

[Influence of light element incorporation on poly-Si/SiO_x passivated contact]

Shuo Deng, Angus Gentle, Udo Roemer, Yalun Cai, Yuhao Cheng, Fiacre Rougieux, Martin Green, and Ning Song

School of Photovoltaic and Renewable Energy Engineering, UNSW, Sydney, AUSTRALIA
E-mail: shuo.deng@unsw.edu.au, n.song@unsw.edu.au

Introduction

The fabrication of poly-Si/SiO_x passivated contacts has garnered considerable attention recently, particularly with Jinko (n-type) achieving a record efficiency of 25.3±0.4% in TOPCon solar cells [1]. Owing to the high conversion efficiency and the relatively straightforward adaptability of the fabrication process, numerous companies are redirecting their production lines toward n-type TOPCon solar cells. As per the International Technology Roadmap for Photovoltaic (ITRPV), the market share of TOPCon cells is projected to reach 15% in 2023, surging to 60% by 2033 [2].

Both the academic and industrial sectors are actively exploring techniques to push the efficiency limits of TOPCon structure solar cells. The utilization of poly-Si passivated contacts on both polarities exhibits significant potential for further increasing the open-circuit voltage (V_{OC}), which also could be applied in tandem solar cell. The high absorbency of the poly-Si layer results in substantial current loss when applied to the front surface in a single junction solar cell. Consequently, employing two polarities of poly-Si on the back surface, integrated with an interdigitated back contact (IBC) structure, proves to be a more promising approach [3]. To augment the optical and electrical performance of poly-Si/SiO_x contacts, researchers are diligently investigating various modifications to the existing deposition methods. Recent studies suggest that the introduction of light elements into the poly-Si layer can enhance passivation and optical performance [4-6]. Nonetheless, the underlying mechanism is still under exploration.

The exploration of the potential for incorporating light elements holds significant academic and commercial value. This research aims to delve into the optical properties of plasma-enhanced chemical vapor deposition (PECVD) a-Si/poly-Si and investigate the impact of nitrogen incorporation on the optical and passivation performance of poly-Si.

Experiments

In this investigation, intrinsic poly-Si is deposited through plasma-enhanced chemical vapor deposition (PECVD), and the incorporation of light elements is facilitated by introducing Ammonia (NH₃) gas during the deposition process. For optical assessments, poly-Si is deposited on a single side of highly transparent quartz samples, followed by annealing with rapid thermal processing (RTP) to attain various crystallinity levels, which are subsequently measured using Raman spectroscopy. The optical constants of the films are ascertained through ellipsometry measurements and fitted with Wvase software. Raman spectroscopy is employed to gauge the crystallinity of poly-Si and the variation of hydrogen content in amorphous silicon (a-Si) films. Additionally, optical microscopy is utilized for micro-structure analysis. The acquired data are then input into OPAL2 [7] and SunSolve [8] simulations to estimate front and rear surface current losses. The cell structures used in the simulations are depicted in Figure 1.

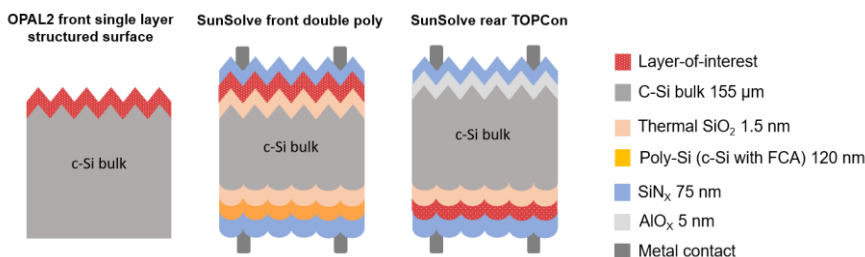


Figure 1. Illustrations for cell structure used in OPAL2 and SunSolve simulations for current loss estimation in this work

The process flow and structure of the lifetime samples are depicted in Figure 2 a) and b), respectively. The lifetime samples are fabricated using n-type Cz-Si wafers. The laser-cut tokens undergo RCA cleaning and HF dipping to eliminate any oxide, followed by thermal oxidation to cultivate a thin layer of tunnel oxide. Subsequently, they are double-side deposited with PECVD poly-Si, incorporating varying NH₃ gas flows to introduce nitrogen elements into the films. After diffusion, the phosphosilicate glass (PSG) is removed. The samples undergo characterization using a Sinton lifetime tester.

