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COMPARATIVE STUDY OF POSITIVE AND NEGATIVE ION FLOWS EXTRACTED FROM DOWNSTREAM PLASMAS BEYOND MAGNETIC AND ELECTROSTATIC ELECTRON FILTERS

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In the present paper we compare the positive and negative ion flows created using a recently developed electrostatic grid-type filter with the flows formed using a magnetic filter. Langmuir probe measurements show electron cooling with both filters, allowing effective formation of negative ions via electron dissociative attachment in the region of low electron temperature. The energy distribution functions of positive and negative ions extracted from the filtered plasmas are measured in both systems showing an almost monoenergetic nature of the ions with the energy corresponding to the imposed extraction potential. It is shown that in both cases strongly electronegative plasmas where the negative ion density is much larger than the electron density can be formed downstream of the filter. Biasing an internal electrode or the electrostatic filter grid allows control of the plasma potential. In the case of the electrostatic filter the plasma could be biased negatively compared to ground and effective extraction of negative ion was achieved.

Keywords: negative ion source, electron filtering, ion-ion plasma, electronegative plasma, ICP.

В данной работе проведено сравнение потоков положительных и отрицательных ионов, генерируемых с использованием недавно разработанного электростатического сеточного фильтра с потоками, формируемыми с использованием магнитного фильтра. Измерения ленгмюровскими зондами показали эффективное “охлаждение” электронов при использовании обоих фильтров, обеспечивающее условия для эффективного образования отрицательных ионов в области с низкой электронной температурой в результате диссоциативного прилипания. Функции распределения по энергии положительных и отрицательных ионов, извлекаемых из вторичной плазмы, измеренные в обеих системах, показали моноэнергетичность генерируемых потоков ионов с энергией, соответствующей приложенному извлекающему потенциалу. Показано, что в обоих случаях возможно формирование сильно электроотрицательной плазмы на выходе фильтра с плотностью отрицательных ионов значительно превышающей плотность электронов. Смещение внутреннего электрода либо сетки фильтра позволило достичь управления потенциалом плазмы. В случае электростатического фильтра потенциал плазмы может принимать отрицательные значения по отношению к заземленному электроду, благодаря чему было достигнуто эффективное извлечение отрицательных ионов.

Ключевые слова: источник отрицательных ионов, фильтр электронов, ион-ионная плазма, электроотрицательная плазма, индукционный разряд.

У даній роботі проведено порівняння потоків позитивних і негативних іонів, що генеруються з використанням недавно розробленого електростатичного сіткового фільтру з потоками, що формуються з використанням магнітного фільтру. Вимірювання ленгмюрівськими зондами показали ефективне “охолоджування” електронів при використанні обох фільтрів, що забезпечує умови для ефективного утворення негативних іонів в області з низькою електронною температурою в результаті диссоціативного прилипання. Функції розподілу по енергії позитивних і негативних іонів, витягуваних з вторинної плазми, виміряні в обох системах, показали моноенергетичність потоків іонів, що генеруються, з енергією, відповідною до прикладеного витягуючого потенціалу. Показано, що в обох випадках можливе формування сильно електронегативної плазми на виході фільтру з щільністю негативних іонів що значно перевищує щільність електронів. Зсув потенціалу внутрішнього електроду або сітки фільтр дозволив досягти керування потенціалом плазми. У разі електростатичного фільтру потенціал плазми може приймати негативні значення по відношенню до заземленого електроду, завдяки чому було досягнуте ефективне витягання негативних іонів.

Ключові слова: джерело негативних іонів, фільтр електронів, іон-іонна плазма, електронегативна плазма, індукційний розряд.

INTRODUCTION

There are commonly two ways to reduce the electron temperature in low temperature plasmas, either by pulsing the plasma where the electron temperature decrease rapidly in the afterglow [1] or by electron filters or barriers [2 – 7]. Plasmas with low electron temperature are desirable in electronegative plasmas where the aim is to effectively create negative ions by electron dissociative attachment. Strongly electronegative plasmas, where the negative ion density is much higher than the electron density are used in a variety of applications from very high selectivity etching [8], negative ion sources [9] and recently in electric propulsion [10, 11]. These low temperature plasmas without energetic electrons might also be beneficial for low-damage surface treatments [12].

