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Roth & Rau Oberflächentechnik AG,
Gewerbering 3, OT Wüstenbrand
09337-Hohenstein- Ernstthal

muegge electronic GmbH
Hochstr. 4-6, 64385 Reichelsheim,

Large scale industrial silicon nitride deposition at photovoltaic cells with linear microwave plasma sources

H. Schlemm, A. Mai, S. Roth, D. Roth,
Roth&Rau, Oberflächentechnik AG, Gewerbering 3, OT Wüstenbrand, 09337 Hohenstein-Ernstthal,
K.-M. Baumgärtner, H. Muegge,
Muegge Electronic Gmbh, Hochstr. 4-6, 64385 Reichelsheim

Abstract:

Microwave plasmas have some outstanding features like high charge carrier concentrations at ion- and electron energies below 10 eV, which predestine these plasmas for thin film deposition technologies requiring a non-remarkable ion impact.

The plasma deposition of the passivating Si_3N_4-layers on multi-crystalline solar cells without formation of ion impact induced surface recombination centres is an example for such kind of process. By using the process gases SiH_4 , NH_3 and H_2 a hydrogen rich plasma is generated resulting in excellent passivation properties of the silicon nitride layers on photovoltaic cells.

In order to achieve stable plasma conditions on large-scale industrial deposition dimensions (150 nm/min at an area of 20 x 100 cm) over long times, magnetic field enhanced linear microwave plasma sources based on the plasmaline® principle were applied.

Following, some results for this remote microwave PECVD of Si_3N_4 on multi-crystalline silicon solar cells are presented.

1. *Introduction*

Microwave plasmas have some outstanding features like high charge carrier concentrations at ion- and electron energies below 10 eV, which predestine these plasmas for thin film deposition technologies without any remarkable ion damage.

The plasma enhanced chemical vapour deposition (PECVD) of passivating Si_3N_4-layers on poly-crystalline silicon solar cells without formation of ion impact induced surface recombination centres is an example for such kind of process.

There are several ways existing to introduce microwaves for large scale plasma excitation by coupling the microwave:

- through horn-antennas,
- dielectric windows [1],
- through a set of $\lambda/4$ – antennas [1],
- by surface waves [2]

to the plasma.

Using the first three methods the microwave is coupled at well defined but local positions to the plasma, so that a homogeneous large size plasma can be observed at longer distances away from the microwave inputs only.

Microwave surface wave guide plasmas have the principal advantage of linear homogeneous plasma generation over long distances with a nearly linear axial decay in the plasma density [2]. A linear plasma with homogeneous plasma density in axial direction can be generated by applying two microwave generators on both ends of a surface wave guide setup [3]. Most of these types of surface wave guide plasmas had been generated inside dielectric tubes and are therefore without any remarkable application in thin film deposition.

Therefore, it has been an important step towards thin film applications to investigate a new type of surface wave guide plasma outside a dielectric tube [4,6]. The plasma is generated as an outer surface wave guide plasma on the outer surface of an isolating tube (e.g. quartz tube) containing an inner conductor [4-6] whereby the isolating tube and the inner conductor form a coaxial system. Using this principle large scale microwave plasma sources for linear dimensions in the meter-range can be designed [5].

2. *Principle of plasma generation with linear microwave sources*

Fig.1 shows a typical linear microwave plasma source with two microwave generators one on each side of the linear plasma source.

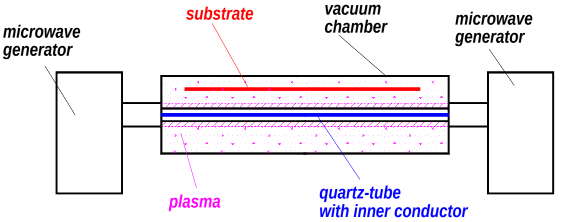

Fig.1: Principle of a linear microwave plasma source plasmaline

Typical dimensions of these plasmas are 200 mm in diameter and up to 1.5 m in length (plasma source length). Like shown in Fig.1, the substrates are placed on a carrier and moved through this plasma by over-passing the quartz tube arrangement perpendicular to it's axis. An excellent deposition uniformity in moving direction can be achieved. By using a parallel arrangement of two or more linear plasma sources , higher deposition rates can be obtained.

