HIGH-THROUGHPUT PECVD PRODUCTION TOOL FOR IN-LINE SILICON-NITRIDE DEPOSITION ON SILICON SOLAR CELLS

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ABSTRACT: At OTB Engineering a new PECVD tool for the deposition of silicon-nitride has been developed. With some of these tools already operational in the field, the so-called DEPx has proven to have some powerful and unique features: a small foot print and a fast deposition speed. An intelligent wafer transport system provides a way to deal with long-term contamination, and allowing accurate positioning for fast load locking. The DEPx is suitable for processing mono-Si, mc-Si and EFG wafers, providing a uniformity of 5% (thickness) and 2% (refractive index). Furthermore, excellent hydrogen passivation has been achieved on mc-Si cells, boosting the cell efficiency above 15%.

Keywords: silicon-nitride, passivation, anti-reflection coating

1 INTRODUCTION

Today's silicon solar cell processing is mainly batch-wise. However, an in-line production process requires much less space, less operators, and thus reduces the solar cell production costs. OTB Engineering has manufactured the first in-line solar cell equipment, covering all the required process steps until cell efficiency measurement and sorting. In-line equipment manufactoring is OTB's main activity, covering applications in PV (DEPx, TABx for cell tabbing), OLED-display and more.

In this article, one of the in-line modules, the DEPx, is described. With the DEPx the solar cells are coated with a silicon-nitride anti-reflection layer. Several unique features of this tool will be highlighted, the most pronounced ones being the very small foot print, intelligent transport mechanism, fast load-locking, and ultra fast plasma deposition.

Table I: Specifications of the DEPx

Throughput	960 wafers/h
Wafer sizes	up to 150 x 150 mm^2
Dimensions	2,4 x 4,0 x 2.8 m (wxlxh)
Vacuum volume	1300 l
Number of carriers	9 – 11
Production time	7 x 24 h (cont. operation)
Cleaning time	2 h / day
Process gases	Ar / SiH_4 / NH_3
Max. gas flows (slm)	7.5 / 0.45 / 3.0
Pumping system	2-stage rootsblower system
Pumping capacity	500 - 5200 m^3 / h
Wafer handling	in-line / cassette

2 DESCRIPTION OF THE DEPx

2.1 Modular, in-line system

The DEPx is a vacuum tool in which the solar cells are coating with a silicon-nitride anti-reflection layer by means of PECVD. It is schematically shown in Figure 1. Since the DEPx can be part of an in-line solar cell production system, there is a continuous loading of wafers into and out of the tool. To be more precise, every 15 seconds, 4 wafers are load-locked on a carrier, and 4 wafers are load-locked from a carrier. Each carrier equipped with 4 wafers is transported through the vacuum-track counter clock wise as shown in Figure 1 and 2, and passing though the different modules. Each module has its specific function: load-lock in, pre-heat (PHT), deposition chamber (DCH), cooling, load-lock out and carrier cleaning.

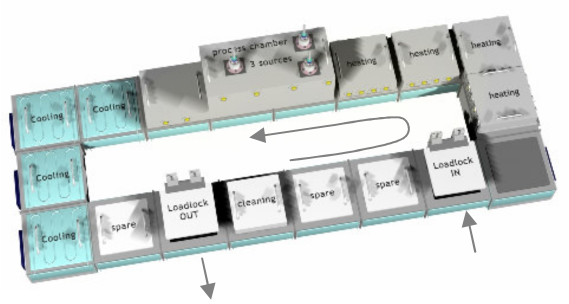

Figure 1: Schematic layout of the PECVD tool. The carriers travel on a closed track, passing through various process chambers (load-lock in, pre-heat, deposition, cooling, load-lock out and cleaning).

2.2 The linear motor system (LMS)

The carriers can be moved on a track by electro-magnetic interaction. Therefore it possible to separate the vacuum from the actuators, thus leaving no contaminating parts or feed-troughs in the vacuum. A permanent magnet is connected to the bottom of each carrier, so that it can be moved by electromagnetic coils located *outside* the vacuum. The separation between the actuators and carrier vacuum also has the advantage that the system is insensitive to dust formation or even broken wafers, while maintaining a high sensitivity of 0.1 mm for carrier positioning. Each carrier can *independently* be moved, making this system flexible for all types of processes, whether stationary of continuous. In the latter case, the carriers propagate with constant speed in the deposition region, while forming a closed train. With a clever design of the carrier, the outer edges used for load-lock sealing are protected from the process gases. The LMS is designed for redundancy: it can to handle 9, 10 or 11 carriers. This redundancy makes a carrier exchange during production, if desired, possible.

