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유도결합 플라즈마를 이용한 집속이온빔용 고휘도 이온원의 개발 및 특성연구

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Development and characteristic study of high brightness ion source using inductively coupled plasma for focused ion beam

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Abstract

A ion source using inductively coupled plasma has been tested in order to test its feasibility as a high brightness ion source for focused ion beam. When operating the ion source with filter magnets in front of plasma electrode for a negative ion source, lower emittances are expected. Extracted beam emittances are measured with an Allison-type scanning device for various plasma parameters and extraction conditions. The normalized emittance has been measured to be around 0.2 πmmmrad with beam currents of up to 0.55 mA. In particular, noting that multicusp magnets have a role in decreasing the emittance as well as increasing plasma discharge efficiency, transverse magnetic field has been confirmed to be a useful tool for decreasing emittance via electron energy control.

Key Words : High brightness ion source, Focused ion beam, Inductively coupled plasma, Emittance

1. Introduction

Nanofabrication can be regarded as consisting of material removal, addition, or measurement with nanometer resolution. It is also the key technology both in the integrated circuits industry where gate lengths of transistors are now shorter than 100 nm, and in the micro or nano scale machining industry.[1,2] A focused ion beam (FIB) system, which can produce a nano scale ion beam, is getting important as the interest in nanofabrication increases. Virtually, all commercial FIB systems have employed the gallium liquid metal ion source (Ga-LMIS)

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in order to use its superiority on high brightness. However, LMIS has several drawbacks to overcome, i.e. low current yield, limitation of producing only certain metallic elements. Moreover, the gallium ion generated by a LMIS can cause contaminations in many FIB applications. For example, when Ga-LMIS is used for sputtering of copper, a Cu_3Ga phase alloy can be formed, which is particularly resistant to milling and contributes to the uneven profiles.[3] This can be overcome by using plasma ion sources which can handle heavy inert gas species such as Xe, Kr. In case of direct lithography, it is also reported that lighter ion species (H, He) is more efficient rather than using Ga ion. Because of these facts, it would be of crucial value if reliable, stable, and long-life alternative sources which can produce various ion species including heavy or light ion could be developed. As alternatives of Ga-LMIS, gas field ionization sources (GFIS) and plasma ion sources have attracted attentions in recent years. GFIS, however, is not a favorable candidate for FIB due to its features of low current density and inconvenience of cryogenic systems.[2] Plasma ion sources such as Penning ion source and filament multicusp ion source have been also attempted for FIB in many research groups.[4,5] Contamination and life-time problems due to immersed electrodes or filaments, however, are still needed to be improved.

Recently, a high brightness ion source using inductively coupled plasma (ICP) is being investigated at Seoul national university for the next generation FIB systems. It has many advantageous characteristics as following. First of all, it can provide various gaseous ion beams, such as light ions (H, He) and heavy ions (Xe, Kr), so that many improvements which are difficult with FIB based on Ga-LMIS are expected. Second, inductively coupled plasma can produce a high density plasma without external magnetic field which is neccesary in other high density plasmas (helicon plasma, electron cyclotron resonance plasma), so that various methods of plasma parameter controls can be used. For instance, transverse magnetic field or electrostatic grid can divide the source chamber into a plasma region and an extraction region, which is essential for control of plasma and beam qualities. Finally, possible contamination from immersed filaments or electrodes can be avoided for longer source lifetime since rf antenna is located outside of the plasma chamber.

In order to evaluate the feasibility of high brightness, we have built and tested the ion source using ICP. It would be of significant value if the ion source showing beam qualities comparable to those of LMIS could be developed. For the successful development, the main issue would be achieving high current with low emittance, which means high brightness. In this article, optimum conditions for low emittance are pursued at various operating conditions, especially by utilizing transverse magnetic field as a possible control knob.

2. Characteristics of a high brightness ion source

A focused ion beam system can be thought of as composed of three main parts; the ion source, the ion optics column, and the sample displacement table. Among these parts, the ion source and the ion optics column (especially, ion lenses) play a significant role to determine the spot size of beam on the sample. The total diameter of the beam spot at the exit of the ion column is given by[6]

$$d = (d_0^2 M^2 + d_c^2 + d_s^2)^{1/2} \qquad (1)$$

where M is the magnification of the lens system, d_0 is virtual source diameter, and d_c and d_s are the contributions to beam diameter from chromatic aberration and spherical aberration of lens, respectively. In the typical case of FIB, the contribution terms from lens aberrations can be reduced at the expense of total current. Therefore, the virtual source diameter is considered to dominate the final spot size. This leads to the keen necessity of an ion source with low emittance (high brightness) because the virtual source diameter depends on the emittance.

