Research Progress of Crystalline Silicon Solar Cells

Muyang Jin[a]
The College of Physics and Materials Science, Tianjin Normal University, Tianjin, China

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Abstract: Crystalline silicon solar cells have long dominated the photovoltaic market due to their high conversion efficiency, stability, and mature industrial chain. This paper systematically reviews the research progress of crystalline silicon solar cells, with a focus on analyzing the working principles and characteristics of Passivated Emitter and Rear Contact (PERC) cells, Silicon Heterojunction (SHJ) cells, Tunnel Oxide Passivated Contact (TOPCon) cells, and Metal Oxide Selective Contact cells. It is found that PERC significantly reduces recombination losses through localized backside contacts. SHJ achieves full-area passivation by utilizing amorphous silicon and crystalline silicon heterojunctions. TOPCon combines ultra-thin oxide layers with doped polycrystalline silicon, offering both high passivation and process compatibility. Metal oxide selective contact technology simplifies doping processes through band engineering, but interface stability still needs improvement. Despite the efficiency improvements brought by these technologies, they still face challenges such as the high purity requirement of n-type silicon substrates for SHJ, the uniformity control of ultra-thin oxide layers in TOPCon, and the adhesion of metal oxide interfaces. High material costs, process complexity, long-term reliability, and the consistency of large-scale production remain challenges. Future research should further balance efficiency and cost, develop new passivation materials, optimize interface engineering, and promote the efficient transition of technologies to industrialization, to support the sustainable development of the photovoltaic industry.

1 INTRODUCTION

Crystalline silicon solar cells have a series of advantages such as high efficiency, good stability and low cost, and they occupy a dominant position in the solar cell industry (Xiong & Zhu, 2009). The basic principle of solar cells is the photovoltaic effect. When incident light with energy greater than the band gap width irradiates the p-n junction, electron-hole pairs are excited in the junction area and the space near the junction. Under the action of the junction electric field, the electron-hole pairs separate and drift to form photogenerated current. Through calculation, it can be obtained that the theoretical conversion efficiency limit of the solar spectrum of AM1.5 is 33%, and the corresponding optimal band gap is 1.4 eV.

Since the first single-crystal silicon solar cell with an efficiency of 6% was developed by Bell Labs in 1954, crystalline silicon technology has undergone multiple technological iterations (Zhang et al., 2021). In the 1980s, the aluminum back surface field (BSF) cell increased its efficiency to 17%-18% through a full aluminum back electrode design. After 2000, the passivated emitter and rear locally diffused contact (PERC) cell broke through the efficiency bottleneck with a rear point contact passivation technology, achieving a laboratory efficiency of over 24% and quickly becoming the mainstream commercial technology. In recent years, silicon heterojunction (SHJ) and tunnel oxide passivated contact (TOPCon) technologies have further pushed the laboratory efficiency above 26%, gradually approaching the theoretical efficiency limit of crystalline silicon of 29% (Green et al., 2023; Yoshikawa et al., 2017; Feldmann et al., 2019). Currently, high-efficiency new crystalline silicon solar cells mainly include passivated emitter solar cells, silicon heterojunction solar cells, tunnel oxide passivated contact solar cells, and metal oxide selective contact solar cells.

However, how to continuously improve efficiency through material innovation and structural optimization, while reducing manufacturing costs and

[a] https://orcid.org/0009-0009-2254-941X

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ensuring long-term reliability, remains the core challenge in current research. This article mainly introduces the recent application research progress of crystalline silicon solar cells. The aim is to focus on the core principles, efficiency improvement strategies, and industrialization bottlenecks of PERC, SHJ, TOPCon, and metal oxide selective contact technologies.

2 CHARACTERISTICS OF CRYSTALLINE SILICON

Crystalline silicon is an indirect bandgap semiconductor with a bandgap of 1.12 eV, which is close to the optimal bandgap of 1.4 eV. The theoretical conversion efficiency limit of its cells is 29% (Zhang et al., 2021). Among them, monocrystalline silicon and polycrystalline silicon are the two main types. Monocrystalline silicon is composed of a single crystal, with a continuous and ordered lattice, high carrier mobility, and excellent photoelectric conversion efficiency. However, its production cost is relatively high. Polycrystalline silicon contains multiple grains, with increased carrier recombination at grain boundaries, resulting in slightly lower efficiency. However, its production process is simple and the cost is low, making it suitable for large-scale application. Both have their own advantages, respectively meeting the requirements of high efficiency and cost-effectiveness.

