Particle Analysis at the Electrode Surfaces of an rf Discharge

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Ion kinetic investigations are performed on a 13.56 MHz parallel plate rf discharge configuration using argon as the process gas. The discharge potential conditions are controlled by an external dc biasing of the powered rf electrode. Dependent on the rf and dc voltage amplitudes, we observe and discuss the resulting ion energy distributions at the grounded and powered electrode. It will be shown, that this method enables to control mean ion energy and ion flux density.

Introduction

The investigation of the direct interaction between plasma and sample surface is an essential section in understanding of plasmachemical processes. Mass spectroscopic methods can provide for information about flux density and energy of neutral particles /1/, radicals /2/ and ions /3,4/ from the discharge. Especially the energy transfer by ions and neutrals is known to determine process characteristics, as etch rate, anisotropy, and surface layer composition and structure.

Ion energy distributions in an rf discharge are influenced by many superimposing process parameters, as the potential conditions, plasma sheath characteristics, discharge pressure, and frequency. A defined control of the sheath voltages and the ion energy can be achieved by an external dc biasing of the rf electrode or a combination of rf and dc discharge in a triode arrangement.

In this report, we present first results on ion energy distributions and ion flux obtained in a directly biased rf discharge.

Experimental apparatus

A cylindrical stainless steel chamber with a volume of 180 l contains the discharge arrangement. The process pressure p_{tot} of between 1 and 100 Pa is maintained by a two-stage rotary pump coupled to the chamber by a throttle valve. The gas flow Q of up to 200 Pa*l/s is set using a mass flow controller.

The discharge arrangement consists of two circular stainless steel electrodes, 9 cm in diameter, and with a variable spacing d of between 1 and 10 cm. Both electrodes are

build up electrically insulating with a grounded shield around it, so that each can be driven as powered or grounded electrode respectively. Because no confinement is used, the spatial expansion of the discharge depends on the external parameters with a resultant asymmetrical discharge geometry.
The discharge is powered by a broadband amplifier (1..50 MHz, 500 W, 1500 V-pp) with the powered electrode capacitively coupled to the amplifier by a matching network. An additional dc power supply (600 W, ±600 V) is connected to the powered electrode by an rf filter and provides for a defined dc bias voltage. rf and dc power, rf and dc voltage, and the dc current are measured carefully.
A differentially pumped plasma monitor system EQP 300 (Hiden Analytical) samples through a 100 µm aperture in one of the electrodes and provides for information about the particle flux to the electrode surface. Using the computer controlled plasma monitor, mass, energy and time resolved spectra of neutral particles, positive and negative ions and radicals from the discharge may be obtained.
Energy analysis is performed by an electrostatic sector field analyser, which transmits ions of up to 1 keV with a resolution of 0.7 eV. A triple quadrupole mass filter is used for mass separation in the range of up to 300 amu, and the ions are finally detected by a gated channeltron secondary electron multiplier with counting electronics. For the detection of neutrals and radicals an electron impact ion source with variable electron energy is available. Because the acceptance angle of the ion optics in front of the system and the angle of sight of the ion source are only a few degree, the measurements represent only the nearly vertically incident particles.

