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Influence of deposition power of PECVD intrinsic a-Si:H buffer layer on n^+ poly-Si/SiO_x/c-Si passivating contacts

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ARTICLE INFO	ABSTRACT
Keywords: TOPCon passivating contacts Pinhole density Plasma etching effect Plasma-enhanced chemical vapor deposition	Optimizing the deposition parameters in the fabrication of passivating contacts for crystalline silicon solar cells is critical for improving efficiency. This study explored the influence of varying RF power of Plasma-Enhanced Chemical Vapor Deposition (PECVD) on the quality of hydrogenated intrinsic amorphous silicon (<i> a-Si:H) films. The aim is to manufacture in-situ phosphorous-doped poly-Si/SiO_x/c-Si passivating contacts with <i> a-Si: H as buffer layer between the tunnelling oxide and the n-type poly-Si. The microstructure factor of our intrinsic layers increases from 0.176 to 0.804, that is from higher to lower film density, as the RF power increases from 5 W to 55 W. Analysis using X-ray Photoelectron Spectroscopy and Optical Microscopy indicates that the Si content in SiO_x is correlated with the formation of pinholes. Our detailed analysis showed that varying the RF power when depositing <i> a-Si:H contacting layer is crucial in altering both the Si⁴⁺ content in SiO_x and the pinhole density, due to the interplay between the plasma etching and the buffering effects during of the <i> a-Si:H layer growth. Notably, the sample processed with 25 W exhibited the maximum pinhole density, the lowest Si⁴⁺ content in SiO_x and the deepest phosphorus in-diffusion, potentially yielding superior results in passivation quality and contact resistivity under optimized PECVD conditions.</i></i></i></i>

1. Introduction

The development of highly efficient photovoltaic (PV) devices hinges on the continuous improvement of materials and techniques used in their fabrication [1]. Crystalline silicon (c-Si) solar cells have long dominated the PV market due to their high efficiency and stability, but further advancements are required to overcome inherent limitations, particularly those related to surface recombination [2]. One promising approach to mitigate these losses is the use of carrier-selective passivating contacts, such as poly-Si/SiO_x structures also known as TOPCon (tunnel oxide passivated contacts), which have been shown to significantly enhance surface passivation and carrier transport [3-6]. The deposition of hydrogenated amorphous silicon (a-Si:H) using Plasma Enhanced Chemical Vapor Deposition (PECVD) is a widely adopted method for fabricating TOPCon passivating contacts [7–11]. In recent years, PECVD has been compared to Low-Pressure Chemical Vapor Deposition (LPCVD), a method known for producing high-quality films with less defects. Although LPCVD offers advantages in passivation quality, it is more complex and less preferable in industrial-scale production processes [12-15].

The process conditions critically influence the microstructure, integrity, stoichiometry, and electrical properties of the resulting TOP-Con passivating contacts [10,16–19]. The study by Truong et al. found that the crystallographic structures, optoelectronic properties, and nanoscale surface morphologies of phosphorus-doped TOPCon (n⁺ poly-Si/SiOx/c-Si passivating contact or N-TOPCon) passivating contacts are affected by the manufacturing technologies, such as sputtering, PECVD and LPCVD [20]. Li et al. developed an ultrafast, high-quality method for depositing a-Si thin films for N-TOPCon passivated contacts using Hot-wire Chemical Vapor Deposition (HWCVD). Their research reveals that while porous silicon layers are prone to oxidation and low passivation quality during high-temperature annealing, dense silicon layers, though resistant to oxidation, may experience blistering [16]. Tunneling oxide properties like stoichiometry and layer thickness