One of the promising directions of the broad-beam ion source evolution is the PEGASES concept [10,11] where simultaneous extraction and acceleration of both positive and negative ions ensure the space charge and current neutralization of the beam [10]. The choice of propellant for such sources is restricted within the group of electronegative gases among which halogen-containing compounds are most attractive. Besides, beams of negative halogen ions are also promising in reactive ion-beam etching [13].

The most known type of the electron filters is the magnetic filter [9]. Despite that such filters or magnetic barriers are known for decades and its efficiency is proven, the physics of the particle transport across these filters are not yet fully understood [14]. The presence of strong magnetic field complicates both the plasma diagnostic and the numerical modeling. The plasma downstream of a magnetic filter might be highly inhomogeneous due to ExB drifts and other anomalous cross-field diffusion or transport [15, 16].

A new promising type of nonmagnetic electron filter, namely a grid-type electrostatic filter, has been recently discovered and characterized [17]. The main features of this filter is reported in [17] showing that the electron temperature decreases downstream of the grid.

The prospective for modern applications using the electrostatic filter technique is not clearly understood. The present paper is therefore devoted to a comparative study of the electronegative plasma and the extraction of positive and negative ions using the magnetic and electrostatic filter technique.

EXPERIMENTAL SETUPS

The paper is built around the comparison of two devices with significant level of similarity. One of them is the system with the electrostatic grid-type filter recently developed at the LDPTP (Laboratory for Diagnostics of Plasma Technology Processes of V.N. Karazin Kharkiv National University and Scientific Center of Physical Technologies, Kharkiv, Ukraine), the other is the PEGASES first prototype using a magnetic filter [10] developed at the LPP (Laboratoire de Physique des Plasmas, Ecole Polytechnique, France).

Both systems are intended to create strongly electronegative plasmas where the negative ion density is much higher than the electron density. The plasmas are divided by an electron filter that segregate the plasmas and forms two regions: a primary inductively coupled plasma (ICP) and a secondary plasma with low electron temperature. In both devices the secondary plasma is terminated by an energy analyzer serving as ion extraction system. The experimental setups are schematically shown in Fig. 1a) and b).

The experimental setup 1 (ES 1) is illustrated in Fig. 1a). The vacuum chamber is divided by a grid into two regions: the primary inductively coupled plasma (ICP) and the downstream cold plasma (CP). The ICP is generated by a 2-turns shielded inductive coil placed inside the metallic vacuum chamber with 250 mm inner diameter and 80 mm length. RF power (13.56 MHz) is applied to the inductor through a matching network. The RF power

