

## HIGH-POWER-PLASMA PECVD OF $\text{SiN}_x$ AND $\text{Al}_2\text{O}_3$ FOR INDUSTRIAL SOLAR CELL MANUFACTURING

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**ABSTRACT:** Excellent surface passivation is a key feature of high-efficiency c-Si solar cell concepts. Manz AG in collaboration with Fraunhofer ISE has developed a high-power-plasma (HPP) vertical plasma-enhanced chemical vapour deposition (PECVD) system that allows the preparation of excellently passivating hydrogenated amorphous silicon nitride ( $\text{SiN}_x$ ) and aluminium oxide ( $\text{Al}_2\text{O}_3$ ) films at high deposition rates, leading to a throughput of about 1200 wafers per hour for one deposited film at a small footprint of the tool. Double layer  $\text{SiN}_x$  front surface anti-reflection coatings (ARC) were outperforming the reference processes at Fraunhofer ISE.  $\text{Al}_2\text{O}_3$  layers reached the same level of passivation compared to the reference PECVD process. Control of carbon and oxygen atoms and the oxidizing gas during the deposition helps to maintain a stable and robust process.

**Keywords:** Antireflection Coating, CVD Based Deposition, Deposition, High Deposition Rate, Interfaces, Passivation, PECVD, Silicon-Nitride, Solar Cell, Aluminum Oxide

### 1 INTRODUCTION

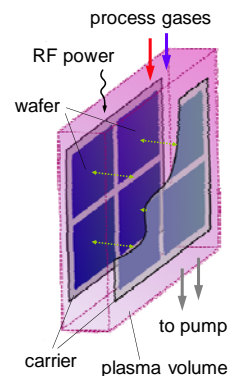
Dielectric layers for surface passivation and to provide optical properties (anti-reflection (solar cell's front) / reflection (rear)) are key features of next-generation crystalline silicon solar cells, e.g., passivated emitter and rear cells (PERC). The step from today's industry standard process sequence applying an aluminum back surface field (Al-BSF) to more complex solar cell structures is necessary in order to reach higher conversion efficiencies and lower cost for solar electricity (€/kWh) [1].

### 2 INTRODUCTION TO THE PECVD TOOL

Manz AG in collaboration with Fraunhofer ISE has designed a novel plasma-enhanced chemical vapour deposition (PECVD) tool for the formation of hydrogenated amorphous silicon nitride ( $\text{SiN}_x$ ) and hydrogenated amorphous aluminum oxide ( $\text{Al}_2\text{O}_3$ ) that combines the following benefits:

- High deposition rates: the high-power plasma is very effectively dissociating the process gases
- High gas utilisation: 2 carriers in deposition process on 2 sides of deposition zone → doubled throughput
- Novel carrier concept: upright carriers in deposition process eliminate shading due to dust or flitters, electrostatic wafer holding allows the processing without holder marks.

In Figure 1, a sketch of the process chamber is shown including the vertical wafer position and 2 carriers in the plasma at a time.



**Figure 1:** Sketch of the process chamber. 2 carriers are holding 8 wafers during one deposition process. The upright position allows processing free of holder marks and parasitic flitter marks.



**Figure 2:** View into the wafer loading/unloading unit of the VCS1200 including wafers which are placed on deposition carriers.

### 3 SILICON NITRIDE FRONT SURFACE LAYER

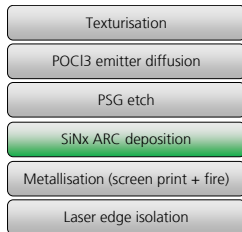
Hydrogenated amorphous silicon nitride is widely used for front surface anti-reflection coating of c-Si solar cells that at the same time provides surface and c-Si bulk passivation, especially for multicrystalline silicon wafers. These multifunctional properties are the main reason for the success of this layer type.

Typically, PECVD is used for the formation of SiN<sub>x</sub> layers in c-Si photovoltaics. In this paper, the Manz PECVD tool VCS1200 was examined for the deposition of SiN<sub>x</sub> layers.