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can be analyzed using X-ray Photoelectron Spectroscopy (XPS) and Spectroscopic Ellipsometry (SE) [18,21]. Consistent with previous findings, effective surface passivation was achieved with a minimum oxide layer thickness of approximately 1.3 nm and a high presence of oxygen-rich suboxide species with different formation methods [17,18]. Findings from Peibst et al. suggest that localized current flow through the oxide, possibly due to thinning or pinholes, plays a significant role [22–24]. Boron-doped poly-Si/SiO_x samples were analyzed by Morisset et al. using Conductive-Atomic Force Microscopy (C-AFM) to explore the formation of conductive pinholes in the SiO_x layer. Their findings indicate that oxide growth on the poly-Si surface influences detected current levels. Their results also suggest that the conductive spots detected are related more to the poly-Si layer than to pinholes in the SiO_x layer [9]. A disclosure of the effect of RF power on hydrogenated intrinsic amorphous silicon ($\langle i \rangle$ a-Si:H) contacting layer in n⁺ poly-Si passivating contacts using PECVD technology is missing in literature.

This study explores the influence of varying <i> a-Si:H contacting layer RF power settings on n⁺ poly-Si passivating contacts and compares the results with those obtained using LPCVD <i> a-Si contacting layer, aiming to identify the optimal conditions for achieving high-performance N-TOPCon passivating contacts. The development of this work was first carried out by exploring the deposition rates. Secondly, to examine the relationship between material properties and passivating contact performance, we characterized the properties of <i> a-Si:H and SiO_x, and discussed their effectiveness in passivating contacts.

2. Experimental section

In this study, we investigated the impact of PECVD deposition power of $\langle i \rangle$ a-Si:H contacting layer on the performance of n⁺ poly-Si passivating contacts from thin films deposition to contact resistance measurements as shown in Fig. 1. For the fabrication and characterization of SiO_x , $\langle i \rangle$ a-Si:H contacting layer and n⁺ a-Si:H capping layer are as follows: 260-µm thick n-type FZ c-Si wafers with a resistivity of $2.5 \ \Omega$ cm were used as base material. The ultrathin SiO_x was symmetrically formed by thermal oxidation of silicon with a peak temperature of 675 °C for 3 min, starting from 600 °C (t-SiO_x). The thermal oxidation was carried out using tube furnace system supplied by TEMPRESS. Then, the samples were coated, both front and rear side, with 20-nm thick PECVD <i> a-Si:H contacting layers at various RF power settings (5 W, 15 W, 25 W, 35 W, 45 W, and 55 W). The deposition process was carried out using a PECVD system (Elettrorava S.r.l.). The electrode size is 12 x 12 cm^2 . The flow rate of gases for the $\langle i \rangle$ a-Si:H contacting layer were 4 sccm SiH₄ and 35 sccm H₂. Spectroscopic Ellipsometry (SE) was employed to measure the thickness of the a-Si:H and SiOx films and to determine their deposition rates. Fourier Transform Infrared (FTIR) analysis was used to study the deposited thin films' chemical composition and bonding structure [25,26]. However, since FTIR measurement relies on detecting the absorption of infrared light, thicker silicon wafers with a thickness of around 525 µm were used. Afterwards, pre-annealing process was performed for transforming the thin-film <i> a-Si:H into a multicrystallized phase and open pinholes on the SiO_x [23]. The annealing time is 1 min with a temperature of 1000 °C, starting from 600 °C. A KOH-based etch-back process was executed to expose the interfacial oxide, which will be presented in detail in section 3.2. XPS-based surface study was carried out using PHI 5400 ESCA system supplied by Physical Electronics, Inc. This is equipped with a non-monochromatized Aluminium (Al) K α X-ray source (hv = 1486.7 eV), operated at 200 W power with 13.5 kV accelerating voltage. The take-off angle during the full-survey and high resolution measurements was maintained at 45° . The region of analysis for all sample in XPS has a circular scanning area of 0.4 mm and the subsequent depth of analysis was in the range of 3-5 nm. XPS was used to assess the stoichiometry of the SiO_x layers. Such samples were processed in the same PECVD chamber as the following hydrogenated doped amorphous silicon (n⁺ a-Si:H) layers, serving as in-situ doped capping layers (Elettrorava S.p.

