SiliconPV 2025, 15th International Conference on Crystalline Silicon Photovoltaics

Advances in Industrial Silicon Solar Cells

https://doi.org/10.52825/siliconpv.v3i.2694

Maskless Patterning of Laser Activated p+ poly-Si Layers and the Fast Firing Stability of Patterned p+ poly-Si layers

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Abstract. Advanced TOPCon solar cells with local p+ poly-Si/SiO_2 passivation stacks under the front metal contacts can be a future replacement for the current TOPCon baseline design. The local p+ poly-Si/SiO_2 layers eliminate the metal-induced recombination on the front side, and the local placement of these layers prevents high parasitic absorption losses. Laser activation of p+ poly-Si/SiO_2 layers provides an etch stop layer and allows for maskless patterning of these layers in alkaline solution. Patterning in this work refers to removing the poly-Si layer and texturing the substrate in the areas that are not laser-activated. In the laser activation step, the laser processing parameters must be carefully selected to entirely melt and activate the poly-Si layer without damaging the SiO_2 layer beneath. Since partially activated poly-Si layers are not fully etch resistant in alkaline solution, patterning step removes the partially activated poly-Si layer and lowers the passivation quality. Even though the fully activated and patterned p+ poly-Si/SiO_2 layers show similar passivation quality as non-patterned p+ poly-Si/SiO_2 layers before the fast firing step, the fast firing step degrades the passivation quality of the patterned samples. However, an additional re-hydrogenation step in the fast firing furnace can restore the passivation quality of the patterned samples. This fast and industrially feasible re-hydrogenation method ensures a good passivation quality of p+ poly-Si/SiO_2 layers in the final fabricated solar cell.

Keywords: Laser Activation, p+ poly-Si, Passivated Contact, Advanced TOPCon Solar Cells, Fast Firing Stability, Re-Hydrogenation

1. Introduction

Tunnel oxide passivated contact (TOPCon) solar cells are currently the mainstream in industrial mass-production of crystalline silicon (c-Si) based solar cells. One of the main limiting factor towards higher conversion efficiency of TOPCon baseline solar cell is the metal-induced recombination on the front side due to the direct screen printing of the Ag/Al metal contacts at the front boron diffused emitter [1]. Recently, the introduction of Laser Enhanced Contact Optimization (LECO) process paved the way to use pure Ag-paste on front side emitter not only resulting in low contact resistivity on the front side, but also in reduction of metal-induced recombination losses to some extent [2]. To further suppress this metal-induced recombination source, however, and obtain the recombination values similar to that of rear layers (n+ poly-Si/SiO_2), a stack of p-type doped poly-Si and silicon oxide layer (p+ poly-Si/SiO_2) can be used on the front side. However, to avoid the high parasitic absorption from the doped poly-Si layer as well as reflection losses from the flat poly-Si layer on the front side [3], p+ poly-Si/SiO_2

stacks must be implemented locally under the front metal contacts, which requires the patterning of these passivation stacks. In 2021, a mask-less patterning method of p+ poly-Si/SiO_2 layers was introduced to avoid complex masking steps [4]. In this method, laser irradiation is used to increase the active boron concentration in the laser treated areas [5,6]. The high active boron concentration in the laser treated area provides an etch stop layer in an alkaline solution. Thus, the laser irradiated parts of poly-Si layer remain after the wafer is immersed in an alkaline solution, while the not irradiated regions are etched and results in a local p+ poly-Si layers. This method is already successfully demonstrated in lab-scale fabrication of advanced TOPCon cells as schematically shown in Figure 1 and described in Ref. [7], and poly-Si passivated IBC solar cells [8].

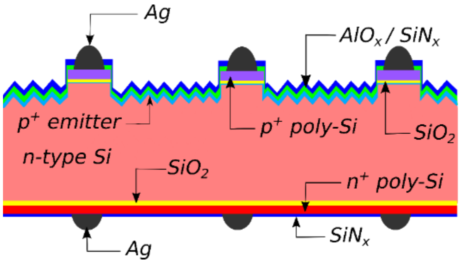

Figure 1. *Advanced TOPCon solar cell with a local p+ poly-Si/SiO_2 passivation stack under the front metal contact [7].*

This work studies the influence of laser activation process on the etching resistivity of laser activated local p+ poly-Si/SiO_2 stacks, by observing changes in the passivation quality of p+ poly-Si/SiO_2 layers. Additionally, the firing stability of the passivation quality of local p+ poly-Si/SiO_2 stacks is investigated.

