ION ENERGY DISTRIBUTION FUNCTIONS IN MICROWAVE AND RADIO FREQUENCY PLASMAS

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Abstract

Ion energy distribution functions (IEDF) were measured at the surface of a grounded or RF-powered electrode exposed to a microwave (MW, 2.45 GHz) or a radio frequency (RF, 13.56 MHz) discharge in argon and nitrogen. We observe structured IEDFs in all discharges. On the grounded electrode, the ion energy in RF plasma is systematically twice as high as in the MW plasma, and different trends of the mean and maximum ion energies are observed when varying the discharge parameters. We show that in the dual-frequency plasma, on the RF electrode exposed to the MW discharge, the ion energy and ion flux can be selectively controlled.

1. Introduction

Bombardment of material surfaces by low-energy ions can lead to sputtering, breakage of chemical bonds, ion incorporation, heating, surface diffusion, and other forms of energy dissipation. In low-pressure plasma deposition these effects can be optimized to achieve film densification and improved adhesion, allowing to deposit high quality coatings at a low substrate temperature. It has been shown that certain critical ion energies and ion fluxes are required for selective adjustment of the materials microstructure and properties during the deposition of dielectric, metal and semiconductor films [1-3].

In plasma-enhanced chemical vapor deposition (PECVD) or reactive ion etching (RIE) the ion bombardment is usually controlled by applying a negative bias voltage to the substrates [4]. In radio frequency (RF) or other single-frequency plasma systems the ion bombardment parameters, namely the ion energy (E_i) and the ion flux (F_i), cannot be controlled independently. This drawback can be overcome by using a dual-mode microwave/radio frequency (MW/RF) plasma: the substrates are placed on an RF-powered substrate holder, where a self-induced negative d.c. bias, V_B, develops [7], while they are simultaneously exposed to a principal microwave (MW) discharge, which contributes a high bulk plasma density [5,6].

The maximum energy of ions, E_{max}, is determined by the free fall energy eV_{sh}, where V_{sh}, the potential drop across the sheath, corresponds to the difference between the plasma potential (V_p) and the surface potential [7]. The ion energy distribution function (IEDF) at the substrate is usually complex, and it is largely affected by the following parameters [7-10]: (i) time-varying $V_{sh}(t)$ values and frequency of the alternating electric field, (ii) sheath thickness, ion charge to mass ratio, and (iii) charge exchange, ionization and other inelastic collisional processes within the sheath region.

Our previous results have shown that by choosing the dual-mode MW/RF plasma process one can achieve up to 10 times higher ion flux at the same V_B value, compared to a simple RF plasma [11]. Recent evaluations of the IEDFs in the MW/RF system in argon have revealed [12] that E_i and F_i can selectively be controlled. In the present work we include also nitrogen, and we systematically study the effect of discharge parameters on the ion energy characteristics.

2. Experimental

The experiments were carried out in a dual-mode MW/RF plasma system described earlier [5,6]: It consists of a substrate holder-electrode (18 cm in diameter) facing a fused silica window, through which MW (2.45 GHz) power is supplied from a 30 cm long slow wave structure. The window can be replaced by a grounded metal plate, containing an RF (13.56 MHz) electrode. This arrangement enables us to perform measurements on the substrate holder-electrode which is either grounded or RF powered, while being simultaneously exposed to the main RF or MW discharge.

A differentially pumped ion energy analyzer (IEA) [13,14] is located in the center of the substrate holder electrode. The entrance aperture (1 mm in diameter) of the IEA is covered by a Ni grid with openings smaller than the estimated Debye screening length. The analysis system consists of two electrodes: the first one serves for electron repelling, and it is at a fixed potential of -75 V, the second one is at a variable ion-retarding potential. A Faraday cup, held at -30 V, is used as a collector. The electrode potentials are applied with respect to ground when the electrode is grounded, or with respect to V_B when the electrode is RF-powered. In the latter case, the ions transiting the region between the electrode and the analyser aperture are still subjected to an alternating electric field, but they do not experience an additional acceleration. Therefore, in combination with additional collisions near the entrance to the IEA, some effects on the modulation and on the low-energy side of the IEDF cannot be fully excluded at this moment.

The current to the collector is measured with a Keithley (Model 487) picoampermeter. The IEDFs are obtained by calculating the first derivative of the current-voltage characteristics.