Experimental Design



Fig. 1. Experimental design and sample fabrication process for investigating the impact of PECVD 20 nm $\langle i \rangle$ a-Si:H contacting layer deposition power on n^+ poly-Si passivating contacts.

A., deposition area: 100 cm²). The flow rates of gases we introduced to the chamber to realize n^+ a-Si:H capping layer were: 4 sccm SiH₄, 35 sccm H_2 and 4.8 sccm PH_3 (2 % diluted in H_2). The thickness of n^+ a-Si:H capping layer was also 20 nm. The post-annealing process was performed to activate and drive the dopant towards the Si bulk to realize the N-TOPCon structure. The annealing time was 30 min with a temperature of 850 °C, starting from 600 °C. Electrochemical Capacitance-Voltage (ECV) measurements were performed to analyse the doping profiles of the poly-Si layers. This overall process is executed on both the front and back sides of the silicon wafer, forming a symmetrical configuration. The passivation quality was measured using the WCT-120 Sinton instrument, applying the quasi-steady-state photoconductance (QSSPC) method to extract the implied open-circuit voltage (iV_{OC}) at the excess carrier density of 1×10^{15} cm⁻³. The samples were then subjected to a double side deposition of PECVD SiN_x (see details in [27]) and subsequent Forming Gas Annealing (FGA) for hydrogenation purposes and further enhancement of the passivation quality. The FGA time was 30 min at a temperature of 400 °C. Before double-sided silver films were evaporated

through resistive thermal evaporation, the SiN_x film was removed using 3 % hydrofluoric acid. Following these steps, the specific contact resistivity (ρ_c) was extracted using the Cox and Strack method [28].

3. Results

3.1. Silicon thin films properties

A possible bombardment damage might occur onto the sensitive interfacial silicon oxide layer by the radicals formed in SiH₄/H₂ plasma during the <i> a-Si:H layer deposition. Therefore, the formation rate of the first few nanometres of *<*i*>* a-Si:H as contacting layer for interfacial oxide should be studied. Fig. 2(a) presents the relationship between the thickness of <i> a-Si:H films and the deposition time under six different RF power settings. Each line represents one of the six different RF power settings used in the deposition process, specifically at 5 W, 15 W, 25 W, 35 W, 45 W, and 55 W. The lines show a clear positive correlation between deposition time and film thickness for all RF power settings. As the RF power increases, the slope of each line also increases, indicating that higher RF power leads to faster deposition rate. Low RF power (5 W) shows the slowest deposition rates. Medium RF power (15 W, 25 W) demonstrates a moderate increase in deposition rate, with the thickness of the a-Si:H films growing steadily over time. High RF power (35 W, 45 W, 55 W) exhibits the most rapid increase in film thickness, indicating that higher RF power significantly enhances the deposition rate. Fig. 2 (b) displays the relationship between RF power and the deposition rate of <i> a-Si:H layer. The scatter plot is represented by symbols in various colors to indicate the actual measured deposition rates of <i> a-Si:H layer, while the red line shows the trend fitting these data points. As the RF power increases, the deposition rate of <i> a-Si:H layer shows an upward trend. Several key data points are marked on the figure (e.g., 0.09, 0.25, 0.91, 1.79, 2.20, 2.83 nm/s), indicating significant increase in deposition rate with the rise in RF power.