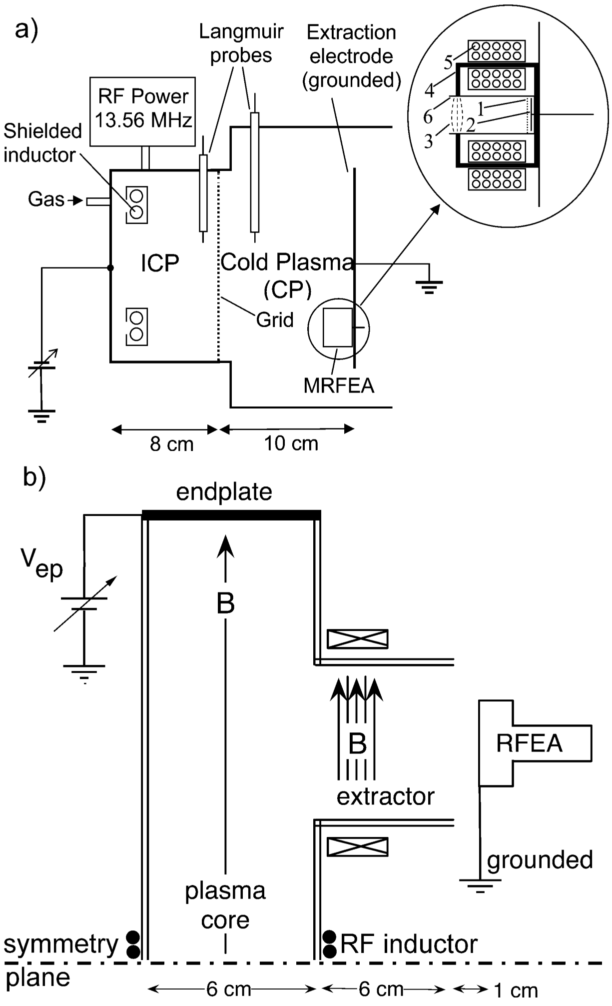

Fig. 1. Scheme of the experimental setups with electrostatic (a) and magnetic (b) filter, ES1 and ES2, respectively.

absorbed by the ICP is 300 W in all the experiments presented here. The ICP chamber is connected to a flange holding the electrostatic grid. This stainless steel grid is 0.12 mm thick with 0.24 mm apertures. The total area of the grid is 450 cm^2 and the optical transparency is 40 %. The flange holding the grid is connected to the metallic chamber with 350 mm inner diameter where the CP is created. At the opposite side of the grid, the CP is terminated by a 250 mm diameter grounded extraction electrode placed 100 mm from the grid. The ICP chamber, the filter grid and the CP chamber are electrically connected and have the same potential which is controlled by an external DC power supply in the range from –50 V to +50 V. All potentials in this work are measured with respect to the potential of the grounded extraction electrode.

In order to analyze the flux of charged particles to the extraction electrode a 20 mm diameter single-grid magnetically filtered retarding-field energy analyzer (MRFEA) is used and illustrated in the insert in Fig. 1a). In contrast to our previously described analyzer [18-20], the MRFEA used in the present work is modified by a magnetic filter placed at the MRFEA inlet in order to suppress the electron flow while keeping the flow of negative ions unchanged. Similar technique has been described in detail previously [21].

For measurement of the plasma parameters two Langmuir probes are inserted in the ICP and CP regions. The probe tips, 5 mm long and 0.09 mm diameter, are made of tungsten. The probe measurements were conducted using the Plasma Meter device [22]. Preliminary experiments revealed problems of fast (within 1 sec) contamination of the probe surface by insulating films in SF$_6$ plasma especially at high electron current to the probe. The probe measurements were therefore conducted in pulsed regime with the probe voltage ramp time about 10 ms. Between the pulse intervals (>1 sec) the probe potential was highly negative for cleaning by positive ion bombardment. Besides, sufficient decrease of the film growth rate was achieved using addition of the oxygen into the gas mixture. Since the insulating films are deposited throughout the chamber mechanical cleaning of electrodes was performed every hour of operation.

The filling gas mixture was fed into the ICP chamber and pumped from the CP chamber. Since ICP discharge operated in SF$_6$ is often complicated by instabilities [23]. Argon was added to the mixture for discharge stabilization. Two standard gas mixtures were used in the experiments. Mixture 1 consisted of Ar and O$_2$ at partial pressures of 1 mTorr each (total gas pressure 2 mTorr), while in mixture 2 SF$_6$ was added to mixture 1 at a partial pressure of 2 mTorr (total gas pressure 4 mTorr). All pressures were measured by a hot-filament ionization gauge with the plasma switched on. The chamber was pumped by a turbo pump with 700 l/s throughput. The residual pressure in the system was better then 10^{-5} Torr.

The experimental setup 2 (ES 2) is illustrated in Fig. 1b) and known as the first PEGASES thruster prototype. This experiment has been detailed previously [10, 24] and for simplicity Fig. 1b) illustrates only half of the PEGASES body with a symmetry plane indicated on the figure. The thruster body consists of a quartz cylinder 35 cm long and 6 cm diameter with two rectangular extractor tubes

(4 by 4 cm and 6 cm long) attached perpendicular to the cylinder axis. The gas is introduced in the centre of the cylinder and since the system is placed inside a large vacuum chamber the system is pumped through the extractor opening. The plasma is created with a three-turn loop antenna wrapped around the middle of the quartz tube and continuously excited at 13.56 MHz through a matching network using a π-circuit; the power supplied to the matching box is 300 W with less than 10W reflected. Four solenoids are placed symmetrically around the cylinder to create a 110 G magnetic field with field lines parallel to the cylinder axis. A set of two neodymium magnets 20 mm wide, 40 mm long and 10 mm thick are placed on each side of one extractor between $x = 45$ and 65 mm (x is measured from plasma core tube axis) to enhance the magnetic filtering in the extraction zone. The maximum magnetic field is about 800 G located in the extractor.

