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SPATIAL DISTRIBUTION OF OPTICAL EMISSION IN SiH_4/H_2 RF DISCHARGES

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ABSTRACT. Spatially resolved optical emission spectroscopy is used to study the variation of atomic hydrogen emission (H_β) and SiH* ($A^2\Delta$) in the interelectrode space of a parallel plate configuration, usually employed for the deposition of amorphous or microcrystalline silicon. Space integrated emission measurements are presented as a function of power consumed in the process, for pure silane discharges and for hydrogen diluted silane discharges. Atomic hydrogen intensity profiles are also compared with the respective profiles recorded in pure hydrogen plasmas. The origin of atomic hydrogen emission and the effect of silane related gas phase chemistry on the discharge characteristics is discussed.

1. INTRODUCTION

It is known that silane-processing discharges, even though intensively investigated and used in the microelectronics industry, are not completely described concerning several aspects of gas-phase kinetics and plasma-surface interaction mechanisms. This is due to the complex interconnection and the variety of the numerous elementary processes involved in RF plasmas.

For several years continuing efforts have been devoted to improve the fabrication of amorphous and microcrystalline silicon thin films by means of enhancement of the desired film properties, reproducibility of deposition conditions, increase of deposition rate, etc. Compared to a-Si:H, μc-Si:H exhibits more interesting properties such as higher doping efficiency, improved electrical conductivity and carrier mobility and no light induced degradation [1]. In keeping with this trend, a better understanding of the deposition process is essential in order to find more efficient production conditions, since the low optical absorption of μc-Si:H makes necessary the increase of the deposition rate.

Optical emission spectroscopy (OES), commonly used as a diagnostic tool, is well adapted in such processes, providing information on either the energy content or the relative abundance of the species in the process. The main advantage of OES concerning plasma-processing environments is the non-perturbing nature of these techniques and the flexibility to fit easily in the various experimental arrangements. More specifically, it has been found that atomic hydrogen plays a crucial role in the deposition of μc-Si:H by affecting the formation of a highly porous phase where the nucleation of crystallites can take place [2].

In this work spatially resolved optical emission spectroscopy is used to study the relative intensities of atomic hydrogen through Balmer β line and of SiH* through $A^2\Delta$

transition utilizing also the ability to control and measure the power actually consumed in a low-pressure RF 13.56 MHz discharge [3].

In particular, the dependence of space integrated emission profiles on power consumed in the discharge is investigated in pure silane discharges and in highly hydrogen diluted silane discharges. Emission from pure hydrogen discharges is also investigated for comparison.

2. EXPERIMENTAL

Experiments are performed on a cylindrical stainless steel parallel plate chamber with 5.5 mm in diameter electrodes and adjustable electrode separation, which is 25 mm in this series of experiments. The chamber is equipped with four quartz windows suitable for optical measurements.

The setup used to obtain spatially resolved emission intensity profiles is described in detail elsewhere [4]. Briefly, two 0.5 mm wide slits are placed in a distance of 10 cm between them and 5.5 cm focal length lens is used to focus the emission collected from a pure silane discharge to the entrance slit of a 1m JY-THR1000 monochromator. This configuration provides a spatial resolution of about 0.5 mm at the axis of the chamber, ensuring that the light from a 0.5 mm slice of the plasma is actually gathered. The monochromator is equipped with a 3600 gr/mm ruled grating and a side-on PMT. Spatial profiles are obtained by moving the chamber axis perpendicularly to the static slit-lens system.

Pressure is measured by a capacitance manometer and can be adjusted independently from the flow rate. In the pure silane series of experiments, constant flow rate of 10 sccm and a pressure of 50 mTorr are maintained constant while changing the peak to peak voltage. Similarly, in the high dilution regime, pressure is kept constant at 500 mTorr and a constant ratio of H_2/SiH_4: 150/1 is fed in the chamber.

