A HIGH THROUGHPUT PECVD REACTOR FOR DEPOSITION OF PASSIVATING SIN LAYERS

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ABSTRACT: A new high throughput PECVD reactor for deposition of passivating SiN layers is presented. It is shown that the throughput of the reactor is easily upscalable to industrial demands of more than 1000 wafers/hr and that the deposited SiN layers have excellent surface- and bulk passivating properties. Solar cells with an efficiency of more than 14.5% have been made.
Keywords: Silicon-Nitride - 1: Passivation - 2: PECVD -3.

1. INTRODUCTION

Amorphous hydrogenated silicon nitride (SiN) layers, deposited by Plasma Enhanced CVD processes have been demonstrated to be - besides good anti-reflection layers - excellent means for surface passivation [1]. Moreover, in a mc-Si cell processing scheme in which the metallization pattern is printed on the SiN layer and subsequently is fired through the layer by means of a short high-temperature step, the minority charge carrier lifetime in the bulk of the mc-Si can improve significantly. This improvement of the quality of the bulk is due to diffusion of hydrogen from the SiN layer into the silicon during the firing step [2,3].

For these reasons there is a great interest from the silicon PV industry in the process of PECVD deposition of SiN, but until so far, actual industrial implementations have been very limited due to limited throughputs and/or high costs of the PECVD reactors which are available on the market.

In this paper we present the pilot version of a new industrial PECVD reactor which will meet the low cost/wafer demands imposed by the PV industry. Design and construction of this reactor took place in a co-operation of Roth&Rau, Pfeiffer Vacuum and ECN.

2. SYSTEM

The pilot reactor consists of an entry load-lock chamber, a deposition chamber with a linear remote plasma source and an exit load-lock chamber, in which trays with 25 wafers are sequentially processed (see Figure 1). The throughput of this system can easily be enlarged to industrial demands (1000-1500 wafers/hr) by the addition of extra plasma modules.

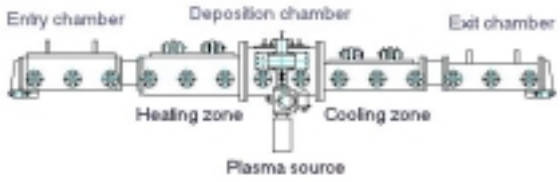

Figure 1: Side view of the pilot PECVD reactor.

In the entry chamber, the wafers are pre-heated by means of IR-lamps. In the first part of the deposition chamber the wafers attain the deposition temperature (typically 350 C). The deposition takes place in the central part of the deposition chamber, where the wafers under-pass a linear plasma source.

Before the wafers enter the exit load lock chamber, they cool down in the third part of the deposition chamber. Each vacuum chamber has an individual pumping system such that the evacuation of the chambers is not a major limiting factor for the throughput. The limiting factors for the throughput are the deposition time and the time needed for transport of the trays from one chamber to the next one.

For a single plasma module, the deposition time for a tray of 5×5 wafers with a size of 10×10 cm^2 is in the range of 3-6 min (i.e. the deposition rate is about 1 nm/s).

The plasma source in the reactor is a new remote microwave plasma source, developed by Roth&Rau, consisting of two parallel quartz tubes with a Cu antenna inside. The source is operated at a microwave frequency of 2.45 GHz. The source also includes an arrangement of permanent magnets for electron confinement in the plasma (see Figure 2). Different gasses can be used in the pressure range of about 0.01 to 500 mbar, depending on the plasma application [4].

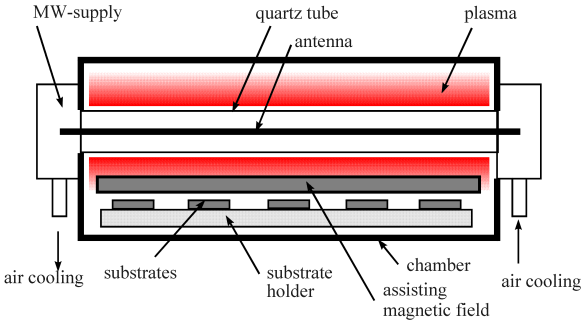

Figure 2: Schematic view of the plasma source.

In comparison with older and more conventional direct plasma sources, this remote plasma source has the following advantages.

- Wafer handling is more convenient since the wafers do not need an electrical contact with one of the electrodes. The trays can be completely removed from the reactor for loading/unloading.
- Due to the GHz frequency at which the source is operated, the plasma self bias is very low. Consequently the ion bombardment of the wafers does not cause a deterioration of the surface.
- The utilisation of the process gases (silane and ammonia) is very efficient. The dissociation rate (depletion) in the plasma of both gases is more than 90 %. The deposition efficiency, that is the fraction of the process gases that is converted in SiN **on** the wafers, is about 4 %.

