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A Low Energy Ion Beam Plasma Source with Low Electron Temperature

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1. Introduction

High-power and high-energy ion beams have been developed, for example in NBI, and utilized in the various fields for last 20-30 years. On the other hand, high density, high mass, large scale and low-energy ion beams with a low-emittance are required in near future for the plasma deposition or etching. However, it is difficult to produce the beams overcoming the space charges, which are generated by the ion beams themselves. As the ion beams themselves certainly charge up a target or samples, the low-energy beam plasmas, where ions have given velocity and narrow divergence, and electron temperature is less than 1 eV, may be most effective for studying the plasma processing. The electrons work to eliminate not only the space charge but also the surface charge of the target. The lower energy and heavier ion beams are more divergent than the higher energy and light beams. In this experiment, a production of the low-energy (30-200 eV) ion beam plasma, which ion species is of H_2, Ne, Ar, Kr, Xe or CH_4, has been studied. The results are presented.

2. Experimental Setup

The ion source [1] is the bucket type, in which H_2, Ne, Ar, Kr, Xe or CH_4 gas is discharged, and the ions are extracted by multi-aperture Molybdenum electrodes. The beam voltage V_E is supplied to the cathode or the extraction electrode against the third electrode and the chamber, which are grounded. Then, the real beam energy E_{ion} is V_E plus the discharge voltage in the case of the cathode supplied and is about V_E in the case of the extraction electrode supplied. The effective extraction area is 7 cm x 7 cm. To eliminate the ion space charges, electrons, which are emitted from 32 Tungsten filaments, are added to the ion beam, and then the ion beam (E=30-200 eV) plasma is attained [1-3]. At the optimum value of the electron emission, the ion beam current is maximum, which is about one order higher than without the electron source, the divergence in energy is minimum (2.5-3 eV at 50 cm from the plasma source in the case of E_{ion}=100 eV), and the divergence in space is minimum (~5”), furthermore the electron temperature (<1 eV), and the space potential are minimum (<1 V).

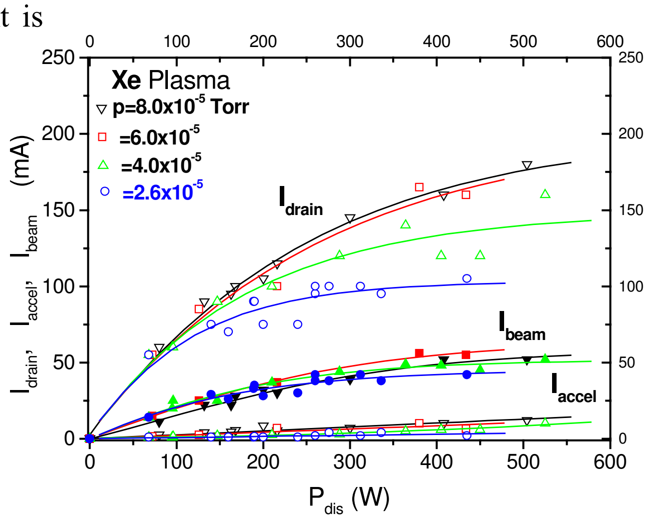

Fig.1 *I_{beam}, I_{drain} and I_{accel} of Xe beams are plotted against P_{dis} for various gas pressure.*

3. Experimental Results

A. Beam current

I_{beam}, I_{drain} and I_{accel} of Xe ion beam are plotted against the discharge power P_{dis} in **Fig.1**. The parameters are the gas pressures p of the chamber. The gas pressure of the ion source is 6-8 times higher than of the chamber. I_{beam} and I_{drain} increase with P_{dis} in the low P_{dis} region. Here, I_{drain} is the total extraction current from the ion source, I_{accel} is the current flowing into the accel-electrode. I_{beam} is the total ion beam current within divergence of 10° (total), which is measured by a collector of 14 cm ϕ at the position of 30 cm from the extraction electrode. One third of ion beams extracted from the electrode arrive at the collector and the remainders flow mainly to the chamber wall and a few part of that to the decel-electrode and the neutralizer. The gradients of I_{beam} and I_{drain} against P_{dis} decrease with increase of P_{dis}, and the gradient becomes gentle above P_{dis} ~200 W. When p is increased, the saturation point of I_{drain} extends to the higher P_{dis} region, while I_{beam} does not increase with p and with I_{drain}, then the beam efficiency and the beam diverges deteriorates. In order to produce intense beams, at first, the high I_{drain} is required. To produce the high I_{drain}, the density of the source plasma should be higher, and then the gas pressure of the source plasma should be higher. However, the pressure of the chamber increases with the source pressure because of insufficient differential pumping. The saturation of the beam current is caused mainly by the charge exchange and partly collision scatter with the neutral gas and may be caused by the divergence of beams, which is caused by the high ion space charge and insufficient neutralization when the beam density is increased. As the thermal flow to the collector increases nearly with the extraction current, the charge transfer or collision scattering of ions by neutrals causes the saturation of convergent ion beams. To produce the high current, low-energy, heavy ion beams, the ionization rate in the ion source and the pumping speed of the chamber must be higher, and the neutralization of the space charge should be carefully optimized.