3. Results and Discussion

The IEDFs measured on the grounded electrode in the RF and MW single-frequency modes for nitrogen are shown in Fig. 1 for different pressures. For both discharges the IEDFs are generally broader and exhibit a more pronounced structure compared with the plasma in argon [12], possibly related to the mass difference of the typically most abundant N_2^+ vs. Ar^+ ions. Contribution of low-energy ions is seen to increase with pressure. In RF plasma the IEDFs are broader and both the mean ion energy, E_m, and E_{max} values are about a factor of two higher than in the MW discharge.

Modulation of the IEDF (Fig. 1a) is usually more pronounced at lower (RF) frequencies [15]. It is linked to the instantaneous phase of electric field acting on the ions upon their entry into the sheath region, and to the phase they experience immediately after charge transfer collisions (for a detailed discussion, see ref. 9). The origin of multiple peaks in a higher-frequency (MW) mode (Fig. 1b) is more difficult

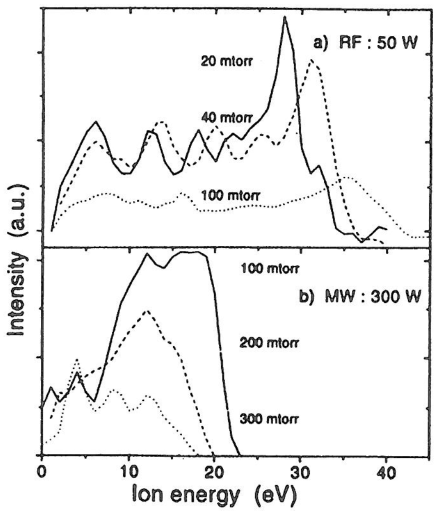

Figure 1: IEDF on the grounded substrate holder exposed to: a) an RF discharge, b) a MW discharge in nitrogen.

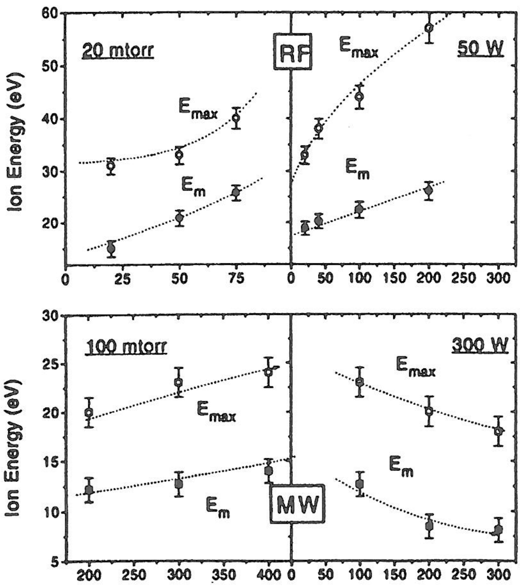

Figure 2: Effect of power and pressure on the maximum ion energy, E_{max}, and the mean ion energy, E_m, on the grounded substrate holder exposed to an RF or a MW discharge in nitrogen.

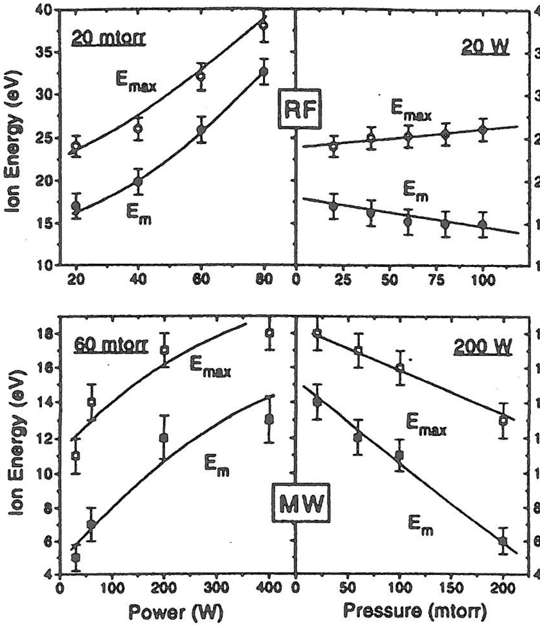

Figure 3: The same as in Figure 2, but for argon.

