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Optimization strategies for metallization in n-type crystalline silicon TOPCon solar cells: Pathways to elevated fill factor and enhanced efficiency

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A R T I C L E I N F O

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A B S T R A C T

In advancing photovoltaic technology, optimizing the metallization process is crucial for balancing electrical conductivity and optical performance in solar cell fabrication. This process directly impacts the efficiency and quality of solar cells, traditionally measured by the fill factor (*FF*). Historically, efforts have focused on evolving metal contacts to reduce optical shading and series resistance, which degrade solar cell efficiency. Our study enhances n-type Tunnel Oxide Passivated Contact (*n-TOPCon*) solar cells by optimizing screen-printing metallization, particularly by examining the effects of squeegee speeds. Employing a mix of experimental and analytical methodologies, we aimed to identify optimal conditions that improve electrical and optical performance, thereby elevating cell efficiency. Our findings indicate that a squeegee speed of 170 mm/s substantially boosts solar cell performance, evidenced by a current density (J_{sc}) of 38.96 mA/cm^2, open-circuit voltage (V_{oc}) of 684.29 mV, fill factor (*FF*) of 78.77 %, and a power conversion efficiency (*PCE*) of 21.00 %. Further, dark I–V measurements confirmed a shunt resistance (R_{sh}) of 6.25×10^6 Ω and a reduced series resistance (R_s) of 6.48 Ω, underscoring the significance of precise metallization in reducing resistive losses and enhancing efficiency. Future research will explore innovative materials and cutting-edge printing techniques beyond squeegee speed adjustments. The potential incorporation of nanomaterials and conducting polymers aims to refine the metallization process further, promising to push the boundaries of efficiency and cost-effectiveness. This progression is essential for advancing n-TOPCon solar cell development, setting new industry standards, and propelling the sustainable energy movement.

1. Introduction

Solar cell technology stands as a beacon of Progress in the quest for renewable energy sources, with n-TOPCon solar cells emerging as a prominent figure due to their superior efficiency and durability [1]. These cells are a breakthrough in PV technology, offering a sustainable alternative to traditional energy sources [5]. The stage in manufacturing these advanced solar cells is the metallization process, which involves the strategic application of metal contacts onto the cell surface [2]. This stage is critical for harnessing and conducting solar energy effectively, intending to minimize the absorption of sunlight by the metal contacts themselves. Thus, The metallization process directly impacts the solar cell's overall efficiency and operational reliability [3]. The paradox in solar cell metallization lies in the necessity of metal contacts for electrical conduction versus their potential to obstruct solar irradiance and escalate series resistance, adversely affecting the solar cell's power conversion efficiency [4,5]. Achieving an optimal balance between these cells' electrical conductivity and optical transparency is imperative. The fill factor, a key metric of solar cell quality, is a gauge for this balance, indicating the efficiency with which a solar cell converts light

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into electricity [6–9]. Our investigation delves into optimizing the metallization process of n-TOPCon solar cells, focusing on the effect of different squeegee speeds 170 mm/s, 100 mm/s, and 30 mm/s on the quality of metallization [10,11]. This research is motivated by the premise that variations in squeegee speed during the screen printing of silver paste have a pronounced impact on the formation of metal contacts [12]. These contacts are crucial for the cell's efficiency, as they influence both the uniformity of metal deposition and the electrical properties of the contacts [13].

By examining the relationship between squeegee speed and its consequent effects on the metallization quality, the study aims to unearth the conditions that lead to the enhancement of n-TOPCon solar cell performance. The empirical analysis of this research reveals that a reduced squeegee speed significantly improves solar cell performance metrics [14,15]. This outcome suggests that lower squeegee speeds facilitate the creation of more precise and uniform metal contacts, thereby reducing shading and series resistance while enhancing the cell's light absorption capability. Moreover, dark I–V measurements crucial for detecting performance impediments indicate a shunt resistance of $6.25 \times 10^6\ \Omega$ and a series resistance of 6.48 Ω, further supporting the enhanced performance achieved through optimized metallization. These findings illuminate the significance of meticulously calibrated metallization parameters in realizing the full potential of n-TOPCon solar cells. The study highlights the influence of squeegee speed on metallization quality and sets a benchmark for future research to refine the fabrication processes of advanced solar cells [16,17]. By contributing to the body of knowledge on solar cell manufacturing, this research paves the way for future advancements in photovoltaic technology, underscoring the critical role of optimized metallization in the quest for high-efficiency solar cells [18].

Screen printing is a widely used and versatile technique with a long history, not only in textile and poster printing but also in the production of various electronic devices such as thin-film transistors, displays, touch panels, low-temperature cofired ceramic devices, and photovoltaic cells [34]. Almost all commercial silicon solar cells are now metalized through screen printing, making this method a crucial factor in recent efficiency improvements with high throughput. To reduce the width and increase the aspect ratio and uniformity of the finger lines forming silicon solar cells' front or back contacts. These efforts aim to enhance cell efficiency and reduce silver consumption. Fig. 1 ideally, electrodes should be narrow in width, thick in shape, and low in resistance, which