The brightness of ion beam can be expressed as[2]

$$B = \frac{\eta I}{\pi^2 \epsilon^2} \qquad (2)$$

where η is the form factor describing the nature of the beam distribution (typically, η=2), I is the total beam current, and ϵ is, so called 'emittance', the phase-space area of the beam particles which describes transverse momentum of particles. As seen by Eq. (2), therefore, a high brightness ion beam can be obtained by extracting a high current beam with a high current density and a low emittance. These characteristics are closely related to plasma parameters such as plasma densities and temperatures as well as extractor geometries.

It is well known that the extracted current from a charged particle source is limited either by the emission capability or by space charge force. By these factors, a high density plasma is strongly required for the ion source to have a high current density. In our work, a inductively coupled plasma has been employed for a high density plasma source due to its advantageous features described in the previous section. It has been reported that the emittance can be decreased by lowering ion temperature of plasma and by optimizing the aspect ratio of extraction geometry, $s = r/d$, where r is aperture radius, and d is gap distance between electrodes.[7] Optimizing extraction condition also affects beam qualities significantly because the shape of emitting surfaces in plasma ion sources strongly depends on the electrical field distribution and the plasma density unlike electron beam source with a solid (fixed) emitting surface.

3. Experimental setup

A schematic diagram of the ion source is shown in Fig. 1. The source chamber is made of stainless steel (85 mm inner diameter by 75 mm height). The quartz disk is used for the dielectric windows through which rf field generated by external antenna can penetrate. The 13.56

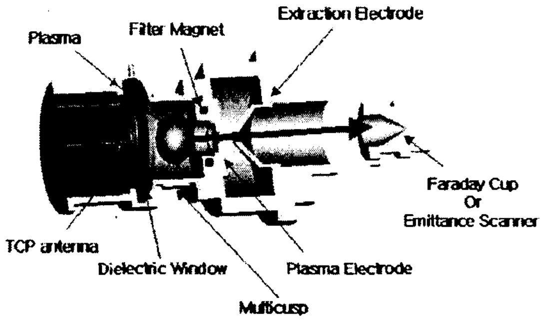

Fig. 1 The schematic diagram of the ion source using ICP with diagnostics system.

MHz, 1.3 kW rf power is used to generate high density plasmas with an L-type impedance matching network, and discharge is operated in cw mode. A extraction system with single aperture is constructed to extract the ion beam. Extraction geometry is arranged in a simple two-electrode system with the extraction aperture diameter of 5.0 mm and the extraction gap distance between plasma electrode and ground electrode can be adjusted from 7.0 mm to 13.0 mm.

Between main plasma and the extraction system, a set of permanent magnets generating transverse magnetic field of 65 G are located to filter out fast electrons in front of the plasma electrode. This can be used to get lower beam emittance by providing lower ion temperature with fast electrons eliminated. The source chamber was surrounded by 16 columns of Nd-Fe-B permanent magnets (10 mm width by 30 mm length each) in order to generate the multicusp field configuration for a good plasma confinement. It is noticeable that fringe field (radial component) of the multicusp magnet due to the space between multicusp magnets and filter magnet could also have a role to filter out the high-energy electrons. As a result, filtering effects could be observed by changing the strength of the multicusp field.

In order to measure the total beam current and the transverse component of an ion beam trajectory (emittance) precisely, a simple Faraday cup and a two-slit electric-sweeping type emittance scanner known as the Allison-type scanner are used, respectively. The

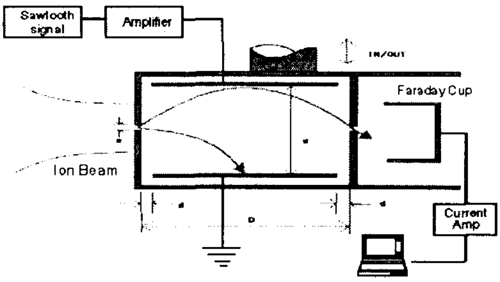

Fig. 2 The schematic diagram of the Allison-type emittance scanner.

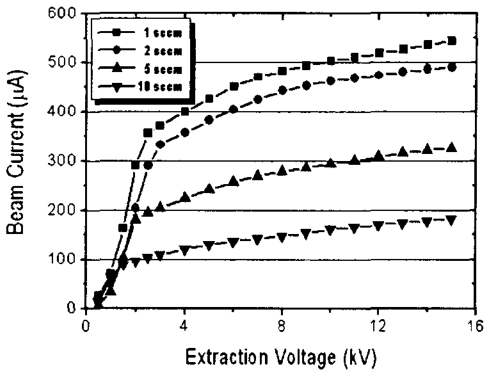

Fig. 3 Extracted ion beam currents as a function of the extraction voltage for various gas feeding ratios at the fixed rf power of 1kW and gap distance of 7.0 mm.