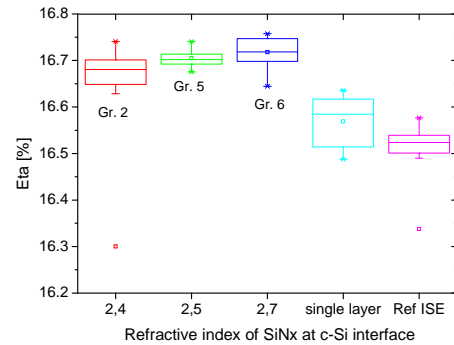
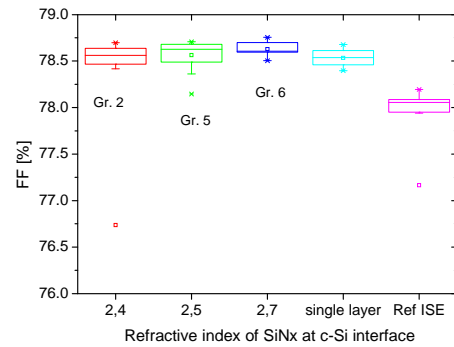
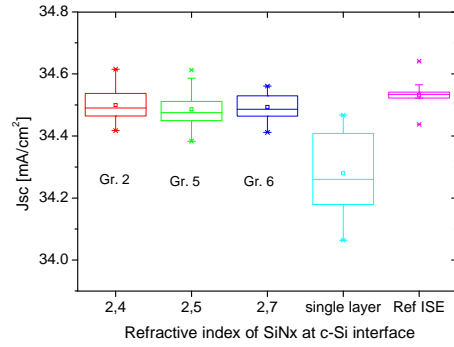
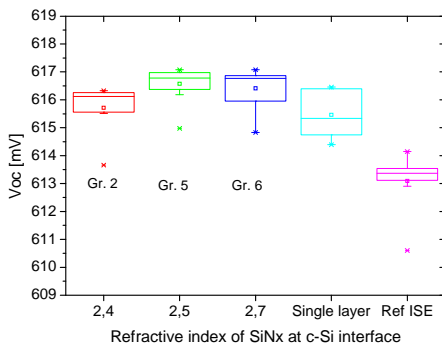
A single-layer baseline process was developed and first results were published at last year's EUPVSEC [2].

c-Si Al-back surface field (Al-BSF) solar cells using medium-grade multicrystalline silicon wafers were fabricated to compare the front-surface performance of different SiN<sub>x</sub> ARC layers. Partly, two-layer SiN<sub>x</sub> film systems were deposited with SiN<sub>x</sub> layers of higher refractive index at the interface to the c-Si. A variation of the refractive index (silicon content) in these thin interfacial SiN<sub>x</sub> layers was performed and revealed no clear benefit comparing n in the range of 2.4 to 2.7. However, a benefit in comparison to the reference layers could be achieved. The ISE reference cells suffered from a misprocessing which lead to a higher sheet resistance of the cells and thus to a higher series resistance and a lower fill factor. However, also taking this effect into account, a benefit of the novel stack layer system compared to the single-layer reference is still clearly visible. The results are shown in Figure 4.

The solar cells were manufactured according to the process flow displayed in Figure 3.



**Figure 3:** Process flow for the manufacturing of the solar cells within this investigation. In the highlighted step, a variation of the SiN<sub>x</sub> ARC layers was performed.



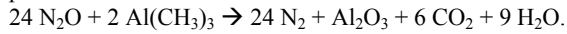
**Figure 4:** Results of the Al-BSF solar cell processing applying the optimized SiN<sub>x</sub> layer stacks made up of a thin high-n SiN<sub>x</sub> layer at the c-Si surface and a “standard” ARC SiN<sub>x</sub>. The results can be compared to the single-layer reference process in the VCS1200 and the single-layer reference process at Fraunhofer ISE. Open-circuit voltage (Voc), short-circuit current density (Jsc), fill factor (FF) and the energy conversion efficiency are shown. Here, the stack layer systems are outperforming the reference layers by 0.1 ... 0.2 % absolute in efficiency.

#### 4 ALUMINUM OXIDE / SILICON NITRIDE REAR SURFACE LAYER STACK

Aluminum oxide ( $\text{Al}_2\text{O}_3$ ) is very well suited for the passivation of p-type c-Si surfaces like the rear of p-type PERC cells due to its fixed negative charges and reachable low density of interface trap values. Although  $\text{Al}_2\text{O}_3$  layers in the last years were often deposited by ALD (atomic layer deposition) which allows a very defined control of the layer growth and thickness [3, 4], PECVD is often preferred by solar cell manufacturers due to its compatibility to  $\text{SiN}_x$  layer deposition and its high deposition rate [5, 6].

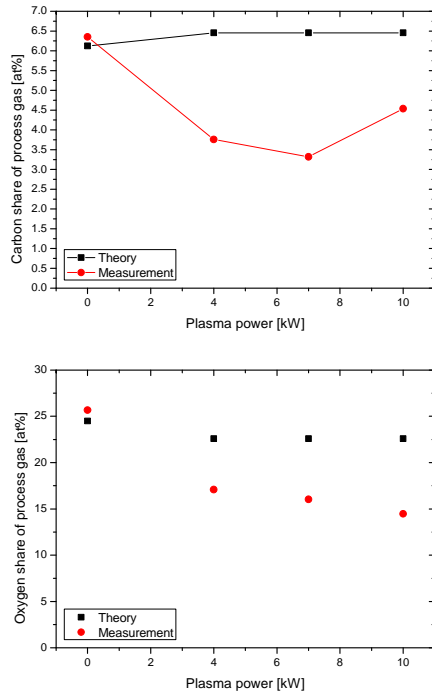
The VCS1200 was examined as PECVD tool for  $\text{Al}_2\text{O}_3$  layers. In PERC solar cells that apply screen printed Al rear metallization, a capping of the  $\text{Al}_2\text{O}_3$  is necessary by a layer that is stable against the Al paste during the firing process. Here,  $\text{SiN}_x$  layers can be applied [7].

