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RF plasma deposition uniformity on square-meter substrates

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Introduction

Plasma assisted deposition or etching of thin solid films such as amorphous silicon or silicon oxide has widespread applications, especially in the field of photovoltaic solar cells and thin film transistors for flat screen production. Industrial applications require high deposition rates over large areas (up to a square meter) with a layer thickness uniformity to better than 5% for flat screens and about 10% for solar cells. The radio-frequency parallel-plate plasma reactor is the most commonly used configuration in industry for large area applications. In the design of such a reactor, special care must be taken in order to obtain the required film thickness homogeneity. Some considerations include the configuration of the RF electrode connections, the flow distribution of the supply gas and the reactor pumping, powder contamination, electrode topology and plasma uniformity near the electrode edges.

Experiment

The plasma reactor presented in Fig. 1 is a modified version of the industrial KAI-S type reactor commercialized by Balzers AG for thin-film deposition. It consists of a rectangular plasma reactor (57 cm x 47 cm) installed inside a larger vacuum chamber. The RF power is capacitively coupled to the RF electrode via a matching network at the input of which the forward and reflected power are measured. The interelectrode RF voltage distribution across the electrode surface in the plasma zone was measured in the absence of plasma with a passive RF voltage probe connected to a floating oscilloscope. The film thickness uniformity was measured by *ex situ* global interferometry by illuminating the substrate with a homogenous white light source and recording the transmitted light through a 700 nm interference filter. Each interference fringe indicates a 80 nm change in the film thickness. The *in situ* deposition rate was measured using a laser interferometer. For powder contamination investigations, the beam-expanded polarised light from an Argon ion laser was scattered from particles and monitored by a CCD camera. For this study, the scattered intensity was simply used as an indicator for the powder quantity. The excitation frequency was varied from 13.56 MHz to 70 MHz. Plasma parameters relevant to the deposition of amorphous silicon were chosen, namely, a 100 sccm flow of silane with a pressure of 0.2 Torr and a reactor temperature of 200°C.

RF voltage uniformity:

For RF frequencies, due to the skin effect, the RF current is confined to a thin surface layer. The RF electrode is therefore a double-skinned electrode in which the RF current continuity between the top and bottom surfaces is via the edge of the RF electrode. The problem of calculating the RF voltage distribution across the electrode area in the complex geometry of the real reactor is then reduced to a driven, two-dimensional Helmholtz equation applied to an equivalent unfolded two-dimensional geometry with periodic boundary conditions. An analytical solution based on the Green function technique was found for our particular rectangular geometry [1]. The physical understanding afforded by the analytical approach shows that the principal non-uniformity is due to a logarithmic singularity in the vicinity of the RF and the ground connections. This singularity

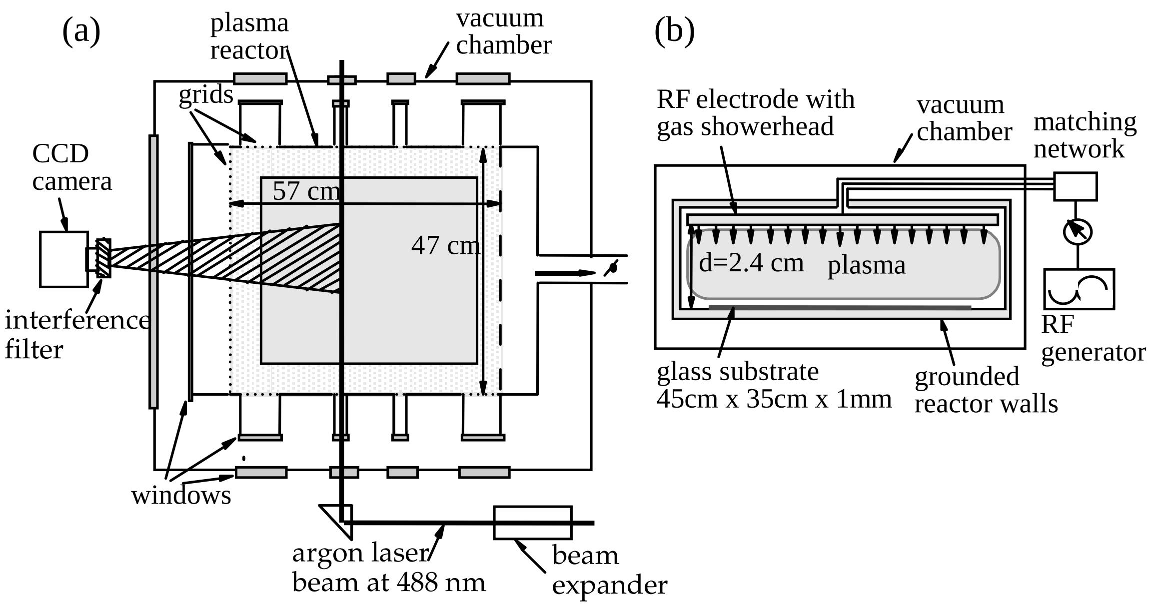

Figure 1: (a) Top view of the plasma reactor with diagnostics; (b) front view of the plasma reactor with the gas shower head.

is a property of the two-dimensional geometry and dominates the standing wave image of voltage distribution obtained from a one-dimensional transmission line model.