2.1. *Magnetic field enhanced linear plasma sources*

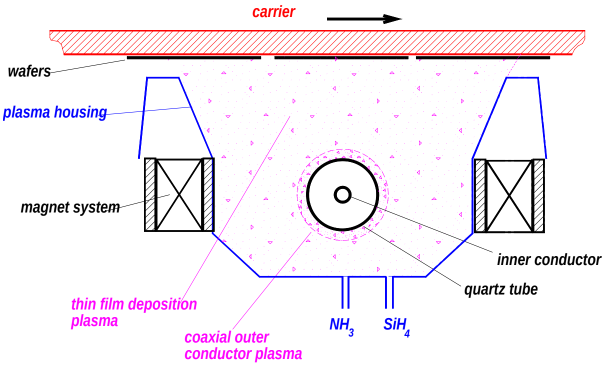

Fig.2: Typical cross section of the magnetic field enhanced microwave plasma source

If linear plasma sources like described in fig.1 are applied for high rate thin film deposition processes using process gases like SiH_4 or C_2H_2, axial plasma instabilities are observed, resulting in a non-stable deposition uniformity. Therefore a magnetic field like shown in fig.2 is added to the plasma source. The magnetic field enhanced plasma source has some specific features and important advantages:

- A magnetic confinement on the plasma border causes lower losses of charged particles enabling higher plasma densities and higher deposition rates.
- The axial plasma homogeneity is stable in a wider pressure range from $1x10^{-2}$ mbar to 1 mbar.
- The magnetic field enhances and stabilises the coaxial outer conductor plasma on the isolator tube, although the magnetic field strength is far away from the ECR-condition (87 mT).

In Tab.1 the properties of the magnetic field enhanced microwave plasma source are summarised.

	range
Deposition length (= carrier width)	50 – 150 cm
Deposition width (= plasma width in carrier transport direction)	200 mm (depending on process parameters)
Deposition rate	50 – 250 nm/min
process pressure	0.01 – 1.0 mbar
magnetic field	5 – 30 mT
Typ. Microwave pulse power (for 1 m length) for noble gas plasmas	2 x <= 2 kW
Typ. microwave pulse power (for 1 m length) for hydrogen containing plasmas	2 x 4 kW

Tab.1: Summary of the properties of the linear microwave plasma source

2.2. *Homogeneous large area plasma generation*

The plasma uniformity in axial direction has been investigated in dependence on several process conditions.

The dependence of the plasma charge carrier density n(z) on the amount of microwave power input on both sides in z-direction (plasma source axis) is shown in fig. 3 schematically.

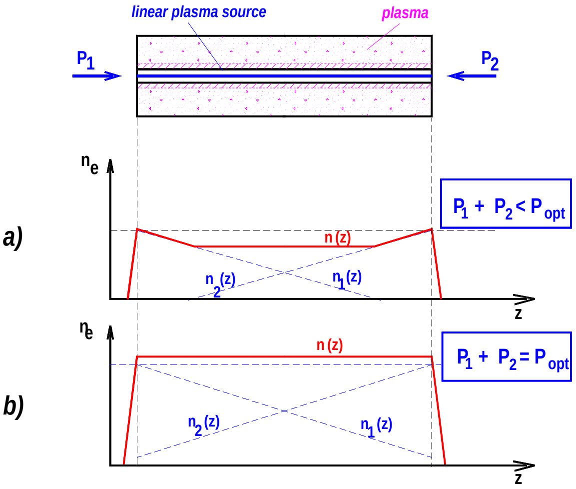

Fig.3: Principle of generation of linear microwave plasmas

Considering the case of operation of the left side microwave generator at the microwave power P_1 only, a linear decay in plasma density $n_1(z)$ is observed because of the linear consumption of microwave power along the quartz tube. The same effect can be observed if the right side generator (with P_2) is in operation only. If both generators operate simultaneously the plasma density n(z) profile is the sum of both single density profiles.