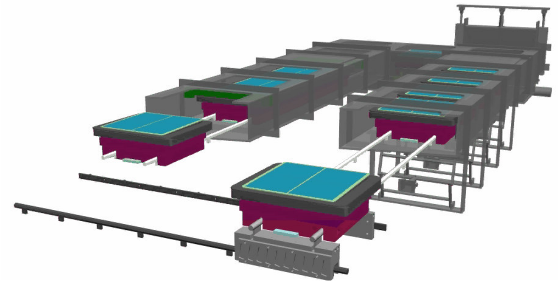

Figure 2: Schematic layout of the LMS. Each carrier transports 4 wafers and can be controlled separately by actuators located outside the vacuum.

2.3 Load Lock out/in

The load-lock is schematically shown in Figure 3. It can be seen that the carrier is actually a part of the load-lock: the carrier can be lifted up, thereby sealing the load-lock volume from the main vacuum by pressing against an o-ring. Consecutively, the load-lock volume (1 litre only) can be vented, and the upper lid can move up. This way, the top of the carrier faces the ambient and wafers can be loaded or unloaded by a handler. In fact, there is a separate wafer plate that lies on top of each carrier that actually carries the wafers. This has several advantages: first, these wafer plates can easily be cleaned by acid etch after extensive deposition. The wafer plate material is fiberglass carbon, that has a very low thermal expansion coefficient, preventing the formation of silicon-nitride flakes during cooling. Secondly, the wafer plate also acts as a heat shielding during pre-heat and deposition that occurs at temperatures between 350 and 450 ^{o}C. Third, the fiberglass carbon can be easily machined to the desired geometry, for example with shallow pockets (0.5 mm) that hold the wafers in place during pumping down and during transport.

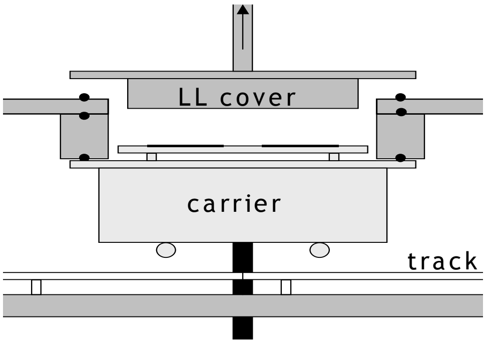

Figure 3: Schematic view of the load lock. The carrier upper edges act as a sealing during load-locking.

The cycle time of the DEPx is about 15 seconds. For the load-lock this means that all the required events should happen within this cycle time. As a result, there is about 5 seconds left for pumping down to 1E-3 mbar (which is equal to the base pressure of the main vacuum). This is not trivial, considering that there is a fast pumping speed required in a large pressure regime, from 1000 down to 1E-3 mbar. Therefore, a special pumping configuration is chosen (see Figure 4), that consist of three stages: first, the air in load-lock volume is dumped into a buffer vessel that has a volume of 600 litres. Consequently the pressure decreases rapidly to below 10 mbar. Secondly, the fore-line pump (20 m^3/h) directly pumps down to about 0.1 mbar, and finally a turbo pump (70 l/s) generates the desired pressure of 1E-3 mbar.

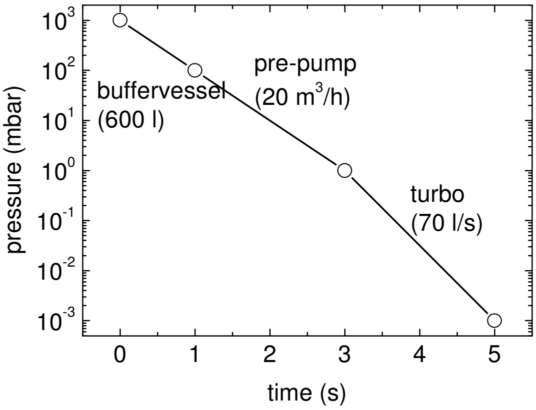

Figure 4: Pump down time of the load lock in three stages, resulting in a decrease of pressure to 1E-3 mbar in 5 seconds.

2.4 Pre-heat

The deposition of the silicon-nitride layer occurs at elevated temperatures in the range of 350 and 450 ^{o}C, depending on the desired process. The wafers are heated by radiation. The heaters (high temperature IR emitters, 2400W each) are located in the pre-heat modules. Each heater is inserted in a quartz tube that sticks into the vacuum and is sealed at both ends. This way, the heaters can easily be exchanged since they remain outside.

