Passivation of p^+-Surfaces by PECVD Silicon Carbide Films – A Promising Method for Industrial Silicon Solar Cell Applications

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Abstract: We present first results of a surface passivation study of p^+-Si by amorphous SiC_x, deposited in a standard PECVD reactor. For comparison, thermally grown SiO_2 and PECVD-SiN_x layers with refractive indices of n=2.0 and n=2.4 were examined on the same test structures. While thermal SiO_2 exhibits passivating properties comparable to those on n^+-Si, PECVD-SiN_x is found to even deteriorate the surface passivation. On the other hand, PECVD-SiC_x yields, to our knowledge, the best p^+-Si pasivation so far obtained by an industrially relevant low temperature process.

Key Words: p^+-Passivation, n-Type Si, PECVD Silicon Carbide

1 Introduction

There are two important applications for the passivation of p^+-silicon (Si) surfaces: one is at back side of p-type Si solar cells in cell concepts with open rear contacts and rear side passivation. The second is for the emitter of n-type Si solar cells which might, for several reasons, hold a major and possibly even the dominant share in silicon solar cell production in the future [1].

2 Review of p^+ surface passivation

Thermally grown SiO_2 has shown excellent surface passivating properties of both n^+- and p^+-Si layers, but does not provide hydrogen for defect passivation which is especially important for the industrially dominating mc-Si and therefore requires an additional annealing step under a H-atmosphere. Another drawback are the high temperatures needed to achieve acceptable growth rates, as they usually deteriorate the bulk lifetime. Using wet oxidation, this effect is reduced, but still present in mc-Si like for the recently presented record-efficiency mc-Si solar cell from the Fraunhofer ISE [2].

The high growth temperatures also cause a surface depletion in the doping concentration of the emitter, assumed to reduce the cell efficiency due to increased surface recombination and to deteriorate the long-term stability [3].

The problem of the low refractive index of SiO_2 (n≈1.5) can indirectly be solved by growing very thin oxides (10 to 15 nm) and depositing an additional single or double layer ARC of different materials on the top. This can yield very good results, but increases the number of necessary processing steps even further.

Another principal drawback for industrial mass production is the necessity for sophisticated surface cleaning and the fact that a thermal oxide requires tube furnace processing due to the sensitivity of its passivating quality to a very well cleaned surface. Both is disadvantageous for industrial mass-production.

For those reasons, PECVD-SiN_x is the present industrial standard for the n^+-emitter of p-type Si solar cells, as it combines the advantages of good surface passivation of n^+-emitters, low deposition temperatures (usually ca. 400°C), bulk hydrogenation and a refractive index which can be adapted for various purposes by altering the Si-content of the deposited layer.

However, reported experiments on PECVD-SiN_x for the passivation of p^+-Si surfaces by Kerr [5] and Fischer [6] were unsatisfactory when using different sets of parameters approved for n^+-Si surfaces. As an explanation, both Kerr and Dauwe et al. [7] supposed independently the formation of an n-type inversion layer underneath the SiN_x due to a high fixed positive charge density within the SiN_x films, even under illumination. This leads to an injection-level dependent "depassivating" effect which could also be observed in experiments at our group.

3 Experiments

Symmetrical p^+np^+ test structures were formed using one of our standard tube-furnace BBr_3-diffusions on shiny etched 5 x 5 cm² sized 2,8 Ωcm n-type Cz-Si wafers with high initial bulk-lifetimes of ca. 500µs and a thickness of 280 µm. They exhibited a sheet resistance of 90 Ω/sq and a boron doping concentration of $4{\cdot}10^{19}$ cm^{-3} at both surfaces.

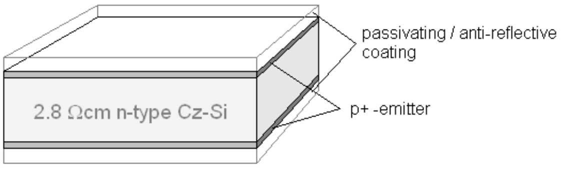

Figure 1: Structure of the samples used for the experiments

A symmetrical sample allows for easier and more precise extraction of the surface parameters by the QSSPC measurement method introduced by Sinton et al. in 1996 [4].

As the J_{oe} determined from QSSPC data does not make sense for SiN_x due to its special behaviour on p^+ Si (see also [5]), the implied V_{oc} at 1-sun illumination was used as an indicator of the surface passivation quality for comparison of the applied passivation schemes.

4 Results

The unpassivated samples exhibited a J_{oe} of ca. 1000 fA/cm^2 and an implied V_{oc} of 596±4 mV, averaged over 10 samples.