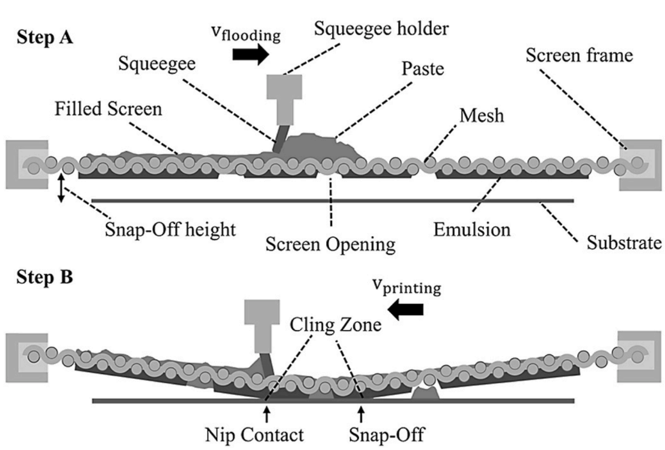

Fig. 1. The screen-printing process for solar cell metallization involves two key steps: In step A, a squeegee moves across a screen at a certain angle and velocity, pushing metallic paste into the mesh. In step B, the squeegee, moving at a printing speed and under constant pressure, presses the screen onto the substrate, allowing the paste to transfer through the screen openings onto the substrate. After the squeegee passes, the screen lifts, leaving the metallic structure on the substrate. This process is critical for creating precise metallic contacts for solar cell efficiency [18].

is challenging. In the manufacturing process of solar cells, the metallization stage typically uses a single printing method that employs a screen printer. Research has explored using nickel, copper, and silver-wired electrodes, showing steady Progress in minimizing optical and electrical losses caused by the electrodes. The screen-printing process is influenced mainly by four factors: screen mesh, paste material, screen-printing adjustment, and curing temperature [35]. Achieving the desired properties for electrodes through screen printing is primarily affected by the discharge of paste, controlled by the snap-off distance (the space between the sample and screen mesh) and the pressure and speed of the squeegee. These factors are crucial in attaining the optimal metallization for high-efficiency solar cells. The screen-printing process uses Ag/Al paste on the front side, and Ag paste on the cell's back.

Metallization involved critical parameters such as paste composition, curing temperatures at 790 °C, and specific screen mesh types. We thoroughly analyzed how these parameters would perform in a large-scale manufacturing environment to ensure the industrial applicability and scalability of the proposed optimization parameters. The optimized squeegee speed of 170 mm/s and snap-off distance of 1.4 mm, which showed significant improvements in small-scale experimental setups, need to be validated for mass production. In a large-scale setting, maintaining uniform squeegee speed and snap-off distance across multiple cells can present challenges due to variations in equipment calibration and material properties [36]. Therefore, implementing advanced automation and control systems is essential to replicate the precise conditions required for optimal performance.

Furthermore, the paste composition and curing temperatures play pivotal roles in the metallization process. Using Ag/Al paste on the front side and Ag paste on the back side requires careful curing temperature control to ensure proper adhesion and conductivity. At 790 °C, the curing process must be finely tuned to avoid issues such as paste burnout or insufficient bonding, which could affect the cell's efficiency and longevity. The scalability of these processes also depends on the consistency and quality of the materials used. Variations in paste composition, such as the proportion of silver and aluminium, can impact the metal contacts' electrical properties and mechanical stability.

Similarly, the screen mesh type influences the resolution and uniformity of the printed patterns, which are critical for minimizing resistive losses and maximizing light absorption [37]. The paper could benefit from a more rigorous statistical analysis to strengthen the conclusions drawn from our experimental data. This includes providing detailed error margins and assessing the statistical significance of the observed improvements in FF and PCE. By employing statistical methods such as analysis of variance (ANOVA) or regression analysis, we can better understand the variability and reliability of the results. Reporting confidence intervals and p-values will offer a clearer picture of the improvements' robustness and potential impact on large-scale production [18]. In conclusion, while our study demonstrates promising advancements in the metallization process for n-TOPCon solar cells, further research is necessary to address the challenges of industrial applicability and scalability. By incorporating comprehensive statistical analyses and refining our understanding of the critical process parameters, we can better position these optimizations for successful implementation in a commercial manufacturing environment.

In advancing photovoltaic technology, optimizing the metallization process is crucial for balancing electrical conductivity and optical performance in solar cell fabrication. This process directly impacts the efficiency and quality of solar cells, as measured by key metrics such as FF, J_{sc}, and PCE. Historically, efforts have focused on improving metal contacts to reduce optical shading and series resistance, which degrades solar cell efficiency. Our study aims to enhance n-TOPCon solar cells by optimizing screen-printing metallization, specifically examining the effects of squeegee speeds. Through a combination of experimental and analytical methodologies, we identified that a 170 mm/s squeegee speed significantly boosts solar cell performance. This optimization improved electrical and optical performance, achieving a J_{sc} of 38.96 mA/cm^2, a

V_{oc} of 684.29 mV, an FF of 78.77 %, and a PCE of 21.00 %. Future research will explore additional variables, such as paste materials and environmental conditions, to further refine the metallization process and push the boundaries of solar cell efficiency and cost-effectiveness.

Future studies should encompass a broader range of variables that impact the metallization process to provide a more comprehensive understanding and further optimize the performance of n-TOPCon solar cells [37]. Key focus areas should include paste material properties, environmental conditions during printing, and post-printing treatment methods. Investigating different compositions of metallization pastes, including variations in the proportions of silver, aluminium, and other additives, is crucial for understanding their effects on conductivity, adhesion, and overall cell efficiency. Additionally, exploring alternative materials, such as conductive polymers or nanomaterials, could offer innovative solutions for enhancing metallization quality. Assessing the influence of environmental factors, such as humidity, temperature, and air quality, on the screen-printing process is also essential [38]. These conditions can significantly affect the viscosity and drying behaviour of the paste, thereby impacting the uniformity and quality of the printed patterns. Controlled studies manipulating these environmental variables will help identify optimal conditions for consistent and high-quality metallization.

