Biased-electrode operation of electron cyclotron resonance ion sources

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In order to supplement our investigations on the biased electrode in electron cyclotron resonance ion sources, we have carried out dedicated measurements with a special double structure (ring plus disk) electrode. This geometry allows to separate two mechanisms contributing to the ''biased disk effect'': the creation of secondary electrons at the disk and the reflection of plasma loss electrons by the potentials of the disk. At sufficiently high ring-electrode potentials the axial electron losses can be blocked completely. From the experimental results, it is suggested that electrostatic blocking is the main contribution to the biased electrode effect.
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I. INTRODUCTION

Biased electrodes are used in most modern electron cyclotron resonance (ECR) ion sources now, both in continuous and in pulsed mode of operation.[1–6] The most common explanation for this biased-electrode effect is enrichment of the plasma density by injection of cold electrons, leading to additional ion breeding. This injection is considered to be due to the reflection of the plasma electrons back to the plasma and/or the emission of secondary electrons from the electrode.[1] Recently, it was found[6] that the extracted ion currents respond so fast to changes of the electrode voltage that the effect cannot be explained in terms of increased rates of ion production but, rather, by redirection of the already existing ion fluxes inside the source. In this article, we describe the results of an experimental study aimed at separation of the two contributions to the biased disk effect. These two contributions are the creation of secondary electrons, created by primary particles at the disk, and the reflection of plasma electrons by the electrode's electric field.

II. EXPERIMENT

The Frankfurt 14 GHz ECRIS[7] was equipped with a ''double electrode'' assembly consisting of coaxial ring- and disk-shaped electrodes biased separately. The ring (∅36×9 mm^2, 4 mm thick) was mounted 3 mm in front of the disk (∅36 mm). This assembly was attached to the top of a tube, which could be moved axially to optimize the double electrode's position, which was always kept close to the maximum of the magnetic field. The voltages on both electrodes were limited to values of ±500 V. The currents to both electrodes were measured by separate meters. Negative currents indicate that the electrode collected net currents of electrons. Up to 400 W of microwave power was applied in these experiments. The extracted ion currents were measured in a Faraday cup directly in front of the analyzing magnet. The extraction voltage of the source was chosen as 10 kV. The experiments were performed with pure argon and pure helium as the working gases. The gas pressure, measured at the microwave injection side of the source, was varied between 1×10^{-7} and 1×10^{-6} mbar. As one example, in Fig. 1, disk current as a function of the disk voltage are plotted for different negative voltages at the ring electrode for helium as the working gas. The characteristics measured for argon as the working gas were essentially the same. At sufficiently large negative ring-electrode voltages (above −200 V) a significant drop in the electron currents to the (positively) biased disk is clearly visible. The currents do not approach the zero level but, rather, saturate at about 0.2 mA. This current is due to the non-negligible amount of energetic electrons, which escape the plasma, indicating that the hot component of the plasma electrons in both optimized cases of working gases was essentially the same. The disk's floating potentials were about −20 V for helium and −75 V for argon, consis-

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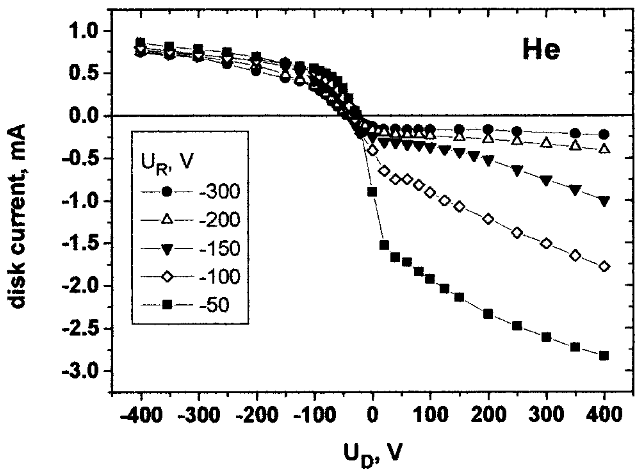

FIG. 1. Currents to the biased disk as a function of the disk voltage at different voltages at the biased ring. The ECR discharge is sustained in pure helium gas.

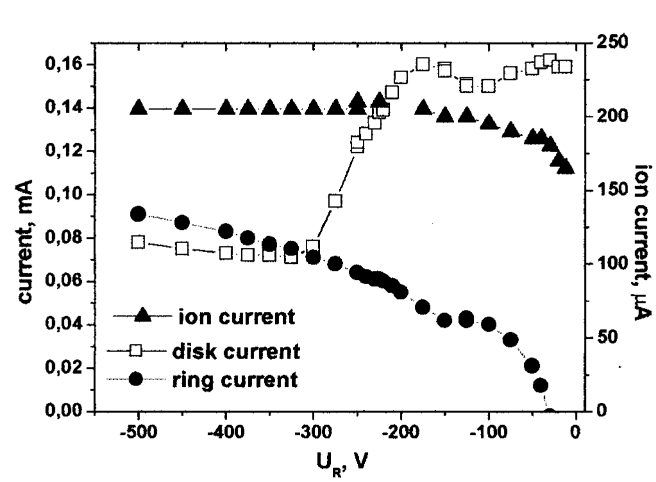

FIG. 2. Currents to the biased disk and to the biased ring (left scale) and ion currents to the Faraday cup (right scale) as a function of the ring voltage at a fixed biased disk voltage of −200 V. The ECR discharge is sustained in pure argon gas. The ionic currents are measured in a Faraday cup directly in front of the magnet for charge-state analysis.

tent with the tendency determined by the well-known relation between the plasma potential V_p and the floating potential V_f:

$$V_p - V_f = \frac{kT_e}{2e} \times \ln\left(0.43 \times \frac{M_i}{m_e} \times \frac{T_e}{T_i}\right). \tag{1}$$

At low ring-electrode voltages, net electron currents of up to 3 mA were collected by the disk for the case of helium discharge, and up to 1 mA for argon discharges at approximately the same operational conditions and electrode voltages.