2. Experimental approach

The process for fabricating symmetrical lifetime samples began with the saw damage etching and cleaning of the n-type Czochralski (Cz) silicon substrates in a mixture of sulfuric acid (H_2SO_4) and hydrogen peroxide (H_2O_2). The cleaned substrates were then thermally oxidized in a tube furnace to form an interfacial SiO_2 layer. This step was followed by low-pressure chemical vapor deposition (LPCVD) of intrinsic poly-Si layers. These intrinsic poly-Si layers were lightly doped in the subsequent furnace boron diffusion. The subsequent laser activation step was performed on square fields using a green laser with various laser pulse energy densities (H_P). In order to assess the effect of the patterning step on the passivation quality of the laser-activated p+ poly-Si/SiO_2 layers, one group of samples underwent a patterning step of wet etching in KOH solution, whereas the patterning step was skipped for another group. Subsequently, these lifetime samples were annealed at optimum annealing temperature of T_{anneal} = 985°C for 30 minutes in nitrogen ambient to increase the passivation quality [6]. The passivation quality was measured in terms of implied open circuit voltage (iV_{oc}) using the quasi-steady-state photoconductance (QSSPC) method after silicon nitride (SiNx:H) deposition and after a fast firing step.

3. Observation and discussion

3.1 Effect of the patterning process on passivation quality

Figure 2 compares the iV_{oc} of the samples with and without the patterning process after SiN_x:H deposition without the firing step. The dependence of iV_{oc} on laser pulse energy density is divided into four zones, based on the definition in ref [5]. Samples including the patterning process show significantly lower iV_{oc} compared to samples without a patterning step in zones

I and II. In zone I, the laser pulse energy density is not high enough to start the melting/activation of the poly-Si layer, and therefore the active boron concentration in the poly-Si layer is not high enough to provide sufficient etch resistivity. In zone II, the laser pulse starts to melt the poly-Si layer from the surface. Nevertheless, the passivation quality of the patterned samples is lower than that of the non-patterned samples in this zone. We assume that the superficial melting of the poly-Si layer is not sufficient to make the poly-Si layer etch resistant, potentially due to local under-etching via grain boundaries. We speculate that the grain boundaries in poly-Si layers are etched during the patterning step because the boron atoms located in grain boundaries are not electrically active and do not provide etch resistance. This leads to the removal of the poly-Si/SiO_2 stack due to the under etching and thus reduced passivation quality of the patterned samples in zone II. In zone III, the entire poly-Si layer is activated and becomes etch resistant (the minimum laser pulse energy density required to melt the entire poly-Si layer is marked as H_T). Here, similar iV_{oc} values are measured for both samples with and without the patterning step. This shows that good passivation quality can be achieved even with patterning step if the entire layer is fully melted and activated. The lower iV_{oc} of the patterned samples compared to non-patterned samples for high $H_p \geq 4.6$ J/cm^2 suggests a reduced etching resistivity for samples processed with these laser pulse energy densities. The observed reduction in iV_{oc} of patterned samples is attributed to crack formation on poly-Si layers for samples irradiated with these laser pulse energy densities.

