Advanced Materials Science and Technology Vol 7 Issue 2 2025

Original Research Article

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Performance Optimization of Crystalline Silicon Solar Cells Based on a Novel Passivated Contact Structure

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Funding project: This study was supported by the Sichuan Provincial Science and Technology Achievement Transfer and Transformation Demonstration Project (Grant No. 2024ZHCG0132).
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Abstract: With the global energy transition and the advancement of the "dual-carbon" targets, photovoltaic power generation, as one of the major clean and renewable energy sources, has placed increasing emphasis on improving the efficiency and reducing the cost of its core device—the crystalline silicon solar cell. On the basis of the currently mainstream Passivated Emitter and Rear Cell (PERC) technology, further breakthroughs in efficiency are urgently required to overcome existing performance bottlenecks, which calls for innovative optimization of passivated contact structures. This study focuses on a novel passivated contact structure based on a silicon oxynitride (SiO_xN_γ) composite dielectric passivation layer, and systematically presents its design principles, fabrication processes, performance characterization, and industrial-scale verification. The results demonstrate that by introducing multilayer composite passivation and anti-reflection films on both the front and rear sides of the cell—particularly by exploiting the combined advantages of silicon oxynitride, which integrates the excellent anti-reflection properties of silicon nitride (SiN_x) with the superior field-effect passivation capability of silicon dioxide (SiO_2)—the surface recombination velocity can be effectively reduced, minority carrier lifetime enhanced, short-wavelength spectral response improved, and long-wavelength reflection mitigated. Experimental results indicate that this novel structure can achieve an absolute conversion efficiency gain of more than 0.1% on conventional monocrystalline PERC production lines, while simultaneously improving reliability parameters such as resistance to potential-induced degradation (PID). This work provides a practical and feasible technological pathway for breaking the efficiency limits of crystalline silicon solar cells and achieving cost reduction and performance enhancement in industrial applications.

Keywords: crystalline silicon solar cells; PERC; passivated contact; silicon oxynitride; composite passivation anti-reflection film

Introduction

Against the backdrop of global efforts to address climate change and energy security challenges, renewable energy sources such as solar energy have experienced rapid growth. As the core technology of the photovoltaic industry, crystalline silicon solar cells dominate more than 95% of the market due to their technological maturity, complete industrial chain, and continuously decreasing costs. Since large-scale industrialization, PERC cells have achieved mass-production efficiencies approaching their theoretical limits. However, driven by the urgent market demand for higher-power modules and the advent of the "grid parity" era, further exploiting efficiency potential and reducing non-silicon costs within existing PERC technology have become focal points of competition among enterprises. The core of PERC technology lies in its rear-side passivation structure. Nevertheless, conventional structures exhibit inherent limitations: the tensile stress of SiN_x protective films can easily cause wafer warpage; stacked rear structures provide limited reflection enhancement for long-wavelength solar radiation, thereby constraining improvements in short-circuit current; and the passivation performance of front-side SiN_x anti-reflection coatings still has room for improvement, making it difficult to simultaneously achieve optimal optical and electrical performance [1]. Therefore, the development of novel passivated contact structures compatible with existing production lines is of critical importance. In this context, silicon oxynitride (SiO_xN_γ), owing to its unique material properties, has attracted increasing attention. Introducing SiO_xN_γ into both the front and rear sides of PERC cells is expected to enable the construction of a more advanced passivated contact system.

1. Experimental Methods

1.1 Experimental Equipment and Materials

This study was conducted on a complete pilot-scale PERC solar cell production line, equipped with 342 sets of advanced R&D and characterization instruments, including atomic layer deposition (ALD) systems, tube-type PECVD systems, laser selective emitter (SE) equipment, rear-side laser grooving systems, in-line electroluminescence (EL) testers, a WCT-120 minority carrier lifetime measurement system, and an SE800 spectroscopic ellipsometer. The experimental substrates were standard p-type monocrystalline silicon wafers with dimensions of 158.75 mm × 158.75 mm, resistivity of 1–3 Ω•cm, and a thickness of approximately 160 μm.