Considering case a) in Fig.3 each microwave generator for itself wouldn’t generate a plasma profile over the complete quartz tube length. In result, the sum of both plasma profiles is inhomogeneously like shown in Fig.3a) (P_1+P_2< P_{opt}). The microwave power on both sides has to be increased until case b) (P_1+P_2= P_{opt}) is obtained. Under this condition the plasma will be homogeneously. A further increase of the microwave power at both sides will lead to more excessive microwave power at the microwave systems and won’t improve the plasma density or the plasma density profile.

The necessary microwave power input is determined by the kind of process gases and by the length of the quartz tube (see tab.1). How shown in Tab. 1, a linear plasma source of 1 m length requires a microwave power of up to 4 kW on each side. Unfortunately, this amount is higher than the maximum permissible microwave power load on a quartz tube (danger of thermal distortion). In order to prevent microwave power overload on the quartz tube, pulsed microwaves at frequencies between 10 and 100 Hz are applied. The deposition rate can be controlled by the microwave pulse length.

Fig.4 shows the observed axial deposition rate profile for silicon nitride for the cases a) and b) from fig.3. Similar deposition profiles for a plasma lengths of 650 mm are presented in Refs [6,7].

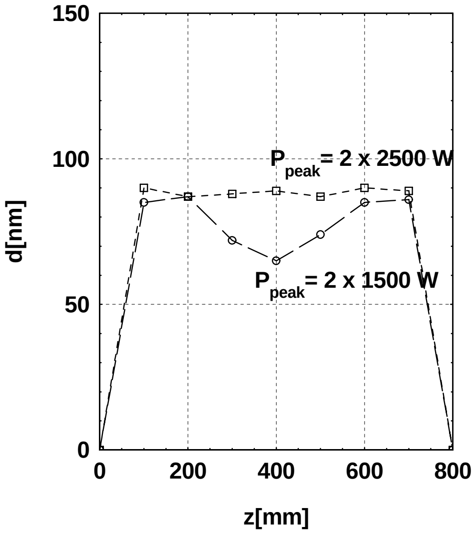

Fig.4: Axial deposition rate profile for silicon nitride deposition at different microwave peak powers (pressure: 0.1 mbar, total gas flow: 350 sccm, substrate temperature: 350 C, total mean microwave power: 2000 W).

The required microwave peak power is given by the plasma length and the kind of process gases. But nevertheless, the deposition rate can be controlled independently by applying different microwave pulse duration leading to a variable mean microwave power which influences the deposition rate as shown in Fig.5.

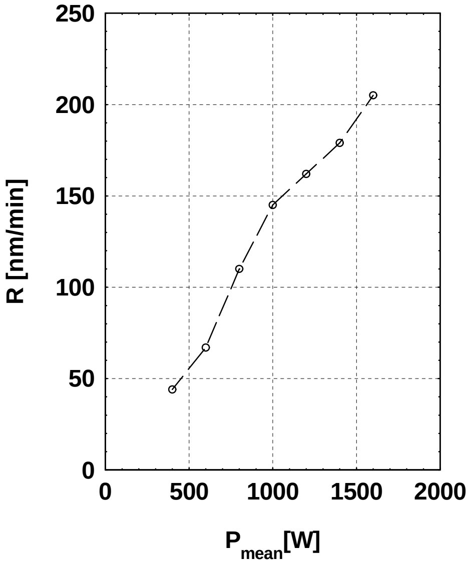

Fig.5: Silicon nitride deposition rate in dependence from the mean microwave power of the magnetrons (pressure: 0.1 mbar, total gas flow: 350 sccm, substrate temperature: 350 C, P_{peak}= 2500 W).

3. Silicon nitride deposition at photovoltaic cells

Amorphous hydrogenated silicon nitride layers, deposited by Plasma Enhanced CVD processes have been demonstrated to be - besides good anti-reflection layers - excellent means for surface passivation [8]. 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 improved 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 [9].

An array of four linear microwave plasma sources is applied to obtain a rapid industrial-scale deposition of silicon nitride layers on solar cell wafers placed on carriers of 1m x 1m size which are processed with a speed of up to 1 m/min with a throughput of up to 1500 solar cell wafers per hour .

