether the additional manufacturing cost is offset by increased power output and reduced balance-of-system costs. Industrial development must consequently consider production yield, throughput, equipment utilization, and process compatibility rather than laboratory efficiency alone [2], [10].

5. DEVELOPMENT PERSPECTIVES

Future development of c-Si photovoltaics is expected to focus on improving cell efficiency while reducing material consumption and manufacturing costs. Thinner wafers, improved crystal-growth techniques, and reduced kerf losses offer opportunities to use silicon more efficiently.

However, these improvements must be accompanied by better mechanical handling and effective surface passivation to prevent efficiency losses associated with thinner absorber layers [3]–[5].

Advanced cell architectures also provide important opportunities for further performance improvement. PERC, IBC, and silicon heterojunction designs demonstrate how improved passivation, reduced shading, and optimized electrical contacts can increase conversion efficiency. The independently confirmed 25.6% heterojunction result reported in 2014 illustrates the potential of combining c-Si with advanced contact and passivation technologies [6]–[8].

Manufacturing development should also prioritize module reliability and sustainable production. Improvements in encapsulation, interconnection, and resistance to moisture and thermal stress are necessary to maintain performance over extended operating periods. In addition, reducing energy consumption during silicon purification and wafer production, improving material utilization, and strengthening recycling practices can improve the overall environmental profile of c-Si photovoltaics [2], [9], [10].

6. CONCLUSION

c-Si photovoltaic technology remains an important platform for solar electricity generation because of its mature manufacturing processes, reliable material properties, and continuously improving cell performance. Monocrystalline silicon generally offers higher electrical performance, while multicrystalline silicon has historically provided an alternative with less demanding crystal-growth requirements. By 2014, advances in surface passivation, PERC, back-contact designs, and silicon heterojunction structures had demonstrated the potential to achieve research-cell efficiencies above 25%. Nevertheless, challenges involving wafer production, material defects, recombination losses, temperature sensitivity, and long-term module degradation remain important. Future development should therefore combine improvements in cell architecture with thinner wafers, more efficient manufacturing, better module reliability, and sustainable material utilization. Ultimately, the competitiveness of c-Si photovoltaics will depend not only on higher conversion efficiency but also on reducing the cost of electricity over the complete operating lifetime of photovoltaic systems.

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