1.2 Solar Cell Fabrication Process

The entire fabrication process was optimized based on the conventional PERC process. The detailed steps are described as follows.

1.2.1 Front-Side Processes

P-type silicon wafers were sequentially subjected to alkaline texturing, $POCl_3$ diffusion to form the n^+emitter, laser selective emitter (SE) doping, alkaline polishing etching to remove phosphorus silicate glass (PSG) and achieve edge isolation, followed by annealing.

1.2.2 Deposition of Rear-Side Al_2O_3 Passivation Layer

An ALD system was employed to deposit a high-quality Al_2O_3 passivation layer at a low temperature of 70 °C. Ozone (O_3) and trimethylaluminum (TMA) were used as precursors, with 25 pulse cycles, resulting in an Al_2O_3 layer thickness of 2–7 nm.

1.2.3 Deposition of Front-Side Composite Passivation and Anti-Reflection Films

A tube-type PECVD system was used to sequentially deposit four layers:

(1) The first SiN_x layer (adjacent to the silicon surface), deposited with a high silane flow rate and rich hydrogen content to enhance passivation;

(2) The second SiN_x layer, optimized in refractive index and serving as the main anti-reflection layer;

(3) A SiO_xN_γ layer, introduced to improve overall optical matching and reduce short-wavelength reflection;

(4) An outermost SiO_2 layer with high density, which effectively suppresses hydrogen out-diffusion and enhances long-term passivation stability.

1.2.4 Deposition of Rear-Side Composite Passivation/Reflection Films

Using the same PECVD system, a five-layer stack was deposited on the rear side:

(1) A SiN_x layer directly on top of the Al_2O_3, acting as a critical protective layer to prevent plasma damage to Al_2O_3 during subsequent N_2O-based processes;

(2) A SiO_2 layer with a large refractive index contrast, forming an efficient long-wavelength reflector;

(3) Three additional SiN_x/SiO_2 layers to provide further passivation, protection, and color adjustment, resulting in a light-yellow appearance of the finished cells.

1.2.5 Rear-Side Laser Grooving

Precise local openings were formed using a circular laser spot with a diameter of 35 μm and a power of 20 W, creating contact windows for the formation of a local back surface field (LBSF).

1.2.6 Metallization and Firing

Front silver paste, rear silver paste, and aluminum paste were screen-printed, followed by high-temperature firing with a peak temperature of approximately 780 °C to form stable ohmic contacts.

1.2.7 Electrical Injection (LeTID Suppression)

A nine-zone electrical injection furnace was employed to perform regeneration treatment at temperatures ranging from 100 to 220 °C, effectively suppressing light- and elevated-temperature-induced degradation (LeTID).

1.3 Performance Characterization Methods

(1) Electrical performance: A Berger IV tester was used to measure key parameters, including conversion efficiency (η), open-circuit voltage (Uoc), short-circuit current (Isc), and fill factor (FF).

(2) Minority carrier lifetime: A WCT-120 microwave photoconductive decay (μ-PCD) system was used to evaluate bulk minority carrier lifetime and surface passivation quality [2].

(3) Optical properties: Reflectance was measured using a spectrophotometer, and internal/external quantum efficiency (IQE/EQE) was obtained using a QE/IPCE measurement system.

(4) Film characterization: Film thickness and refractive index were determined using an SE800 spectroscopic ellipsometer.

(5) Reliability testing: PID (−1000 V, 85 °C, 85% RH, 96 h) and damp heat (DH, 85 °C, 85% RH, 1000 h) tests were conducted strictly in accordance with IEC standards.

(6) Microstructure and composition: Laser-grooved morphologies were observed by scanning electron microscopy (SEM), and elemental distributions were analyzed by energy-dispersive spectroscopy (EDS).