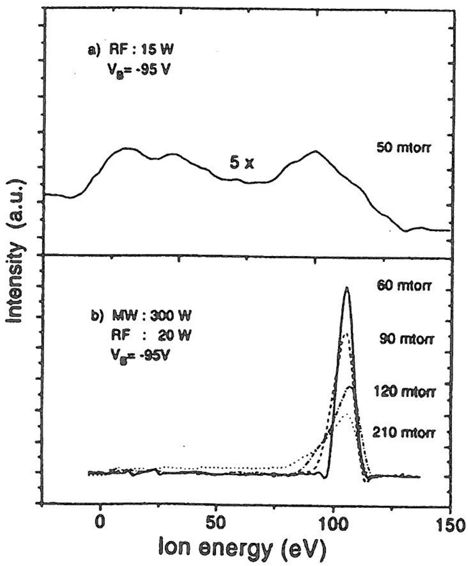

Figure 4: IEDF on the RF-powered electrode in a single mode RF plasma and in a dual-mode MW/RF plasma in nitrogen.

to explain: The expected energy separation predicted by the formula proposed by Okamoto et al. [16] should not exceed a fraction of an eV at 2.45 GHz. Two possible explanations can be suggested: (i) additional ionization in a limited region of the sheath may contribute to the creation of a number of ions which experience only part of the acceleration by the sheath potential, and thus give rise to additional low energy peaks, and (ii) discontinuity of the sheath potential which may render the simple models of ion acceleration in the sheath invalid.

The effects of power and pressure on E_{max} and E_m for N_2 and Ar plasma are illustrated in Figs. 2 and 3. In the RF power range studied here, the V_B values varied from -280 V to -400 V for N_2, and from -240 V to -520 V for Ar. For both gases the ion energy values are seen to increase with the applied power, as expected due to an increased plasma density [11], possibly leading to higher V_p and V_{sh} values.

Different effects of gas pressure on the ion energy are seen in both types of discharges. In the MW plasma, E_{max} and E_m are seen to continuously decrease with pressure over the whole range, as expected from dominating collisions within the sheath region. In RF plasma the rising pressure leads to IEDF broadening (Fig. 1a). Increased E_{max} values (Figs. 2 and 3) may result from higher V_p due to a slightly rising plasma density [11], higher plasma confinement [10], and from collisional processes related to a reduced sheath thickness and electric field modulation [9].

We could see above that the E_{max} (and hence the V_p) values in the RF mode are typically twice as large as in the MW mode. This can be understood by using an equivalent circuit which represents the sheath characteristics [7,17], consisting in the most simple case of a resistor and a capacitor in parallel. The overall impedance can be calculated as a function of frequency of the applied electric field [18]. A resistive sheath with a higher V_{sh} value can be expected for the RF discharge, while V_{sh} should be smaller for the capacitive sheath in a higher frequency (MW) case [17]. However, V_p, and therefore the E_{max}, values also depend on the electron energy distribution function (EEDF) in the plasma bulk. It has been shown [19] that the EEDF in MW plasma exhibits a higher population of energetic electrons, compared to RF plasma, and that they both deviate considerably from a Maxwellian distribution. It is, however, difficult to estimate in which way this deviation in the EEDF may influence the sheath structure, and therefore the V_p value.

In the second series of experiments, the IEDFs were measured on the RF-powered electrode, on which V_B develops, in the simple RF and in the MW/RF modes (Fig. 4). For RF plasma (Fig. 4a) the IEDF exhibits a multiple peak structure on its low-energy side, and E_{max} is around 1.2 eV_B. Splitting of the peaks can be associated with the collisional RF-modulated sheath, as it is commonly observed for light ions and at high bias voltages [15].

Addition of MW power simultaneously with the RF discharge (the dual-mode MW/RF case) not only leads to a higher ion flux [11], but it completely changes the shape of the IEDF (Fig. 4b). At a higher N_2 pressure the ion flux decreases due to collisions, but the peak around V_B remains relatively narrow. This suggests a considerable decrease of the sheath thickness compared with the RF-only case. However, such shrinking of the sheath has not been confirmed experimentally, and visual estimates reveal its thickness of about 8 - 10 mm. The same value also applies to a simple RF discharge, which has been found to obey the Child-Langmuir law [11]. This implies that the dual-frequency plasma cannot simply be regarded as superposition of the two single-frequency modes, but the structure of the sheath is distinctly different from either the RF and MW case.

4. Conclusions

We compared differently structured ion energy distrubution functions in MW, RF and MW/RF plasmas in nitrogen and argon. It is concluded that the sheath processes in MW plasma are predominantly controlled by inelastic collisions, while in RF plasma the ion transit is further strongly affected by electric field modulation. Even if the sheath phenomena in MW/RF plasma are not yet fully understood, the present results have an important practical value: They confirm that the MW/RF approach can be used for a selective adjustment of ion energy and ion flux.

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