3.1. Silicon nitride as antireflection coating

Silicon nitride is deposited on photovoltaic cells after doping of the emitter zone. As an anti-reflective coating with a film thickness of λ/4 the silicon nitride layers ensure the improvement of the light incoupling. The AR layers have been designed for an optimum wavelength of 580 to 600 nm corresponding to a layer thickness between 70 and 80 nm and refractive indices between 2.0 and 2.2 in dependence on the specific photovoltaic cell technology. Using the described linear plasma source technique the film thickness can be controlled very simply and precisely by varying the carrier transportation speed. The refractive index is controlled by variation of the flow ratio of the process gases while keeping all other process parameters constant. In fig.6 the dependence of the refractive index on the NH_3/SiH_4 ratio is shown.

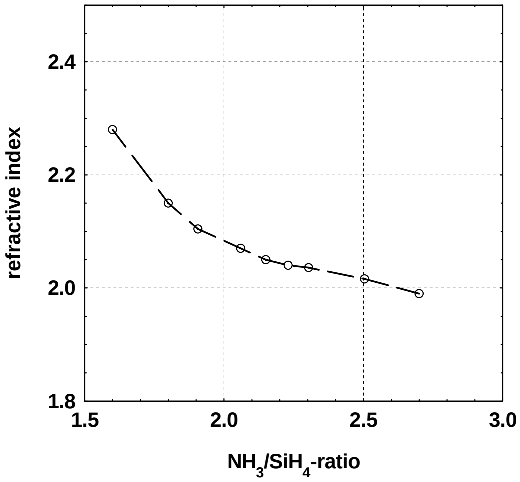

Fig.6: Refractive index in dependence on the NH3/SiH4 ratio
(T = 350C; p = 0,15 mbar; P_{peak}= 2x 2500W)

The film thickness uniformity and the refractive index uniformity strongly depend on the overall deposition homogeneity of the plasma source. Fig. 7 and 8 show that both optical parameters can be kept in small tolerance ranges, which fulfil the requirements of the solar cell technology.

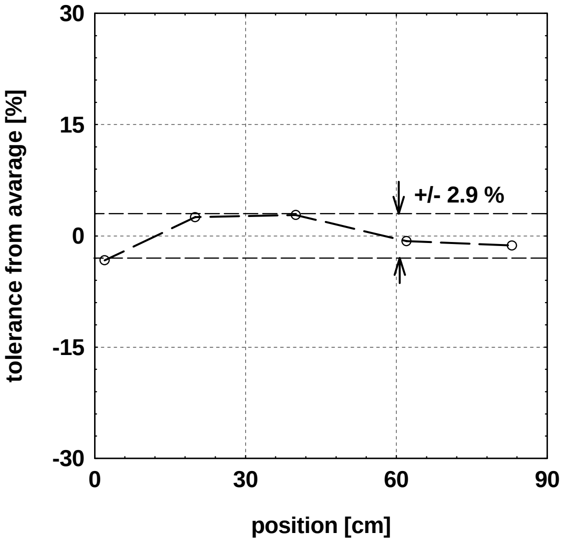

Fig.7: Film thickness uniformity over the tray perpendicular to the moving direction

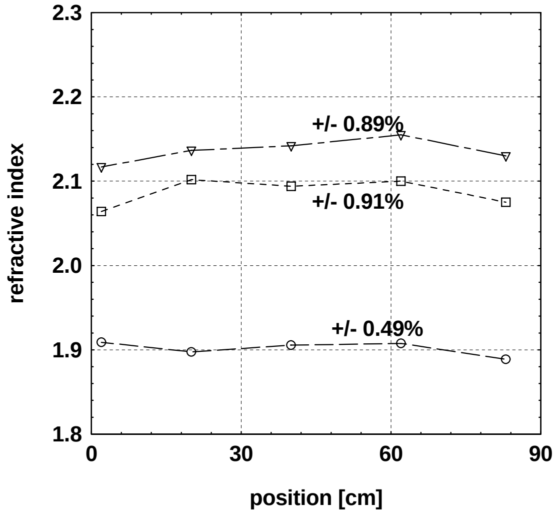

Fig.8: Refractive index in dependence on the position on the tray perpendicular to the moving direction of the tray for NH3/SiH4 ratios of 2,5, 1,9, 1,8

3.2. Plasma process hydrogen passivation of photovoltaic cells

Fig.9 shows the process gas composition for a running linear microwave plasma source under typical process conditions. SiH_4 and NH_3 are nearly total plasmachemically converted into hydrogen and nitrogen (gas phase) and hydrogen enriched silicon nitride.