To explore the impact of PECVD power on the properties of $\langle i \rangle$ a-Si: H contacting layer, aiming to better understand how variations in power influence Si-H bonding structures and overall film morphology, infrared absorption was employed to characterize the as-deposited $\langle i \rangle$ a-Si:H thin film. Fig. 3(a) illustrates the FTIR spectra of thin intrinsic a-Si:H layers, approximately 20-nm thick, measured across a wavenumber range from 400 cm⁻¹ to 2500 cm⁻¹. Each spectrum corresponds to a different RF power setting, as indicated by the legend (P = 5 W–55 W). As the RF power increases (from 5 W to 55 W), notable shifts in the intensity and the position of these peaks can be observed. Fig. 3(b) showcases the fitted FTIR spectra focusing on the low-stretching mode (LSM, peak locates at 1980–2010 cm⁻¹) of thin intrinsic a-Si:H layers

grown at various RF power settings, highlighting the absorption behavior attributed to the low- and high-stretching modes of Si-H bonds in a-Si:H films [29]. Fig. 3(c) displays a microstructure factor (R*) graph as a function of RF power applied during the PECVD process of intrinsic a-Si:H contacting layer. The structural analysis was performed by calculating the microstructure factor R* of the <i>a-Si:H thin film, which is defined as follows [30]:

$$R^* = rac{I_{HSM}}{I_{LSM} + I_{HSM}}$$

At the lowest RF power setting (5 W), R* starts at a low value, indicating a higher proportion of monohydride bonding configurations. As RF power increases to 15 W and 25 W, a noticeable increase in R* suggests a shift towards more dihydride bonding configurations in the film. Beyond 25 W, R* slightly increases, suggesting an increasement in the relative amount of dihydride bonds compared to 25 W. The increased R* value implies that the density and/or size of nanosized voids have increased [25].

3.2. SiO_x integrity and stoichiometry

To characterize the SiO_x integrity and stoichiometry, the samples were subjected to crystallization at a high temperature of 1000 °C to form polycrystalline silicon (poly-Si). Subsequently, chemical selective etching was employed to expose the SiO_x layer [23]. Given that pinhole density critically influences the doping tail and interface trap density at the crystalline silicon surface, establishing precise methods to measure pinhole density post-annealing is essential for optimizing N-TOPCon passivating contacts [23,31]. Fig. 4(a) illustrates the methodology used for calculating the pinhole density on SiO_x layer, depicting how samples are selected and analyzed across different areas of a 100 mm FZ wafer [23]. Five areas, labelled A through E, are selected across the wafer to ensure representative sampling. Each area is marked by a dashed rectangle, indicating the specific regions where Optical microscope observations are carried out. The dimensions of each area are given as 1.5 imes1.5 mm², providing a standardized size for consistency in data collection across the wafer. Fig. 4(b) provides a closer look at Area B, chosen as a representative sample for detailed analysis. Within Area B, five subareas (B1-B5) are identified for even more granular observations or measurements. These subareas are marked by smaller dashed rectangles. The entire observation area in Fig. 4(b) is specified to have dimensions of 200 \times 200 μ m², indicating the scale at which detailed observations are made within each subarea. This schematic represents a methodical approach to data collection for pinhole quantities, ensuring that pinhole density is not biased by location on the wafer. By selecting multiple areas across the wafer and further subdividing these into smaller



Fig. 2. a) <i> a-Si:H contacting layer thickness for different deposition time when 6 different RF powers are applied. (b) <i> a-Si:H contacting layer deposition rate increases with PECVD RF power. The fitting lines are linear and a guide to the eye.



Fig. 3. a) Fourier Transform Infrared (FTIR) α/ω spectra of 20-nm thick $\langle i \rangle$ a-Si:H contacting layer grown at different RF power, showing all peaks in the range from 400 cm⁻¹ to 2500 cm⁻¹. (b) Fitted spectra investigating low- and high-stretching modes over the wavenumber from 1800 cm⁻¹ to 2300 cm⁻¹. (c) Microstructure factor R* of 20-nm thick $\langle i \rangle$ a-Si:H contacting layer as functions of the RF power.



Fig. 4. Schematic of pinhole density calculation. In (a) we indicate the five areas (A–E) selected on each wafer, and in (b) we further highlight the five sub-areas selected on area B (B1-B5). (c) Pinhole density was calculated in different RF power cases with a constant <i> a-Si:H contacting layer thickness of 20 nm.

subareas, we aim to gather comprehensive and statistically significant data. More details can be found in the part 1, supplementary information.