Furthermore, examining various post-printing treatment methods, such as different curing temperatures, annealing processes, and laser sintering techniques, is necessary. These treatments can alter the microstructure and electrical properties of the metal contacts, thus affecting the overall performance of the solar cells. Comparative studies on these methods will provide insights into the best practices for achieving robust and efficient metallization. By including these additional variables in future research, we can develop a more holistic approach to optimizing the metallization process. This will enhance the performance and reliability of n-TOPCon solar cells and ensure their scalability and applicability in industrial manufacturing environments.

Future research should also evaluate optimized parameters' scalability and industrial feasibility [39]. This involves conducting studies that assess the long-term stability and performance of n-TOPCon solar cells under real-world conditions. Firstly, scalability tests should ensure that the optimized parameters, such as the 170 mm/s squeegee speed and 1.4 mm snap-off distance, can be consistently reproduced in large-scale manufacturing environments. This includes examining the uniformity of metallization across multiple production batches and identifying any potential challenges when scaling up the process. Secondly, long-term stability tests are crucial for determining the durability and reliability of the solar cells over extended periods. These tests should simulate various environmental conditions, including temperature fluctuations, humidity, and exposure to ultraviolet light, to evaluate how these factors impact the performance and longevity of the cells. By understanding the degradation mechanisms, researchers can develop strategies to mitigate performance losses and enhance the lifespan of the solar cells.

Moreover, performance evaluations in real-world conditions are essential to validate the practical applicability of the optimized parameters. This involves installing the solar cells in different geographic locations and monitoring their performance over time. Factors such as temperature, light intensity, and weather conditions should be considered to assess how the cells perform under diverse environmental conditions. Data from these field tests will provide valuable insights into the efficiency, reliability, and overall viability of the optimized metallization process in actual deployment scenarios. Incorporating these comprehensive studies will ensure that the advancements made in the metallization process are theoretically sound and practically viable for industrial application. This holistic approach will contribute to developing more efficient, durable, and scalable n-TOPCon solar cells, thereby advancing the field of photovoltaic technology.

Future research should also include more detailed statistical analyses and error discussions to provide a robust validation of the results. This can encompass the use of confidence intervals, variance analysis, and replication studies, all of which are critical for ensuring the reliability and reproducibility of the findings. Confidence intervals should be calculated for all key performance metrics, such as FF and PCE. Confidence intervals will provide a range within which the actual values of these metrics are likely to fall, giving a clearer picture of the precision and reliability of the results. For instance, reporting a 95 % confidence interval for the FF and PCE will illustrate the degree of certainty around the observed improvements and allow for better comparison with other studies. Secondly, variance analysis (ANOVA) should be employed to examine the variability within the data. ANOVA can help determine whether the differences observed in the performance metrics across different squeegee speeds and snap-off distances are statistically significant [40]. This analysis will also identify potential interactions between different process parameters, providing a deeper understanding of their combined effects on solar cell performance. Replication studies are another crucial aspect of robust validation. By replicating the experiments under the same conditions, we can ensure that the observed improvements are consistent and not due to random variation or experimental error. Multiple sets of experiments should be conducted to verify the reproducibility of the optimized parameters. The results from these replication studies should be statistically analyzed to confirm their consistency and reliability.

Additionally, a thorough discussion of potential errors and their sources is necessary. This includes systematic errors that could arise from the measurement instruments, environmental factors affecting the screen-printing process, and variability in paste composition. By identifying and addressing these errors, we can improve the accuracy and reliability of the findings. Incorporating these comprehensive statistical analyses and error discussions will significantly enhance the robustness of the study. It will provide a more rigorous validation of the optimized metallization parameters, ensuring that the reported solar cell performance improvements are statistically significant and reproducible. This approach will strengthen the overall credibility of the research and its potential application in industrial-scale manufacturing of n-TOPCon solar cells.

2. Experimental methods

2.1. Sample preparation

The fabrication of n-TOPCon solar cells is an intricate process that involves several critical steps, beginning with the base material selection and culminating in the final metallization. This detailed procedure ensures the production of highly efficient solar cells by methodically enhancing their material and surface properties [19]. The initial step in this process involves the procurement of n-type Cz silicon wafers. These wafers are characterized by their doping with elements that introduce excess electrons, serving as charge carriers, a fundamental aspect of the operational efficiency of solar cells [20]. The selected wafers are then cut into dimensions of 4 × 4 cm^2, setting a uniform foundation for subsequent processing.

Following the sizing, the wafers undergo treatment with a potassium hydroxide (KOH) solution to remove saw damage. This step is vital for maintaining the silicon wafers' structural integrity, ensuring they are in optimal condition for further processing. Next, the wafers are subjected to the Radio Corporation of America cleaning process, which is crucial for removing organic residues and potential metallic contaminants. This cleaning ensures the wafers' surface is pristine, essential for high-quality device fabrication [21]. The formation of the boron emitter, a pivotal step in the process, involves exposing the wafers to boron tribromide (BBr_3) gas within a furnace to facilitate boron diffusion. This step creates a p-type region necessary for the p-n junction in the solar cell. Any unwanted diffusion on the backside of the wafer is meticulously removed through an etching process using a solution of nitric acid and hydrofluoric acid (HF/HNO_3). The surface of the wafer then undergoes a thermal growth of a tunnelling SiO_x layer following a chemical cleaning step. This oxide layer plays a crucial role in surface passivation, reducing recombination and thus enhancing the cell's efficiency. Subsequently, a phosphorus-doped amorphous silicon *(n-a-Si: H)* layer is developed through plasma-enhanced chemical vapour deposition (*PECVD*), using silane (*SiH_4*), hydrogen (*H_2*), and phosphine (*PH_3*) as precursor gases. This layer is critical for forming the TOPCon structure.