B. Mass dependence of the beam currents

H2, Ne, Ar, Kr, Xe or CH4 is used as the discharge gas and the ion beams corresponding to the gas species are extracted from the source. I_{beam}, I_{drain} and the efficiency, which is the ratio of I_{beam} to I_{drain}, are plotted against relative mass number in **Fig.2**. In this ion source, H_3^+ is main ion beam in the H2 discharge, and CH_3^+ is dominant in the CH4 discharge. The gas pressure of the source is generally less than 1 mTorr. When the pressure is decreased, H_3^+ beams decrease and H^+ beams increase. In the case of CH_3^+, the phenomena are same. I_{drain} of various gas discharges are nearly same except Ne beam, but I_{beam} decreases with the increase of ion mass number. The efficiency decreases with the relative mass number. Then, the beam currents of 100 eV of H, Ar and Xe beams are 170 mA, 100 mA and 50 mA (at discharge power of 500 W) and the efficiencies are 70 %, 50 % and 35 %, respectively. In the case of Ne, as the density of the source plasma is low because of high ionization potential, I_{drain} is smaller, and then I_{beam} is smaller than the other ion beams. In the case of CH4 in the figure, P_{dis} was about 300W, in which the discharge voltage is high comparing with the other plasmas and then the real ion energy is higher than 100 eV.

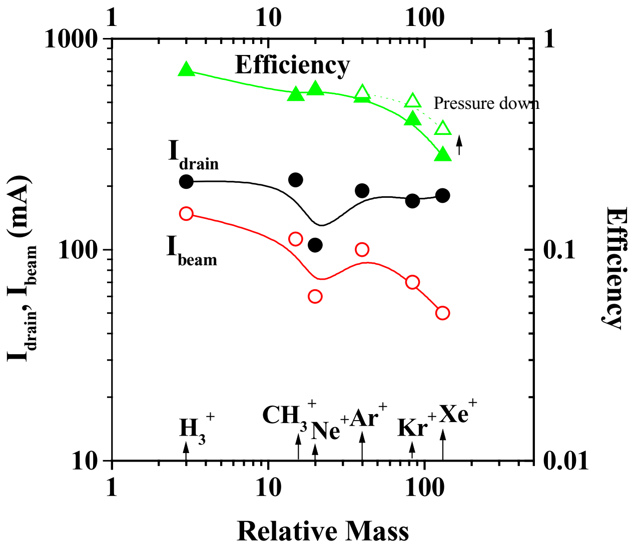

Fig.2 *I_{beam}, I_{drain} and the efficiency are plotted against relative mass number.*

C. Beam Energy

The beam current $I_{col.}$(30 cm) at the position of 30 cm is nearly proportional to the square root of the beam energy, as shown in **Fig. 5a**. The energy profiles of the beams are measured by an energy and mass analyzer, are shown in **Figs. 3(a)&(b)**. The analyzer is set at 90 cm from the extraction electrode. (a) is the case that V_E is supplied to the extraction electrode to produce the low energy ion beams (E_{ion} ~ V_E). (b) is that V_E is supplied to the cathode (E_{ion} ~ V_E + discharge voltage). The energy profiles are sharp. The half widths of the energy are 5-6 eV and almost the same for the various beam energies. The ion current is obtained by the counting methode.

The ion counts increase with E_{ion}, especially the ion counts at E_{ion}<20 eV was very low, while I_{drain} of each beam is roughly same. In (b), the slow ions are observed near 0 eV because the chamber pressure is higher than in (a), where the slow ions are not observed. In this measurement, the divergent beam, which angle is more than 2° cannot enter the analyzer because it is set at 90 cm.

