PLASMA OXIDATION FOR THE FRONT SIDE PASSIVATION OF PERC SOLAR CELLS

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ABSTRACT: A thin silicon oxide film is grown using microwave plasma oxidation (MW-PO) for improving the surface passivation quality of silicon nitride SiN_x anti reflection coating layer on crystalline silicon wafers without affecting the optical properties of the layer. The SiN_x layers deposited at different conditions of chamber pressure are found to have different optical properties. Meanwhile, inclusion of thin oxide layer did not lead to change in optics of the front-side passivation stack. The oxide thickness was varied from 1.5-2.5 nm and is found to be influenced mainly by the change in the microwave power, chamber pressure and the substrate temperature. A comparison of single layer SiN_x and the SiO_x/SiN_x stack is made for PERC solar cells, which revealed an enhancement of open-circuit voltage V_{OC} up to 7 mV for the stack layer suggesting a positive effect of plasma-based oxidation on the emitter surface passivation.

Keywords: Plasma oxidation, PECVD, PERC solar cells

1. INTRODUCTION

Excellent passivation of surface and bulk of the solar cell is the basis to reach high conversion efficiencies. Plasma-enhanced chemical vapour deposited (PECVD) SiN_x is the most widely used dielectric layer deposition technology in solar cell manufacturing [1] due to its excellent anti-reflective property and a reasonably good passivation of textured and diffused surfaces. The passivation property of PECVD SiN_x is mainly attributed to the presence of significant amounts of hydrogen species that are incorporated in the layer during the deposition process [1]. Losses in the emitter region still dominate the total recombination losses in the solar cell. Thus, improving the surface passivation quality of the textured front side gets very important for high-efficiency PERC cells with optimized emitters. In terms of passivation quality, a layer stack of PECVD-deposited SiO_x/SiN_x is known in literature to potentially provide a benefit over single layer PECVD SiN_x. For instance, using a stack of PECVD SiO_x/SiN_x, Duttagupta et. al. reached a low effective surface recombination velocity (S_{eff}) of 8.15 cm s^{-1} on n-type Si (base resistivity $\rho_b \approx 1.5\ \Omega$ cm), and 35 cm s^{-1} on p-type Si ($\rho_b \approx 1.5\ \Omega$ cm) respectively [2], [3], [4]. Stacking of thermal oxide with PECVD SiN_x, Schmidt et. al. achieved S_{eff} in a range of 5-10 cm s^{-1} on p-type Si with $\rho_b \approx 1\ \Omega$ cm [5]. Bonilla et al. and Larionova et al. reached to S_{eff} of 0.17 cm s^{-1} and 0.42 cm s^{-1} using n-type Si with $\rho_b \approx 1\ \Omega$ cm and $\rho_b \approx 2.5\ \Omega$ cm respectively [5–7]. More recently, Mazzarella et al. achieved an impressive minority carrier lifetime of 1.6 ms and an implied open-circuit voltage of 686 mV by forming thin a-SiO_x:H layers of 1.5 nm thickness stacked with an amorphous silicon layer [8]. Lee et al. reached to $D_{it} = 1x10^{10}$ cm^{-2} eV^{-1} by doing pre-deposited treatment using N_2O remote plasma on p-type epitaxial Si wafers with $\rho_b \approx 5\text{-}20\ \Omega$ cm [9].

In this paper, we prepared different thin SiO_x layers by applying plasma oxidation of crystalline silicon surface using N_2O as precursor gas. First, a variation of the plasma oxidation process parameters is performed to investigate the optical properties of SiO_x/SiN_x stacks. Afterwards, SiO_x/SiN_x stacks with different optical properties are chosen and applied to symmetric lifetime samples in order to investigate the influence of plasma oxidation process parameters on minority charge carrier lifetimes (τ_{eff}) and are compared to the passivation achieved with typically used single layer PECVD SiN_x layer. Finally, PERC solar cells following a typical industrial process sequence are fabricated to investigate the benefit of applying plasma-based oxidation process, before PECVD SiN_x layer deposition, for the front-side passivation.