schematic diagram of the emittance scanner is depicted in Fig. 2. The scanner consists of a water-cooled beam dump at the entrance, two slits (s = 0.1mm) at the beginning and the end of the scanner, two electrostatic deflection plates, and a Faraday cup at the end with electrode for suppressing the secondary electrons. Applied sweep voltage across the two parallel plates analyzes ions entering the front slit. Ions passing through the rear slit are then measured and the corresponding divergence angle is identified by the value of the instantaneous sweep voltage.[8]

4. Experimental results and discussion

High density plasmas in the regime of "H-mode" have been generated with at least 250 W rf power provided. Hydrogen gas has been used as a working gas, and argon gas is added only at initial breakdown to help H-mode transition by seeding electrons with high ionization efficiency.

For various gas feeding ratios, extracted beam currents are plotted as a function of extraction voltages in Fig. 3. It is clearly shown in the figure that the extracted ion currents are limited either by the space charge force ("Child-Langmuir limit") where extraction voltages are below 3 kV, and by the emission capability ("ion saturation limit") where extraction voltages are above 3 kV. It is also noticeable in Fig. 3 that ion currents are higher as gas flow rates are lower. Note that actual gas pressure inside the source chamber is proportional to mass flow rate, and it is approximately 10 mTorr when gas flow rate is 2 sccm. In our previous work, the optimum gas pressures for high density in the ICP have been observed as well as its dependency on rf power by measuring H-alpha intensity.[9] In this operating regime, therefore, it can be explained that plasma densities is decreased as operating gas pressures are increased, resulting in lower ion currents with higher gas flow rates. Further study is planned to investigate the physics of hydrogen ICP resulting in such a behavior in this gas pressure range.

High current ion beam with a low divergence can be obtained with good beam optics of ion source as well as plasma parameters appropriate for a low emittance. By comparing beam currents collected by the Faraday cup with total beam currents read from the extraction power supply extracted beam optics can be roughly understood. Fig. 4(a) shows that ion optics with gap distance of 7.0 mm has an optimum condition around 5 kV, where almost all extracted beam currents are collected at the Faraday cup. If the extraction voltage is too high, the plasma meniscus will become too concave so that this will result in an overfocused ion beam trajectory. Optimum condition of ion optics can be confirmed by looking at the extraction voltage where normalized emittance becomes minimum. Fig. 4(b) shows minimal emittance around 5 kV, indicating good beam optics at this extraction electric field. We also investigated the

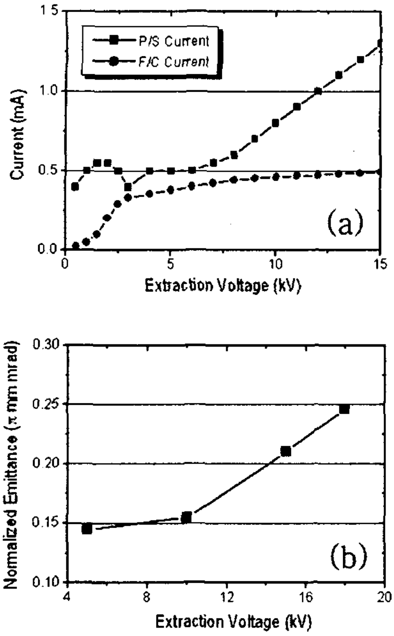

Fig. 4. (a) Comparison between total beam currents from extraction power supply and ion beam currents collected by Faraday cup. (b) Measured emittances for different extraction voltage, showing optimum emittance near 5kV. All experiments were performed in the condition of 1kW rf power, 2 sccm gas feeding rate, and 7.0 mm gap distance.

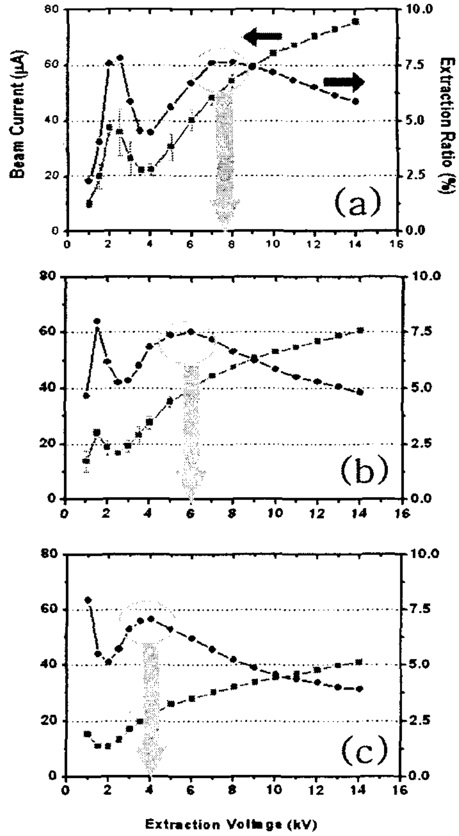

Fig. 5 Plots of extracted beam current and extraction ratio (current measured by Faraday cup over current read from HV power supply), which implies the optimum condition of ion optics, in the conditions of (a) 2 sccm, (b) 5 sccm, (c) 10 sccm. Note that gap distance is 13.0 mm, and that plasma density tends to decrease as the gas flow increases.