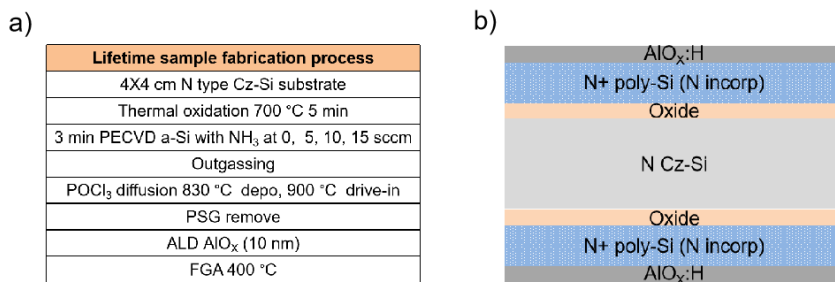


Figure 2. a) Process flow for lifetime sample preparation; b) lifetime sample structure

Results and discussion

1. Absorption coefficient of PECVD intrinsic a-Si/poly-Si on quartz

In Figure 3a), the alteration in the absorption coefficient of intrinsic a-Si:H deposited at 250 °C using PECVD is illustrated. The absorption coefficient of a-Si increases, and the bandgap decreases from the as-deposited state at 250 °C to 660 °C. Figure 3c) suggests that this change is associated with the effusion of hydrogen from the films. For annealing temperatures above 660 °C, the absorption coefficient decreases from 300-800 nm, correlating with the subsequent increase in crystallinity, as demonstrated in Figure 3d). Figure 3b) displays the simulated current loss at the front surface. With a single-layer structure, the front surface current loss escalates from 250 to 660 °C, subsequently decreasing as the film undergoes crystallization. The front surface current loss then stabilizes with further increases in anneal temperature. In terms of rear surface current loss, the variation is less pronounced, remaining approximately constant at 0.11 mA/cm²/10 nm, irrespective of crystallinity and hydrogen content.

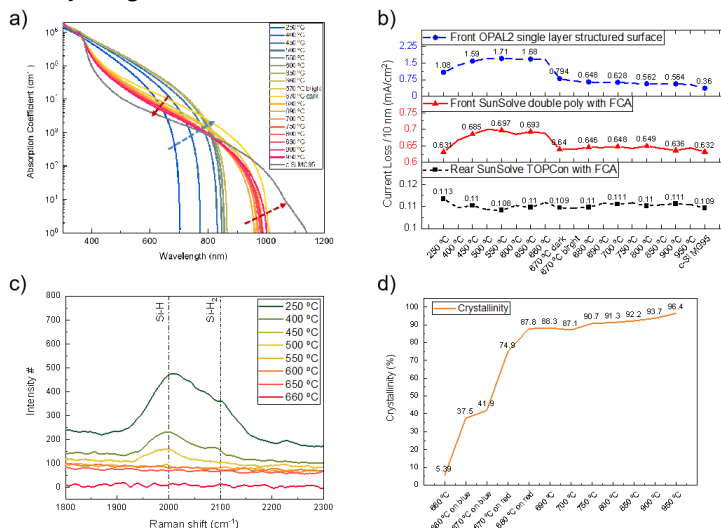


Figure 3. a) Absorption coefficient of PECVD intrinsic a-Si deposited at 250 °C, annealed up to 950 °C; b) front and rear surface current loss from OPAL2 and SunSolve simulations

Figure 4 below displays microscopy images capturing the crystallization process of a-Si on quartz, commencing at 660 °C, where small crystals begin to emerge (depicted as red dots). Other regions exhibiting a blue colour indicate amorphous silicon. As the temperature increases to 670 °C, the crystals grow larger, covering a greater portion of the film. By the time the temperature reaches 690 °C, the film is visually fully crystallized. It is important to note that although the film may appear fully crystallized, further enhancement of crystallinity can be achieved through additional annealing, either by adjusting the temperature or extending the duration of the process.