In principle, the silicon wafers can only be heated by visible and UV radiation, that has an energy above the silicon band gap of 1.2 μm.. However, slightly doped silicon will still have a small absorption in the infrared (depending on the dopant concentration), but still the highest absorption occurs at the lower wavelength regime. Figure 5 shows the spectral absorption of a silicon wafer, and the light spectrum of the heaters for different powers (between 25 and 100% of the maximum power). It can be seen that indeed the highest absorption occurs in the visible and UV part of the spectrum, however, infrared radiation is the largest part of the heater spectrum, especially at a low power (see Figure 6). It seems that this way the heaters are not used efficiently, however, the infrared part that goes through the wafer is used to heat up the wafer plate. This is desirable, since the fiberglass carbon wafer plate will serve as a heat buffer, thus providing a stable temperature profile during deposition.

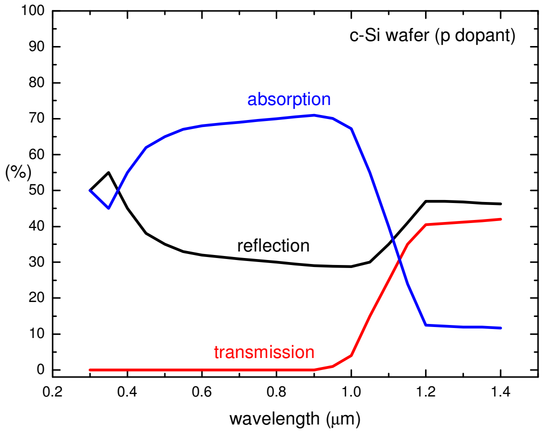

Figure 5: Absorption spectrum of a p-doped silicon wafer. Absorption is highest in the visible range of the spectrum. Below the band-gap energy, a low absorption is stil present due to wafer doping.

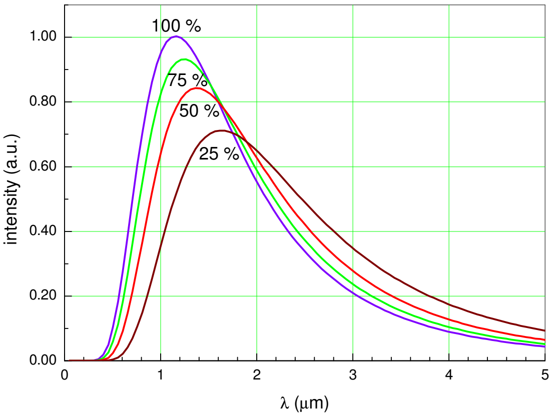

Figure 6: Spectrum of the high-temperature IR heaters at different powers represented by percentages.

The wafer temperature can be measured in two ways: first, two infrared sensors just behind the deposition chamber monitor the wafer temperature during production. Secondly, an in-situ temperature profile can be obtained by using a thermo couple data collector. The thermocouples (up to 6) are connected to the wafers or to the wafer plate. The data collector is inserted in one of the carriers. Up to two hours of data can be collected.

Figure 7 shows three examples of a temperature profile during one roundtrip. By using different heating powers the temperature during deposition can be controlled up to 440°C. Starting up from a cold vessel takes about 15 minutes, after which the temperature has stabilized.

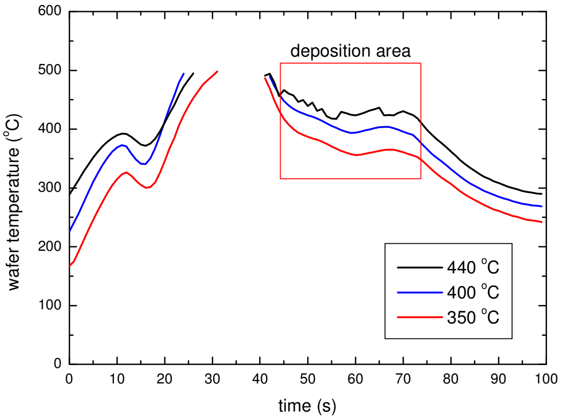

Figure 7: Temperature profile of the wafer during pre-heat, deposition and cooling. Due to the settings of the data logger, temperatures above 500 °C have not been registered.