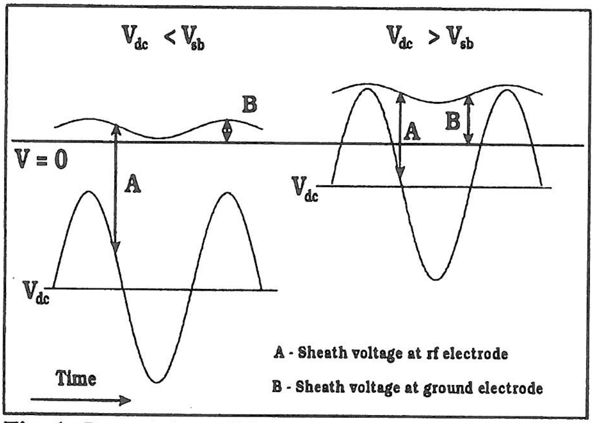

Fig. 1: Potential conditions in an rf discharge with external dc bias

Results and discussion

The potential conditions in an rf discharge can be explained by a capacitive sheath model /5/. In an unconfined discharge configuration the rf modulation of the plasma potential is small according to the ratio between the sheath capacitance of powered and grounded electrode. The absolute value of the plasma potential is controlled by the most positive electrode voltage in time. At a dc bias voltage V_{dc} lower than the self bias voltage of a capacitively coupled rf discharge V_{sb}, the plasma potential is controlled by the grounded electrode. With a value of V_{dc} more positive than V_{sb} the plasma potential is dominated by the powered electrode (Fig. 1).

Fig. 2 shows ion energy distributions of the Ar^+ ion at the grounded and powered electrode respectively. All distributions are normalised, so that the integral with respect to energy gives a value of one.

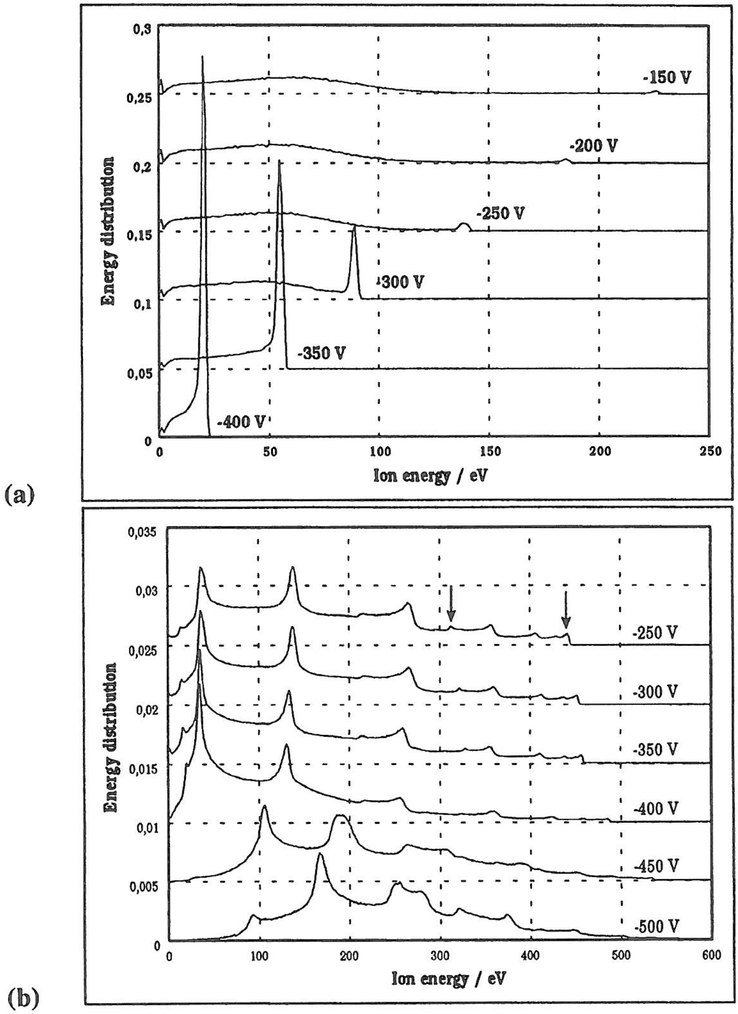

Fig. 2: Ion energy distribution of the Ar^+ ion at different dc bias voltage V_{dc} (V_{rf}=940 V-pp, p_{tot}=5 Pa, Q=8 Pa*l/s, d=4 cm).
(a) Grounded electrode (b) Powered electrode

