THERMALLY STABLE SURFACE PASSIVATION BY A-SI:H / SIN DOUBLE LAYERS FOR CRYSTALLINE SILICON SOLAR CELLS

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ABSTRACT: The thermal stability of the amorphous silicon / silicon nitride double layer surface passivation on *p*-type crystalline silicon surfaces is investigated for various deposition temperatures of the silicon nitride capping layer. An increase of deposition temperature from 300°C to 400°C results in a significant improvement of the thermal stability of the surface passivation. The minimum surface recombination velocity achieved on *p*-type (1.5 Ωcm) silicon wafers is (0.75 ± 0.6) cm/s and remains at (10 ± 0.5) cm/s even after 30 min annealing at 500°C.

Keywords: amorphous silicon, surface passivation, thermal stability.

1 INTRODUCTION

Surface passivation with intrinsic, hydrogenated amorphous silicon (a-Si:H) deposited by plasma-enhanced chemical vapour deposition (PECVD) at around 225°C, results in the same low effective surface recombination velocity as thermal oxidation.[1,2,3] The much lower process temperature of a-Si:H reduces both, energy consumption and the risk of impurity diffusion into the crystalline silicon bulk.[4,5,6,7] Effective surface recombination velocities of around 2 to 5 cm/s were typically shown in literature.[4,5,6,8] Therefore, surface passivation by a-Si:H is an attractive alternative to thermally grown silicon oxide for highly efficient silicon solar cells. However, process steps like contact annealing or even screen printing require a certain thermal stability of the passivation layer. In case of screen printed pastes the passivation should withstand a few minutes at 400 to 500°C for low temperature pastes or 1 to 3 s at 900°C for standard pastes.[9]

When deposited onto the front side, an a-Si:H-film requires particularly thin films due to the strong absorption of a-Si:H for photon energies above the bandgap E_g = 1.7 eV.[10] A good compromise of high transmission and efficient passivation is achieved for approximately 10 nm-thick a-Si:H-films [11]. Up to now, the thermal stability of amorphous silicon based passivation schemes utilizing such thin a-Si:H films is only demonstrated to be sufficiently stable for process temperatures up to 400°C. Plagwitz et al.[5] and Bentzen et al.[8] showed that placing a silicon nitride (SiN_x) layer on top of the a-Si:H film improves the thermal stability of the surface passivation. Their SiN_x films were deposited in the temperature range $T_{dep,SiN}$ = (220…250)°C, which is identical to the range for depositing a-Si:H films. Their a-Si:H / SiN_x double layer passivation with a 10 nm thick a-Si:H layer and $T_{dep,SiN}$ = 230°C is stable for 10 min at 400°C but degrades significantly at 500°C.[5] Furthermore, Bentzen et al.[8] demonstrated that the thermally-induced degradation of the surface passivation is due to the effusion of hydrogen from the a-Si:H film.

A further improvement of the thermal stability of a-Si:H/SiN_x double layer passivation schemes may therefore result from further increasing the density of the SiN_x capping layer, or by increasing its ability to release hydrogen towards the passivating a-Si:H layer during annealing. The density of PECVD-deposited silicon nitride is known to increases with increasing deposition temperature.[12] In this work we therefore deposit the SiN_x capping layer at higher temperatures (300°C and 400°C) than the passivating a-Si:H film was deposited. Our aim is to provide an effective surface recombination velocity in the range of (10…100) cm/s even after annealing at temperatures of 500°. Such recombination velocities are sufficient for PERC-type solar cells, which typically feature rear contact coverages from 1% to 5% of the cell area. Recombination in these non-passivated areas alone would typically contribute to the *total* rear surface recombination velocity with (50…150) cm/s.[13]

2 EXPERIMENTAL

The samples are shown in Figure 1 and are prepared in the following way: The *p*-type, boron-doped, float zone silicon wafers with a resistivity of 1.5 Ωcm and a thickness of 300 µm are RCA-cleaned: 10 min in NH_4OH / H_2O_2 / H_2O, followed by a dip in diluted HF (1%), then 10 min in HCl / H_2O_2 / H_2O, followed again by a dip in diluted HF (1%).