3 SILICON-NITRIDE PLASMA DEPOSITION

3.1 ETP source

One of the reasons for the very small foot print of the DEPx is the fact that the plasma deposition of silicon-nitride is extremely fast. Common PECVD techniques are microwave plasma, rf-plasma and parallel plate, some of them being remote or direct. For all these methods, the power coupling is directly related to the plasma composition, and deposition rates are mostly limited by maximum gas flow in order to maintain a stable plasma. The DEPx uses a different technique, based on ETP (expanding thermal plasma) sources.

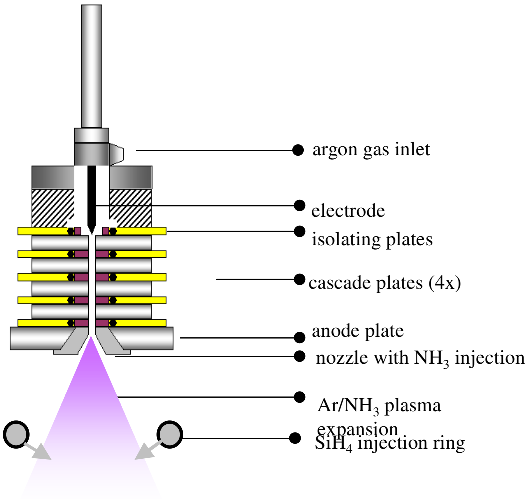

Figure 8: Schematic view of the ETP source.

Figure 8 shows the principle of an ETP source. High pressure argon (500 mbar) is injected through a small channel (4 mm diameter) into the vacuum, resulting in a supersonic expansion of argon. The argon can be ignited by applying a small high-voltage peak from the cathode tip, and a plasma is generated in the small channel and in the expansion.

Table II: ETP source properties

Plasma	remote
Plasma power	2-4 kW
Ion/electron energy	0.1/0.5 eV
Ar seed gas flow (slm)	2 – 2.5
Ar inlet pressure	300 – 500 mbar
Ar ionization rate	10 – 15 %
Precursor gases	SiH_4/NH_3

Typical plasma characteristics are shown in Table II. It can be seen that a high current and power can be put in the plasma (40-70A, 50-60V), which is characteristic for a high-density plasma. Due to the huge number of collisions, the ion and electron temperature is only in the order of 0.1 to 0.5 eV. The argon gas acts primarily as a seeding gas, that will decompose precursor gases that are added downstream. This has several advantages: first, the upstream conditions are not affected by the downstream plasma chemistry, since the expansion is supersonic. Secondly, the low temperature of both the seeding gas and precursor gas ions will not damage the substrate; this type of plasma is in fact the ultimate remote plasma. Third, because of the large flux of argon ions (ionization rates up to 15%), the precursor gas flows can be set extremely high compared to other PECVD processes. Mainly because of this, deposition rates of up to 30 nm/s can be achived (see Figure 9).

3.2 Uniformity and deposition rate

The DEPx uses three ETP sources to obtain a sufficient degree of layer uniformity. Table III illustrates this uniformity in terms of thickness and stoichiometry (refractive index). It can be seen that the uniformity in layer thickness over the active area of the carrier (300x300 mm^2) is within +/- 5%, determined with a 9-point measurement on a 125x125 mm^2 wafer from the middle up to 5 mm to the edges. Using the same definition, the uniformity in R.I. (refractive index) is even better: within 2%.

The depostion rates that can be achieved in this configuration are shown in Figure 9. It can be seen that the deposition rate increases with increasing precursor flow (silane and ammonia) and with plasma power. Deposition rates well above 10 nm/s can easily be achieved. The extremely high deposition rates result in a deposition time of only a few seconds for a 75 nm SiNx:H layer. So far, these rates have not been required because of other limiting process steps in the production lines, such as screen printing.

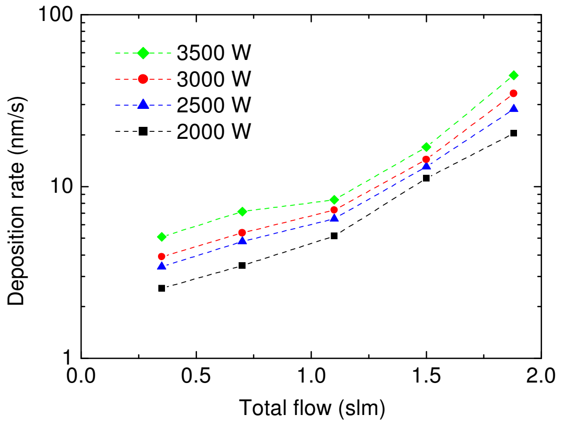

Figure 9: Deposition rates of the ETP source at different input powers and precursor gas flows.

