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REAR SURFACE PASSIVATION FOR INDUSTRIAL SOLAR CELLS ON THIN SUBSTRATES

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ABSTRACT

The use of hydrogenated silicon nitride is one of the most significant technological evolutions that has taken place in solar cells industry, due to its ability to act simultaneously as antireflective coating as well as a source of hydrogen for surface and bulk passivation. These very same properties make it an ideal candidate for rear surface passivation in structures with local contacts, yet its application has led so far to results below expectation. This work analyses limits and phenomena that prevent the use of standard nitride as rear surface passivation layer in commercial solar cells and presents a convenient process that can be used to overcome these problems and allows the fabrication of industrial, fully screen printed, PERC-type solar cells on ultrathin substrates. By means of this technology the cell's open circuit voltage shows a significant improvement with respect to the conventional aluminum BSF and is retained all the way down to 100µm thick devices.

INTRODUCTION

The central, short term priority for photovoltaic industry is a significant reduction of the silicon content per wafer. That is, the ability to process silicon solar cells on very thin substrates. Thinner wafers would offer the possibility for higher cell efficiencies, provided that the effective rear surface recombination velocity is brought below the critical threshold of D/L (D being the diffusion coefficient and L the bulk diffusion length in the material; D/L ~900cm/s on standard material), a goal that commercial technology has so far failed to reach. A higher surface recombination velocity than D/L would mean a reduction of the cell efficiency on thinner substrates, and this is precisely what happens in the current production, with full coverage aluminium metallisation.

This paper considers the possibility to use silicon nitride as a rear surface passivation layer in commercial silicon solar cells, in different configurations. It compares different options and it presents a convenient process based on a stack system comprising a dielectric layer that can be deposited at low temperatures, capped by a dedicated silicon nitride layer.

Such dielectric shows poor surface passivation properties as it is deposited on the silicon surface, but it gets significantly improved during solar cell processing. The stack systems works at solar cell level irrespective of whether it is capped by a metallisation layer or not.

REAR SURFACE PASSIVATION BY MEANS OF HYDROGENATED SILICON NITRIDE

Amorphous hydrogenated silicon nitride layers have found a wide application in microelectronics and in particular in thin film transistors (TFTs) and solar cell technology. One of the reasons of its success in these area-driven market segments is the scalability and high throughput that can be reached with PECVD (and recently sputter) deposition systems, at an effective cost and without compromising on the electrical qualities of the layers. Moreover, the ability of SiNx:H to act simultaneously as an antireflective coating (ARC) with tunable refractive index, as well as a source of hydrogen for surface and bulk passivation, made it a mainstream technology as emitter coating in solar cell industry.

Silicon nitride, on paper, should also be the layer of choice for rear surface passivation in solar cell structures with local contacts. Very low surface recombination velocities can be attained on commercial substrates with the very same SiNx:H deposition systems which are used for ARC; nevertheless the integration of silicon nitride for rear surface passivation in solar cells with local back contacts has not led to a real breakthrough: on lab scale, high efficiency locally SiNx:H passivated solar cells are still performing worse than their SiO_2 counterparts [1]; in industrial research SiNx:H passivated solar cells do not seem to be able to perform better than standard screen printed aluminum [2].

It may be argued that the nitrides that are known to be best in surface passivation (e.g. Si-rich nitrides) are not thermally stable and therefore it is to be expected that they degrade during the repeated high temperature processing steps that occur in cell manufacturing. On the other hand any skilled user can deposit nitrides which show low surface recombination velocities after deposition as well as after a typical firing RTP profile.

In nitrides, surface passivation of silicon relies on the presence of a high density of (net) positive charges Q_f present in the layer. While the total effective fixed charge is always positive, trapped charges (Q_t) can either be positively or negatively charged, and in very rich silicon nitrides tend to increase to a value in the same order of magnitude of Q_f [3]. However, in normal operating conditions in almost any nitride the effective traps charge is positive and $Q_{eff}>1\cdot10^{12}cm^{-2}$, sufficient to generate a surface potential greater than 0.2 eV, which leads to expect effective surface recombination velocities below 100 cm/s when the density of interface states D_{it} is in the order of $10^{11}cm^{-2}eV^{-1}$ or less. Q_f and Q_t are only slightly reduced after firing.