The annealing of the n-a-Si: H layer at 900 °C in an N_2 atmosphere for 25 min transforms it into phosphorus-doped polycrystalline silicon (n + -poly-Si) layers. These layers are integral to the electrical properties of the TOPCon cell. Furthermore, a stack of 8 nm of Al_2O_3 on the front side and 80–90 nm of SiN_x (via *PECVD*) on the back side is deposited. These layers serve as passivation and anti-reflection coatings, significantly contributing to the cell's optical and electrical performance. The final step in the fabrication process involves the metallization of the cell, which consists of applying metal contacts through screen printing with A_g busbars. This step also includes a continuous peak temperature cofiring at 790 °C. The front side employs an Al/A_g paste, while the back uses Ag paste, which is applied through single printing. This metallization is crucial for establishing influential electrical contacts to the solar cell, marking the culmination of the intricate n-TOPCon solar cell fabrication process. The outline steps of sample preparation of n-TOPCon solar cells are shown in Fig. 2. Through this detailed methodology, the produced solar cells can convert solar energy into electricity with high efficiency, showcasing the complex interplay of materials science, chemistry, and engineering in their production.

2.2. Characterization

The precision assessment of photovoltaic cell architecture is pivotal in characterizing solar cell performance [22]. In this detailed analysis, the spatial configuration of the conductive fingers of solar cells was meticulously evaluated using an AmScope digital microscope camera. This advanced imaging system is outfitted with a 14 MP Aptina Colour CMOS sensor, which provides high-resolution imaging capabilities, and an ultra-fine Colour Engine, ensuring accurate color reproduction and detail capture. Such high-fidelity imaging technology was instrumental in determining the precise spacing between the conductive fingers on the solar cells. This factor can significantly influence the efficiency of solar energy conversion. Light current-voltage testing was conducted to further comprehend the solar cells' performance parameters. These tests were performed within a voltage sweep ranging from −0.8 to 0.8 V, employing a granular step size of 0.02 V. The choice of this voltage range and step size was dictated by the need to capture a comprehensive profile of the cell's operational characteristics under illuminated conditions. Such I–V characterizations are essential for mapping the power output and deducing the energy conversion efficiency of the solar cells under simulated sunlight. Solar cells' dark I–V characteristics were also scrutinized. Solar cells involve measuring the electrical characteristics in the absence of light, providing insight into the intrinsic properties of the cell, such as diode quality and junction characteristics. Dark I–V measurements are critical as they shed light on potential performance losses that may not be apparent under illuminated conditions. The structure of n-TOPCon solar cells is depicted in Fig. 3.

Additionally, the research encompassed the measurement of series resistance and shunt resistance. These resistive components within the solar cell can markedly affect performance. Series resistance is associated with the resistance of the material itself and the contacts on the cell. In contrast, shunt resistance pertains to the pathway for current leakage across the p-n junction. Both forms of resistance have profound implications on the fill factor and overall efficiency of the cell, with higher series resistance leading to voltage drops under load and significant shunt resistance indicating leakage paths that can reduce the open-circuit voltage. The investigation also aimed to dissect the solar cells' external quantum efficiency (*EQE*). The EQE measures the cell's ability to convert photons into charge carriers at various wavelengths. EQE was accomplished using a spectral response system, typically called QE/IPCE (Quantum Efficiency/Incident Photon to Converted Electron) or QEX system. This specialized equipment allows for quantifying the cell's response to different wavelengths of light, thereby mapping its sensitivity across the solar spectrum. Understanding the EQE is vital as it directly relates to the capacity of the cell to harness energy from the spectrum of light it receives. Through these thorough evaluations, the study provides deep insights into the operational efficacy and potential areas for optimization in solar cell design.

3. Results and discussion

In photovoltaic technology, the squeegee speed during the screen-printing process of solar cell metallization stands as a critical parameter. It denotes the rate at which the squeegee moves to spread the

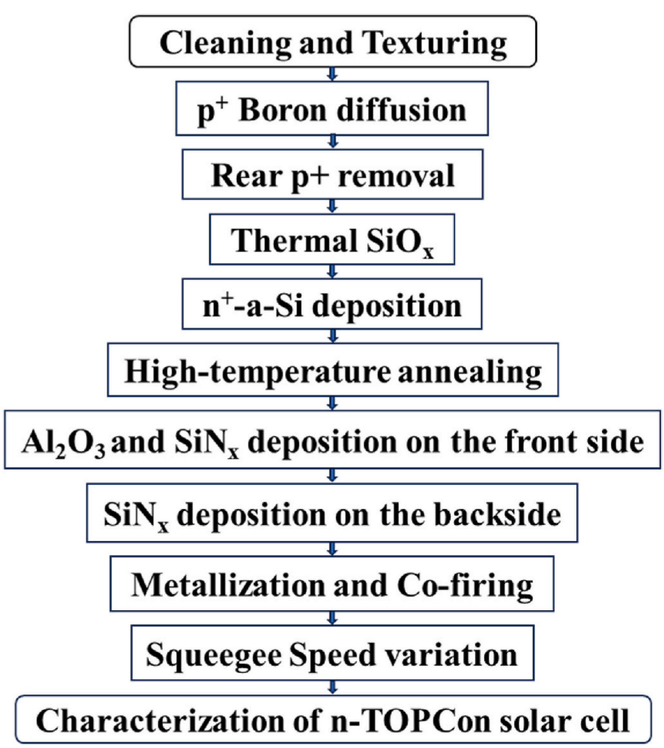

Fig. 2. Fabrication Process for n-Type Tunnel Oxide Passivated Contact Solar Cells.