Fig. 4(c) illustrates the variation in pinhole density across a range of RF power settings while maintaining a constant thickness of 20 nm for the deposited $\langle i \rangle$ a-Si:H contacting layer. Additionally, it compares these RF PECVD processes to the LPCVD method. Error bars associated with each point suggest the variability or uncertainty in the pinhole density measurements. Pinhole density increases with the RF power, reaching a peak pinhole density of 4.75×10^7 cm⁻² at 25 W. Beyond the peak at 25 W, pinhole density decreases with further increases in RF power. The LPCVD method shows a relatively low pinhole density.

To explore the relationship between the quality of SiO_x films and its structural integrity, we quantify the Si^{4+} content by fitting Si 2p XPS spectra. This signature indicates stoichiometric SiO_2 , providing insights into the structure of our SiO_x films [32]. The higher the Si^{4+} ratio, the greater the fraction of high-quality SiO_2 within SiO_x . Fig. 5(a) displays XPS spectra for SiO_x layers impacted by the deposition of 20-nm thick <i>a-Si:H at various RF power settings, in addition to a comparison with LPCVD method. The spectra have been normalized and calibrated

for consistent comparison by referencing the C1s peak at 284.8 eV. The curves are vertically offset for clarity, starting from 5 W at the bottom, increasing through 15 W, 25 W, 35 W, 45 W, and 55 W, and concluding with LPCVD at the top. Each spectrum features a primary peak around 103.5 eV, characteristic of SiO_x, with variations in peak shape and intensity reflecting changes in the Si environment [33]. As RF power increases, there are noticeable changes in the shape and the position of the primary Si 2p peak. The subtle shifts in peak position and changes in peak shape with increasing RF power suggest alterations in the chemical environment of silicon atoms within the SiO_x matrix. The spectrum of the LPCVD sample, placed at the top for comparison, shows distinct characteristics compared to the spectra obtained from PECVD processes at different RF powers. Fig. 5(b) illustrates the peak fitting of XPS spectra for SiO_x layers subjected to <i> a-Si:H deposition under various RF power settings. It focuses on the detailed contributions of different silicon states (Si 2p_{3/2} and Si 2p_{1/2}, including Si¹⁺, Si²⁺, Si³⁺, and Si⁴⁺) within the SiO_x matrix [34,35]. Fig. 5(c) compares the percentage of Si^{4+} content in SiO_x films, derived from fitting the Si 2p XPS spectra across seven cases. The Si⁴⁺ content decreases from low RF powers to a minimum value of 24.26 % at 25 W. After reaching a minimum value at



Fig. 5. (a) Comparison of SiO_x XPS normalized spectra after $\langle i \rangle$ a-Si:H contacting layers have been stripped off (both RF-PECVD and LPCVD cases). (b) Zoomed-in peak fitting (Si $2p_{3/2}$ and Si $2p_{1/2}$, Si¹⁺, Si²⁺, Si³⁺ and Si⁴⁺) of XPS spectra. (c) Comparison of the percentage of Si⁴⁺ in the SiO_x films.

25 W, the percentage of Si^{4+} slightly increases at higher RF powers (35 W, 45 W and 55 W). The LPCVD method shows the highest percentage of Si^{4+} , suggesting that LPCVD results in a higher proportion of fully oxidized silicon compared to the PECVD method at the specified RF power settings.