Concerning the electrical configuration of the system, one of the electrodes is powered by an ENI ACG-3 13.56 MHz RF generator isolated with an L-type matching network, while the other electrode as well as the chamber walls are grounded. The measured voltage and current waveforms are transformed to the equivalent ones at the surface of the powered electrode using a proper characterization of the stray impedance of the cell [3].

3. RESULTS AND DISCUSSION

Figure 1 presents the variation of space integrated emission intensity from SiH* and H_β as a function of the power consumed by the discharge together with the ratio of the H_β to SiH* emission intensity. Both intensities exhibit a second order increase with power, tending to saturate at high power density [4]. As is observed, hydrogen emission is much weaker than SiH* emission, which is the main emitting fragment in silane containing discharges. In fact, the ratio of total emission varies from 0.1 at 0.5 mW/cm^2 to about 0.32 at 5 mW/cm^2. A previous investigation of Balmer α emission from Kampas and Griffith in silane RF discharge has led to the conclusion that this is a two-electron impact process [5]. On the other hand, Perrin and Schmitt found Balmer line emission intensities to be strictly proportional to the fast electron density [6]. Furthermore, Tsurubuchi et al. have found that optically forbidden states of SiH_4 play an important role in producing excited H atoms while they also measured the emission cross sections of Balmer lines and SiH ($A^2\Delta$) for electron impact on silane [7]. One must consider also that in pure silane plasmas, hydrogen emission due to electron impact on atomic hydrogen is expected to be of minor importance. More specifically, even though the Balmer line emission cross sections for electron impact on H are 10 times larger than for H_2 [8], the relative density ratio $[H]/[H_2]$ is very low due to the consumption of hydrogen atoms in various gas phase reactions. This means that all experimental data must be interpreted in terms of competitive emission due to one electron impact either on SiH_4 or H_2. Therefore, the behavior of the ratio on figure 1 must be due to the different cross sections of the two processes. More specifically, the excitation threshold for SiH ($A^2\Delta$) is 10.5 eV while for H_β is about 20 eV, and in addition, the maximum cross section value is about 5 times smaller for H_β. Following the reasoning mentioned above, the second order behavior for SiH* reflects the change of the effective electron density (electron density above the threshold) with power which appears to be non-linear. This stands for H_β too, but in this case, we must also consider the possible contribution due to H_2 dissociative excitation. However, the density of molecular hydrogen in our experimental conditions is expected to be at least two orders of magnitude less than that of silane. In addition, the emission cross section is smaller for electron impact on hydrogen [7]. This leads to the conclusion that emission from atomic hydrogen results mainly from one electron impact dissociative excitation of silane.

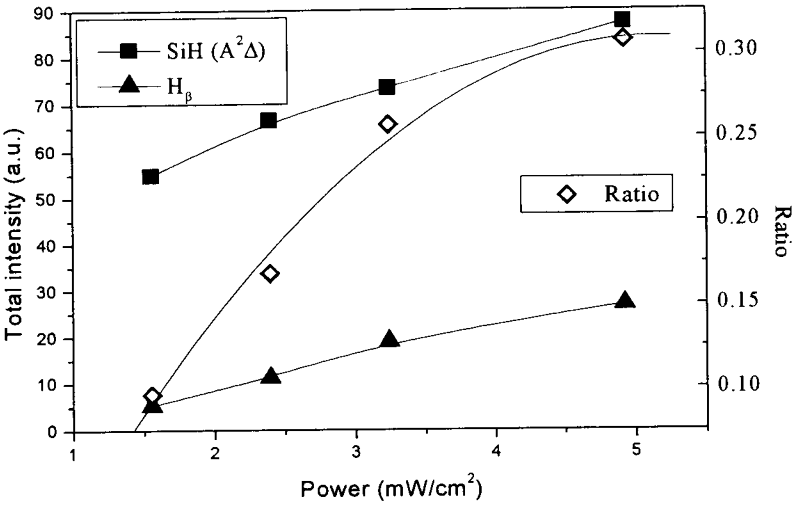

Figure 1. Total emission intensity as a function of power, from SiH ($A^2\Delta$) and H_β excitation, in a 50 mTorr pure silane discharge.