Furthermore, crystalline silicon has high mechanical strength and is suitable for large-scale production. However, it is sensitive to impurities and requires doping processes to optimize its electrical properties. For example, n-type silicon with phosphorus doping and p-type silicon with boron doping. Typically, single-crystal silicon rods required for solar cells are prepared using melt pull technology and suspension zone melting technology.

The development of crystalline silicon solar cell technology is leading the trend of photovoltaic power generation. From the perspective of scientific development, improving the photoelectric conversion efficiency of crystalline silicon solar cells, reducing light attenuation, and lowering the cost of power generation are the directions for the future development of crystalline silicon solar cells. The continuous progress in the quality of crystalline silicon materials and the design of battery structures will be the key to achieving these goals. (Yang, 2014)

3 HIGH-EFFICIENCY CRYSTALLINE SILICON SOLAR CELLS

3.1 Passivated Emitters Solar Cell

The Passivated Emitters Solar Cell (PESC) was proposed in 1985. The structure of the cell is shown in Figure 1.

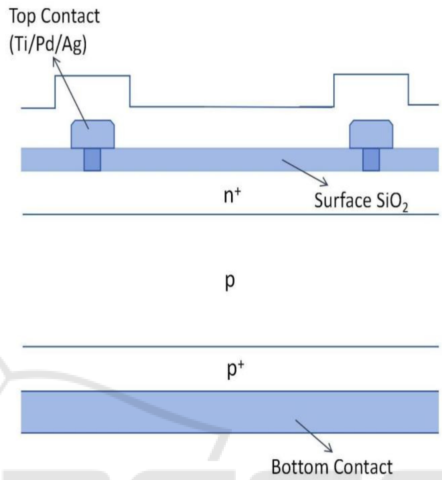

Figure 1: PESC solar cell structure(Xiong & Zhu, 2009)

Passivated emitter and rear local contact (PERC) cells use back-point contact instead of the entire aluminum rear field. The recombination on the back surface decreases with the reduction of the back electrode area, but the existence of "edge effect" makes the recombination larger in small-pitch and small-contact-point patterns under the same electrode area ratio (Shen & Li, 2014).

Passivated emitter and rear surface localized diffusion (PERL) cells are representative of high-efficiency crystalline silicon cells. The substrate material of this cell is a single-crystal silicon wafer fabricated by zone melting, with low resistivity, p-type boron doping, (100) crystal orientation, a diameter of 5 ㎝, and a thickness of 280 μm, and double-sided polished (Li et al., 2019). Its core lies in reducing carrier recombination through surface passivation technology and combining selective doping to improve contact performance. The front of the PERL cell adopts a "inverted pyramid" textured structure, reducing light reflection to below 5%, as shown in Figure 2.

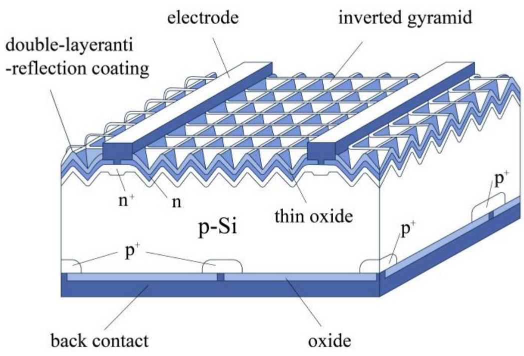

Figure 2: PERL battery structure(Zhang et al., 2021)

The passivated emitter and rear surface full diffusion (PERT) cell structure retains the characteristics of PERL while adding a light boron diffusion layer along the entire rear surface of the cell, providing a low-resistance path. However, PESC cells still have limitations such as complex high-temperature processes, difficulties in fully passivating metal oxides and silicon interface defects, material stability affected by the environment, and difficulties in controlling large-area uniformity, which restrict their industrial application.

