Development of a hollow cathode plasma source for microcrystalline silicon thin films deposition

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Abstract. The development of a hollow cathode plasma source and its implementation in an already existing plasma reactor used for the deposition of \(\mu\)-Si:H thin films is presented. Electrical measurements of hydrogen discharges at 13.56 MHz were carried out for two different designs of hollow electrodes and the electrical parameters were compared with a previous Capacitively Coupled source installed in the same reactor. The results show a significant enhancement of discharge current and higher power dissipation for the same applied voltage. At reduced gas pressures that are necessary to minimize the dust formation, the hollow electrode with the larger cavity geometry showed better performance, achieving high electron densities of above \(10^9\) cm\(^{-3}\). Microcrystalline silicon thin films were deposited from SiH\(_4\)/H\(_2\) discharges and an enhancement of the growth rate was found for the hollow cathode source as compared with the CCP source.

1. Introduction

Hydrogenated microcrystalline silicon (\(\mu\)-Si:H) thin films have attracted intense scientific interest due to their application in thin film solar cells of single and tandem structure [1-3]. Although this material presents wider-spectrum response and enhanced stability against light exposure than the technologically mature hydrogenated amorphous silicon (a-Si:H), thicker films of \(\mu\)-Si:H are required to sufficiently absorb the light due to its indirect band gap [1,4]. Thus, an issue that emerges inevitably is how the film deposition process can be less time-consuming, aiming to reduce the production costs, while preserving the desired film quality for application in photovoltaic industry. The most widespread method used industrially for deposition of \(\mu\)-Si:H is Capacitively Coupled silane/hydrogen glow discharges (CCP-GDs), though with this technique the growth rate for device grade films is rather low. This is the main reason why the research is directed to the implementation of different, non-conventional plasma sources with enhanced electron density, which can lead to higher gas usage efficiencies and deposition rates. Many novel plasma techniques have been proposed in this field, such as the very high frequency (VHF) and the high pressure depletion method (HPD) [5-7]. Other high density methods using microwave plasma [8,9], inductively coupled plasmas [10,11] and electron cyclotron resonance plasmas [12,13] have also been proposed. Hollow cathode discharges (HCDs) present noticeably high electron density due to the electrons entrapment and oscillation inside narrow cavities and are promising for deposition processes [14-17]. The advantage of hollow cathode against other high density plasma sources is that only small changes are needed on the already existing industrial reactors. Hollow cathode sources for \(\mu\)-Si:H deposition can be found in literature in diverse configurations with very interesting results concerning the deposition rate and the film quality [18,19].
Other interesting issues related to hollow electrodes can also be found, such as electrical measurements, optical emission spectroscopy analysis and quality evaluation of films deposited at high growth rates [20-22].

In this work, we present the development of a hollow cathode (HC) electrode and the implementation of the source in an already existing parallel plate Capacitively Coupled plasma reactor. The basic aims of the study are to investigate the role of hollow geometry on the deposition rate of μc-Si:H thin films as well as to study the film growth rate under relatively low total gas pressure in order to minimize the problems of dust formation. For that reason we developed two different in geometry hollow cathode sources and electrical measurements were performed for both of them, in hydrogen discharges. The measurements of voltage, current and phase impedance in the plasma and the calculation of discharge power revealed the conditions required for operation in the hollow cathode mode. A comparison of the different sources with the existing CCP source was also implemented and the differences in the power dissipation and the electron densities are presented. Finally, thin silicon films depositions were performed as a function of various experimental parameters and the changes on the film growth rates for the HCD and the CCP source are discussed.

2. Experimental

The experiments were carried in an ultrahigh vacuum reactor having a base vacuum of $10^{-7}$ Pa. The 12 cm in diameter RF powered hollow cathode electrode is fixed to the chamber in the place of the already existing capacitively coupled planar electrode and the measurements were performed in two different in geometry hollow electrodes, the first (HC1) consisting of 40 holes of 0.5 cm length and 3 cm diameter (Figure 1) and the second (HC2) of 12 holes of 1.8 cm length and 2 cm diameter (Figure 2). The substrate holder (grounded electrode) can be freely moved to adjust the distance between the HC source and the substrate. All the films were deposited in Corning 7059 at substrate temperature of 200 °C using high purity gases and the deposition rate was measured in-situ using Laser Reflectance Interferometry (LRI).