Figures 2 and 3 present the distribution of emission from H_β in the interelectrode space in a 50 mTorr pure silane and in a 500 mTorr silane – hydrogen discharge, for a concentration ratio SiH_4/H_2: 1/150. A comparison of these figures shows that H_β in the pure silane case exhibits a relatively wide distribution in space, while at 500 mTorr emission decreases drastically beyond 12 mm. In addition at 500 mTorr, a second emission peak is observed near the grounded electrode. This indicates that there is a significant contribution of the ground sheath heating mechanism.

Furthermore, in this pressure the electron penetration depth in the bulk of the plasma is significantly reduced, resulting in a minimum emission region around 15 mm, while at 50 mTorr electrons gain energy mainly from the RF sheath and

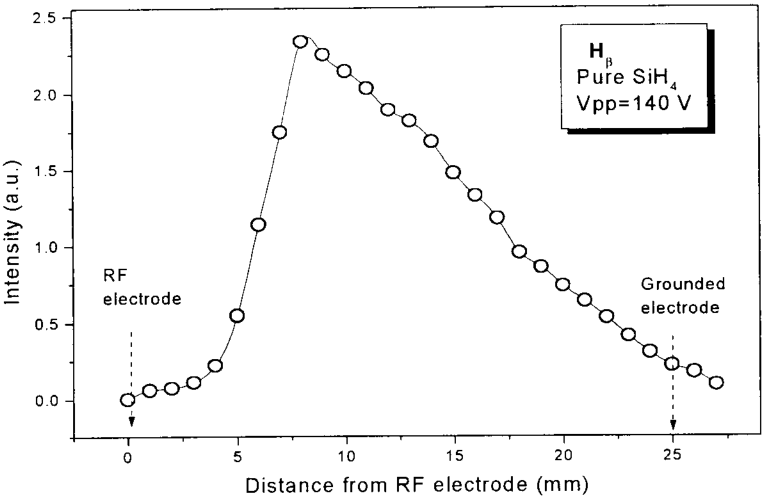

Figure 2. Spatial distribution of H_β emission intensity in a 50 mTor pure silane discharge.

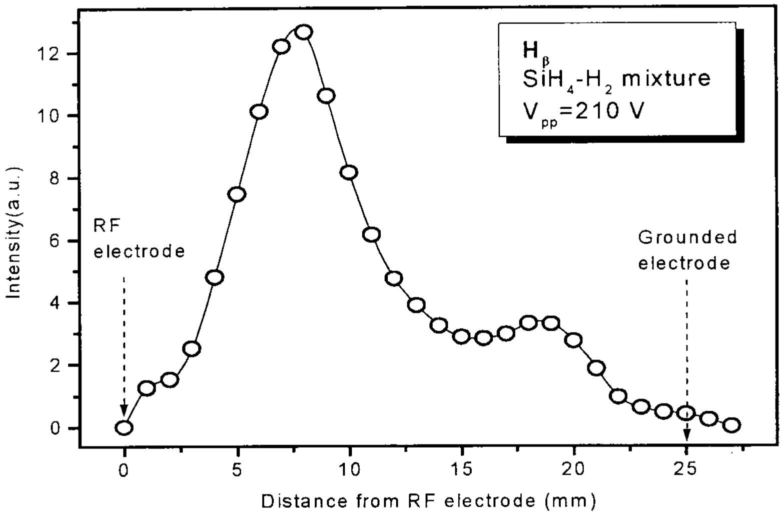

Figure 3. Spatial distribution of H_β emission intensity in a 500 mTorr hydrogen diluted silane discharge.

spread in the interelectrode space. At 50 mTorr one can also observe a dark region adjacent to the RF electrode, which extends almost 4 mm away. The most important feature in these figures is the drastic increase of emission near the grounded electrode at 500 mTorr. For instance at 19 mm, 6 mm from the deposition electrode, emission intensity is almost twice the maximum intensity at 50 mTorr pure silane plasma.

