LARGE AREA DEPOSITION OF AMORPHOUS SILICON BY VERY HIGH FREQUENCY PLASMA

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Plasma enhanced chemical vapor deposition (PECVD) of thin films such as amorphous and microcrystalline silicon 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 and uniform film thickness over large areas. The most commonly used deposition technique uses silane as working gas at low pressure (mbar) in a parallel plate reactor with 13.56 MHz excitation frequency to generate a plasma. The silane is dissociated by electron impact collisions into hydrogen and radicals, which deposit on the reactor walls. The choice of the excitation frequency is dictated by convention rather than by optimization of the physical process in the discharge.

Since the previous work of Curtins et al. [1], Very High Frequency (VHF: 30 - 300 MHz) excitation has been demonstrated to be a good alternative to the conventional 13.56 MHz frequency for depositing good quality amorphous and microcrystalline silicon at high deposition rates [2,3]. VHF plasmas are now the subject of a growing body of theoretical and experimental studies, but the observed increase of the amorphous and microcrystalline silicon deposition rate with the frequency at constant power is still not well understood. Generally, high-frequency experiments are performed in small reactors and they need to be upscaled in order to meet the large-area requirement for industrial applications.

We present two aspects of VHF plasma deposition in a large area reactor:
1) Interelectrode RF voltage uniformity across the electrode area.
2) Effects of the frequency on the plasma properties.

The final aim of this work is to identify the physical and practical factors determining the choice of the excitation frequency for a given application.

The plasma reactor used for these experiments is a modified version of the industrial KAI type reactor commercialized by Balzers SA for thin film deposition. It is shown in fig. 1 and described in more details in [4]. 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, which is suspended 24 mm above the reactor floor. The process gases are introduced through a showerhead incorporated in the RF electrode and residual gases are pumped out through the back wall designed as a coarse grid. The glass substrates used for deposition were centrally placed on the reactor floor (grounded electrode). Large windows positioned at the end of 10 cm long extension tubes were introduced into our reactor for plasma diagnostics, and grids were placed at the reactor wall to preserve electrical continuity and plasma confinement.

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 as shown in Fig 1(b). In situ FTIR absorption spectroscopy technique,
described in details in [5], was used to measure the silane gas concentration and the degree of dissociation $D$ defined by: $D = (n_{SiH_4} - n_{oSiH_4}) / n_{oSiH_4}$, where $n_{SiH_4}$ and $n_{oSiH_4}$ are respectively the SiH$_4$ density with and without plasma at constant total pressure. A microwave resonant cavity technique was used to measure the electron density as described in [6]. The film thickness uniformity was measured by an ex situ global interferometry technique [7] and the in situ deposition rate was measured at one point using a laser interferometer.

Figure 1. (a) Top view of the plasma reactor with the FTIR instrument for absorption spectroscopy measurements and the microwave device for electron density measurements; (b) front view of the plasma reactor with the central RF connection and the RF voltage probe used for voltage uniformity measurement.

Plasma parameters relevant to the deposition of amorphous silicon were chosen for the frequency study, namely, a 100 sccm flow of silane with a pressure of 0.2 Torr and a reactor temperature of 200°C. The excitation frequency was varied from 13.56 MHz to 70 MHz and the power dissipated in the plasma was kept constant at 80 W.

1) Interelectrode RF voltage uniformity:

Since the plasma characteristics depend largely on the RF voltage, a uniform voltage distribution across the electrode area is a prerequisite for obtaining a uniform film thickness. Non-uniformity of the interelectrode voltage appears when the electrode dimensions approach a quarter of the free-space wavelength associated with the excitation frequency ($\lambda/4 = 0.75$ m at 100 MHz). For RF frequencies, due to the skin effect, the RF current is confined to a 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 [4]. 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 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 an RF connection located on the edge of the RF electrode and for an RF connection centred on the top of the RF electrode. 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.

In Fig. 2, the film interferograms 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 and it was found that in absence of any other inhomogeneity sources, a square power law between the local RF voltage and the deposition rate for a-Si:H reproduces the measured film inhomogeneities to a good agreement [4].

Effect of the frequency on the plasma properties:

Fig. 3(a) shows an increase of the degree of dissociation of SiH₄ with the frequency. This corresponds to an increase in the production of radicals (reactive species for the deposition) which could be the direct source of the observed increase of the deposition rate.
with the frequency. These measurements shows clearly that the increase of the deposition rate with the excitation frequency is not only due to an increase of the surface reactivity, as proposed by Heintze [8,9], but is also due to an increase of the gas phase reactions.

Figure 3. (a) SiH4 degree of dissociation D and deposition rate R versus frequency; (b) electron density n_e versus frequency.

Fig. 3(b) shows an increase of the electron density with the frequency. Since the dissociation rate is the product of the electron density by the rate constant \((K = n_e k(T_e))\), the higher dissociation rate at VHF is therefore principally due to the increase of the electron density with the frequency.

CONCLUSIONS

Two aspects of VHF plasma deposition in a large area reactor have been investigated. From the point of view of plasma properties and deposition rate, it is favorable to increase the frequency in the VHF domain, but from the point of view of film thickness homogeneity, there is an upper limit for the frequency depending on the substrate dimension and the electrical connection geometry. The final choice of the excitation frequency for a given application is therefore a compromise between these two tendencies.

REFERENCES