2. EXPERIMENTAL

Large area (15.6 cm x 15.6 cm) p-type Czochralski (CZ) wafers of $\rho_b \approx 4.8\ \Omega$ cm are used as precursors to characterize the passivation quality of dielectric films. SiO_x films are grown using 1000 sccm N_2O gas as a precursor of oxygen in Meyer Burger MAiA PECVD tool using one linear microwave (MW) plasma source driven at 2.45 GHz at substrate temperature of 400°C. The effective power of microwave source is kept high. For SiN_x deposition, silane (SiH_4) flux of 200 sccm and ammonia (NH_3) flux of 600 sccm are applied with different temperature and pressure conditions to get different SiN_x layers (see table I) :

Table I: Parameters for SiN_x deposition.

Layer	p (mbar)	T (°C)
SiN_x 1	0.10	400
SiN_x 2	0.15	400
SiN_x 3	0.25	300

The refractive index n of the SiN_x layers was determined at a wavelength of 633 nm by using M-2000 spectroscopic ellipsometer (J. A. Woollam Co.). The thickness of the oxide films were measured by spectral ellisometry. We used a native oxide model as described in ref [10]. The carrier lifetimes on symmetric p-tape Czochralski (Cz) - Si saw damaged etched for two different SiN_x 2 and SiN_x 3, and the stacks of the SiN_x layers with the same plasma oxide film are evaluated using quasi state (QSSPC) Sinton WCT 120 after firing the samples in an industrial belt furnace. For the solar cell batch as shown in Fig.1, industrially used large area *p*-type Cz-Si precursors with alkaline texture, homogeneous emitter and rear-side passivation were supplied to Fraunhofer ISE by Solar World Innovations (SWI) [11]. The test groups are passivated in the front-side by SiO_x/SiN_x layer stacks by using various plasma oxidation parameters for SiO_x and plasma deposition parameters for SiN_x layers respectively. For the reference groups, a single layer PECVD SiN_x is deposited on the front side. All the samples are then processed together into industrial PERC-type architectures by SWI and characterized.

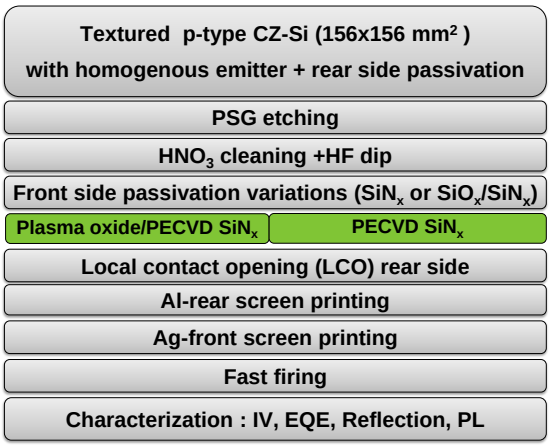

Fig. 1: Schematic of the process sequence for preparation of PERC solar cell.

3. RESULTS AND DISCUSSION

3.1 The plasma Oxidation and its Effect on Passivation

The schematic diagram of the PECVD reactor is shown in Fig.2.

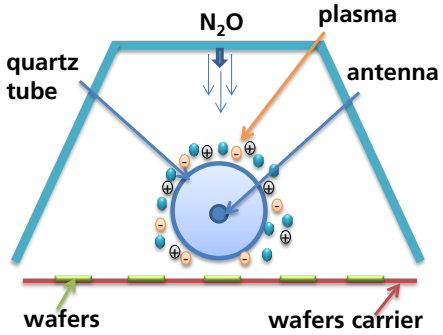

Fig. 2: Schematic diagram for the used PECVD reactor.

Here, it can be observed that N_2O flux is inserted into the reaction chamber from the top shower.
A thin SiO_x was grown at different temperatures and pressures applying a higher and a lower microwave plasma power on different samples (see parameters in Fig.3)

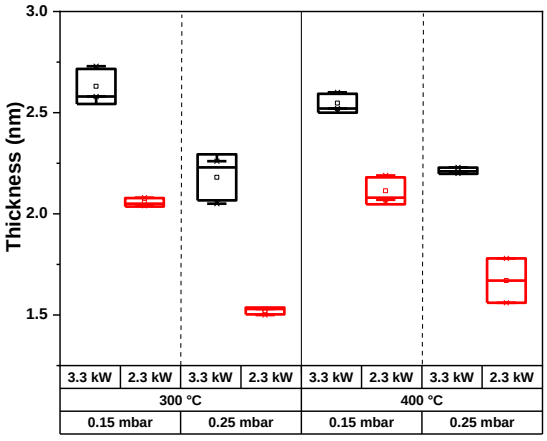

Fig. 3: Oxide thickness measured by spectroscopic ellipsometry versus, plasma power temperature and process pressure.