The shape of the energy distribution at the ground electrode in Fig. 2a is typical for nearly a dc plasma sheath. Ions passing the sheath without collision cause the upper peak with the position characterising the mean plasma potential. The small rf modulation of the plasma potential and the sheath thickness determine together the width of the peak structure.
The low energy part of the distribution is caused by ions, which are produced mainly by charge transfer, less by electron impact, inside the sheath and experience only a part of the sheath voltage. Because there is no additional structure in the low energy region, the electrical field inside the sheath must be a stationary dc field.
As can be seen from the potential conditions in Fig. 1, only dc bias voltages positive against the corresponding self bias, which is -410 V in Fig. 2, can significantly influence the plasma sheath at the ground electrode.
The intensity ratio between the collision free and collision dominated part of the distribution in Fig. 2a shifts with increasing sheath voltage towards the collisional part. The thickness d_{sh} of a collision less sheath scales with Debye length λ_D and sheath voltage $V_{sh}^{3/4}$. At a nearly constant ion mean free path, the larger sheath thickness at higher sheath voltage increases the probability of collisions inside the sheath.
The shape of the ion energy distribution at the powered rf electrode in Fig. 2b is quite different form the grounded electrode, because the rf amplitude of the sheath voltage is now larger against the dc component.
The rf modulation of the sheath voltage manifests in multiple peaks in the collision influenced part of the distribution. The multiple peak structure is caused by the effect of the rf modulated electron density inside the sheath and ions which are produced by charge transfer or electron impact outside the actual electrical field. During expansion of the electrical field, these ions are accelerated together and cause the observed peak structures /6/.
Ions passing the plasma sheath without collision suffer now a modulation by the sheath voltage with a resulting saddle shape in the energy distribution. The two peaks caused by these ions are marked in the upper curve of Fig. 2b by an arrow. In opposite to the ground electrode, the energy distribution can be significantly influenced now by dc voltages lower than the bias voltage of a capacitively coupled rf discharge.
Fig. 3 shows the mean plasma potential determined from the position of the upper peak in the energy distribution at the ground electrode. The plasma potential is shown versus the normalised bias, which is the sum of the half rf amplitude and the dc bias: $V_{rf}/2 + V_{dc}$. As expected from the capacitive sheath model, at a negative normalised bias voltage the plasma potential is controlled by the ground electrode, and is constant, whereas in the upper region the plasma potential increases together with the bias potential. The position of the sharp bend in the curves is determined by the rf modulation of the plasma potential, and is larger for higher rf amplitudes at the powered electrode.
Fig. 4 shows the mean energy of the dominating Ar^+ ions at the ground electrode versus the sheath voltage. The larger energy values at higher rf voltage can be

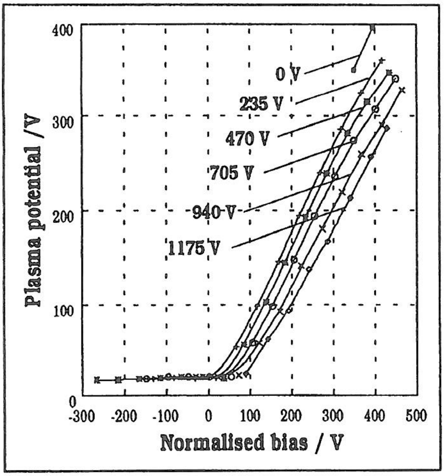

Fig. 3: Mean plasma potential dependent on the normalised bias $V_{rf}/2 + V_{dc}$, Parameter: rf peak-to-peak voltage (p_{tot}=5 Pa, Q=8 Pa*l/s, d=4 cm)