For the development of the  $\text{Al}_2\text{O}_3$  deposition process, theoretical and experimental work was performed. From theory, the used process gases  $\text{N}_2\text{O}$  and  $\text{Al}(\text{CH}_3)_3$  need to be dissociated and need to rearrange to form  $\text{Al}_2\text{O}_3$  and other molecules. The following equation solves this problem:



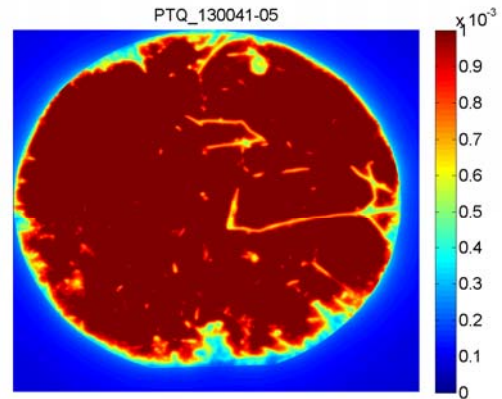
However, this equation can only be valid when all process gases are (almost) fully dissociated, enough time is available, no significant other gases are in the process chamber, etc. Then, the theoretical best mixing ratio would be 12:1 ( $\text{N}_2\text{O} : \text{Al}(\text{CH}_3)_3$ ). In reality, an oversupply of  $\text{N}_2\text{O}$  was found to be beneficial.

See **Figure 5** for a comparison of theoretical and measured process gas shares of carbon and oxygen and their dependency on the plasma RF power.



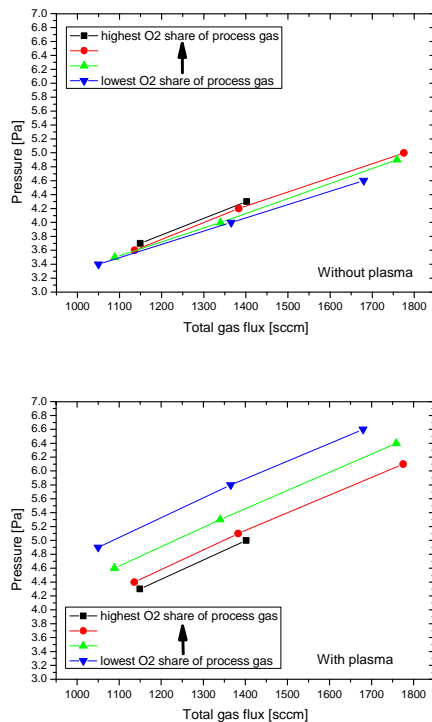
**Figure 5:** Carbon and oxygen share of process gas as a function of the plasma power. A comparison of theoretical (black ■) and experimental values (red ●) as measured by mass spectroscopy is shown.

Very homogeneous surface passivation can be achieved with  $\text{Al}_2\text{O}_3$  passivation layers. In an experiment using a  $1 \Omega \text{ cm}$  float zone Si wafer (p-type, shiny etched surfaces, 6" diameter), homogeneous lifetime distributions  $>1 \text{ ms}$  was observed. In **Figure 6**, a calibrated photoluminescence signal is displayed with a large area share above 1 ms. The small marks below 1 ms at this image are probably due to manual wafer handling prior to the deposition.



**Figure 6:** Image of a calibrated photoluminescence measurement showing the lifetime distribution of a 6" FZ wafer ( $1 \text{ Ohm cm}$ , p type, shiny etched surfaces,  $250 \mu\text{m}$ ). The wafer was passivated by  $\text{Al}_2\text{O}_3$  deposited in the Manz VCS1200 sequentially on both sides of the wafer. Most of the low-lifetime marks are probably due to handling of the wafer prior to the deposition. Using automated handling these marks are expected to disappear. The color legend is scaled in s (green equals 0.5 ms).

For a stable deposition process, it is important that the deposition process parameter changes are small when switching on the plasma. By lowering the share of  $\text{N}_2\text{O}$  in the oxidizing gas flux, a lower shift in process pressure can be reached when comparing the situation with and without plasma. Since the first few atomic layers of  $\text{Al}_2\text{O}_3$  are very important for an efficient surface passivation process, this can have a strong influence. See **Figure 7**.



**Figure 7:** Without plasma, the process pressure is depending on the total gas flux. When the plasma is switched on, the  $O_2/N_2O$  ratio in the process gas is additionally determining the process pressure conditions.

## CONCLUSION

Manz AG in collaboration with Fraunhofer ISE has developed a high-power plasma (HPP) PECVD tool for excellent front ( $SiN_x$ ) and rear surface passivation layers ( $AlO_x$  and  $AlO_x / SiN_x$ ) that combines small footprint, high throughput, efficient gas utilization with a vertical wafer position that allows coating without holder marks or risk of parasitic shading by flitters.

The control of carbon and oxygen as well as the pressure dynamics were shown to be important for a stable and robust process.

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