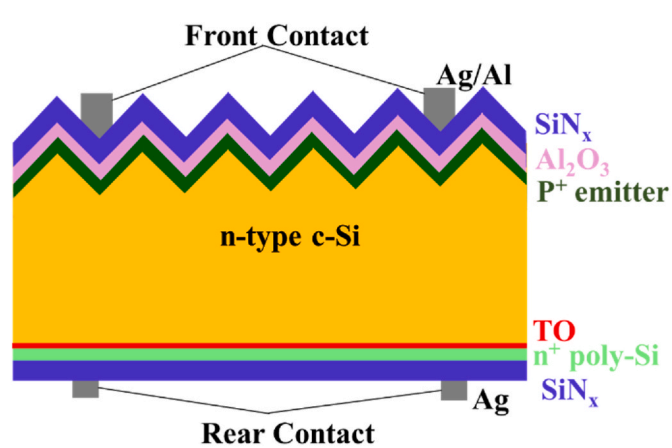

Fig. 3. Structural Diagram of n-Type Tunnel Oxide Passivated Contact Solar Cells.

conductive paste over the wafer through a patterned mask [23]. This speed directly influences the separation distance between the printing mask and the wafer, thereby affecting the volume of the residual paste post-application. An excessive squeegee speed can impede adequate paste deposition by not allowing sufficient contact between the paste and the wafer, necessitating a minimized squeegee speed to ensure efficient paste transfer. In an empirical investigation into optimizing the metallization process for n-TOPCon solar cells, variations in squeegee speed were methodically evaluated [24–26]. Three distinct speeds 30 mm/s, 100 mm/s, and 170 mm/s were compared to discern their impact on the electrical performance and the morphological characteristics of the metal contacts. At the upper limit of 170 mm/s, the solar cells demonstrated reduced series resistance and augmentation in *FF*, indicative of a superior charge carrier collection efficiency.

Conversely, at squeegee speeds of 100 mm/s and 30 mm/s, there was a discernible increase in series resistance and a corresponding decrement in *FF* and overall efficiency, illustrating the delicate balance required in this fabrication phase. Notably, the metal fingers' physical uniformity was improved at the lowest assessed squeegee speed. This observation points to a more consistent metal deposition process, which can significantly affect the electrical interconnectivity within the cell's circuitry [27–30]. Hence, the precise adjustment of the squeegee speed, and by extension, the squeegee speed, is of paramount importance for the finesse of the metallization process. The micrographic analysis compared the front and back side metallization in n-TOPCon solar cells. As illustrated in Fig. 4, both the front and back metallization comprise silver (A_g) paste, with the metal finger widths registering at 36.1 μm (μm). On the front side, the finger spacing is approximately 1.17 mm (*mm*), a critical dimension that requires optimization to reconcile the trade-offs between electrical conductivity and optical absorption. The backside finger spacing is slightly more compressed at 0.75 mm, potentially contributing to reduced series resistance and enhanced current flow within the cell. This granular analysis underscores the significance of metallization parameters in solar cell performance, confirming the intricacies of balancing structural and functional aspects to achieve optimal energy conversion efficacy. Fig. 5 is based on the significant improvements observed at this speed, including a current density of 38.96 mA/cm^2, an open-circuit voltage of 684.29 mV, a fill factor of 78.77 %, and a power conversion efficiency of 21.00 %. These metrics indicate that 170 mm/s is the optimal speed for enhancing the performance of n-TOPCon solar cells.

In the realm of photovoltaic technology, optimizing manufacturing parameters is pivotal for enhancing the performance of solar cells. The presented graph elucidates the correlation between squeegee speed during fabrication and several key performance indicators of solar cells. Fig. 5 shows a squeegee speed of 170 mm/s; the data denote a significant fill factor and efficiency augmentation, with values ascending to 78.77 and 21.00 %, respectively. The fill factor, an essential determinant of the power conversion capability, intimates an elevated 'squareness' of the current-voltage curve, thereby implying a reduction in resistive losses

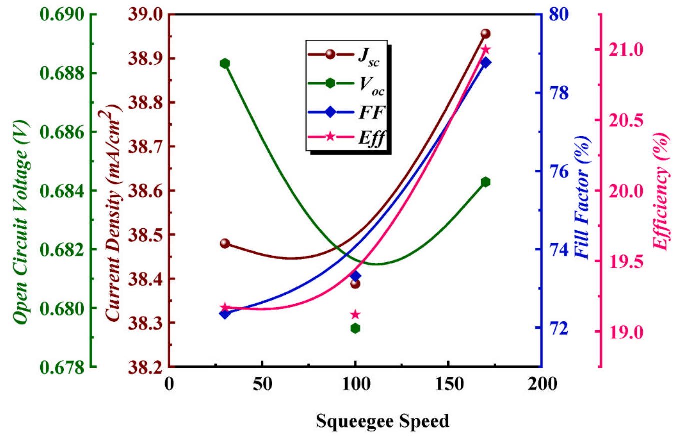

Fig. 5. The I–V data of the n-TOPCon solar cell included a squeegee speed variation with the parameter cell.

and a boost in electrical output. Concurrently, the efficiency, a holistic measure of a cell's ability to convert incident solar energy into electrical energy, suggests that a squeegee speed of 170 mm/s fosters an optimal interaction between the incident light and the cell's active materials.