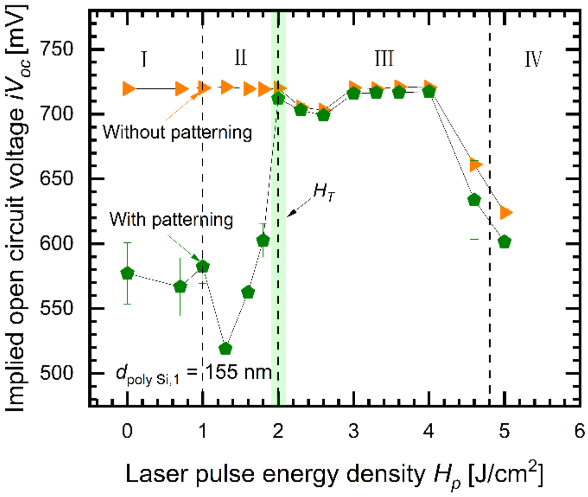

Figure 2. *For $H_p < H_T$, where laser pulse energy densities are too low to melt and activate the entire poly-Si layer, the patterning process significantly reduces iV_{oc}. Once the activation of the poly-Si layer is complete, similar iV_{oc} values are measured for samples with and without the patterning step. Excessive laser pulse energy densities of $H_p = 4.6$ J/cm^2 and $H_p = 5$ J/cm^2 lead to a reduction in the passivation quality of patterned samples. This figure is taken and edited from [9].*

3.2 Firing stability of p+ poly-Si/SiO_2 stacks

Figure 3 shows the stability of the passivation quality of patterned and non-patterned p+ poly-Si/SiO_2 stacks after the fast firing step. For non-patterned samples in (a), the fast firing step improves the passivation quality in all laser processing zones with minor improvements in iV_{oc}. However, for patterned samples in (b), the fast firing step shows different effects on the passivation quality in different laser processing zones. In zones I and II, where the etching resistance is not established, the patterning process results in a textured c-Si surface. In these zones, the passivation of textured c-Si surfaces relies only on passivation from the SiN_x:H layer. On the contrary, the passivation quality in zone III is provided by the poly-Si/SiO_2 passivation stack, which provides a higher passivation quality compared to SiN_x:H passivation in zones I and II. However, the fast firing step degrades the passivation quality in zone III.

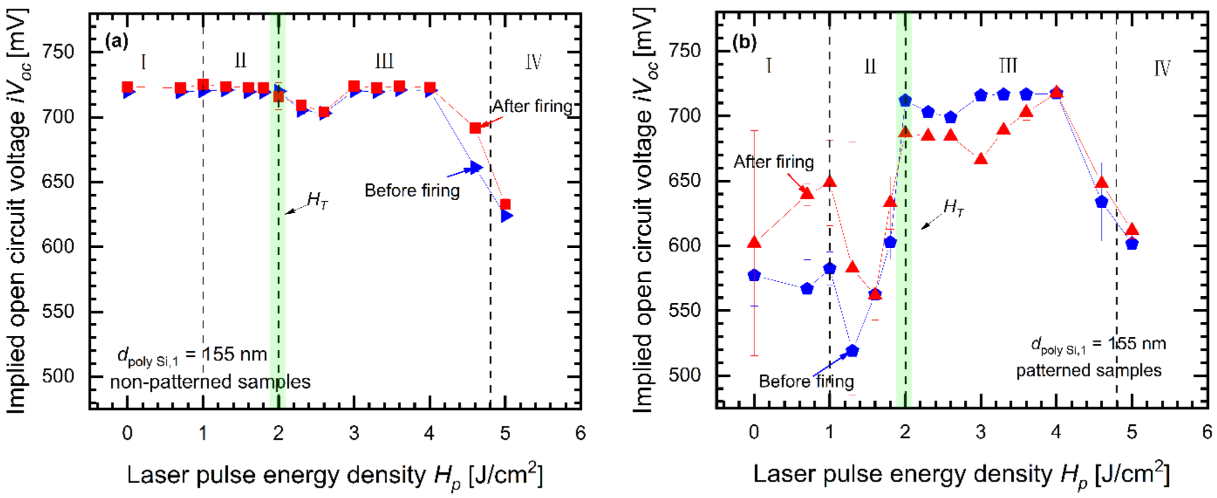

Figure 3. *For non-patterned samples in (a), slightly higher iV_{oc} values are measured in all laser fluence zones after the fast firing step. For patterned samples in (b), in zones I and II, poly-Si layers are removed during the patterning step due to incomplete etching resistivity, and hence the remaining textured c-Si surface is passivated only with the SiN_x:H layer. The increased hydrogen release during the fast firing step improves the passivation quality of textured c-Si in these zones. In zone III, however, the etching resistivity is established, and hence the surface is passivated with poly-Si/SiO_2 stacks. The fast firing step reduces iV_{oc} values in this zone.*