Fig. 2 shows the measured and calculated RF voltage distributions across the electrode area at 70 MHz for two different RF connection geometries. The edge RF connection geometry corresponds to the case with the RF connection located midway on the longer side of the RF electrode and the ground connection located on the corresponding side wall of the reactor, while the central RF connection geometry corresponds to the case with the RF connection centered on the top of the RF electrode and the ground connection located at the same place on the reactor cover as shown in Fig.1(b). For these two geometries, the calculated RF voltage distributions are in good agreement with the measurements. For the edge connection (Fig. 2 i)), the RF voltage amplitude strongly decreases towards the electrical connection location as predicted by the analytical two-dimensional model. For the central connection (Fig. 2 ii)), a good RF voltage uniformity is obtained. This is due to the fact that in this geometry the distance between the plasma zone and the singularity associated with the electrical connections is maximized. At 13.56 MHz, the reactor dimensions are well below a quarter of the wavelength and therefore the RF voltage was uniform even with the edge connection.

The film interferograms in Fig. 2 show the different film thickness uniformity obtained in each case. With the edge connection, the film thickness inhomogeneity was about ±38% while with the central top connection, the inhomogeneity was reduced below ±5%. The presence of a plasma does not short-circuit the voltage inhomogeneity. To conclude, RF voltage inhomogeneity is a major limiting factor for VHF plasma deposition in large surfaces.

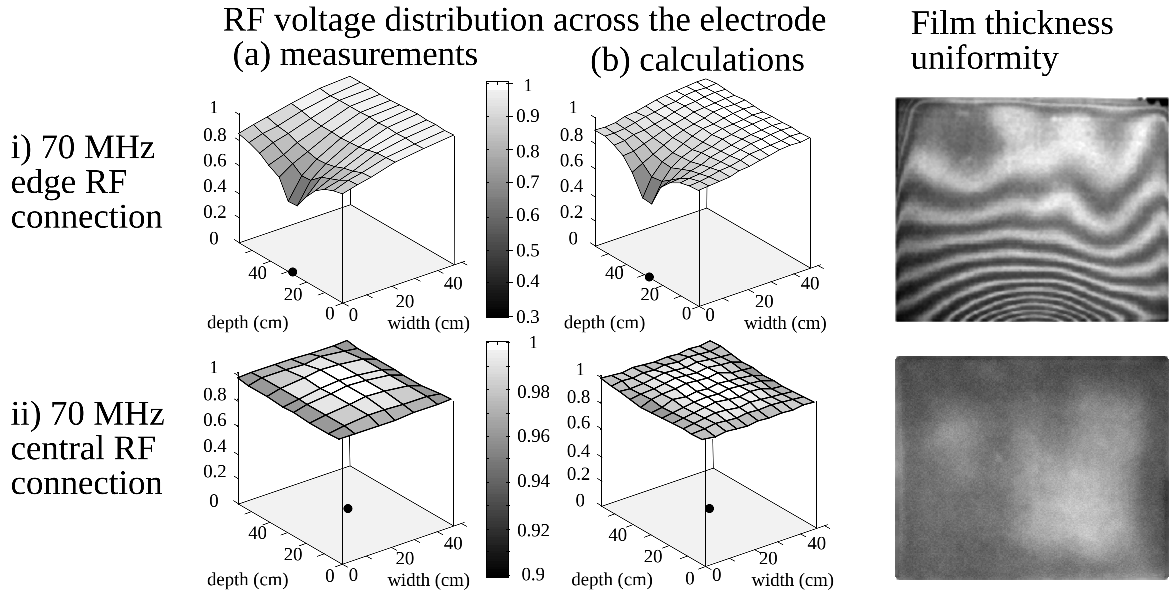

Figure 2: Measured and calculated interelectrode RF voltage distribution at 70 MHz for the edge and the central RF connection cases. The black point indicates the position of the RF and ground connections. The film interferograms show the uniformity of the film thickness for each case.