3.3. Influence of (i) a-Si:H deposition power on N-TOPCon passivating contacts

To elucidate the influence of different (i) a-Si:H contacting layer deposition power settings on the suppression of surface recombination and carrier transport in N-TOPCon passivating contacts, iV_{OC} and ρ_c are studied. 20-nm thick phosphorus-doped amorphous silicon layers ($\langle n \rangle$ a-Si) were deposited on both sides of each sample as a capping layer. The sample was then subjected to crystallization at 850 °C for 30 min, forming N-TOPCon. An 80-nm thick SiN_x layer was deposited on both sides of the poly-Si. FGA was applied to hydrogenate the samples. Fig. 6 (a) presents the iV_{OC} values of n^+ poly-Si passivating contacts. Two sets of data points are plotted: squares represent samples after postannealing, and circles represent samples after FGA hydrogenation, each set connected by lines to illustrate trends. For both post-annealed and FGA hydrogenated samples, iV_{OC} increases with RF power from 5

W to 25 W, indicating improved passivating contact quality. Beyond 25 W, iV_{OC} decreases, whereas FGA samples maintain higher iV_{OC} values. The LPCVD method at the right end of the x-axis shows the highest iV_{OC} for both treatment processes, underscoring the superior quality of passivating contacts when the $\langle i \rangle$ a-Si:H film is deposited via LPCVD. Fig. 6(b) showcases the specific contact resistivity of contact samples as a function of <i> a-Si:H deposition power used in the deposition process. The contact resistivity was extracted using the Cox and Strack method following the double-sided silver metallization on the poly-Si, which was achieved through the PVD method after removing the SiN_x layer [28]. The graph shows an initial decrease in specific contact resistivity from 5 W to 25 W, indicating that lower RF powers are associated with lower contact resistivity, and an increase in RF power within this range leads to a drop in resistivity. Notably, after reaching a nadir at 25 W, the specific contact resistivity increases with further increases in RF power, reaching a higher level at 55 W. The specific contact resistivity for samples prepared via LPCVD is provided as a reference, showing a value that is competitive with those obtained at optimized RF power settings but is higher than the nadir value observed at 25 W.



Fig. 6. (a) The iV_{OC} and (b) the specific contact resistivity of symmetric n^+ poly-Si passivating contacts samples after FGA as a function of $\langle i \rangle$ a-Si:H contacting layer deposition power, involving LPCVD samples as reference.

3.4. Doping profile

To unveil the variations in doping profiles across different $\langle i \rangle$ a-Si:H deposition RF power settings, ECV measurements were conducted to assess how these changes affect the distribution and concentration of dopants within the n^+ poly-Si passivating contacts. Fig. 7 presents the measured effective doping concentration profiles in n^+ poly-Si passivating contact. The effective doping concentration decreases sharply as the depth increases, reflecting the transition from the heavily doped poly-Si layer into the less-doped or intrinsic layers beneath. The doping profiles are similar across PECVD settings, but slight variations in the slope and depth of the concentration drop-off may indicate differences in dopant in-diffusion. It can be noted that the 25 W sample, which had a lowest Si⁴⁺ content and highest pinhole density, exhibited the deepest in-diffusion depth of about 100 nm. In contrast, the LPCVD sample and other PECVD <i> a-Si:H samples with higher Si⁴⁺ content and lower pinhole density exhibited shallower internal diffusion depths than 25 W sample, such as 5 W, 45 W and 55 W.

4. Discussion

4.1. Silicon film properties

A positive correlation between the <i> a-Si:H contacting layer deposition rate and RF power from 5 to 55 W in the Fig. 2(b) can be explained by the fact that higher RF power density enhances the electrical potential difference (U) between the two electrodes in PECVD. As a result, the concentration of free radicals in the plasma zone increases. It provides more opportunities for free radicals to react, thus <i> a-Si:H contacting layer deposition rate rises [36]. However, higher RF power density also intensifies the etching process on the substrate surface due to the increased ion bombardment effect [37]. Kobayashi et al. noted that although the etching rate slightly reduces the ideal deposition rate, the overall increase in growth rate remains significant and can still be observed with higher RF power density [38]. It can be speculated that with increasing RF power, the enhanced ion bombardment not only promotes etching at the film surface but also affects the formation and stability of Si-O bonds within the SiO_x layer. Higher plasma energy may disrupt existing Si-O bonds, leading to a local reduction in oxygen content or a restructuring of the bonding network. Simultaneously, the elevated concentration of reactive oxygen species at higher RF power