3.2 Silicon Heterojunction Solar Cells

In 1991, Sanyo Corporation of Japan first proposed a structure that combines monocrystalline silicon and amorphous silicon films and inserts a thin intrinsic layer in the middle, namely the silicon-based hetero junction solar cell SHJ (silicon hetero junction) with an intrinsic layer, as shown in Figure 3.

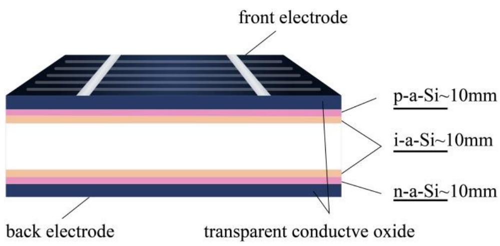

Figure 3: SHJ battery structure(Zhang et al., 2021)

SHJ batteries have the advantages of full-area passivation characteristics, low-temperature process compatibility, and double-sided power generation. By using high-quality N-type silicon substrates, both bulk recombination and interface recombination of the battery have been effectively controlled. As a result, the open-circuit voltage of SHJ batteries is much higher than that of conventional batteries, and a higher photoelectric conversion efficiency can be achieved (Li et al.,2019). In addition, the temperature rise coefficient of SHJ batteries is low, making them suitable for high-temperature environments. In recent years, SHJ batteries have made remarkable progress in efficiency improvement, process optimization and industrial application. In 2023, domestic research teams increased the efficiency to 26.8% by optimizing the interface passivation and the transparent conductive oxide (TCO) layer (Li X et al.,2023).

Despite significant progress, SHJ batteries still face multiple challenges. For example, high manufacturing cost, photoinduced attenuation (LID), and the need for optimization of the TCO layer, etc.

3.3 Tunnel Oxide Passivated Contact (TOPCon) Solar Cells

The tunneling oxide layer passivation contact (TOPCon) technology has been a research hotspot in recent years. Firstly, a layer of ultrathin silicon oxide is prepared on the back of the battery by chemical methods, and then a thin layer of doped silicon is deposited, as shown in Figure 4.

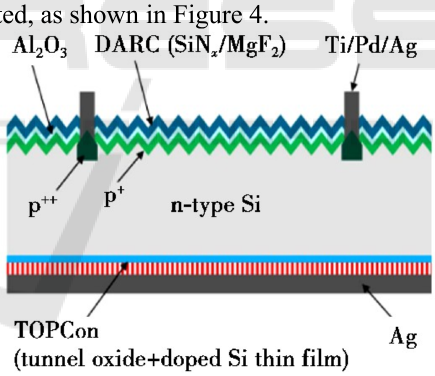

Figure 4: TOPCon solar cell structure(Chen et al., 2019)

According to the doping type of the silicon thin layer, it is divided into p-TOPCon and n-TOPCon. Silicon oxide reduces the surface state and lowers the tunneling resistance. Doped polycrystalline silicon provides field-induced passivation. Together, the two form a passivation contact structure, providing good surface passivation for the back of the silicon wafer (Fu et al., 2012).

Tunneling oxide passivated contact (TOPCon) solar cells have advantages such as high passivation performance, process compatibility, and material optimization. In recent years, atomic layer deposition (ALD) technology has been used to prepare uniform and dense silicon oxide layers with thickness control accuracy reaching the sub-nanometer level. Meanwhile, the in-situ doping of polycrystalline silicon technology has improved the carrier mobility (Ding et al.,2021). In 2023, a Chinese research team further increased the efficiency to 26.5% by optimizing the doping concentration of polysilicon and the interface passivation process (Wang et al.,2023). The TOPCon structure combines excellent surface passivation effect with low contact electricity. Its process is compatible with existing production lines and is regarded as the mainstream direction of the next-generation high-efficiency batteries.

With the advancement of technology, there are still some challenges. For instance, enhancing the uniformity of the oxide layer, improving the doping process of polysilicon, and controlling costs, etc.