Aluminum plates, with a surface of 16 cm^2 each, terminate the cylinder ends and are perpendicular to the magnetic field lines. These endplates are in direct contact with the plasma and are either grounded or dc biased. The endplates bias, addressed as V_{ep}, is set between –100 and +100 V. Note that in Fig. 1b) only one of the endplates are shown, and the figure is symmetrical around the RF antenna.

A Langmuir probe is used to measure current–voltage characteristics and thus provides information on whether an ion-ion plasma is formed in the extractor. The probe tip, 6 mm long and 0.25 mm diameter, is made of platinum to avoid etching by SF_6. It is RF-compensated for the driving frequency 13.56 MHz and its harmonic 27 MHz with RF chokes [25].

A retarding field energy analyzer (RFEA) is used to obtain the ion energy distribution functions (IEDFs), and has been described previously [26]. For the experiments carried out here, it is important to note that the RFEA housing is grounded and the size (external dimensions) is in the order of the extraction surface. Voltage distribution across the RFEA is described in [24].

EXPERIMENTAL RESULTS AND DISCUSSION

The measured current-voltage traces of the Langmuir probes placed in the CP region of ES 1 and in the extraction region of ES 2 are shown in Fig. 2a) and b), respectively. Comparison of the plasma parameters derived from the I – V curves shows strong influence of both the magnetic and electrostatic grid-type filter. The electron temperatures in the plasma cores of both systems are about 5 – 6 eV [17, 24], while the temperature downstream of the filters are 0.7 eV for Ar and 1.5 eV for SF_6-containing plasma in ES 1 and 1 – 2 eV for Ar and SF_6 plasmas in ES 2.

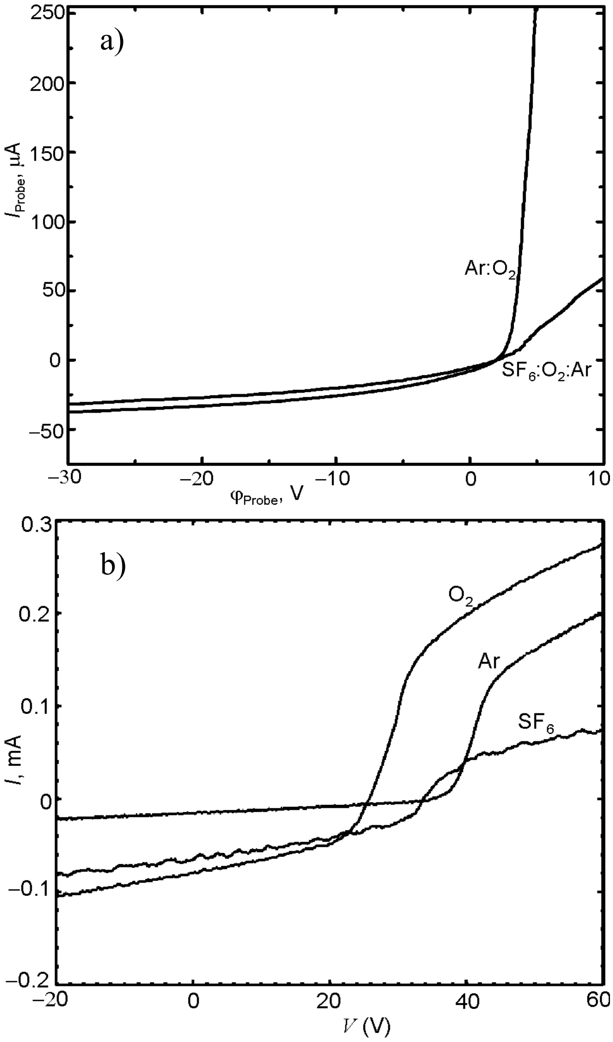

Fig. 2. Current-voltage traces of the Langmuir probes placed in the CP region of ES 1 (a) and in the extraction region of ES 2 (b).