The short-circuit current density is 38.96 mA/cm^2, indicating a proficient charge collection within the solar cell. Meanwhile, the open-circuit voltage is observed at 0.68, providing insights into the potential electronic band alignment and charge carrier separation efficiency. This intricate interplay of parameters at the specified squeegee speed underscores the importance of process optimization, presenting an avenue for maximizing the efficacy and commercial viability of solar cell technology [31]. In exploring advanced photovoltaic technologies, the intricate I–V characteristics of n-type Tunnel Oxide Passivated Contact solar cells have been meticulously investigated to ascertain the impact of fabrication process variations on their operational performance. One such variable, the squeegee speed during the deposition of layers, has been methodically varied to discern its influence on the I–V parameters of these cells. This study encompasses an analysis where the squeegee speed is adjusted, thereby modifying the physical deposition dynamics of the silicon layers, which are fundamental to the cell's electrical characteristics [32]. Researchers empirically scrutinize the resultant I–V data to illuminate the relationship between the squeegee speed and the solar cell's efficiency, fill factor, open-circuit voltage, and short-circuit current density. The findings from this investigative approach are poised to refine the understanding of n-TOPCon cell behaviour under different fabrication velocities, ultimately contributing to optimizing production processes and enhancing cell performance.

The graph and accompanying data table offer a detailed overview of the current-voltage (I–V) characteristics of n-TOPCon solar cells, with particular attention given to the influence of squeegee speed variations

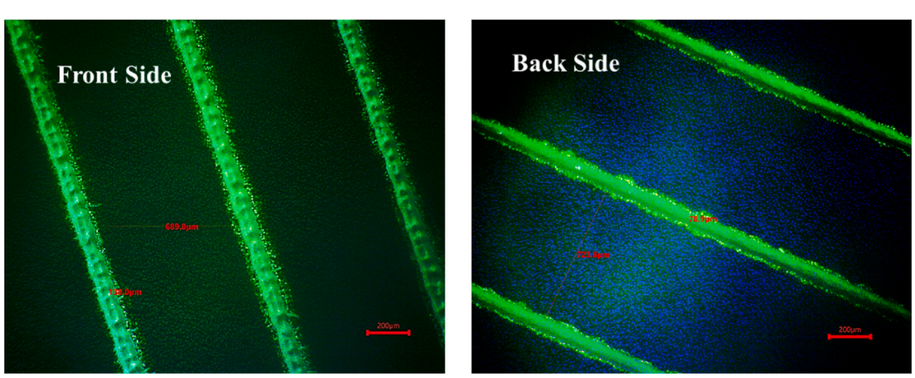

Fig. 4. The optical microscope of the n-TOPCon solar cell from both sides focuses on the surface of the 170mm/s squeegee speed: the front side and the backside.

on key performance metrics. In our investigation, the metallization process using a squeegee speed of 170 mm/s yielded the best performance for n-TOPCon solar cells. This optimal speed resulted in a J_{sc} of 38.96 mA/cm^2, a V_{oc} of 684.29 mV, an FF of 78.77 %, and a PCE of 21.00 %. The optical microscope images at this speed showed enhanced uniformity and precision in the metal contacts, which is crucial for reducing shadowing effects and improving electrical connectivity. The dark I–V measurements confirmed an R_{sh} of 6.25 × 10^6 Ω and a R_s of 6.48 Ω, indicating high-quality metallization with minimal resistive losses. The detailed analysis of the optical microscope images at 170 mm/s demonstrated the significant impact of optimal squeegee speed on metallization quality. These images revealed well defined and consistent metal finger patterns, which contribute to the overall efficiency of the solar cells by minimizing shading and ensuring better electrical pathways. The superior performance metrics achieved at this speed underscore the importance of precise control in the screen-printing process. Future studies should include various variables affecting the metallization process, such as paste material properties, environmental conditions during printing, and post-printing treatment methods.

Additionally, evaluating the scalability and industrial feasibility of the optimized parameters is crucial. This involves long-term stability tests and performance assessments under real-world conditions to ensure the robustness and applicability of the findings. The graph (Fig. 6) depicts the I–V curves for three different squeegee speeds: 170 mm/s, 100 mm/s, and 30 mm/s. It is immediately apparent that the solar cell processed at the highest speed of 170 mm/s achieves the most favorable I–V curve, marked by a higher current density across the entire voltage range. The data table quantitatively supports these observations; at the highest squeegee speed of 170 mm/s, the cell exhibits a J_{sc} of 38.96 mA/cm^2, a V_{oc} of 0.68 V, an *FF* of 78.77 %, and an overall efficiency of 21.00 %. These values indicate optimal metallization quality, which translates to reduced resistive losses and efficient light absorption and conversion capabilities. With the squeegee speed decreasing to 100 mm/s, all performance metrics decline: J_{sc} drops to 38.39 mA/cm^2, V_{oc} to 0.68 V, *FF* to 73.32 %, and efficiency to 19.12 %. This reduction suggests that there may be suboptimal paste deposition at this speed, leading to increased resistive losses and decreased efficiency. The slowest speed tested, 30 mm/s, presents slightly higher J_{sc} than 100 mm/s at 38.48 mA/cm^2, yet still lower than 170 mm/s, while V_{oc} is marginally higher at 0.68 V. However, *FF* and efficiency remain the lowest, at 72.36 % and 19.17 % respectively. The poorer performance metrics at this speed may be due to excessive paste, leading to more significant shadowing and increased series resistance. This graphical and tabulated analysis demonstrates the critical role of squeegee speed in the screen printing process of solar cell metallization [33]. It elucidates the necessity for a balanced squeegee speed, highest at 170 mm/s, to achieve the optimal trade-off between line width, electrical connectivity, and minimal shadowing, maximizing the efficiency and overall performance of n-TOPCon solar cells.