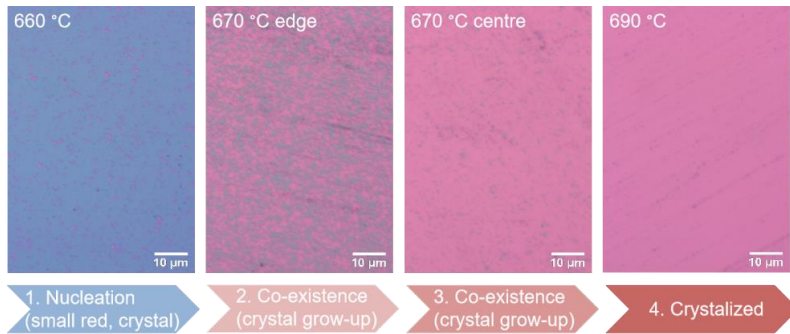


Figure 4. a) Microscopy images showing crystallization process of PECVD i-a-Si/poly-Si

2. Absorption coefficient of N incorporated PECVD a-Si/poly-Si on quartz

N-incorporated PECVD a-Si films were produced by introducing NH₃ during deposition, employing various gas flows of 10, 15, 20, and 25 sccm, followed by annealing at 950 °C for 20 minutes. In Figure 5a) and c), the absorption coefficient and bandgap variations of a-Si/poly-Si with different NH₃ gas flows are presented. Figure 5b) and d) exhibit opposing trends in front current loss from OPAL2 single-layer and SunSolve double poly structures for a-Si and 950 °C annealed poly-Si as NH₃ gas flow increases, suggesting the correlations with the topping layer within a multi-layer structure solar cell. While the rear surface current loss shows a slight increase with gas flow in Figure 5b), no significant change is observed in Figure 5d).

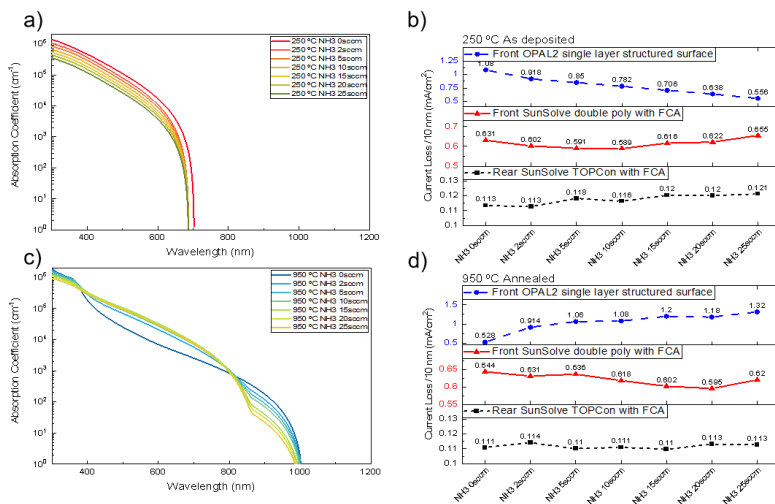


Figure 5. a) absorption coefficient, b) current loss simulation of 250 °C as-depo a-Si with N incorporated; c) absorption coefficient, d) current loss simulation of 950 °C annealed poly-Si with N incorporated

3. Lifetime of light element incorporated poly-Si/SiO_x contacts

Figure 6 illustrates that the incorporation of nitrogen (N) improves the passivation of PECVD-deposited poly-Si/SiO_x contacts. The most favourable results for poly-Si without N incorporation include a lifetime of 2.117 ms, an intrinsic open-circuit voltage (iV_{OC}) of 722 mV, and a saturation current density ($J_{0,S}$) of 4.21 fA/cm². On the other hand, the best-performing N-incorporated sample, introduced with NH₃ at 15 sccm, attains a lifetime of 2.85 ms, an iV_{OC} of 732 mV, and a $J_{0,S}$ of 2.47 fA/cm². The improvement could be resulted from the crystallinity, H content, or doping profile et al., changes introduced by N incorporation. Further investigation on the underlying mechanism is underway.