Figure 4 presents atomic hydrogen emission as recorded from a 500 mTorr pure hydrogen discharge. It is clearly seen that the second emission peak is smaller. It must be noticed also, that in the pure hydrogen discharge the H_β distribution is narrower compared to the silane – hydrogen mixture. A comparison of figures 3 and 4 with figure 2 shows that there is a step-like increase of emission in both H_β distributions, adjacent to the powered electrode, in contrast to the dark region observed at 50 mTorr. In all cases, a maximum value at 8 mm is obtained but the discharge structure is completely different in the two cases.

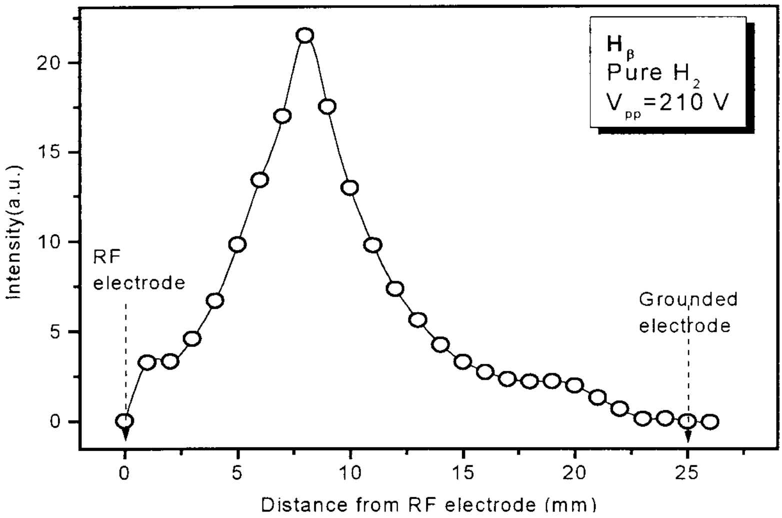

Figure 4. Spatial distribution of H_β emission intensity in a pure hydrogen discharge.

The variation of the total emission with power, for a 500 mTorr 1/150 silane – hydrogen mixture, and the respective variation of H_β emission for a pure hydrogen discharge, are presented on figure 5, together with the ratio of H_β to SiH* total emission. Cocerning total emission, in all cases a linear dependence with power is observed, while a different slope is encountered for each process. Furthermore, atomic hydrogen emission emerging from pure hydrogen plasma is stronger compared to the silane – hydrogen plasma. The ratio of H_β to SiH* total emission ehxibits a similar second order dependence with power as in the 50 mTorr case, however less saturated.

In order to analyze this phenomena one has take into account the relative emission cross sections for electron impact on silane and hydrogen. Thus, the linearity of total emission in figure 5 implies first order dependence of the effective electron density for SiH* emission resulting from one-electron dissociative excitation of silane. In the case of H_β emission, however, things are more complicated. In the pure silane case, ground state H excitation is ruled out, while in highly hydrogen diluted discharges this contribution cannot be neglected. This is because, the observed linearity depends both on the contribution of the dissociative excitation of H_2 and the possible ground state excitation of H, produced by the dissociation of H_2. In fact, as mentioned earlier the Balmer line emission cross sections for electron impact on H are 10 times larger than for H_2 and in addition the threshold is closer to SiH*, i.e. 12.75 eV. This rationale is also supported by the fact that both H_β and SiH* appear to have almost the same total intensity in the low power regime. This means that ground state H excitation has possibly a non-negligible contribution on the observed emission.