The provided semi-logarithmic plot portrays the dark current-voltage characteristics of n-TOPCon solar cells across a spectrum of squeegee speeds employed during metallization as shown in Fig. 7. This graphic representation, delineating the I–V response at 170 mm/s (black curve), 100 mm/s (red curve), and 30 mm/s (blue curve), is instrumental in elucidating the subcellular electrical phenomena absent of photoexcitation. The y-axis, rendered on a logarithmic scale, displays the current density (mA/cm^2), while the x-axis, on a linear scale, indicates the voltage (mV). In analyzing the curves, the low-voltage regime showcases an exponential increase in current density, characteristic of diode-like behavior driven by the thermal generation of charge carriers. The slope's starkness within this regime reflects the intrinsic semiconductor material properties and the recombination kinetics of carriers. The curves approach a saturation point indicative of the inherent saturation current, quantifying the cell's recombination rates under dark conditions. Upon further extension to higher reverse biases, the curves exhibit a linear increase, conforming to ohmic behaviour dictated predominantly by the solar cell's internal resistive elements. Crucially, the variance observed among the curves at differing squeegee speeds signifies the impact of the metallization process on the recombination and resistive characteristics of the solar cells. The 170 mm/s squeegee speed is marked by a lower dark saturation current and diminished ohmic losses in the reverse bias, intimating a superior metallization quality that presumably minimizes recombination and enhances resistive properties as seen on Table 1).

In contrast, the elevated dark saturation currents and more pronounced ohmic behaviour observed at reduced squeegee speeds could denote augmented recombination activities and elevated resistive losses, likely due to less precise metallization features. This figure provides pivotal insights into optimizing the squeegee speed within the screen printing metallization stage, underscoring its paramount importance in fine-tuning the electrical performance and efficiency of n-TOPCon solar cells. Table 2 shows the detailed R_{sh} and R_s of a cell. A high R_{sh} is desirable to improve the V_{oc} and FF of the solar cell, and R_s should be as low as possible.

The External Quantum Efficiency of n-TOPCon solar cells at various

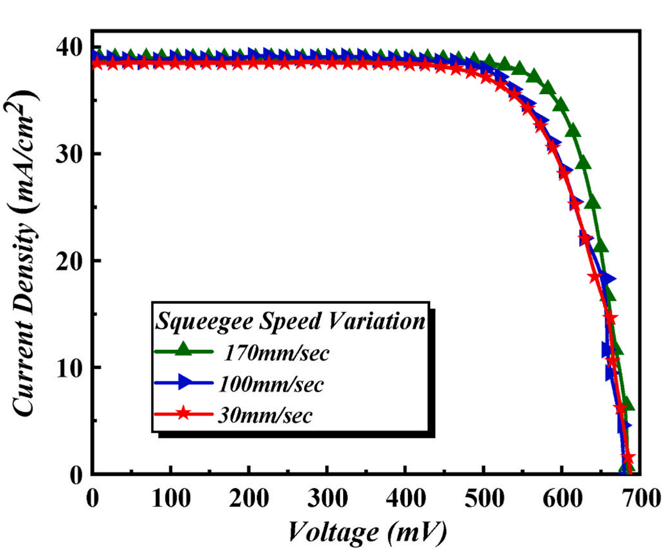

Fig. 6. The I–V data of the n-TOPCon solar cell included a squeegee speed variation with the parameter cell, J_{sc}, V_{oc}, *FF*, and efficiency.

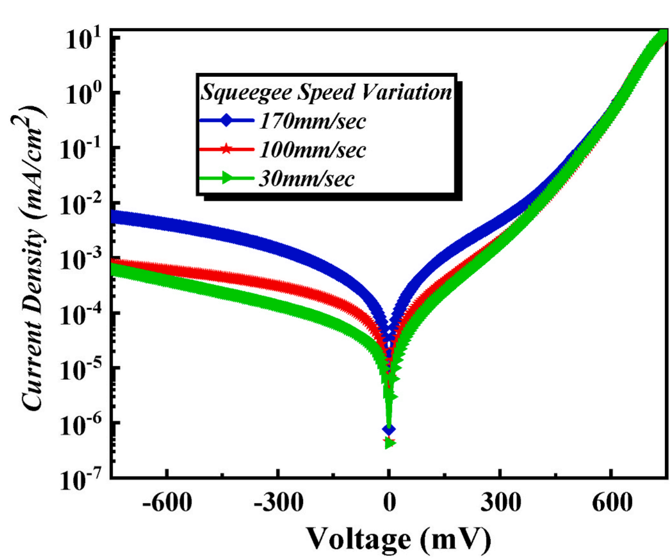

Fig. 7. The dark I–V curve corresponds to the different squeegee speeds of the n-TOPCon solar cells.

Table 1
The parameters resulting from the illuminated I–V at three different n- TOPCon solar cell squeegee speeds.

Squeegee Speed variation *(mm/sec)*	J_{sc} *(mA/cm²)*	V_{oc} *(mV)*	*FF (%)*	Efficiency *(%)*
170	38.956	0.684	78.77	21.00
100	38.389	0.679	73.32	19.12
30	38.479	0.680	72.36	19.17

Table 2
The parameters were obtained from the dark I–V measurements at three distinct squeegee speed points of n-TOPCon solar cells.