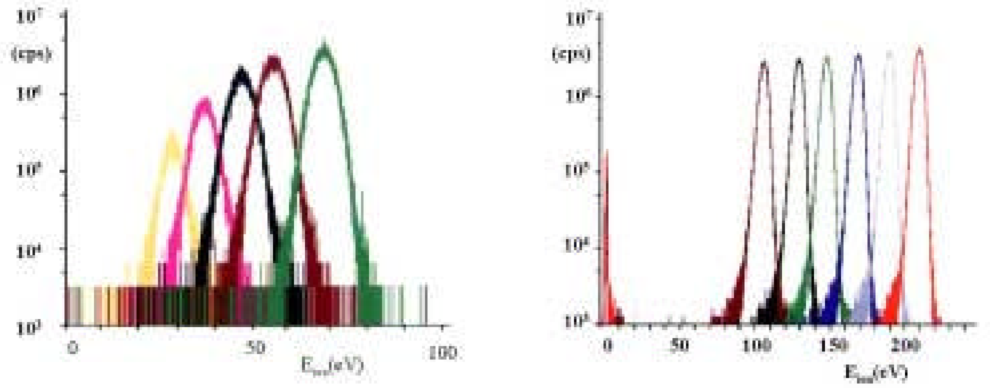

Fig. 3 *Energy profiles of the ion beams. (a) the left, V_E is supplied to the extraction electrode, $p=8.8x10^{-5}$ Torr. (b) the right, V_E is supplied to the cathode, $p=1.3x10^{-4}$ Torr. Ar beams*

The energy profiles of the ion beams at 90 cm from the extraction are shown for various p in **Fig. 4**. When p_{source} is increased to attain the intense ion beam, the ion counts decrease. In the high-pressure region, the beam counts decrease extremely and the slow ions (<10 eV) increase to the same counts level of the main ion beams, and in some case the width of the beam energy increases. In this figure, the beam energy decreases with increasing p because of the decrease of the discharge voltage.

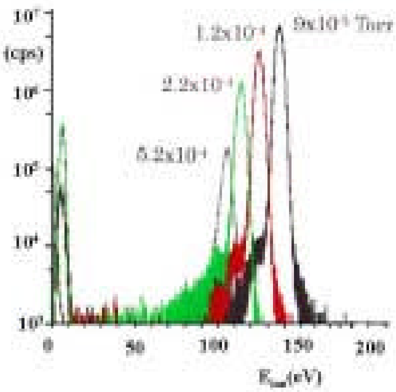

Fig. 4 *Energy profiles of the ion beams for various pressure of the chamber.*

D. Beam divergence

The beam quality is important for the application. The beam divergence was measured by Faraday cup at 46 cm from the extraction. The half angles of E_{ion} =40, 100 eV were 8°, 5°, respectively. The divergences are obtained alternatively by a slit at 33 cm and a probe at 66 cm. The example of the profile is shown in **Fig.5c**. The beam consists of a narrow angle part and a broad part. The angle of the narrow part is 1° and of the broad part extendes to 5°. The ion counts are plotted in Fig. 5a when 75ϕ obstacle is placed at 30 cm and hides the center of the analyzer by 3 cm, that is, the divergent beams with angle lager than 2.8° are measured. The 75ϕ obstacle works as a movable collector. At p<$2.6x10^{-4}$ Torr, $I_{col.}$(30 cm) are nearly proportional to the square root of E_{ion} and do not depend on p. Convergent ion counts versus E_{ion} are plotted for various p in **Fig. 5b**. In low E_{ion} region, convergent beams decrease especially in high p region and the divergent beams increase relatively. The divergent angle is estimated by the measurement of the analyzer and the movable collector and shown in **Fig. 5d**. The divergence of the beam increases extremely with decrease of the beam energy (E_{ion}<40 eV). The convergent beam counts are measured against P_{dis} and p, which is shown in **Fig.6**. When P_{dis} increases, I_{drain} and $I_{col.}$(30 cm) increase, however I_{col}(90 cm) remains almost constant and the convergent beam counts decrease at high P_{dis}. As p increases, P_{dis} increases and then I_{drain} and I_{col} increase, however, I_{col}(90 cm) is nearly constant and the convergent beam counts decrease.

4. Summary

To obtain the high-density, low-energy (<100 eV) and high mass ion beam plasma with the low electron temperature, the complete elimination of the ion space charge throughout the beam path is essential and key issue.

- $H3^+$, Ne^+, Ar^+, Kr^+, Xe^+ or $CH3^+$ beam plasma, which energy is 40-200 eV, is produced.
- The beam efficiencies decrease with increasing the relative mass, from 70 %($H3^+$) to 35%(Xe^+).
- The molecular ions are dominant in this experiment, but the rate can be controlled.
- The saturation of the beam current against the discharge power shifts to higher power region when the gas pressure increases, but the divergence increase.
- As the beam energy is decreased, the divergence increases with the current and the gas pressure. The good convergent beams with the energy greater than 50 eV are obtained.

References

[1] H. Kiyama and S. Kiyama; 1998 Inter. Congress on Plasma Physics, Praha, 1998, Vol. 22C, 2611. [2] H. Kiyama; Electrical Engineering in Japan, Vol.95 No.4 (1975) 261. [3] H. Kiyama et al., 26th EPS Conf. on Contr. Fus. and Plas. Phys., Maastricht (1999) 509.