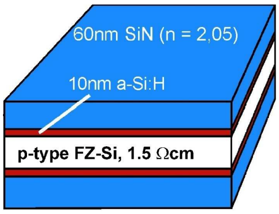


Figure 1: Schematic structure of the investigated *p*-type, boron-doped wafers. The 10 nm thick a-Si:H passivation layer is on both sides capped by a 60 nm thick SiN_x (n = 2.05) layer.

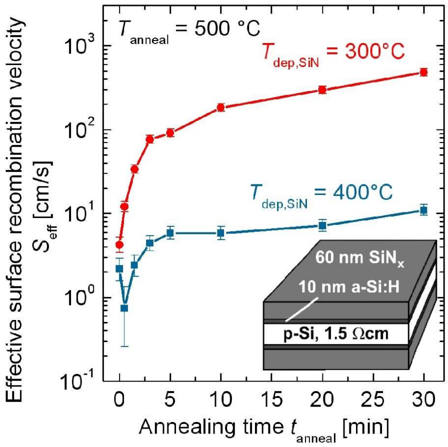
Subsequently the surfaces are covered by a 10 nm-thick a-Si:H film deposited by PECVD at $T_{dep,a\text{-}Si}$ = 225°C. A 60 nm-thick SiN_x layer with a refractive index of n = 2.05 deposited by PECVD at $T_{dep,SiN}$ = 300°C and 400°C caps the a-Si:H-film.

The samples are annealed at either 500 or 600°C on a hotplate for up to 30 min. We deduce the effective surface recombination velocity S_{eff} of the *p*-type wafers from quasi-steady state photoconductance (QSSPC) measurements.[14,15]

3 RESULTS AND DISCUSSION

Figure 2a shows the effective surface recombination velocity of the a-Si:H / SiN_x passivated *p*-type wafers as a function of the annealing duration at 500°C. $S_{eff} = (3 \pm 2)$ cm/s is obtained before annealing for both $T_{dep,SiN} = 300°C$ and $T_{dep,SiN} = 400°C$.

a) Annealing at 500°C



b) Annealing at 600°C

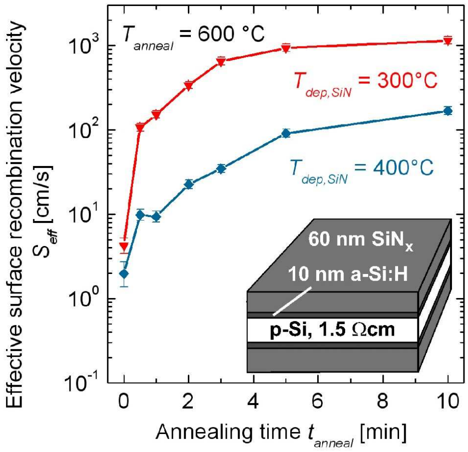


Figure 2: Effective surface recombination velocity of low-resistivity boron-doped (1.5 Ωcm) FZ-Si wafers passivated by a-Si:H / SiN_x as a function of annealing time **(a)** at 500°C and **(b)** at 600°C. The thermal stability of samples with $T_{dep,SiN} = 400°C$ is significantly better than that of samples with $T_{dep,SiN} = 300°C$. The lines are guides to the eye.

The effective surface recombination velocity of samples with $T_{dep,SiN} = 400°C$ stabilizes at around $S_{eff,400} = (10 \pm 0.5)$ cm/s even after 30 min annealing at 500°C. A short anneal of 30 s at 500°C even improves the surface passivation, providing an effective surface recombination velocity of $S_{eff,400} = (0.75 \pm 0.6)$ cm/s. In contrast, samples with $T_{dep,SiN} = 300°C$ show a steady increase of S_{eff} during annealing: Their effective surface recombination velocity is around 100 cm/s already after three minutes at 500°C. It increases continuously to more than 500 cm/s after 30 min. Thus samples with $T_{dep,SiN} = 400°C$ show up to 1.5 orders of magnitude lower effective surface recombination velocity than samples with $T_{dep,SiN} = 300°C$.