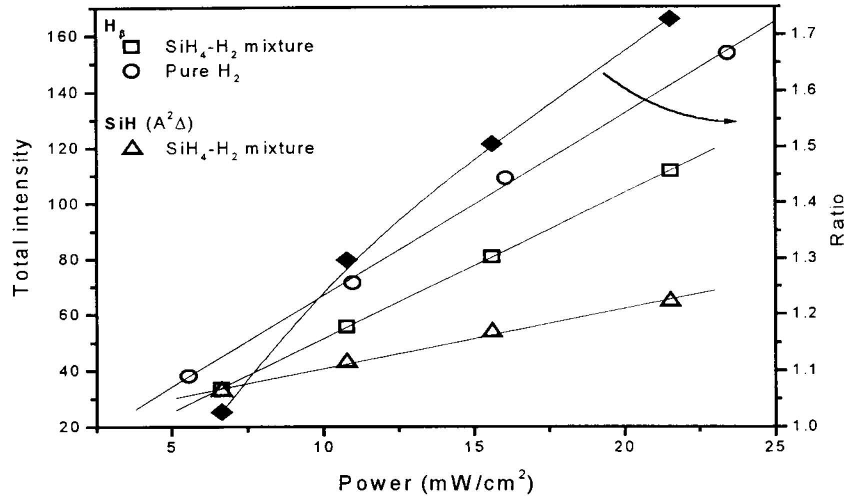

Figure 5. Total emission intensity as a function of power, from SiH ($A^2\Delta$) and H_β excitation, in a 500 mTorr hydrogen diluted silane discharge and in a pure hydrogen discharge

The different slopes observed in figure 5 in the H_β emission are related to the respective modification of the electron density and the electron energy distribution function due to the presence of silane. These results are compatible with electron density measurements in silane RF discharges for various dilution gases [9]. More specifically, in the case of hydrogen dilution it was found that the electron density slightly increases with increasing silane content between 5% and 35%, while k_{em} (the rate constant of X leading to X*) and I_n (the normalized emission intensity proportional to $k_{em}n_e$) decrease with silane content. This behavior is interpreted based on the relative change of electron production rate versus electron loss rate. An important aspect of this approach is that silane is more easily ionized than hydrogen and that the modification of the electron density is mainly due to a change in the electron loss rate as silane fraction increases. Indeed, a closer look on figure 5 shows that atomic hydrogen emission retain only a small difference in the slope between the pure hydrogen and the mixture case, while the major characteristic is a symmetrical vertical displacement of the observed line when a small amount of silane is added. This behavior is attributed to the presence of a large molecule like silane in the discharge, which is known to affect drastically the electrical characteristics of the plasma [4].

Concerning the deposition of μc-Si: H it is obvious that high dilution ratios and high power conditions are preferable in order to achieve a sufficient production of hydrogen atoms. As mentioned earlier, hydrogen radicals impinging onto the growing film surface are expected to affect both etching and crystallization. As is known, the use of silane-hydrogen mixtures by itself does not lead do the production of microcrystalline thin films. The transition from amorphous to microcrystalline growth depends on both gas phase processes and substrate temperature.

4. CONCLUSIONS

The variation of optical emission in the interelectrode space of a parallel plate configuration, usually employed for the deposition of amorphous or microcrystalline silicon is investigated using power actually consumed by the process as a parameter.

More specifically, atomic hydrogen emission through Balmer β line and SiH* emission through $A^2\Delta$ transition are recorded in a pure silane discharge and compared to the respective emission from a highly hydrogen diluted silane plasma.

In the first case, space integrated emission exhibits a second order dependence on power, while the ratio increases also with a second order law. In this case, both processes are believed to arise from the dissociative excitation of silane. The total intensity behavior is attributed to the relative change of the effective electron density for the two processes, due to the differences in their cross sections.

Concerning highly hydrogen diluted silane discharges space integrated emission is found to depend linearly on power, yet with different slopes for each process. The ratio of H_β to SiH* total intensity is however, non-linear with power. A comparison of these results with H_β emission from the respective pure hydrogen discharges has revealed a minor change in slope while the main change is a symmetrical vertical increase of total emission. These results are explained based on the modification of electron density and/or electron temperature, due to the presence of silane. In addition, the contribution of ground state H excitation on the observed emission is considered to be non-negligible.

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