4. Passivation loss mitigation

The observed passivation degradation in zone III needs to be overcome as this would be a processing window for manufacturing local p+ poly-Si layer and where the maximum passivation quality is achieved. As mentioned above, we hypothesize that the grain boundaries in the poly-Si layers of patterned samples are etched during the patterning step. This may result in hydrogen effusion from the poly-Si/SiO_2 interface via these etched grain boundaries during the fast firing step, resulting in passivation degradation. Based on this assumption, two different approaches are tested to recover the passivation quality by re-hydrogenation of the poly-Si/SiO_2 interface. In the first approach, the SiN_x:H layer is removed in hydrofluoric acid (HF) after firing degradation and a fresh SiN_x:H layer is deposited. In the second approach, the fast firing furnace is used to stimulate the hydrogen release from the existing SiN_x:H layer.

4.1 SiN_x:H re-deposition

Figure 4 shows iV_{oc} values of lifetime samples directly after the first SiN_x:H deposition, after the fast firing step, and after re-deposition of the SiN_x:H layer on the same samples following removal of the initial SiN_x:H layer. As expected, the samples have a high iV_{oc} value after the first SiN_x:H deposition. However, after the fast firing step, lower iV_{oc} values are measured for the same samples due to the firing degradation that was also shown above. After SiN_x:H removal and re-deposition, the passivation quality increases again to almost the same values as before degradation. This shows that the poly-Si/SiO_2 interface is intact, and that re-hydrogenation of the poly-Si/SiO_2 interface can almost completely restore the passivation quality.

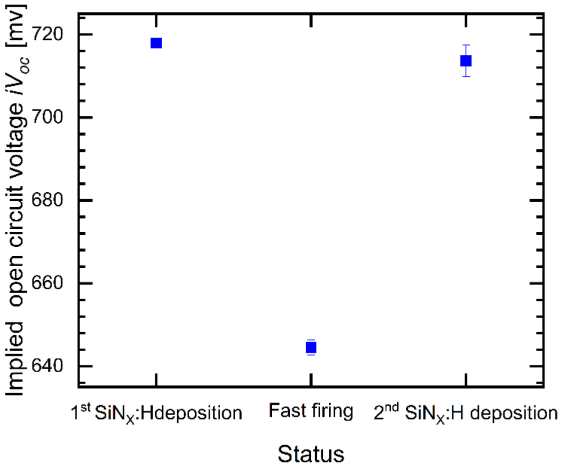

Figure 4. *The high iV_{oc} values measured after the SiN_X:H deposition drops to the lower values after the fast firing step. However, removal of the SiN_X:H layer and re-deposition of the fresh SiN_X:H layer on the same sample results in full passivation recovery as a result of the re-hydrogenation of poly-Si/SiO_2 interface.*

4.2 Novel re-hydrogenation method

Basing from the understanding from Section 4.1, this section addresses toward establishing an industrially favorable process to recover the passivation quality.

Lelièvre J.-F et al., showed that the hydrogen release starts at T = 400°C for the N-rich SiN_x:H layers and a significant amount of hydrogen remains in the layer even after a high temperature firing at T = 810°C [9]. Since the SiN_x:H layers of our test samples were also N-rich layers, we used the existing SiN_x:H layers for re-hydrogenation of the poly-Si/SiO_2 interface. In this method we used the fast firing furnace with a constant peak firing temperature of T = 450°C in all zones to stimulate the hydrogen release from the SiN_x:H layers after processing the samples with a standard firing profile that is typically used for contact firing.

Figure 4 shows the effect of the re-hydrogenation method on the patterned and non-patterned samples. For the non-patterned samples in (a), where the samples were not degraded upon contact firing, the re-hydrogenation method does not significantly change the passivation quality and only slightly increases the iV_{oc} values. However, for the patterned samples in (b), the re-hydrogenation method improves the passivation quality in all processing zones. Notably, also in zone III, where the firing degradation had been observed. The passivation quality in this zone almost fully recovered and the iV_{oc} of the samples raised again to the non-degraded level.