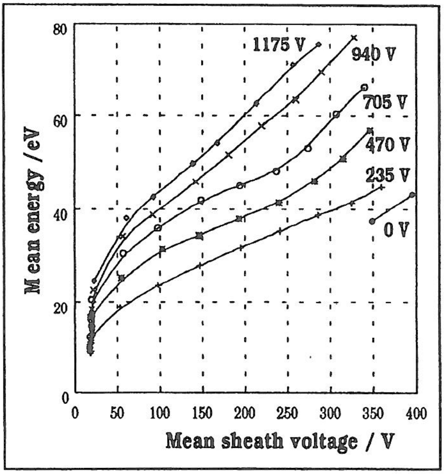

Fig. 4: Mean ion energy at the ground electrode dependent on the sheath voltage, Parameter: rf peak-to-peak voltage (p_{tot}=5 Pa, Q=8 Pa*l/s, d=4 cm)

explained by a larger charge carrier density. For that reason Debye length and sheath thickness are reduced with the consequence that collision processes are less important.

In the relative energy in fig. 5, the ratio between mean ion energy and the maximum energy, a marked maximum is observed at a dc bias which corresponds to the self bias of a capacitively coupled rf discharge. In the region of the normalised bias below zero volts, the sheath voltage is constant (see fig. 3), and the increase of relative energy must be caused by a decrease of the sheath thickness. The decrease of the relative energy in the upper voltage region is dominated by the increase of the sheath thickness with the sheath voltage. The maximum values of relative energy correspond to a sheath thickness of 150 µm, the minimum values to 1.5 cm.

Fig. 6 shows the total ion current intensity at the ground electrode. Because of the additional dc current in the discharge, the ion current density at the ground electrode increases in tendency with a more positive dc bias. At the powered electrode the opposite trend in the dc current is observed.

When the plasma potential reaches higher values, the discharge starts to expand into the whole process chamber. Because the effective plasma region increases dramatically, at the same rf amplitude a higher power is supplied to the discharge, which corresponds to a much higher change of the current at the powered electrode compared to the grounded electrode. The maximum output power of the broadband amplifier acts for that reason as the limit for the most positive dc bias voltage.

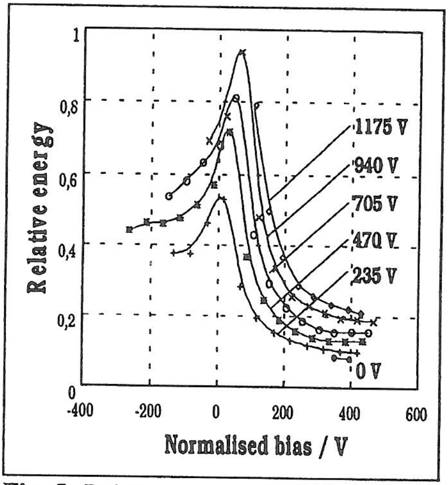

Fig. 5: Relative energy dependent on the normalised bias, Parameter: rf peak-to-peak voltage (p_{tot}=5 Pa, Q=8 Pa*l/s, d=4 cm)

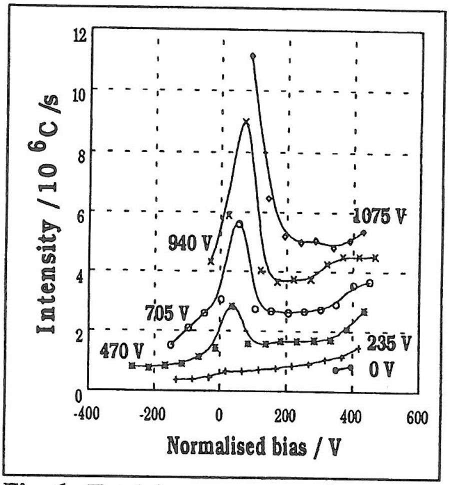

Fig. 6: Total ion current at the ground electrode dependent on the normalised bias, Parameter: rf peak-to-peak voltage (p_{tot}=5 Pa, Q=8 Pa*l/s, d=4 cm)

The total ion current in fig. 6 shows a marked peak at the same position like the relative energy. Both effects must be caused by a maximum of the charge carrier density with consequently high ion current and small Debye length. Exactly at this optimum conditions for the charge carrier balances, the self biased capacitively coupled discharge is found.

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