For all oxide films, the thickness is found to increase with increasing the microwave power, irrespective of the chamber pressure and substrate temperature. During pressure variation, we observed a lowering of silicon oxide thickness with an increasing chamber pressure. Meanwhile, the variation in substrate temperature did not lead to a significant change in the oxide thickness.

The effect of the microwave power can be explained as by Vinckier et al [12]. They showed a linear increase of the oxygen atom concentration in the plasma with increasing the microwave power. The oxide thickness in turn increases with the oxygen concentration in a sub-linear dependence.

The effect of pressure can be explained, N_2O gas is inserted into the reaction chamber from the top shower of the tool which means that confinement of the plasma (happening with higher process pressure) [13] will lead to less oxygen species that can reach to the substrate and grow as an oxide layer.
Fig.3 suggested that the oxide film of lowest thickness forms at the chamber pressure of 0.25 mbar within the investigated parameter range.

An enhancement of the lifetime for the stacks comparing to the corresponding single SiN_x layers can be seen in Fig.4.
Here, a comparison of different SiN_x layers suggests that layers deposited at the lower temperature SiN_x 3 in general show better surface passivation quality.

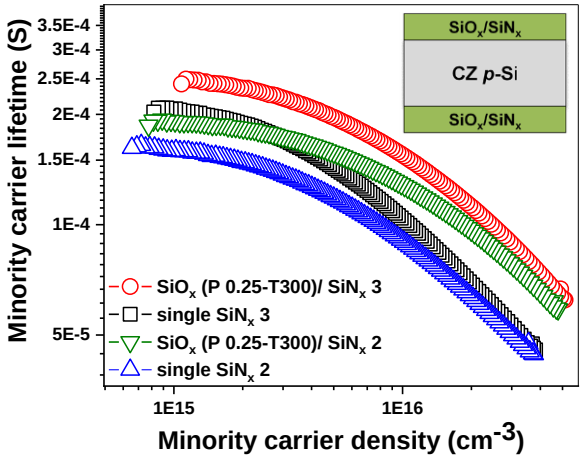

Fig. 4: Comparison of lifetime values for the symmetric samples passivated with either SiN_x or stack of plasma-oxidised SiO_x and SiN_x. The lifetime values are measured by QSSPC after the firing process.

This can be attributed to the higher hydrogen content for the layer deposited at lower substrate temperature. Higher substrate temperature will lead to the effusion of hydrogen [14]. The stack of SiO_x/SiN_x showed better passivation compared to single layer of SiN_x. This could be attributed to an improvement in the passivation of Si-SiN_x interface due to the oxidation process. For instance, Bonilla et.al reported a lower density of states for the stack of thermal SiO_x / PECVD SiN_x in comparison to single layer PECVD SiN_x [15]. The SiN_x hydrogenation is expected either during deposition and/or thermal post-deposition treatment (firing) process, which possibly leads to diffusion of H species to the Si/SiO_x interface and passivation of the

interface dangling bonds to enhance the chemical passivation [16].

3.2 Application of SiN_x and SiO_x/SiN_x in PERC Solar Cells

Finally, SiN_x and SiO_x/SiN_x layer stacks created using selected process parameter combinations (deposition temperature and chamber pressure) are used to test their applicability as front-side passivation and ARC layer in passivated emitter and rear cell (PERC) -type solar cells. For the experiments, stacks of plasma-oxidized SiO_x and PECVD SiN_x were prepared where plasma oxidation parameters are kept identical (2.3 kW, 300°C and 0,25 mbar), whereas varying the SiN_x deposition parameters. In parallel, samples with front-side passivation featuring only a single layer of SiN_x are also prepared for comparison purposes. All other process sequences used for the fabrication of PERC solar cells are kept identical. The current-voltage (I-V) characteristics of the PERC solar cells measured by industrial cell tester are plotted in Fig.6.