The RF (HC or CCP) electrode was powered by a 13.56 MHz generator, through an L-type matching network. A Lecroy PPE 1000:1 voltage probe and a FCC F-35-1 current probe were attached after the matching network. A Lecroy 9400 digital oscilloscope was used to record the voltage and current signals which were then transferred to a computer for Fourier analysis. The real amount of RF power consumed in the discharge was determined using an accurate method described in details elsewhere [23]. With this method we were able to convert the voltage and current waveforms measured outside the chamber to equivalent waveforms at the RF electrode [24].

All sets of electrical measurements were performed for pure H$_2$ discharges while the total gas pressure and the flow rate were kept constant at 133 Pa and 50 sccm respectively. The hydrogen was fed to the reactor through the hollow cathode electrode. The distance between the powered and the grounded electrode was set to 1.5 cm. As for the deposition experiments, the total gas flow rate was maintained constant at 200 sccm while the silane ratio was set at 10 %. The effect of pressure (79.8 to 332.5 Pa), interelectrode space (1.5 to 2.5 cm) and applied voltage (50 V to 150 V amplitude) was...
investigated. Partial flow rates were adjusted by accurate mass flow controllers and the total pressure was controlled by a downstream throttle valve controller as well.

3. Results and discussion

3.1 Electrical measurements

Different electrical parameters were examined on hydrogen discharges comparing the three different plasma sources and configurations; the typical capacitively coupled glow discharge with the two other, different in geometry, hollow cathode sources. The discharge current as a function of the electrode voltage amplitude is shown in Figure 3. In the CCP case the current increases slightly with the voltage with its values limited in a range of 100-200 mA. On the other hand, in the hollow cathode discharges and for both hollow electrodes the current showed a sharp, almost exponential increase with the electrode voltage. Additionally, the second hollow configuration (HC2) presented much higher current values than the two other sources, indicating conditions of higher electron density. It is also worth noticing that for HC2 the current increases abruptly after the 100 V, revealing the breakdown voltage for which the discharge moved from the early capacitive to the hollow cathode mode.

![Figure 3. The total discharge current as a function of the electrode voltage amplitude for three different plasma sources.](image)

In this mode, the increase of the current is attributed to the hollow cathode effect that leads to avalanche multiplication of charge carriers inside the cavities of the electrode. Comparing the two hollow cathodes it is clear that for HC1 there is no mode transition and operates in a purely capacitive mode. The breakdown voltage is totally affected by the hollow geometry and the pressure and follows Paschen’s Law [15]. Thus, for the first electrode configuration with the narrow holes, higher pressures are prerequisite for the mode transition, while the wide cavities in the second hollow electrode allow process optimization at relatively low gas pressures.

Figure 4 presents the real power dissipation in the discharge as a function of the electrode voltage amplitude. The variation of power presents similar behaviour to the discharge current apart from the fact that the values concerning the CC and the HC1 electrode almost coincide, confirming that in those conditions the latter behaves as being in a capacitive mode. On the other hand, the sharp increase of
the discharge power with voltage for HC2 follows the increase of the current that was shown in fig. 3. The variation of applied voltage and modes affects also the reactive and ohmic part of the plasma impedance. The complex discharge impedance is given by the equation [23]:

\[ Z = \frac{V_{el}}{I_{el}} \exp (i\varphi_{el}) = R + iX \]  

where \( \varphi_{el} \) is the phase of the electrode voltage \( V_{el} \), relative to the electrode current \( I_{el} \). The ohmic component \( R \) of the impedance is given by:

\[ R = Z \cos \varphi_{el} = \frac{V_{el}}{I_{el}} \cos \varphi_{el} \]  

and counts for the power dissipation in the discharge due to the acceleration of electrons in the plasma bulk and also of ions and secondary electrons in the sheaths. Figure 5 presents the variation of \( R \) as a function of the applied voltage for the three different sources. The ohmic component drops with voltage for all modes and geometries as a result of the increase of plasma conductivity. This reduction is more pronounced in the case of the second hollow electrode where the impedance falls abruptly at the mode transition region.