3. MC-SI SOLAR CELL RESULTS

We have processed two groups of multi-crystalline Si wafers. The wafer material for both groups was the same: 10×10 cm^2 Baysix (randomly sorted from several blocks). Both groups of cells also received the same alkaline saw damage etch and the same emitter. The emitter characteristics are: a p-n junction at a depth of about 0.5 μm and an sheet resistance of about 50 Ω/sq. The first group (consisting of 150 wafers) received a remote-PECVD SiN layer prior to front and back side metallisation (‘firing through’ process). The second group, the reference group (consisting of 25 crystallographic neighbours of the first group) obtained a PECVD coating of SiN after a screenprinted metallisation. This reference process is comparable with the typical industrial process in which TiO_2 is deposited as AR coating after metallisation [5]. The SiN layers have a thickness of approximately 75 nm and a refractive index of 2.1 at 630 nm. The entire processing at ECN (saw damage etch, emitter formation, PECVD, screenprinting of metallisation) took place on a semi-industrial speed. In Figure 3 a histogram of the cell efficiencies of the ‘firing through’ group are shown. The spread in the results is mainly due to the variation of the quality of the basis material. Median values of the I-V characteristics are displayed in Table I. The mean cell efficiency for the reference group is about 12.8 %. Since the PECVD reactor was installed at ECN recently these results are provisional: both the deposition process and the firing process can be further optimised.

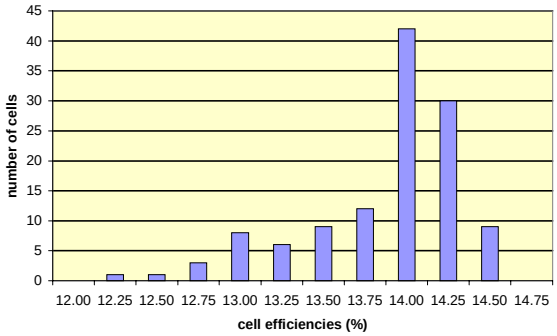

Figure 3: Histogram of mc-Si cell efficiencies for the ‘firing through’ process.

V_{oc} (mV)	J_{sc} (mA/cm^2)	FF (%)	η (%)
605	30.8	75	13.9

Table I: Median I-V characteristics of the cells of the ‘firing through’ process.

The process sequence in which the front side metallisation is fired through the SiN coating leads to an improvement of the bulk quality. This improvement is due hydrogen passivation of bulk defects. The hydrogen diffuses from the SiN into the bulk silicon during the firing process. In Figure 4 the internal quantum efficiency spectrum of one of the best cells of the experimental group plus that of a crystallographic neighbour from the reference group is shown. The improvement of the IQE for larger wavelengths is evident. I-V characteristics of these cells are displayed in Table II. On the average we obtain an increase of the cell efficiency by more than 1 % absolute if the metallisation/PECVD sequence is replaced by a PECVD/metallisation sequence.

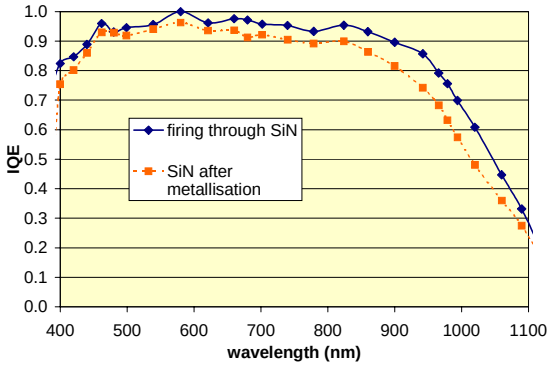

Figure 4: Internal quantum efficiencies for cells of the experimental and the reference group.

Process	V_{oc} (mV)	J_{sc} (mA/cm^2)	η (%)
PECVD-metallisation	610	31.6	14.6
Metallisation-PECVD	587	29.8	12.9

Table II: I-V characteristics of best cell and crystallographic neighbour reference cell.

4. CHARACTERISTICS OF PLASMA AND NITRIDES

4.1 QMS measurements

A Balzers QMS 200 Prisma has been used to monitor the gaseous species in the process chamber during plasma depositions. These measurements showed very high depletion rates (typically more than 90 %) of the process gasses, indicating that the plasma is very reactive. The depletion rates were obtained by monitoring masses 30 and 31 a.m.u. for silane and 16 and 17 a.m.u. for ammonia with the microwave generator switched on and switched off. These high depletion rates are confirmed by the high utilisation rates of the process gasses. For a typical deposition of 80 nm of SiN on 25 wafers of 10×10 cm^2 about 4 % of the process gases is converted in SiN **on** the wafers. This is more than one order of magnitude better than for conventional RF plasma's.

We also monitored the relative abundances of hydrogen versus NH_3 and SiH_4 in the plasma in relation to the V_{oc}'s that were obtained. In Figure 6 the results are shown for a number of cells from the same batch. As we see, the abundance of hydrogen in the plasma is quite high, and highest V_{oc}'s are obtained for highest hydrogen abundances.