beam optics under the condition of 13.5 mm gap distance according to the plasma densities. Compared with the case of 7.0 mm gap distance shown in Fig. 4(a), it can be clearly observed in Fig. 5 that optimum voltage of extraction is increased up to 8 kV when other conditions are same, i.e. 1 kW rf power, 2 sccm gas flow, and total beam current is lowered by approximately one order, which can be roughly expected in Child-Langmuir law. The fact that the optimum point drops to the lower voltage as the plasma density decreases is also shown in Fig. 5. From this, it is considered that higher plasma density is strongly required to obtain not only a higher current density but a good ion optics (low emittance) at desired extraction voltage with maintaining the optimized aspect ratio of extraction geometry which is described in the previous section.

In the previous section, it has been mentioned that fringe fields (radial component) of multicusp magnets generated between a set of filter magnet and multicusp magnets can also filter out high-energy electrons. By filtering high-energy electrons, ion temperature can be reduced and then beam emittance may be decreased as a result. To see this effect, beam emittances are

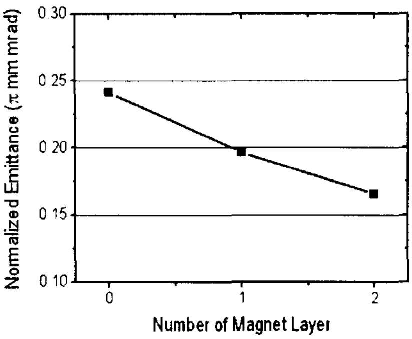

Fig. 6 The normalized emittance as a function of the number of multi-cusp magnet layers (strengths of multi-cusp fields).

measured with the field strength of multicusp magnets by varying the number of cusp magnet layers. Surface magnetic field strengths of multicusp magnet systems are 0G for 0 layer, 3.3 kG for single layer, 4.5 kG for double layer of cusp magnets. The emittances are measured in the condition of 1 kW rf power and 15 kV extraction voltage, and results are shown in Fig. 6. It is clearly seen that the emittance is significantly reduced by high-energy electron filtering with increased fringe fields of multicusp magnet. This effect may be pronounced by improved beam optics with increased plasma densities due to a good confinement at higher cusp field strength. This opens up a new potential of developing a low emittance, high current density ion source with the optimal design of a magnetic field configuration.

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References

(1) Reyntjens, S., and Puers, R., 2001, "A review of focused ion beam applications in microsystem technology," *J. Micromech. Microeng.* Vol. 11, pp. 287~300.

(2) Melngallis, J., 1987, "Focused ion beam technology and applications," *J. Vac. Sci. Technol. B*, Vol. 5, No. 2, pp. 469~495.

(3) Jiang, X., Ji, Q., Chang, A., and Leung, K. N., 2003, "Mini rf-driven ion sources for focused ion beam systems," *Rev. Sci. Instrum.*, Vol. 74, No. 4, pp. 2288~2292.

(4) Guharay, S. K., Sokolovsky, E., and Orloff, J., 1999, "Characteristics of ion beams from a Penning source for focused ion beam applications," *J. Vac. Sci. Technol. B*, Vol. 17, No. 6, pp. 2779~2782.

(5) Scipioni, L., Stewart, D., Ferranti, D., and Saxonis, A., 2000, "Perfomance of multicusp plasma ion source for focused ion beam applications," *J. Vac. Sci. Technol. B*, Vol. 18, No. 6, pp. 3194~3197.

(6) Orloff, J., Utlaut, M., and Swanson, L., 2003, *High resolution focused ion beams: FIB and its applications*, Kluwer Academic/Plenum Publisher, New York, pp. 89~119

(7) Keller, R., 1990, "Ion extraction systems: optics and design," *Nucl. Instrum. Methods Phys. Res. A*, Vol. 298, pp. 247~254.

(8) Allison, P. W., Sherman, J. D., and Holtkamp, D. B., 1983, "An emittance scanner for intense low-energy ion beams," *IEEE Trans. Nucl. Sci.* NS-30, pp. 2204~2206.

(9) Hong, I. S., Cho, Y. S., and Hwang, Y. S., 2002, "Development of a negative hydrogen ion source for tandem proton accelerator using transformer coupled plasma sources," *Rev. Sci. Instrum.* Vol. 73, No. 2, pp. 979~982.