3.4 Selective Contact of Metal Oxides

Metal oxides achieve efficient and stable selective carrier transport through band engineering, interface passivation and optical synergy. Efficient carrier selective contact is the key to improving the efficiency of solar cells, but heavy doping can have adverse effects on the open-circuit voltage, short-circuit current and blue light response of the cells. The selective contact technology of metal oxides achieves efficient separation and collection of carriers through band engineering. Transition metal oxides (MoOx, WOx, V2Ox, CrOx, CuOx), graphene, carbon nanotubes, etc. All materials with high work functions and hole transport capabilities can be attempted as hole transport layers (HTL), which can passivate the interface and reduce the contact resistance (Yu,2019). The core of the selective contact technology of metal oxides lies in material innovation and the improvement of interface stability. Take MoO_3 as an example. As a hole transport layer, it can replace the traditional doping process, simplify the production steps and improve the mechanical reliability of the components. Studies have shown that MoO_3 has a wide band gap (3.0-3.6 eV) and a high work function (5.3-5.7 eV), which enables it to exhibit excellent hole selectivity in perovskite and silicon heterojunction solar cells (Wang et al., 2019). However, the interface adhesion and long-term stability still need to be further optimized.

4 DEVELOPMENT DIRECTIONS

Passivated emitter batteries, as the current mainstream technology, have an efficiency close to the industrialization limit of 24%. In the future, the focus will be on suppressing photoinduced decay (LID) and further reducing costs. The development of new hydrogen passivation processes (such as laser-assisted hydrogen injection) can reduce the center density of boron-oxygen recombination and extend the service life of components (Chen Z et al.,2021).

The future of silicon heterojunction cells (SHJ) lies in cost reduction, efficiency improvement and enhanced adaptability to multiple scenarios. The cost can be reduced by adopting low-purity N-type silicon-based and amorphous silicon coating process optimization (Masuo et al.,2022). SHJ and perovskite tandem technology demonstrated an efficiency potential of over 30%. In 2023, the research team achieved a laboratory efficiency of 28.5% through interface band engineering (Al-Ashouri et al.,2020)

The development direction of tunneling oxide passivated contact cells (TOPCon) lies in process simplification and breaking through the efficiency limit. Research in 2022 showed that double-sided passivated contact could increase laboratory efficiency to 26.8%(Wang et al.,2022). The core of selective contact technology for metal oxides lies in material innovation and the improvement of interface stability, reducing carrier recombination by optimizing the band structure and interface passivation. In recent years, the contact technology of undoped metal oxides has become a research hotspot. For example, the WO3 layers prepared by the all-solution method not only exhibit excellent hole selectivity and high light transmittance, but also can avoid the high-temperature doping process, significantly simplify the preparation process and reduce the production cost (Zhang et al., 2022). In addition, new binary oxides and ternary oxides (such as MoOx, VOx and NiOx) have achieved battery efficiency of more than 20% through band regulation, while the application of atomic layer deposition technology (ALD) has further enhanced the accuracy of interface passivation. In the future, the development of metal oxide materials that can be processed at low temperatures and are environmentally stable will become the key to promoting industrialization.

5 CONCLUSION

Crystalline silicon solar cells enhance their conversion efficiency by reducing the reflection of incident light by the cells and minimizing the recombination loss of photogenerated carriers within the cells. On this basis, solar cells have developed types such as passivated emitter cells, silicon heterojunction solar cells, and TOPCon solar cells. Through passivation optimization, structural innovation and material engineering, the laboratory efficiency has been pushed up to 26%-28%.

Despite significant progress, there are still challenges such as the balance between cost and efficiency, material and process innovation, and consistency in large-scale production. Selective contact of undoped metal oxides has become a new development direction. PERC is limited by photoinduced attenuation and the reliability of the thinning process. SHJ needs to reduce the cost of N-type silicon-based coatings and the complexity of amorphous silicon coating. TOPCon needs to solve the uniformity of the oxide layer and the accuracy of the doping process. Metal oxide technology needs to break through interface stability and consistency in scale.

By breaking through the efficiency limit through layering technology, green manufacturing and intelligent process innovation have become new development directions. Through multi-technology collaborative innovation and vertical integration of the industrial chain, crystalline silicon cells are expected to achieve a balance among efficiency, cost and sustainability, accelerating the progress of the global photovoltaic industry.

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