Fig. 7. Doping profiles from ECV measurements of n^+ poly-Si passivating contacts with different $\langle i \rangle$ a-Si:H contacting layer realized by PECVD (different RF power) or LPCVD (reference).

could facilitate reoxidation processes, resulting in a complex interplay between bond breaking and bond reforming. This dynamic competition might explain the observed variations in the Si⁴⁺ content and the overall stoichiometry of the SiOx layers at different RF power levels. This observation aligns with the trend shown in Figs. 2(b) and 5(c).

The microstructure factor R^* serves as a crucial indicator of the bonding configuration within the a-Si:H films, which can significantly impact the underlying SiO_x properties as shown in Fig. 3(c). The increase in R^* with RF power initially suggests that increasing the power leads to increased hydrogen incorporation in the form of dihydride bonds within the <i> a-Si:H contacting layer [39]. This result aligns with previous findings by Li et al., who observed a similar trend with increasing PH₃ concentrations. This trend can be attributed to the varying nucleation rates of silicon films. Films with a high microstructure factor contain more disordered regions surrounding the surfaces of voids [40,41].

4.2. SiO_x film properties

The impact of PECVD RF power extends beyond the <i> a-Si:H contacting layer to the underlying tunnel SiO_x, particularly due to its ultra-thin nature. Two key properties of SiO_x are examined: the density of pinholes and Si^{4+} stoichiometry within the SiO_x. By analyzing Figs. 4 (c) and 5(c) together, it is observed that a high pinhole density correlates with low stoichiometry of Si⁴⁺. This suggests that intense particle bombardment from strong RF power can weaken or directly break the Si-O bonds in the PECVD process, specifically the t-SiO_x in this instance [42,43]. From a physical chemistry perspective, a lower Si⁴⁺ ratio signifies a departure from stoichiometric SiO₂, indicating the presence of sub-oxide states (e.g., Si^{2+} , Si^{3+}) or oxygen deficiencies within the film. Such non-stoichiometric regions typically possess weaker bonding networks, which can facilitate the formation and growth of pinholes. Consequently, the reduced amount of fully oxidized silicon (Si⁴⁺) correlates with a higher pinhole density. The pinhole density peaks at an intermediate RF power (25 W). It is assumed that when the power of contacting layer is less than or equal to 25 W, the etching effect of the plasma is predominant, which explains why we observe an increase in pinhole density and a decrease in Si⁴⁺ content. However, when the power exceeds 25 W, due to the accelerated deposition rate, the existing layer acts as a buffer to mitigate the impact of the kinetic energy particles on the tunneling oxide, leading to a decrease in pinhole density and an increase in Si⁴⁺ content. From the results in Figs. 3(c) and 4(c), it can be seen that the micro-structure factor does not exhibit a linear relationship with the pinhole density. In contrast, LPCVD samples, which are not affected by the plasma due to their contacting layer, inherently exhibit a lower number of pinholes and the highest Si⁴ content. The total stress in an <i> a-Si:H contacting layer comprises both intrinsic and thermal stresses which also play a role. Thermal stress arises from the differing thermal expansion coefficients of the film and the substrate as the sample cools from the process temperature to room temperature [44]. Thus, in the PECVD case, the alterations in total stress are largely due to varying intrinsic stress levels in the film while the LPCVD sample has a slightly large pinhole density due to the relatively high process temperature. Ong's findings show intrinsic stress (compressive) in a-Si increases with RF power [45]. The high compressive stress in a-Si layers is most likely due to hydrogen incorporation into the a-Si network [46], aligning with the trend observed in Fig. 3(c).