In ES1 the addition of SF_6 leads to significant decrease in the negative particles current to the probe. Since the saturation current of positive ions remains constant this indicate a strong increase in the negative ion density. A similar situation occurs in ES 2 where the I – V curve obtained in both O_2 and SF_6 are more or less symmetrical. However, in this case the probe trace measured in Ar demonstrates clearly the effect of the magnetic barrier, where the strongly reduced electron mobility prevents the plasma from entering the extractor in order to obey quasi-neutrality.

Comparison of the results obtained in ES 1 and ES 2 shows that both systems effectively create negative ions and formation of highly electronegative plasmas is occur. However, it seems like the negative ions are created in the CP region of ES 1 while in ES 2 the electrons are completely blocked by the magnetic barrier and the negative ions are probably created before or in the magnetic filter in this case. The symmetry in the I – V curve indicates that the electronegative plasma in ES 2 is a so-called ion-ion plasma while there are still some remaining electrons in ES 1. Interestingly, the current saturation density (I_{sat}/A_{probe}) for the positive ions is the same in the two systems when operating in SF$_6$, showing that the electrostatic grid-filter and the magnetic filter has very similar effects on the downstream plasma density. It should be noted that absorbed RF power was 300 W in both systems.

The obtained results show that the grid-type filter provides effective electron cooling comparable to the magnetic filter with equivalent density of positive and negative ions downstream of the filter. However, real applications where positive and negative ions are extracted from the plasma also require the possibility of plasma potential control in order to create controlled fluxes of positive or negative ions to the processed surface or to the ion extraction system.

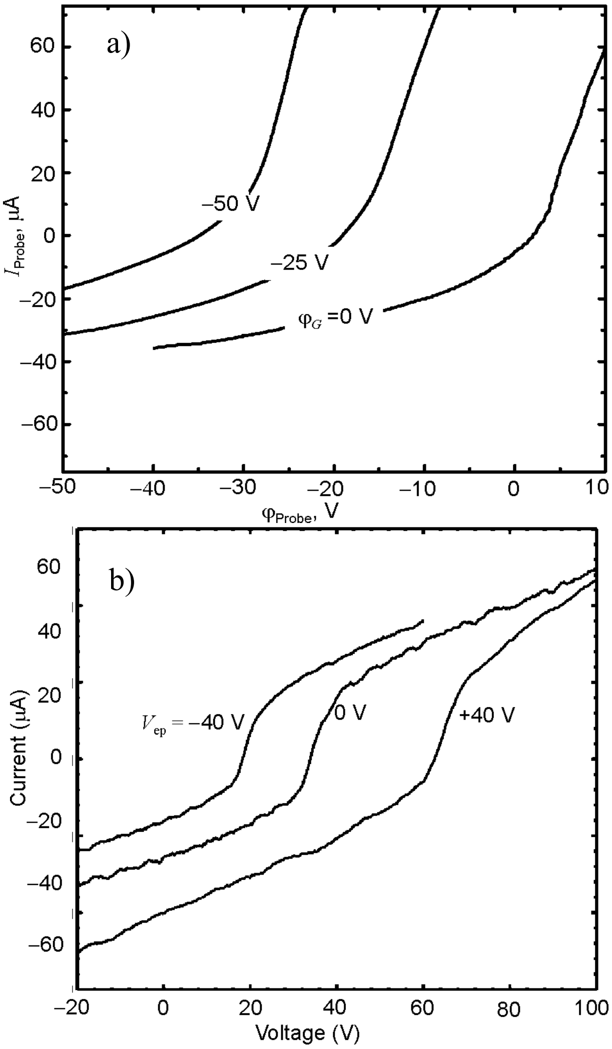

Fig. 3. I – V traces of the probes at different potentials of the filter grid in the ES 1 (a) and endplates in the ES 2 (b). Filling gas is the mixture 2 for ES 1 and SF$_6$ for ES 2.