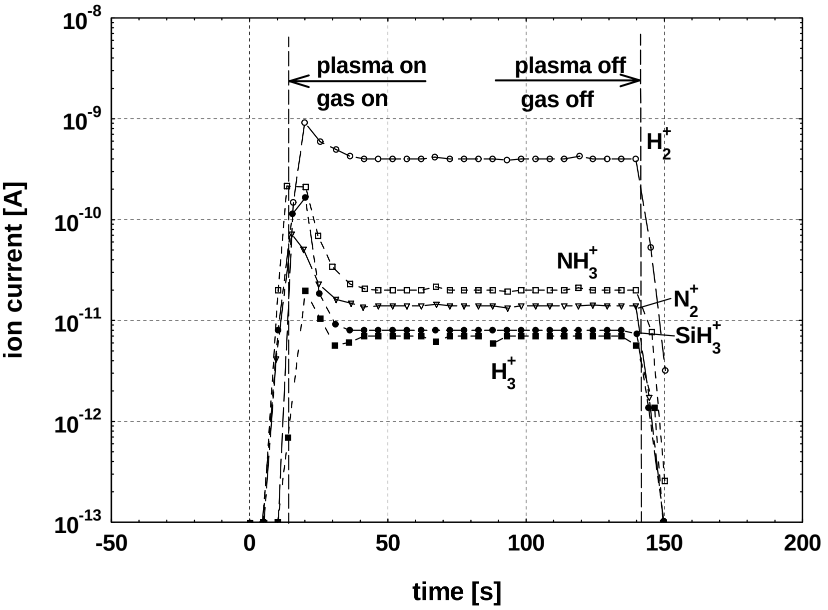

Fig.9: Mass spectrometric analysis of the gas composition for typical process parameters after starting the linear plasma source (T = 350C; p = 0,15 mbar; P_{peak}= 2x 2500W).

Like shown in Fig.9 the steady state gas composition is reached after 30 s and characterised by a very high content of hydrogen (typical over 70%) and a high degradation of the process gases lower to 5% of the gas composition. This high hydrogen content is responsible for the excellent passivation properties of the SiN layers which have been deposited applying the microwave plasma technique. Since the mass spectrometer used for the analysis given in fig.9 has been arranged at 1 m distance from the plasma source, atomic dissociated hydrogen couldn´t be analyzed because of recombination processes. However, in the gas near the deposition area about 10 cm away from the hydrogen generating plasma sources a high atomic hydrogen content can be assumed. At the process temperature of 350°C this hydrogen diffuses very well through the grain boundaries [10,11] of the mc-silicon and furthermore, forms hydrogen enriched silicon nitride which is suitable for bulk passivation [8,9].

4. Conclusions

A magnetic field enhanced linear microwave plasma source and it’s application for deposition of silicon nitride anti-reflective and passivation layers on photovoltaic cells are presented. The results can be summarised as follows:

- Linear microwave plasma sources generating a surface wave guide plasma outside a dielectric tube perform very well in thin film deposition of large scale substrates with dimensions up to 1 m in width.
- A high deposition rate in combination with a plasma- and deposition uniformity better than 5% can be obtained only, if a magnetic field enhanced microwave plasma source is used. A stable plasma generation down to low pressures of 10^{-2} mbar even with process gases like silane and ammonia is possible.
- With three or four parallel arranged plasma sources the silicon nitride antireflection coating of photovoltaic cells can be carried out in industrial scale with a throughput of up to 1500 solar cell wafers per hour, which fulfils the demands of the photovoltaic industry for a high productive PECVD equipment in combination with high performance of the layers regarding uniformity and excellent hydrogen passivation of the mc-silicon wafers.

5. References

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