2. Results and Discussion

2.1 Film Structure Design and Optical Simulation

Optical simulations of the multilayer film stacks were performed using both the vector method and the transfer matrix method, on the basis of which composite film structures for the front and rear sides were designed. The front-side structure adopts a refractive-index–graded configuration, ensuring a smooth optical transition from air to the silicon substrate. This design effectively broadens the anti-reflection bandwidth, with the reflectance in the short-wavelength region of 350–500 nm being significantly lower than that of a conventional single-layer SiN_x film. Owing to the multilayer gradient refractive index design, incident light undergoes multiple destructive interference events at different film interfaces, thereby achieving a lower average reflectance across the entire visible and near-infrared spectral ranges.

Meanwhile, the rear-side structure emphasizes the incorporation of a SiO_2 layer. By exploiting the large refractive index contrast between SiO_2 and SiN_x (≈1.46 vs. ≈2.1), an efficient distributed Bragg reflector (DBR) is constructed. This reflector provides strong reflection for long-wavelength light with wavelengths exceeding 1000 nm, forcing such photons to undergo secondary absorption within the silicon bulk. As a result, the generation of photogenerated carriers is effectively increased, laying a solid optical foundation for the enhancement of short-circuit current density [3]. This front–rear synergistic optical management strategy is a key factor in achieving a comprehensive improvement in overall cell performance.

2.2 Process Feasibility and Key Technological Breakthroughs

The most significant process breakthrough of this study lies in successfully addressing the long-standing challenge of Al_2O_3 degradation caused by N_2O plasma etching. In conventional process concepts, the direct deposition of N_2O-containing SiO_xN_γ or SiO_2 films onto Al_2O_3 results in irreversible physical and chemical damage due to high-energy oxygen plasma, thereby severely impairing the surface passivation capability of Al_2O_3 and ultimately leading to pronounced efficiency losses in solar cells. To overcome this common industrial bottleneck, a dense and chemically stable SiN_x thin film was first deposited on top of the Al_2O_3 passivation layer, serving as the initial passivation layer, i.e., a protective layer. This SiN_x layer plays a critical role as a physical barrier, effectively isolating the underlying Al_2O_3 from direct bombardment and chemical erosion by high-energy oxygen plasma during subsequent PECVD processes. Both spectroscopic ellipsometry measurements of film thickness and minority carrier lifetime test results provide strong evidence for the effectiveness of this protection mechanism. After introducing the protective layer, the structural integrity of the Al_2O_3 film and its excellent passivation performance were fully preserved, regardless of whether SiO_xN_γ or SiO_2 layers were subsequently deposited. It is precisely this key process innovation that enables the flexible and reliable application of high-performance composite dielectric materials such as SiO_xN_γ on the rear side of PERC solar cells, thereby paving the way for further performance optimization.

2.3 Electrical and Optical Performance Analysis

Multiple rounds of trial production, ranging from small-scale to medium-scale batches, consistently demonstrate that solar cells incorporating the novel passivated contact structure exhibit a stable absolute conversion efficiency gain of approximately 0.1% compared with baseline cells fabricated on the same production line. To gain deeper insight into the origin of this efficiency improvement, a detailed decomposition of the electrical parameters was performed. The results indicate that the efficiency enhancement primarily arises from the synergistic improvement of short-circuit current (Isc) and open-circuit voltage (Uoc). Specifically, the average Isc of the experimental cells increased by approximately 50 mA, which can be directly attributed to their superior optical management capability. The external quantum efficiency (EQE) spectra clearly show a pronounced enhancement in the short-wavelength region of 350–500 nm for the experimental cells, resulting from the effective capture of short-wavelength photons by the front-side multilayer composite anti-reflection coating. Meanwhile, a obvious improvement is also observed in the long-wavelength region of 1000–1200 nm, providing direct evidence of the effective function of the rear-side high-efficiency distributed Bragg reflector. On the other hand, the slight increase in Uoc reflects a reduction in internal recombination losses. This observation is fully consistent with the results of minority carrier lifetime measurements obtained by microwave photoconductive decay (μ-PCD), which show that the experimental cells generally exhibit longer minority carrier lifetimes than the baseline cells. These results confirm the excellent effectiveness of the novel passivated contact structure in suppressing both surface and bulk carrier recombination [4]. In addition, the fill factor (FF) remains stable or even shows a slight increase, indicating that the newly introduced film stack and associated processes do not adversely affect the contact properties or series resistance of the cells, thereby ensuring the integrity of their output characteristics.