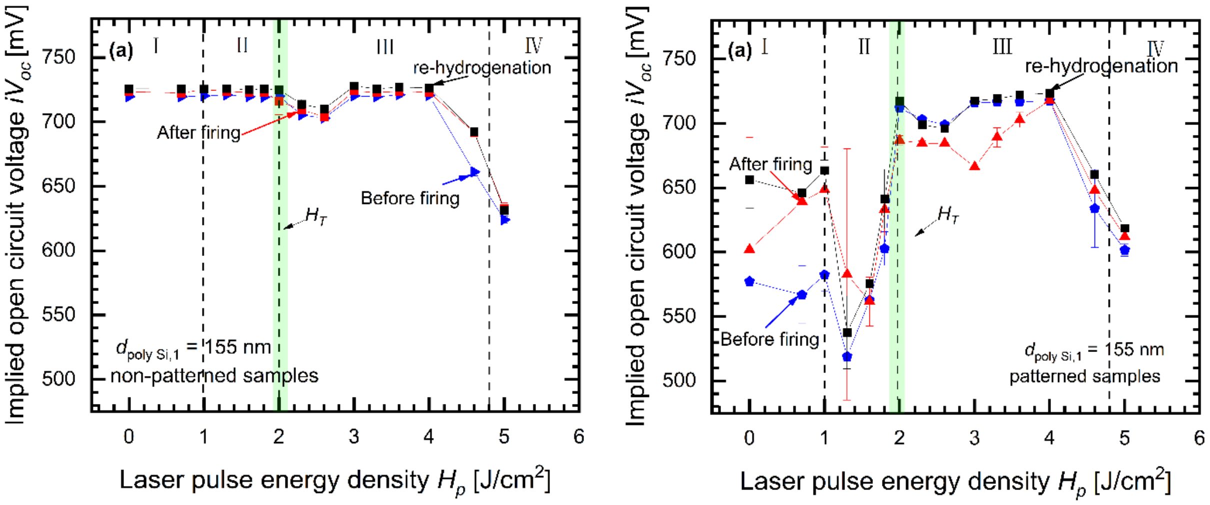

Figure 5. *(a) The re-hydrogenation step results in a minor increase of the iVoc for non-patterned samples in all zones. (b) For patterned samples, the re-hydrogenation step recovers the passivation quality in zone III and results in the same iVoc before the firing degradation step.*

5. Conclusion

Laser activation allows for maskless patterning of p+ poly-Si/SiO$_2$ passivation stacks for advanced TOPCon and IBC solar cell designs. The similar iV_{oc} of the patterned and non-patterned samples leads to the conclusion that the patterning process does not have a detrimental effect on the lower passivation quality of p+ poly-Si/SiO$_2$, provided that the laser processing parameters are properly chosen. Although the passivation quality of the patterned samples is initially degraded after a standard process for contact firing, a fast and simple re-hydrogenation step in a conventional conveyor belt furnace can restore the passivation quality of the patterned passivation stacks. Such local p+ poly-Si/SiO$_2$ passivation stacks can therefore be used in advanced TOPCon and poly-Si passivated IBC solar cells [8].

Data availability statement

Data supporting the figures and tables in this article are available from the authors upon request.

Author contributions

Conceptualization and experiment design: S.S.K., J.H.; Methodology: S.S.K., J.H., J.L., F.B., J.L., L.J.K.; sample preparation: S.S.K.; measurements S.S.K.; writing original draft: S.S.K.; review and editing: J.H., J.L., F.B., L.J.K.; supervision: J.H.; data analysis and visualization: S.S.K.; project administration: J.H. All authors have read and agreed to the published version of the manuscript.

Competing interests

The authors declare that they have no competing interests.

Funding

This research was funded by Bundesministerium für Wirtschaft und Klimaschutz (BMWK), with a funding reference of 03EE1138A.

Acknowledgement

The corresponding author thanks Juergen Heinz Werner for his valuable insights in this study. A special thanks to Radovan Kopecek, the managing director of ISC Konstanz, for setting up the transfer of the corresponding author to ISC Konstanz. We also would like to thank all the colleagues of ISC Konstanz who helped in this study. The corresponding author also acknowledge the support of Michael Saliba, the director of the ipv Stuttgart.

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