D_{it} depends on process conditions as well as on surface preparation. In our case, the density of interface states of various types of hydrogenated nitrides deposited in a low frequency PECVD reactor was measured to be $2\text{-}3{\cdot}10^{12}cm^{-2}eV^{-1}$ after deposition, irrespective of the surface preparation, and $6\text{-}9{\cdot}10^{11}cm^{-2}eV^{-1}$ and $2\text{-}3{\cdot}10^{11}cm^{-2}eV^{-1}$ respectively, on textured and flat etched samples, after firing. Given these conditions, excellent surface passivation properties can be anticipated, and are actually measured, on free-to-air silicon nitride layers deposited on silicon substrates with nearly any recipe. Yet, these very same layers do not work satisfactorily for the rear surface passivation of industrial type PERC solar cells, and clear trends can be identified by varying deposition parameters. The reason for this is not obvious.

It has been shown that a parasitic shunting effect may take place between the SiNx:H induced floating junction and the base of the cell, via the local contacts, with the effect of increasing the effective surface recombination velocity at the nitride/silicon interface, and limiting the cell's efficiency [4]. This is, however, not sufficient to explain the extent of the losses that can be observed. A more fundamental phenomenon takes place, and the main limiting factor for cell efficiency, at present, cannot be put in correlation with a parasitic shunting effect. It is observed that there exists an interaction between the metal capping layer and the underlying silicon nitride, which can increase the effective surface recombination velocity of the rear side electrode to values above 2000 cm/s. Experiments on bifacial solar cells confirm this observation. It is possible to achieve fair open circuit voltages with the same silicon nitride which is used for front surface passivation and ARC, even when there is no separation between the latter and the rear metallization pattern (see Fig. 1).

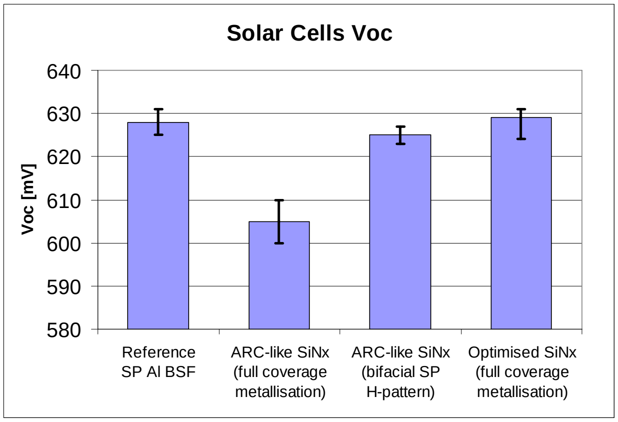

Fig. 1: Open circuit voltages of different groups of solar cells with different rear surface electrodes and surface passivation. ARC-like silicon nitride performs the worst when capped by a metal layer, but shows a significant improvement in bifacial structures. By using different recipes and moving towards nitrogen rich nitrides, it is possible to improve cell's performance. However, even the best nitrides perform, in average, only slightly better than the reference full area screen printed aluminum BSF process. The substrates were 1.5 Ohm.cm Cz, 100cm², 220µm thick.

However subsequent deposition, or print, of a full area metal layer on top of the nitride introduces an additional source of surface recombination. This has been consistently observed with a variety of metals (Al, Ag, Pd, Ti…) and cannot be related to metal diffusion or pinholes, which were carefully controlled and avoided. Removal of the metal layer restores the initial conditions and the surface recombination velocity is improved. These findings have been reproduced and confirmed at solar cell level as well as with QSSPC lifetime measurements, CDI and µ-PCD lifetime mapping on SiNx/silicon/SiNx/metal structures.

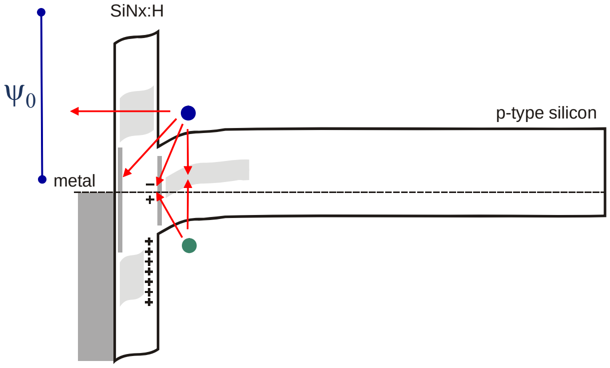

Fig. 2: Possible mechanisms for surface recombination in the Metal/SiNx:H/p-type silicon system. The silicon surface potential, hence the Shockley Read Hall recombination term, can be strongly affected by the metal work function and/or Fermi level pinning. In addition space charge region recombination, and transport-recombination effects in and through the defected SiNx layers have to be taken into account.