4.3. Passivating contact performance

The variation in iV_{OC} and ρ_c with RF power suggests that the deposition conditions significantly impact the electrical properties of N-TOPCon passivating contacts as presented in Fig. 6(a) and (b). In PECVD samples, as the PECVD power increases, there is a consistent pattern of change in iV_{OC} , pinhole density, and in-diffusion depth, while the contact resistivity and Si⁴⁺ exhibit exactly opposite trends. This indicates

that the changes in pinhole density and Si⁴⁺ caused by the power primarily drive the alterations in the passivation contact electrical performance. Effective doping near the surface is critical for establishing strong electric fields aiding carrier separation and reducing recombination [23,47]. When comparing the champion sample to the LPCVD case, although the LPCVD sample has a shallower in-diffusion depth, it demonstrates superior passivation behavior compared to all other cases. Three key factors need to be considered here. First, the shallower in-diffusion depth in the LPCVD sample reduces Auger recombination within the in-diffusion region [48-50], enhancing its performance. Second, as Fig. 5(c) shows, the LPCVD sample exhibits the highest Si⁴⁺ stoichiometry, suggesting that a higher-quality tunnel SiO_x layer provides sufficient surface passivation. Third, the reduced field-effect passivation due to the shallower in-diffusion does not completely negate the passivation improvements achieved by the first two factors [5,23]. According to Yang's work, when the pinhole density is below 2 \times 10⁸ cm⁻², increasing the number of pinholes promotes the field passivation effect. However, when the pinhole density exceeds 2×10^8 cm⁻², excessive doping triggers Auger recombination, which undermines passivation quality. In our experiments, the pinhole density remains below 2×10^8 cm⁻². Consequently, under the 25 W condition-where we observe a higher pinhole density-the passivation effect is actually enhanced [23].

5. Conclusion

This study systematically investigated the effects of varying PECVD RF power settings for $\langle i \rangle$ a-Si:H contacting layers coating the tunneling oxide on the n^+ poly-Si passivating contacts performance, such as $\langle i \rangle$ a-Si:H contacting layer microstructure, SiO_x integrity, pinhole density and Si^{4+} content as well as iV_{OC} and specific contact resistivity of N-TOPCon. The comprehensive analysis revealed that increased <i> a-Si:H contacting layer RF power plays a key role in changing Si⁴⁺ content and pinhole density, which might originate from the competition of the plasma etching effect and existing layer buffering effect from the kinetic energy particle bombardments. The study highlighted that the highest quality of SiOx, as indicated by the percentage of Si⁴⁺ content, was associated with adjusted <i> a-Si:H contacting layer RF power settings, effectively balancing the trade-offs between pinhole density and doping profiles. Moreover, the results from the LPCVD method provided a benchmark for high-quality deposition, suggesting that while PECVD is effective, LPCVD might also offer superior control over film quality under certain conditions. These insights into the relationship between deposition parameters, pinhole density, and doping characteristics are beneficial for developing TOPCon silicon solar cells based on the PECVD route.

CRediT authorship contribution statement

Zhirong Yao: Writing – review & editing, Writing – original draft, Supervision, Project administration, Conceptualization. Wanyu Si: Validation, Resources, Methodology, Investigation, Formal analysis, Data curation. Yingwen Zhao: Resources, Methodology, Formal analysis. Paul Procel Moya: Writing – review & editing, Methodology, Formal analysis, Conceptualization. Engin Özkol: Writing – review & editing, Resources, Methodology, Investigation, Formal analysis. Guangtao Yang: Methodology, Funding acquisition, Conceptualization. Prasad Gonugunta: Writing – review & editing, Resources, Methodology. Prasaanth Ravi Anusuyadevi: Writing – review & editing, Resources, Methodology, Formal analysis. Peyman Taheri: Writing – review & editing, Resources, Methodology, Formal analysis. Olindo Isabella: Writing – review & editing, Supervision, Resources, Project administration, Funding acquisition, Formal analysis.

Declaration of competing interest

The authors declare that there are no conflicts of interest regarding the publication of this manuscript.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.solmat.2025.113709.

Data availability

Data will be made available on request.

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