Squeegee Speed variation *(mm/sec)*	*Rsh (Ω)*	R_s *(Ω)*
170	6.19×10^6 Ω	6.75
100	5.91×10^6 Ω	7.04
30	9.78×10^5 Ω	8.08

wavelengths is systematically depicted in Fig. 8, wherein a comparative analysis is undertaken to assess the impact of three distinct squeegee speeds 170 mm/s, 100 mm/s, and 30mm/s employed during the metallization process. The EQE is an imperative metric that quantifies a cell's proficiency in converting incident photons into electrical charge carriers (electrons) across different wavelengths, indicating the cell's light absorption efficiency and charge collection capabilities. Upon scrutiny of the EQE curves, it is observed that all variants of the n-TOPCon solar cells exhibit a relatively high and uniform EQE across a broad spectrum of wavelengths. This uniformity underscores the cells' adeptness in light absorption and the effective collection of charge carriers, which are critical for high photovoltaic performance. Notably, a discernible deviation is witnessed at specific wavelengths, particularly with the solar cells fabricated using a squeegee speed of 30 mm/s.

These cells demonstrate a noticeable reduction in EQE, suggesting a potential correlation between slower squeegee speeds and diminished efficiency in solar energy conversion. The divergence in EQE at reduced squeegee speeds could be attributed to various underlying mechanisms. One plausible explanation is the alteration in the physical and electrical properties of the metallization contacts, which are integral for the efficient extraction of charge carriers. Slower squeegee speeds may result in a less optimal contact formation, potentially leading to increased recombination losses or hindered charge transport. This empirical evidence underscores the critical role of optimizing metallization parameters in n-TOPCon solar cells' fabrication process. The observed variance in EQE, consequent to slight modifications in squeegee speed, highlights the nuanced balance required in process parameters to achieve optimal photovoltaic performance. Therefore, the data reflects the inherent potential of n-TOPCon solar cells in harnessing solar energy and illustrates the importance of precision in the metallization process to realize this potential fully. Consequently, further research aimed at elucidating the precise impact of metallization parameters on the efficiency and performance of n-TOPCon solar cells would be beneficial, paving the way for advancements in solar technology and its application.

4. Conclusions

In the quest to elevate the efficiency of *n-TOPCon* solar cells, the focus on optimizing the metallization process emerges as a pivotal area of research. This study rigorously examines the impact of squeegee speed variations on key performance indicators, precisely the fill factor and power conversion efficiency, within the metallization phase of solar cell fabrication. The investigation's empirical evidence unequivocally identifies a squeegee speed of 170 mm/s as optimal for achieving significant enhancements in both *FF* and *PCE*, thereby highlighting the critical role of precise metallization in solar cell efficiency enhancement. Contrary to the improvements observed at 170 mm/s, increasing the

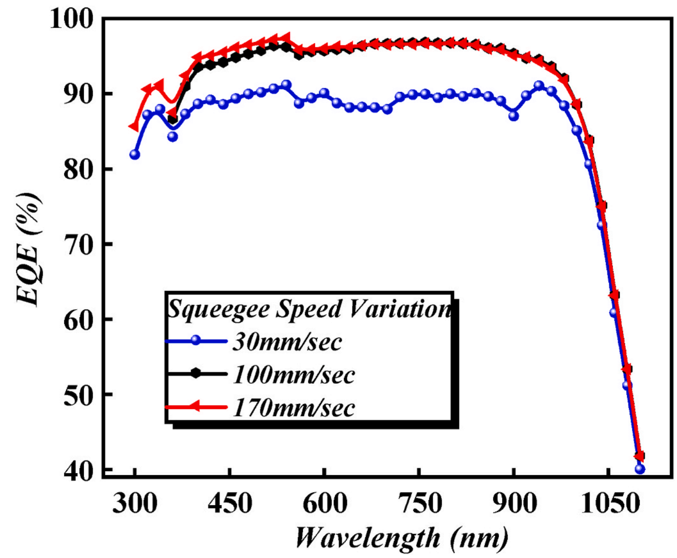

Fig. 8. The external quantum efficiency (*EQE*) spectrum of an n-TOPCon solar cell at three different squeegee speeds.

squeegee speed to 100 mm/s and further to 30 mm/s resulted in a discernible deterioration in the solar cells' performance metrics. This decline is attributed to increased resistive losses and a higher likelihood of charge carrier recombination, which substantially undermine solar cell performance. These findings suggest that higher squeegee speeds disrupt the delicate balance necessary for optimal solar cell functionality, thus detrimentally affecting efficiency. The beneficial impact of a lower squeegee speed is further illustrated by the formation of finer metal fingers, reduction of shadowing effects, and improved electrical contact. These advantages collectively create a conducive environment for superior solar cell performance. The empirical data support these conclusions, with the optimal squeegee speed of 170 mm/s yielding impressive results: a J_{sc} of 38.96 mA/cm^2 and a V_{oc} of 684.29 mV.

Additionally, the *FF* and *PCE* reached peak values of 78.77 % and 21.00 %, respectively. In summary, this research articulates a definitive strategy for enhancing n-TOPCon solar cell efficiency through meticulously optimizing the metallization process. The significant influence of squeegee speed on solar cell performance metrics underscores the importance of precision in the fabrication process. The superior performance metrics achieved at a 170 mm/s squeegee speed conclusively demonstrate that lower speeds are crucial for developing optimal metallization patterns. This optimization process aims to elevate the fill factor and power conversion efficiency and plays a fundamental role in propelling solar cell technology towards new efficiency horizons.

Author contributions

R.U.R. & M.Q.K. performed the conceptualization, data curation, formal analysis, investigation, and writing of the original draft. These two authors contributed equally. M.N.A, J.A.J., P.C.M., A., H.Y., and M. C. performed the data curation, formal analysis, and investigation. S.P. contributed to supervision, investigation, visualization, and project administration. J. Y. contributed to supervision, investigation, visualization, project administration, and fund acquisition.<a name = "Line_manuscript_69">

Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interestsNone.

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