As a first point, it shall not be forgotten that the types of SiNx:H layers which are used in solar cells are far from behaving like ideal dielectrics. Silicon rich nitrides, in particular, have a reduced bandgap and properties similar to those of amorphous silicon. In these cases, the fact that a free-to-air nitride surface has a significantly lower recombination velocity than that of a nitride interface with a metal has a measurable effect on the effective surface recombination velocity of the sample even if it is not at direct contact with silicon. This is easily shown by the non-negligible currents which can be measured at moderate voltages applied on these MIS structures. A second crucial element is that the presence of a metal is likely to induce a shift in the surface potential of silicon, hence affecting the SHR recombination. In theory, for instance, an Al/SiNx/silicon structure should induce a surface potential corresponding to an effective charge in the order of $3\text{-}7{\cdot}10^{11}\ cm^{-2}$, sufficient to induce the semiconductor in weak inversion and therefore strongly increasing the surface recombination velocity. In practice, no correlation has been observed between the degradation of the surface passivation properties and the work function of the different metals which have been used in our experiments, leading to think that there is either a pinning of the Fermi level due to the presence of surface states or that there are concurrent phenomena in play which influence S_{eff}. Finally, space charge region recombination may also play a role at injection levels which are especially relevant for commercial solar cells operation [5].

By moving towards nitrogen rich nitrides we have experienced that it is possible to improve the solar cell performance. However, even in the best cases the cells were only slightly better than the reference cells processed in parallel with full area aluminum BSF; further on, surface passivation at cell level was still not sufficient to maintain Voc on thinner wafers.

REAR SURFACE PASSIVATION BY MEANS OF STACKS CONTAINING SILICON NITRIDE

If, on one hand, the implementation of silicon nitride for rear surface passivation brings about a handful of complications, on the other this material has several properties which are still functional to solar cell processing. To name a few, it is thermally resistant, it can be used as a mask, it contains or can store a significant amount of positive charges, and it can release hydrogen.

For this reason nitrides have already been extensively studied e.g. in stacks with thermal silicon oxides [see e.g. 6,7,8]. Both rapid thermal oxides (RTO) and 'conventional' thermal oxides (CTO) yield good surface passivation in combination with nearly any silicon nitride, irrespective of their thickness. There is a general agreement that this depends on the high density of positive fixed charges that is observed in the system (in the order of 10^{12} cm^{-2}) combined with a reduced density of interface states -even for short oxidation times- of the SiO_2/Si with respect to the SiN/Si interface. It is still argued whether there is any observable hydrogenation effect during nitride deposition and belt furnace treatment of these stacks [cfr. e.g. 5,6,9]. Stacks with thin (<20nm) thermal oxides become particularly attractive, because of their reduced thermal budget, and have been successfully implemented in solar cells, attaining laboratory efficiencies above 20% [9].

The properties of hydrogenated silicon nitride could as well be used to target dielectrics, not necessarily of grown oxide-like quality, that can be deposited at low temperature and benefit from field induced passivation and/or hydrogen release from the layer.

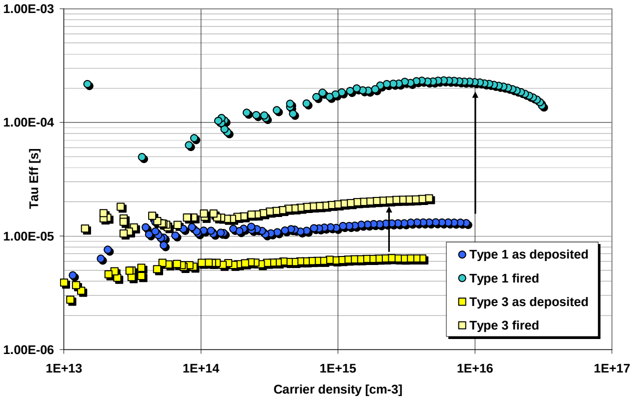

Fig. 3: Effective Lifetime of different PECVD SiOx/SiNx stacks (1.5 Ohm FZ wafers, 200µm, polished). The deposition parameters of SiOx strongly influence the surface recombination velocity of the stack system on silicon after belt furnace firing.

In a first series of experiments we have been working on SiOx deposited by PECVD from SiH_4 and N_2O precursors (Fig. 3). While the initial starting lifetimes of silicon wafers passivated with this oxide/SiNx:H stack was in the range of 8-12 µs regardless of the deposition conditions, a significant spread was observed amongst the samples after firing in a belt furnace. A clear trend was present and some of the samples showed effective lifetimes in excess of 200µs (corresponding to S_{eff}<50 cm/s). The fixed charges density Q_f across the different samples was measured to be 7 to $10{\cdot}10^{11}$ cm^{-2} before firing, and 7 to $9{\cdot}10^{11}$ cm^{-2} after firing. We can infer from these substantially constant values that the reason for the improved surface passivation is to be found in the reduction of D_{it}, due to the release of hydrogen from the SiNx layer in the stack, in a similar way as this happens for bulk silicon passivation.