Figure 2b shows that during annealing at 600°C the effective surface recombination velocity of samples with $T_{dep,SiN} = 300°C$ increases within a few seconds above 100 cm/s. It stabilizes at around $S_{eff,400} \approx 1000$ cm/s already after 3 min annealing at 600°C. The effective surface recombination velocity of samples with $T_{dep,SiN} = 400°C$ increases more slowly and results in only (175 ± 10) cm/s after annealing for 10 min. Note that $S_{eff,400}$ remains below 10 cm/s for one minute annealing at 600°C.

The results shown in Figures 2a and 2b demonstrate that an increase of the SiN_x deposition temperature from 300°C to 400°C results in a significant increase of the thermal stability of the passivation. Increasing the SiN_x deposition temperature above 450°C, however, leads to degradation in the surface passivation quality (not shown in the figures). Stacks with $T_{dep,SiN} = 300°C$ show no improvement compared to results already shown by Plagwitz et al. who investigated the same stack system with $T_{dep,SiN} = 230°C$.[5] These results imply that the optimum deposition temperature of the SiN_x capping layer is in the range of (300 … 450)°C.

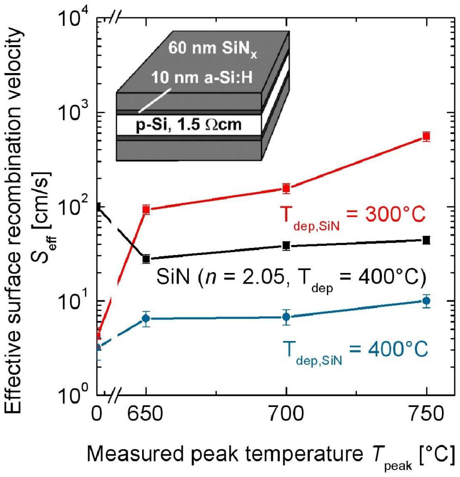


Figure 3: Effective surface recombination velocity S_{eff} of a-Si:H/SiN_x passivated low-resistivity (1.5 Ωcm) boron-doped FZ-Si lifetime samples (see inset) as a function of the measured peak temperature T_{peak} in the belt furnace. The lines are guides to the eye.

We annealed both, *p*-type and n^+pn^+-samples in a belt furnace, in order to simulate the thermal budget during contact firing of conventional metallization pastes. The measured peak temperature was 650, 700 and 750°C. The transit time through the peak temperature zone is in each case 6 s. We obtain $S_{eff,400} = (10 \pm 5)$ cm/s and $J_{0e,400} = (10 \pm 1)$ fA/cm^2 after the firing process even with a peak temperature of 750°C. These values are similar to the ones measured in the as-deposited state, as shown above.

4 CONCLUSIONS

In conclusion, an excellent surface passivation with $S_{\mathrm{eff}} = (0.75 \pm 0.6)$ cm/s on *p*-type surfaces is achieved with our a-Si:H / SiN_x stacks. The obtained surface recombination velocities are as low as to those typically achieved with high-quality passivation by a thermally grown oxide. The thermal stability of the surface passivation by a-Si:H / SiN_x is significantly enhanced by increasing the deposition temperature of the SiN_x layer from 300°C to 400°C. Our double layer passivation scheme allows for a stable $S_{\mathrm{eff}} \approx 10$ cm/s even after 30 min annealing at 500°C, and after firing for a few seconds in the belt furnace. Samples with $T_{\mathrm{dep,SiN}} = 400$°C show a 3 orders of magnitude lower effective surface recombination velocity after 30 min annealing at 500°C than samples with a single a-Si:H layer as shown in Reference [5].

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