It is observed that the inclusion of a thin SiO_x film before depositing SiN_x showed improvements of the cell parameters. We attribute this to the enhancement of the passivation quality of the nitride as shown in the conversion efficiency (η) and open-circuit voltage (V_{OC}). Also, the thin SiOx layer did not affect the optical properties of the front side as no significant differences in short-circuit current density (j_{SC}) are observed when SiO_x/SiN_x is used instead of SiN_x as the front-side passivation layer system. Already in the first trial, we achieved a gain in V_{OC} of PERC cells by applying the plasma oxidation process before SiN_x deposition in comparison to the single layer ARC SiN_x. For the champion solar cell, an open-circuit voltage (V_{OC}) of 660 mV and short-circuit current density (j_{SC}) of 40 mA/cm^2 with a cell efficiency (η) of 20.9% is reached. Here, a higher V_{OC} is attributed to an improved front-side passivation achieved by implementing the plasma oxidation process before PECVD SiN_x.

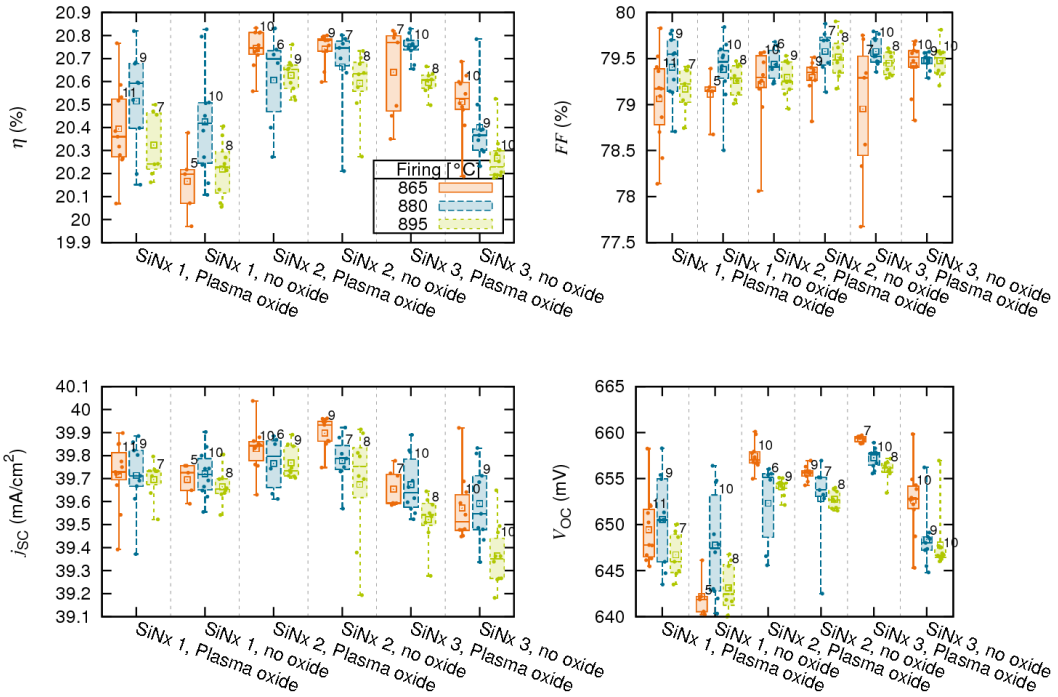

Fig. 5: *I-V* data for PERC-type solar cells with different front-side passivation scheme. The numbers next to the box plots represent the number of solar cells fabricated for each box plot.

4 CONCLUSION

The growth of a thin silicon oxide at the Si wafer surface by applying microwave plasma-activated N_2O as a precursor gas showed an enhancement in the passivation quality of the SiN_x layers without affecting the optical properties due to low thickness of the oxide film. Application of such SiN_x and SiO_x/SiN_x stacks showed a good performance of SiN_x prepared at 0.15 mbar which was enhanced by stacking with plasma oxide layer. For the champion solar cell, an open-circuit voltage (V_{OC}) of 660 mV and short-circuit current density (j_{SC}) of 40 mA/cm^2 with a cell efficiency (η) of 20.9% was reached. An improvement in V_{OC} (ΔV_{OC} up to 7 mV) was achieved corresponding to a superior front-side passivation provided by an inclusion of oxide layer before PECVD SiN_x deposition.

5 ACKNOWLEDGMENTS

The authors would like to thank the German federal ministry for economic affairs and energy for the financial support of this work in project next step under the contract number 0324171B. A. M. O. M. Okasha thanks the Egyptian government for the funding within the scope of her dissertation.

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