The information acquired by the electrical measurements concerning macroscopic parameters can be linked to microscopic parameters in the plasma such as electron number density, energy and collision frequency. The electron density is an essential quantity when one argues about high density plasma sources. An estimation of the average electron density can be given from the electrical measurements as it is strongly related to the ohmic part of the discharge impedance \( R \) [24-26]:

\[ n_{AV} = \frac{v_{m}d_{b}m_{e}}{RAe^2} \]  

where \( v_{m} \) is the electron momentum transfer collision frequency, \( d_{b} \) is the bulk length, \( m_{e} \) is the electron mass, \( A \) is the discharge cross section and \( e \) is the electron charge. As bulk length was considered the whole interelectrode distance (1.5 cm) and the momentum transfer collision frequency was estimated at \( \sim 3.76 \times 10^7 \text{ Pa}^{-1}\text{s}^{-1} \) [25]. Figure 6 presents the variation of the average electron density as a function of the electrode voltage amplitude. The comparison of HC1 with CC source shows that the electron density in the latter is slightly higher, which in turn reveals that in that pressure and electrode

**Figure 4.** The total discharge power as a function of the electrode voltage amplitude for three different plasma sources.
The discharge impedance as a function of the electrode voltage amplitude for three different plasma sources.

In this mode, inside the cavities the electrons multiply rapidly because the sheath voltage increases leading to higher electric field. Electrons in the bulk are trapped between repelling electric fields of the opposite sheaths and are forced to oscillate, gaining more energy and causing ionization collisions with the hydrogen molecules. In addition, the higher sheath voltages accelerate the ions towards the hollow cathode walls causing secondary electron emission, which contributes to the multiplication of electrons and the increase of their number density. However, the increase of the electron density with voltage can also be indirectly affected by pressure, which is higher inside the cavity than in the reactor chamber [15].
Microcrystalline silicon thin films were deposited with the second hollow electrode configuration, which presents the best performance as a high density source, according to the electrical parameters above. The deposition rate was examined as a function of different parameters and at diverse conditions. Initially, the deposition rate was measured for different total gas pressures while the other plasma parameters were kept constant. Figure 7 shows the variation of the film growth rate as a function of the total gas pressure and there is an optimum at 200 Pa, where DR has a value of 0.76 nm/s.

The deposition rate is affected by almost all experimental conditions and its maximum can be shifted for other conditions. Nevertheless, the hollow electrode configuration, except for the relatively high electron densities that derived from the electrical measurements, presents also higher deposition rate at relatively low pressure. Moreover, the effect of the discharge power and the way of SiH₄ introduction to the discharge (through hollow cathode or not) on the deposition rate were examined under conditions of constant total gas pressure for the HC2 configuration. The pressure was set at 133 Pa, the electrode gap at 1.5 cm and the mixture of SiH₄ in H₂ at 10 %.

Figure 8 shows that the deposition rate increases with the discharge power for all configurations. The HC2 mode allows higher energy transfer from the generator to the plasma for the same applied voltage, leading thus to much higher film growth rates compared to the CC configuration, especially in the case that SiH₄ is introduced outside the hollow. The silane in this case reaches the plasma region outside the cavity, where the electrons and H atoms density is relatively high, due to the enhanced ionization and dissociation in this area. The rate increases with the discharge power and presents a maximum of 0.81 nm/s at 44 W power dissipation in the discharge. This enhancement can be attributed to the increase of electron density and the number of electrons with enough energy to induce SiH₄ dissociation towards radicals, which are responsible for the deposition rate. On the other hand, the deposition rate increase is not so pronounced when the silane is fed through the hollow cathode, despite the high discharge power. In this case, the silane dissociation inside the hollow cathode or the preferential ionization of SiH₄ inside the cavities that consume SiH₄ without contributing to the film growth may limit the deposition rate.
4. Conclusions

Two different hollow cathode configurations have been constructed and their operation has been tested and compared to a typical CCP source by using electrical measurements. The hollow configuration of wider cavities had the best performance as far as the electron density is concerned. Electron densities of above $10^9$ cm$^{-3}$ were achieved with the hollow cathode, much higher than the typical Capacitively Coupled discharges.

Microcrystalline silicon thin films depositions were also performed and the effect of the different geometries and sources on the film growth rate was investigated. The hollow cathode configuration was found that allows higher energy transfer from the generator to the plasma as compared to the CC source and this leads to a significant enhancement of the film growth. The introduction of SiH$_4$ directly into the plasma zone instead of through the hollow cathode had also beneficial effect on the deposition rate. Further work is required for optimizing the geometry of the HC source and the gas mass transfer in order to obtain the optimum results on both the film growth rate and the film quality.

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