As reference, a 10 nm thin thermal oxide was grown on both sides of two samples, resulting in a J_{oe} of 80 fA/cm^2 and implied V_{oc}'s of 650 and 647mV, respectively.

Two samples received a PECVD-SiN_x coating with refractive indices of n_1=2.0 and n_2=2.4 in a direct-plasma reactor used for industrial solar cell production where the applied layers usually provide good surface passivation of n^+-emitters. The samples exhibited no improvement when measured directly after deposition, but showed clear deterioration after the usual contact firing step (without the metallic paste!). The implied V_{oc}'s decreased by 21 mV for the n=2.0 SiN_x covered sample and 29 mV for the one with the n=2.4 SiN_x which - on n^+-Si - provides better passivation than the n=2.0 SiN_x.

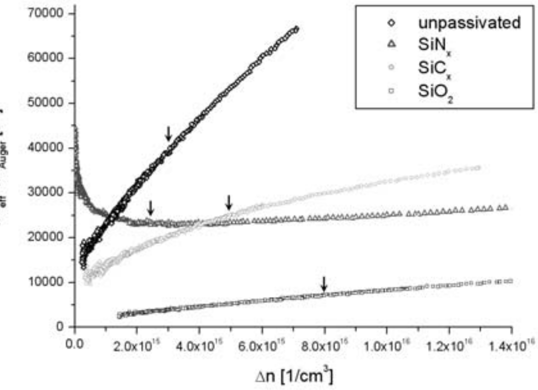

Figure 2: Special behaviour of SiN_x after a standard firing step. The arrows indicate the injection at 1-sun illumination, showing the depassivating effect of SiN_x.

In the PECVD-SiC_x experiments, deposition temperatures from 250 to 350°C were tried. Silicon carbides of two different compositions were applied: a Si-rich SiC_x which exhibited excellent surface passivation of p-type substrates [8] and also yielded the lowest j_{oe}'s achieved with SiC_x in our experiments so far, but shows relatively high absorption for wavelengths λ<500 nm when depositing films with thicknesses of 70nm and more as would be required for ARC. Secondly, a stoichiometric SiC_x which is transparent down to below 400nm wavelength and has a refractive index n around 1.97, not exhibiting an improvement in the surface passivation of p- and n-type Si wafers in past experiments at the UPC in Barcelona, but excellent for anti-reflection coating.

The best passivation was reached using a 40 nm thick layer of the Si-rich intrinsic SiC_x, deposited at 350°C.

The average implied V_{oc} yielded by this Si-rich SiC_x on four samples was 609 mV, the best one 612 mV, without profiting from increased light-coupling into the sample as the film was too thin to provide ARC properties for visible light.

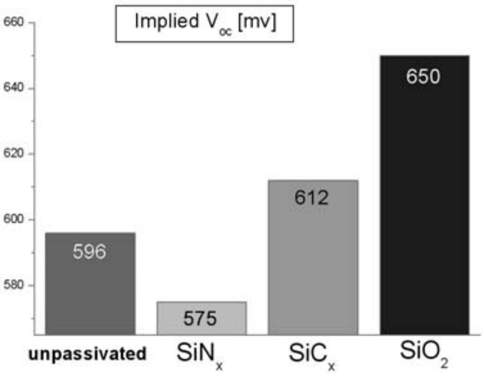

Figure 3: Comparison of p^+ surface passivation achieved in our experiments

Because of the mentioned absorptive properties of this Si-rich SiC_x, a thin layer of ca. 10nm of it was deposited, followed by an 80nm thick layer of the transparent stoechiometric SiC_x on top as ARC. This stack also reached an average implied V_{oc} of 609 mV on three samples and 610 mV as the best, probably indicating that the loss in surface passivation by the thinner Si-rich layer is compensated by the ARC illumination gain.

5 Conclusions and Outlook

PECVD-SiC_x was shown to improve the passivation of p^+-Si surfaces, here surpassing PECVD-SiN_x and, to our knowledge, yielding the best passivation so far reported for p^+-Si using a low temperature process.

Further experiments will be performed to explore the potential of PECVD-SiC_x-layers, balancing in between optimum surface passivation and best optical properties for the application on front-side p^+-emitters in n-type Si solar cells.

Using mc-Si and industrial processing steps, we will also study the firing of screen printed contacts through the SiC_x as well as its bulk hydrogenation properties. These are likely to be comparable to those of PECVD-SiN_x, as the used precursor gases are comparably rich in hydrogen.

PECVD-SiC_x has similar advantages like PECVD-SiN_x: low deposition temperatures, high deposition rates, an adjustable refractive index, and it can be deposited by high-throughput in-line PECVD processing.

6 Acknowledgements

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