2.4 Reliability and Yield Performance

In addition to the improvement in core electrical performance, the novel passivated contact structure also demonstrates outstanding performance in terms of product reliability and manufacturing yield. Statistical analysis of multiple mass-production batches shows that the electroluminescence (EL) yield of cells fabricated using the new process reaches 98.11%, which is even higher than the 97.44% yield of the baseline cells produced on the same line during the same period. This result clearly indicates that the new process exhibits high stability and reproducibility and can be seamlessly integrated into existing large-scale production systems without posing risks to normal line operation or throughput. More importantly, under stringent reliability testing, the cells with the novel structure outperform the baseline products. In potential-induced degradation (PID) tests simulating real power plant operating conditions (−1000 V, 85 °C, 85% RH, 96 h), the experimental cells exhibit significantly lower power degradation than the baseline cells. This advantage is attributed mainly to two factors: first, the outermost dense SiO_2 or SiO_xN_γ layer provides excellent barrier properties against moisture and harmful species such as sodium ions, effectively retarding their penetration into the cell interior; second, the overall improvement in passivation quality enhances the cell's resistance to interface state variations induced by ionic migration. Furthermore, in mechanical and environmental durability tests—including 3M tape adhesion, boiling water, and tensile strength tests—the cells with the novel structure perform exceptionally well, with all indicators meeting or exceeding industry standards. These results provide strong assurance for their long-term stable outdoor power generation.

3. Conclusions

This study successfully develops and validates a novel passivated contact structure based on a silicon oxynitride (SiO_XN_Y) composite dielectric passivation layer for performance optimization of crystalline silicon PERC solar cells. Through innovative multilayer film structure design and key process integration—particularly the Al_2O_3 protection strategy—this approach effectively overcomes several intrinsic bottlenecks of conventional PERC technology. Experimental results demonstrate that, without a significant increase in manufacturing cost, the proposed technology can:

(1) Enhance photoelectric conversion efficiency: An absolute efficiency gain of more than 0.1% is achieved on mass-production lines, mainly attributed to the synergistic improvement of Isc and Uoc.

(2) Improve optical management: Multilayer film designs optimize anti-reflection over the full solar spectrum while enhancing long-wavelength reflection.

(3) Enhance product reliability: Key reliability indicators, such as resistance to potential-induced degradation (PID), are significantly improved.

(4) Maintain high yield: The process is highly compatible with existing production lines, achieving mass-production yields superior to baseline levels.

Overall, this work provides a practical and scalable technical solution for further efficiency enhancement and cost-effective industrial advancement of crystalline silicon solar cells.

References

[1] Zhang, T. J., Qu, X. Y., Guo, Y. G., et al. Crystalline silicon solar cell technology based on POLO passivated contact structures and its research progress[J]. Journal of Synthetic Crystals, 2022, 51(06): 1122–1131 + 1140.

[2] Guo, X. Q. Preparation, characterization, and application of p-type polysilicon passivated contact structures based on different silicon oxide interlayers[D]. Chengdu University of Technology, 2020. DOI: 10.26986/d.cnki.gcdlc.2020.000833.

[3] Luo, Y. E. Research on passivated contact crystalline silicon solar cells and interface modulation[D]. Zhejiang Normal University, 2025. DOI: 10.27464/d.cnki.gzsfu.2025.000700.

[4] Zhang, T., Liu, D. W., Yang, L., et al. Influence of crystalline silicon surface morphology on passivated contact solar cells[J]. Power Technology, 2023, 47(11): 1490–1494.