Ionic currents to the electrodes were measured by applying negative voltages. In helium plasmas, maximum ion currents of about 0.8 mA were measured, whereas for argon plasmas this value was less by a factor of 3, consistent with the ratio of the total extracted ion currents. By applying sufficiently higher negative voltages to the ring than to the disk, it was possible to completely block the secondary electron emission from the disk. This secondary electron emission amounts to about 50% of the total measured disk currents, as can be seen from Fig. 2. In Fig. 2, extracted ion current (right scale) and disk and ring currents (left scale) are shown as functions of the ring voltage for the case of an argon plasma with a fixed disk voltage of −200 V. No changes in the extracted ion currents are observed when the flux of secondary electrons into the plasma is blocked. At identical voltages at the ring and disk, the net currents to the ring electrode amount to about 30% of the disk currents. Raising the microwave power above values of 100 W at fixed gas pressures no longer influenced the disk and ring currents, whereas at fixed microwave powers, the currents varied linearly with the gas pressure.

In Fig. 3, extracted ion currents are plotted as a function of the disk voltage for different negative ring-electrode voltages for the case of a helium plasma. The source conditions were the same as for the cases shown in Fig. 1. At ring voltages higher than −150 V, the extracted ion currents were quenched by approximately a factor of 2 if the disk voltage was set above the floating value. At sufficiently negative ring voltages ($U_R > -200$ V), the disk voltage had no influence on the extracted ion currents for the whole voltage range. By biasing only the ring electrode (i.e., connecting the disk to the source potential), the source could be optimized to deliver the same extracted ion currents as if a single biased disk electrode were used. For both methods of electrode biasing (using either the disk or the ring as a one-electrode system) and for both working gases, the bias voltage for optimized operation was about −300 V.

III. RESULTS

From the data presented, the following general conclusions can be drawn. At zero electrode voltage, the electrodes collect negative currents of a few mA, pointing to the well-known nonambipolarity of the ECR plasma diffusion with its larger radial ion and axial electron fluxes. From the thresholds measured we can conclude that most of the electrons in the ECR plasma near the biased electrodes have “axial en-

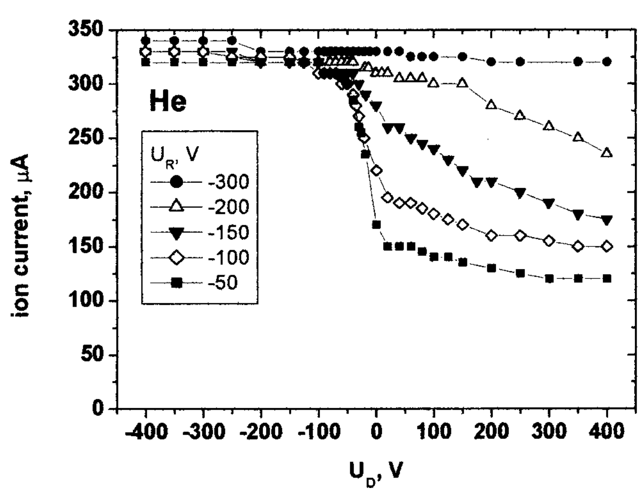

FIG. 3. Total ion currents (not charge state analyzed) from a He plasma as a function of the biased disk voltage at different settings of the biased ring voltages.

ergies'' (energy components parallel to the source axis) below 200 eV. The extracted ion currents are maximal if the electrode voltages are chosen so that most of the electrons are reflected back to the plasma. In reversing this argument, significant electron fluxes to the electrodes are obviously accompanied by a drastic decrease of extracted ion currents. Therefore the biased electrode seems to work as a reflecting ''plug'' for those electrons, which entered into a loss cone and hence otherwise would be lost from the plasma. Due to the potential barriers formed by the electric fields in the extraction region and at the optimally biased electrode, the loss of plasma electrons can be reduced to an almost negligible amount. The additionally created density of these electrons is highest at the turning points, resulting in an increase of the plasma density also near the extraction area, which improves the extraction conditions.

The fact that a ring electrode works as well as a ''normal'' disk is consistent with recent observations,[8] where a small-diam biased rod was used to increase the extracted ion currents. Obviously, the shape and size of the electrode is not of great importance as long as the electric fields are such that the escaping electrons are reflected back to the ECR plasma. In particular, ring-shaped biased electrodes may advantageously be used in sources where open access to the area along the axis is required.

The ''electrostatic plug model'' in a natural way also explains why the optimal bias voltage changes with the electrode's position and with the gas composition of the ECR discharge (see, e.g., Ref. 9). These conditions definitely influence the average axial energy of the electrons, and thus also the voltage required for their reflection.

It is interesting to note that in our experiments a further increase of the extracted ion currents by about 20% above the optimized ''single-electrode'' value could be obtained by carefully optimizing the voltages of the ring and disk independently. We assume that this is connected to the damping of ion-beam oscillations, which limit the performance of optimized single-electrode operation. The frequency of these oscillations was measured in our experiments to be about 200 kHz (see also Ref. 10). Its amplitude was about 10%–20% of the average ion current. This additional optimization of the source equipped with the double biased electrode definitely deserves more detailed study. We plan to continue these experiments, paying more attention to the geometry and material of the disk as well as to the working gas composition (e.g., the gas mixing mode of operation).

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