4 SOLAR CELL EFFICIENCIES

The ETP source not only provides an extremely fast deposition rate, but also provides a silicon-nitride layer will excellent hydrogen passivation (bulk- and surface passivation). As mentioned before, a large number of plasma parameters can be controlled independently, providing a large process window. Hydrogen passivation is still improving since a lot of effort is put in the research of this deposition process [1-3], performed at OTB Engineering within the process development group. Available analysis tools are ellipsometer, FTIR, SEM, and EDAX. It is important to mention that, in contrast to other parties, OTB not only privides (in-line) equipment, but can also provide a firm process know-how to its customers. Table III summarizes the specification of the silicon-nitride layer used on solar cells.

Table III: Specifications of the SiNx:H layer

Cell efficiencies mc-Si, non-textured	up to 15 %
Layer thickness uniformity	+/- 5%
Layer R.I. uniformity	+/- 2%
In-house layer characterization	FTIR, SEM, EDAX, Ellipsometer

Figure 10 shows the improvement in mc-Si cell efficiency due to hydrogen passivation. For a good comparison, the fill factors for all cells have been modified to a constant value of 0.75 (the efficiencies are corrected for this), thus eliminating differences between the reference cells and experimental cells, related to properties other than hydrogen passivation. The reference cells (sister cells) are processed with a reverse scenario (firing before PECVD), resulting in cells without bulk-passivation and minor surface-passivation..

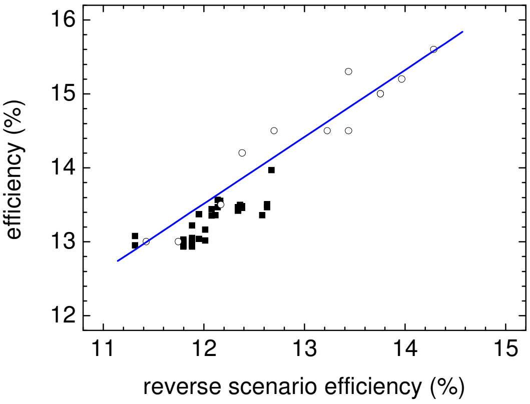

Figure 10: Improvement in mc-Si cell efficiency due to H-passivation as function of the intrinsic wafer material quality, represented by the efficiency of sister cells processed with reverse scenario. For comparison, all efficiency values correspond to a fill factor of 0.75. The symbols indicate different mc-Si wafer materials (all 50 Ohm/sq). Wafer texturing has not been applied.

It can be seen that the bulk passivation can improve the cell efficiency by 2% absolute for lower quality cells and by 1.5% for high quality cells.

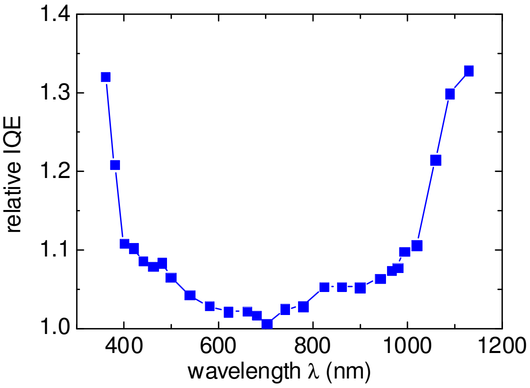

Figure 11: IQE measurement of a mc-Si solar cell, with SiNx:H anti-reflective layer deposited with ETP. Values of the IQE are shown relative to the values of a sister cell without SiNx:H coating.

Figure 11 shows the result of an IQE measurement on one the mc-Si cells. The relative values show the increase in IQE with respect to a non-passivating sister cell. It can be seen that there is a significant increase both in the blue and in the red part of the spectrum, indicating surface and bulk passivation.

5 CONCLUSIONS

The DEPx, a new silicon-nitride PECVD production tool for mono-Si and mc-Si wafers, has proven its capabilities. Due to its clever design with a linear motor system for wafer transport and ultra-fast PECVD process using ETP sources, the foot print of the DEPx is uniquely small.

The process uniformity has been optimized using three ETP sources, resulting in thickness uniformity within 5%, and R.I. uniformity within 2%.

Furthermore, the mc-Si solar cell efficiencies can be increased significantly by excellent hydrogen passivation. The PECVD process has been optimized by extensive in-house research, providing customers not only equipment support, but also process know-how.

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