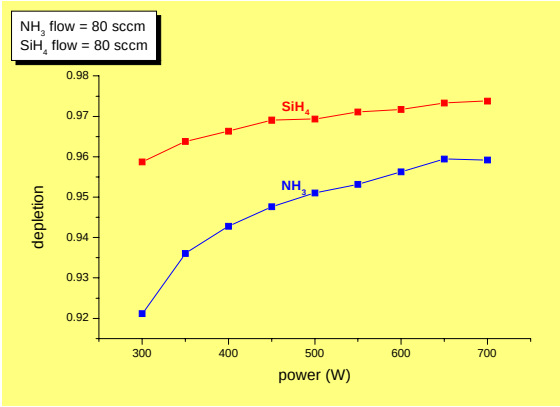

Figure 5: Depletion rates of SiH_4 and NH_3 during deposition of SiN.

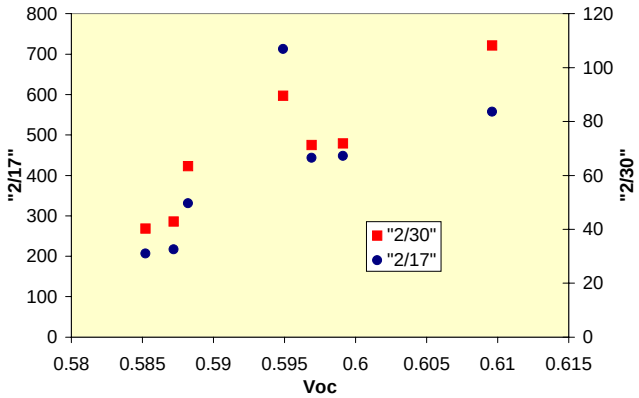

Figure 6: V_{oc} as a function of relative abundancies of NH_3 (17 amu) SiH_4 (30 amu) versus hydrogen (2 amu) as measured by QMS.

4.2 ERD measurements

The composition of a series of SiN layers (deposited on FZ-Si) has been investigated by means of Elastic Recoil Detection (ERD) measurements at the Utrecht University. In this series we have varied the deposition temperature between 300 C and 500 C, keeping constant the NH_3 and the SiH_4 flows, the pressure and the microwave power. Under these conditions we observe a very small decrease of the density of the SiN going to higher temperatures. The N/Si ratio and the hydrogen content (see Figure 7), though, show a very strong decrease in this temperature traject. This decrease of the hydrogen content, however, does not lead to a decrease of the surface passivation. On the contrary, we have found that the surface recombination velocity for FZ-Si, under these conditions decreases from about 5000 cm/s to 50 cm/s if the deposition temperature is increased from 300 C to 475 C.

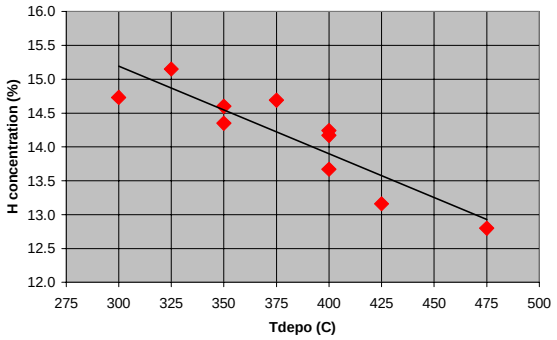

Figure 7: Hydrogen concentration in SiN layers as a function of the deposition temperature.

From these results we could conclude that the amount of hydrogen in the SiN is not very important when it comes to surface passivation. This is very different from the requirements for bulk passivation, as observed in Section 3.2, where large amounts of hydrogen in the plasma and presumably in the SiN layers are desired.

Further investigations of the relation between plasma conditions and growth mechanisms of silicon nitride are obviously needed to improve the understanding of the passivating properties of silicon nitride.

5. CONCLUSIONS

ECN and Roth&Rau have jointly developed a prototype high throughput PECVD reactor. This PECVD reactor has recently been installed at ECN and has been successfully implemented in the ECN mc-Si solar cell processing, for deposition of amorphous silicon nitride.

It is shown that with this PECVD process, SiN can be grown which not only acts as a good AR coating, but which can also improve the quality of the bulk mc-Si material if the deposition is followed by a heat treatment.

We have performed a large experiment on mc-Si wafers in which we have compared the 'firing through' process with a process in which the SiN is deposited on the front side after metallisation. This experiment clearly shows that the hydrogenation which results from the 'firing through' process significantly increases the lifetime of minority charge carriers in the bulk of the mc-Si, leading to an average increase of the cell efficiency of more than 1 % absolute.

The remote microwave plasma source appears to be very efficient in the conversion of the process gasses into SiN. Mass spectroscopy reveals that the depletion of SiH_4 and NH_3 is more than 90 % and that the H_2/NH_3 and H_2/SiH_4 ratios in the plasma are in the range of 100 and 1000, respectively.

Best passivation properties on cells with emitters (highest Voc's) were obtained for plasma conditions which lead to high H_2/NH_3 and H_2/SiH_4 ratios in the plasma.

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