In order to test the possibility of plasma potential control in both systems we have measured I – V traces of the probes at different potentials of the filter grid in the ES 1 and the endplates in the ES 2. The results of these measurements are shown in Fig. 3a) and b), respectively, showing that all the curves follow the applied potential with almost unchanged shape. Fig. 4a) and b) shows the measured dependences of the downstream plasma potentials on the grid bias in ES 1 and the endplate bias in *ES 2*, respectively. It is seen that the plasma potential is in nonlinear dependence on the electrodes (grid or endplates) potential. For positive grid/endplates bias the plasma potential increases linearly with the grid/endplate bias, while for negative bias on the grid/endplates the downstream plasma potential tends to saturation. In the case of ES 1 using an electrostatic filter this saturation depends on the gas mixture, i.e. the electropositive or electronegative nature of the plasma. In the Argon case it is seen that the plasma potential cannot become more negative than the large extraction electrode, while in the electronegative plasma the plasma potential is controlled and is more negative than the grounded extraction electrode. This result indicates that a negative space charge sheath might exist in front of the extraction electrode and the plasma potential is not (as in typical electropositive plasmas) the most positive potential.

In the ES 2 case for positive biasing of the endplate, the plasma potential with respect to the endplate vary slightly with the type of gas, but saturates at a positive potential corresponding to a positive space charge sheath with about 5 eV electrons.

The demonstrated control of plasma potential allows to control the energy and polarity of the extracted ions. The measured ion energy distribution

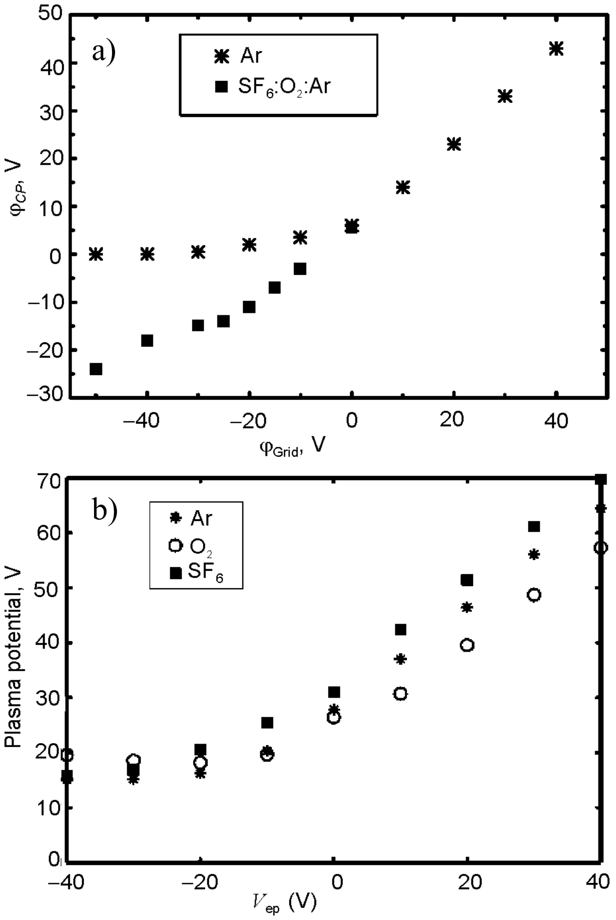

Fig. 4. The dependences of the downstream plasmas potentials on the grid (ES 1) (a) and endplate potential (ES 2) (b).

functions (IEDFs) of the positive Ar ions in ES2 are shown in the Fig. 5. All the measured IEDFs show that the ion flow is close to mono-energetic with mean ion energy corresponding to the plasma potential (see Fig. 4b)).