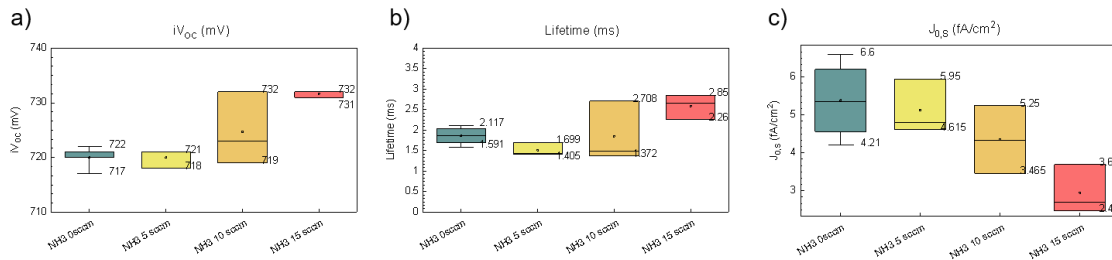


Figure 6 a) Lifetime results; b) iV_{OC} results; c) $J_{0,S}$ results for N⁺ Poly-Si samples fabricated from PECVD intrinsic a-Si and N incorporated a-Si.

Conclusion

In order to gain a more profound understanding of how the incorporation of light elements influences the optical properties and passivation quality of poly-Si/SiO_x contacts, we conducted experiments to explore their impact on the absorption coefficient and crystallinity of PECVD a-Si/poly-Si. Current losses at the front and rear surfaces from PECVD a-Si/poly-Si were extracted from OPAL2 and SunSolve simulations with different sample structures. The results demonstrate that the incorporation of light elements leads to a reduction in current loss at the front surface, particularly when combined with a silicon nitride (SiN_x) antireflective coating (ARC) layer. Additionally, it enhances the passivation quality of PECVD poly-Si/SiO_x contacts.

References

- Green, M.A., et al., *Solar cell efficiency tables (Version 63)*. Progress in Photovoltaics: Research and Applications, 2023: p. 1-11.
- (VDMA), V.D.M.u.A., *International Technology Roadmap for Photovoltaic (14th edition, Mar 2023)*. 2023.
- Kopecek, R., et al. *Interdigitated Back Contact Technology as Final Evolution for Industrial Crystalline Single-Junction Silicon Solar Cell*. in *Solar*. 2022. MDPI.
- Du, H., et al., *Blistering-Free Carbon-Doped Polysilicon Passivating Contact with a High Effective Lifetime of 18 Milliseconds Prepared by Industrial Tube Pecvd*. Available at SSRN 4546666.
- Lin, Y., et al., *Dual-functional carbon-doped polysilicon films for passivating contact solar cells: regulating physical contacts while promoting photoelectrical properties*. *Energy & Environmental Science*, 2021. **14**(12): p. 6406-6418.
- Lin, N., et al., *Excellent surface passivation of p-type TOPCon enabled by ozone-gas oxidation with a single-sided saturation current density of ~ 4.5 fA/cm²*. *Solar Energy*, 2023. **259**: p. 348-355.
- McIntosh, K.R. and S.C. Baker-Finch. *OPAL 2: Rapid optical simulation of silicon solar cells*. in *2012 38th IEEE Photovoltaic Specialists Conference*. 2012. IEEE.
- PVLIGHTHOUSE. *SunSolve Power – v6.20.7*. 2023.