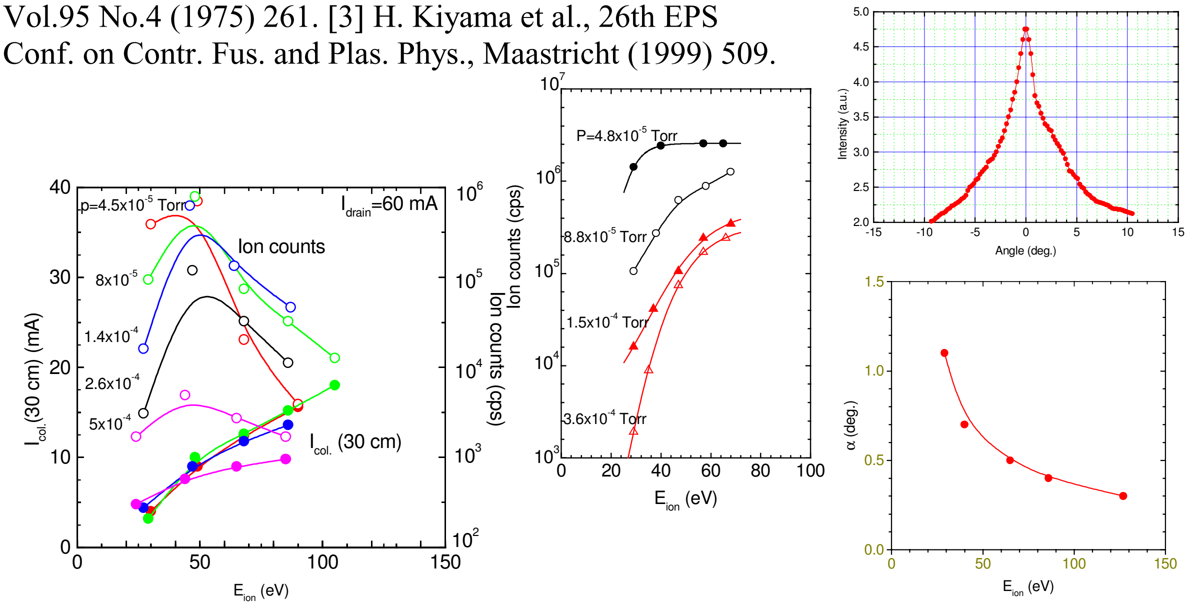

Fig.5 (a) $I_{col.}$(30 cm) and divergent beam (left) and (b) convergent beam (center) versus E_{ion}. (c) Beam profile (right top). (d) The divergent angle versus E_{ion} (right). *Ar beams.*

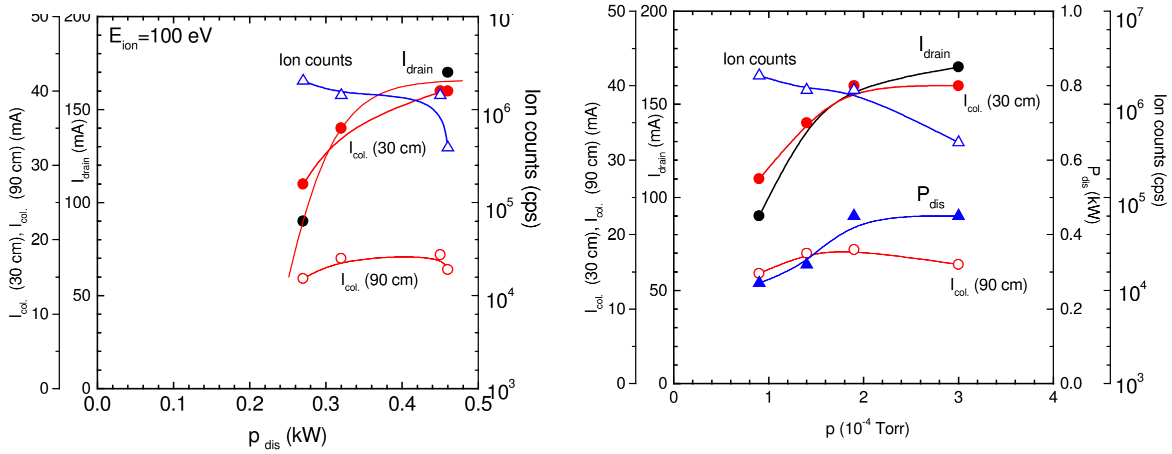

Fig.6 *The convergent beam counts are measured against* P_{dis} (left) *and p* (right). I_{drain}, I_{col}(30 cm), I_{col}(90 cm) are plotted. *Ar beams.*