Yet, none of the stacks worked better than the aluminum BSF reference at cell level. Surprisingly, the surface passivation/open circuit voltage trends mirrored each other and the best relative solar cell results were achieved with the SiOx/SiNx stacks that showed the poorest lifetime performance.

Several other stack systems yield good surface passivation, however it was found out that for proper cell performance in local contact structures it is always necessary to control their interaction with the metal capping layer. This can be done in most cases adopting a simple solution.

Presently, we process industrial type solar cells on ultrathin substrates (down to 100µm) by using one such SiNx/dielectric stack. The dielectric is deposited at temperatures below 600°C and is therefore compatible with any type of commercial substrate. The stack is insensitive to the temperature treatments which are occurring after diffusion, and is inert to the metallization process, allowing for the easy structuring of local contacts [10]. In average these rear surface passivated solar cells have efficiencies 0.5% to 1% absolute in excess of the reference aluminum process.

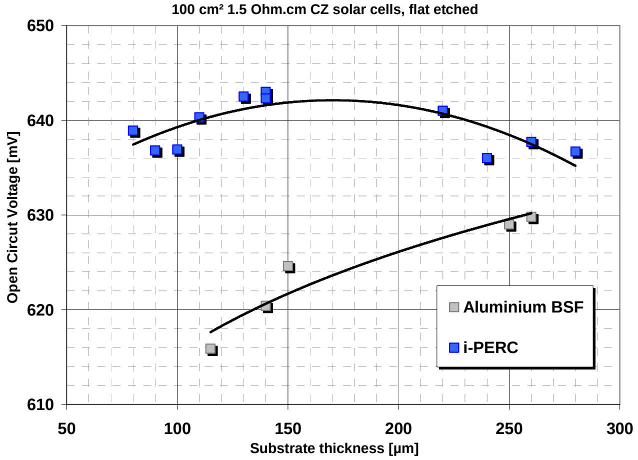

Fig. 4: Comparison of open circuit voltages as a function of substrate thickness for *i*-PERC cells passivated with a SiNx:H/dielectric stack and full coverage aluminum BSF solar cells.

Recent experiments on monocrystalline substrates show that the open circuit voltages of the solar cells are increasing as the cells are thinned down to about 130-140µm (Fig. 4); below this value the cells' FF is becoming softer and affects Voc -to a small extent, given that the voltages measured at 80µm are equal to those attained at 280µm- and the cell efficiency. Jsc is so far slowly but constantly decreasing, indicating the need for a better optical confinement of these structures.

In table 1 we report the latest cell results. All cells are screen printed and, with one exception, are textured in a mask less plasma reactor [11] and feature a single SiNx ARC. Currently, the best efficiencies attained on thin wafers are of 17.3% on Cz material and 16.2% on mc-Si. A remarkable 15.8% has been reached on a 100µm 148.6 cm^2 textured CZ substrate and 16% has been reached on a flat etched 100µm substrate with a DLARC.

1.5 Ohm.cm Cz-Si, 150µm thickness

Surf. finish	Area [cm^2]	Jsc [mA/cm^2]	Voc [mV]	FF [%]	η [%]
Plasma TXT	100	34.7	633	78.7	17.3

1 Ohm.cm Cz-Si, 160µm thickness

Surf. finish	Area [cm^2]	Jsc [mA/cm^2]	Voc [mV]	FF [%]	η [%]
Plasma TXT	100	33.9	620	76.9	16.2

1.5-2 Ohm.cm Cz-Si, 100µm thickness

Surf. finish	Area [cm^2]	Jsc [mA/cm^2]	Voc [mV]	FF [%]	η [%]
SDR +DLARC	100	32.7	635	77.0	16.0
Plasma TXT	148.6	33.9	630	73.8	15.8

Table 1.: Solar Cell Results

CONCLUSIONS

Despite its attractive properties, the implementation of ARC-like silicon nitride layers for the rear surface passivation of industrial solar cells yields results below expectation. Single layers SiNx coatings may find application in bifacial structures, where shunting effects were successfully suppressed. However, in presence of a full rear side metallization the passivation properties of SiNx are strongly reduced. In the latter case a solution is offered by the introduction of SiNx stacks systems, where different functionalities (surface passivation, shunt suppression, masking..) are separated in different layers. By means of this technology the cell's open circuit voltage shows a significant improvement with respect to the conventional aluminum BSF and is retained all the way down to 100µm thick devices.

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The cells were measured against a reference cell which is calibrated (traceable) to the World Radiometric Reference by the European Solar Test Installation (ESTI) of the European Commission Joint Research Centre, an ISO 17025 accredited calibration laboratory

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