It should be noted that in the ES 1 the CP potential becomes negative with SF$_6$ addition at grid potentials lower than –7 V (see Fig. 4a)). Therefore, the flow of negative ions can be extracted from the plasma towards the extraction electrode. Measurements of the energy distribution of the extracted negative ion flow is usually complicated due to presence of significant electron current from the plasma which can’t be separated from the negative ion current. This problem can be solved using the magnetically filtered energy analyzer (MRFEA) developed at the LDPTP [17]. The additional advantage of this analyzer is the capability of simultaneous analysis of both positive and negative ions. In Fig. 6 the IEDFs of positive and negative ion flows from the plasma are shown for different plasma biasing. One can see that at negative plasma potentials negative ion flow is extracted from the plasma while positive ions when the plasma potential is positive.

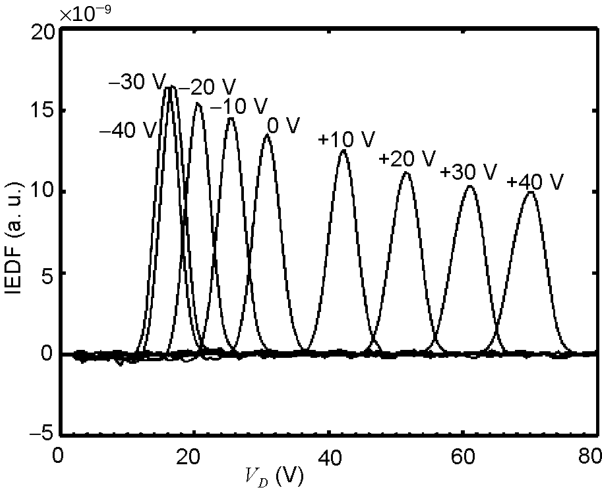

Fig. 5. IEDFs of the positive Ar ions measured in *ES 2* at different endplate bias.

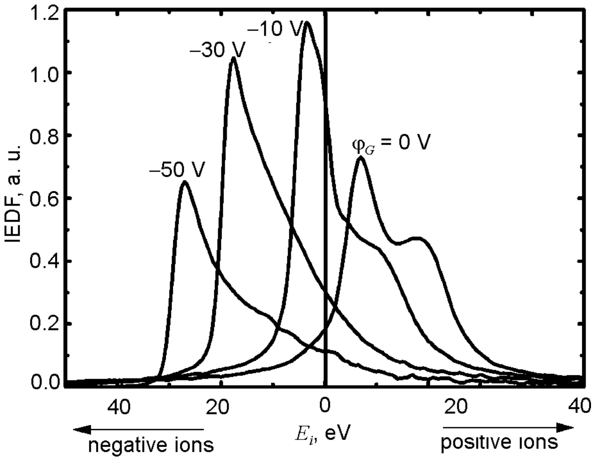

Fig.6. IEDFs of the positive and negative ions measured in ES 1 at different plasma potentials. The filling gas is mixture 2.

Summarizing the presented results we can draw a conclusion that the system with the grid-type filter can be a good basis of wide aperture negative ion source with efficiency similar to systems with magnetic filter. Naturally, the development of a source based on the electrostatic filter requires further extensive investigations. Nevertheless, the obtained results show possibility of practical application of the system with the grid-type electron filter. The first possibility is reactive negative ion etching of samples placed on the extraction electrode. Replacement of this electrode by the gridded extraction system transforms the system to the source of broad accelerated negative ion beam which can be used both in reactive ion etching technology and in space thruster applications. Another promising application is the surface modification of polymers (activation or passivation) where low energy beams are crucial.

SUMMARY

In summary, in the present paper two types of electron filters for the production of electronegative plasmas with high negative ion densities are compared: the recently developed grid-type filter and the more known magnetic filter. The results of probe measurements show the effective electron "cooling" with both filters. The control of the plasma potential via the bias on internal electrode/grid is also investigated and compared. It is observed that the plasma potential follows the electrode potential with nonlinear dependence. The EDFs of the positi-ve and negative ion flows from the filtered plasmas are measured in both systems showing almost monoenergetic nature of the flows. The energy of the IEDF peaks corresponds to the measured plasma potential in all the investigated cases. It is shown that the application of the grid-type filter provides formation of highly electronegative plasma negatively biased with respect to an extraction electrode that allows to extract negative ion flow from the plasma. The main conclusion of the present research is that grid-type electron filter demonstrates similar functionality as the magnetic filter and may be very promising for modern applications.

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