<u>Influence of the gas flow on uniformity</u>

The gas flow distribution in the reactor is another key parameter that will affect the deposition uniformity. Essentially two types of gas flow arrangement are used in industry: the longitudinal flow reactor, and the showerhead reactor. Uniform deposition rate and film composition are difficult to achieve in the longitudinal flow reactor because the working gas is more and more depleted in the direction of the gas flow and, therefore, the composition of the gas depends on the position in the reactor. This non-uniformity of the gas composition causes inhomogeneities in the deposition rate and in the film composition. On the other hand, the solution of the one-dimensional transport equations for plasma deposition in a uniform showerhead reactor [2] shows that the density of each neutral species is constant along the reactor. The plasma and surface reactions are then seen to be independent of position in any showerhead reactor with single-side pumping, which is a prerequisite for uniform deposition. This conclusion is valid for any degree of depletion: for a showerhead reactor, even plasma processes which involve total depletion of any supply gas can still result in uniform deposition

<u>Non uniform deposition due to powder suspended in the plasma</u>

Particles formed during silane plasma processing by plasma state polymerisation are a source of contamination. They are negatively-charged due to electron-ion flux equilibration at their surface and so are trapped by the plasma sheath potentials and accumulate in electrostatic suspension between the electrodes. Even if the film is not damaged by particles which fall onto the growing surface, the powder clouds suspended in the plasma above the growing film can cause inhomogeneous deposition by locally changing the plasma power dissipation, electron density and energy distribution. For example, films deposited at low input power show a very good uniformity but at a low deposition rate, whereas films deposited at higher input power with powder formation have a higher deposition rate, but with a strongly degraded uniformity [3]. The inhomogeneities tend to be concentrated at the edges of the substrate where the thickness increases rapidly over the last 3 cm. The scattered intensity profiles in Fig. 3 show clear differences with and without substrate and it would appear that the substrate greatly influences the powder traps.

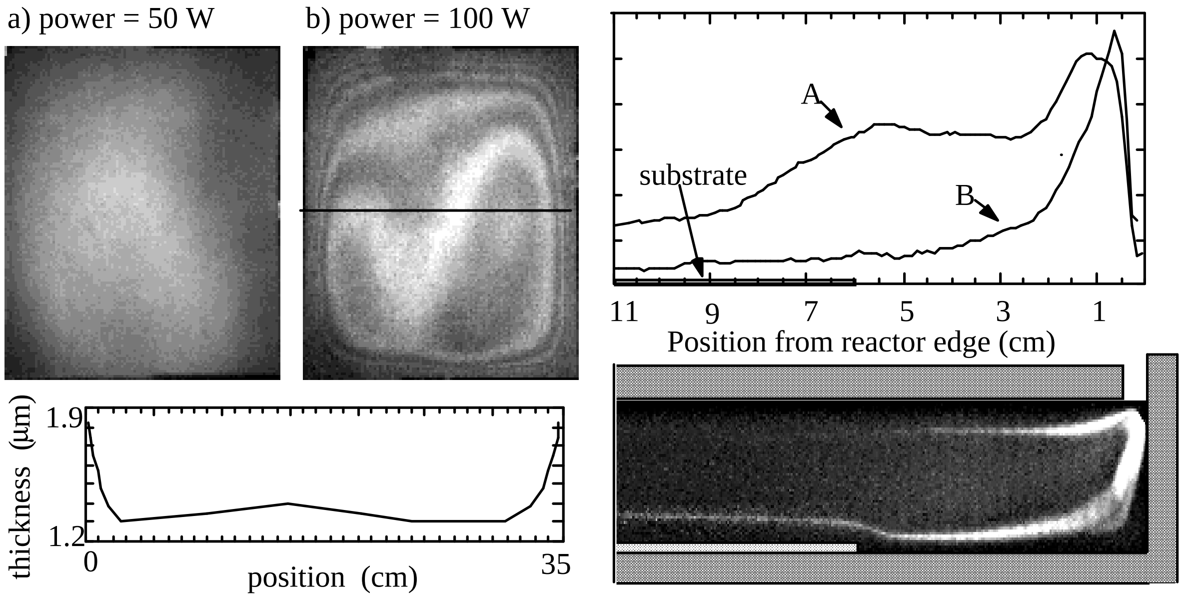

Figure 3: Global interferograms for films deposited a) at 50 W (no powder observed); and b) 100 W input power (with powder). The thickness profile corresponds to film b) along the line shown. Curve A represents the vertically-integrated intensity scattered from the powder measured from the CCD image shown; curve B is for the case without substrate.

Conclusions

Deposition uniformity has been considered from the point of view of RF voltage, gas flow and powder contamination. Further improvements are to be expected from current investigations into RF multi-point connections and segmented electrodes, generalised showerhead and pumping configurations, and novel design of the electrode edge geometry.

Acknowledgments

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