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Abstract

Mini RF-driven ion sources with 1.2 cm and 1.5 cm inner chamber diameter have been developed at Lawrence Berkeley National Laboratory. Several gas species have been tested including argon, krypton and hydrogen. These mini ion sources operate in inductively coupled mode and are capable of generating high current density ion beams at tens of watts. Since the plasma potential is relatively low in the plasma chamber, these mini ion sources can function reliably without any perceptible sputtering damage. The mini RF-driven ion sources will be combined with electrostatic focusing columns, and are capable of producing nano focused ion beams for micro machining and semiconductor fabrications.

INTRODUCTION:

Recently focused ion beam (FIB) systems have been used for circuit inspection, mask repair, micro machining, ion doping, and direct resistless writing. Most FIB systems employ a liquid metal ion source (LMIS). LMIS has a very low current yield and very high angular divergence. The gallium ion generated by liquid metal ion source can cause contamination in many FIB applications. For example, when 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[1]. L. Scipioni and coworkers[2] have demonstrated that when gallium ion beam is used for photo mask repair, implanted gallium ions can absorb 73% of incident 248 and 193 nm ultraviolet light. But only 0.7% of the incident light is absorbed when krypton ion beam is used for mask repair. As a result, to develop a high brightness non-gallium ion source for FIB systems is of great significance. The gas field ion source (GFIS)[3] has been investigated as a potential substitution for LMIS, which has an image-side brightness of 10^9-10^{10} A/cm sr^2 at 30-35 keV. But GFIS is limited to light ions production and the current yield is too low. It is not efficient for high speed milling applications[2].

In our previous work[4], we have built a small filament driven multicusp plasma ion source which can only produce about 3mA/cm^2 krypton ion beams with 80 watts of discharge power. The measured image-side brightness for krypton ion beams was found to be 1650 A/cm sr^2 at 35 keV[2]. In the present work, new mini RF-driven ion sources have been developed which can produce 7 keV 220mA/cm^2 argon ion beams and 140 mA/cm^2 krypton ion beams with only 70 watts of RF input power. The currently available commercial FIB systems with LMIS are not used for lithography because gallium ion is not suitable for lithography application. The backscattering and proximity

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effect of electron beams limit the attainable feature size for lithography applications. Ion beam lithography has the potential to achieve less than 10 nm patterns. Using new mini RF-driven ion source, over 100 mA/cm^2 6 keV hydrogen ion beam has been obtained. If the FIB systems are equipped with the hydrogen mini RF-driven ion source, they can also be used in extremely small dimension lithography application.

The mini RF driven ion source operates in inductively coupled discharge mode. Inductively coupled plasma generators have been studied extensively in the last several decades [5-10]. Several features make this kind of plasma generator attractive. Compared with capacitively coupled RF discharge, inductively coupled discharge has lower plasma potential and higher power efficiency. Low plasma potential can decrease the ion bombardment energy to the chamber walls, thus reducing the sputtering damage[7,8]. The plasma potential in capacitively coupled discharge can be over 100 volts [11], while the plasma potential in inductively coupled discharge can be lower than 30 volts operating with several milli-torr of neutral gas pressure [9]. The sputtering yield for 100 eV argon ion on molybdenum is 2 atoms/ion. But the sputtering yield is almost zero when the energy of the argon ion is lower than 30 eV. When an external antenna is employed in the plasma generator, the quartz wall of the ion source will be coated by a thin metal film if sputtering damage from the metal electrode is significant. The metal thin film around the quartz wall will shield the RF field and decrease the power efficiency, thus limit the lifetime of the ion source. High power efficiency is the result of minimal electron and ion power dissipation. Since the electrons and ions are accelerated through large sheath voltage in capacitive discharge [7,8], they are lost to the chamber walls much faster than the case of inductively coupled plasmas, resulting in low power efficiency.

Mini RF plasma ion sources with 1.2 and 1.5 cm diameter have been tested. They can be operated in inductively coupled mode at relatively low forward RF power. Care has been taken to reduce the capacitively coupled discharge. This will increase the portion of the inductively coupled discharge, thus increasing the power efficiency and lower the plasma potential. Low power will result in the reliability of continuous operation. At tens of watts power consumption, the RF power supply and matching network can be very small. With simple all-electrostatic accelerator columns, it is possible to develop very compact high brightness ion source for many FIB applications.

EXEPRIMENTAL SETUP:

Mini RF-driven ion sources with two different diameters have been tested with a 13.56 MHz power supply. A schematic diagram of the experimental setup is shown in Fig. 1. The chambers of the mini ion sources are made of a cylindrical quartz tube, the two ends of the quartz tube are enclosed by molybdenum flanges, one is for gas inlet and the other is the first electrode for ion beam extraction. Molybdenum has a high sputtering threshold energy and low sputtering yield, which can increase the lifetime of the ion source. The thickness of the quartz wall is ~1.0 mm. The length of the quartz chamber is 5.0 cm. The inner diameters of the two different mini sources are 1.2 and 1.5 cm respectively. Single layer and double layer helical coupler antennas have been tested for the two mini sources. The antennas are made of 1-mm diameter cooper wire or 2-mm diameter copper tubing for water cooling. The surface of the copper wire is coated with a thin insulating layer.

Double layer coils that wound in parallel or in series have been tested.

When double layer coils are wrapped in series, the coils are wound starting close to the first electrode and moving away in successive turns, followed by a Teflon layer of insulation. The coils are then wound in the opposite direction returning to the extraction on the surface of the Teflon. In this case, the two ends of the coils are very close. A good insulation is needed to hold the high voltage drop between the two layers, especially at high RF power. When parallel double layer coils are used, two separate antennas of the same length are wrapped spirally from the extraction to the other end of the plasma chamber with a Teflon insulation layer between the two layers. In this case, the voltage drop across the two layers of the coils is minimized. As a result the parallel double layer coils can sustain higher RF power without voltage breakdown between the insulation layer. The plasma electrode is made of metal molybdenum with a 1-mm diameter extraction hole in the center. For beam extraction, a positive high voltage is applied to the first plasma electrode, while the second electrode is kept at the ground potential. The ion beam is extracted and accelerated, eventually collected by a Faraday cup. A pair of permanent magnet is installed at the Faraday cup entrance for electron suppression.

EXPERIMENTAL RESULTS:

I) Operating conditions

When the RF power is increased from zero, a faint plasma is first observed, this corresponds to the low density capacitively coupled discharge. By increasing the RF power above a certain threshold, a mode jump occurs [9,12]. The light intensity of the plasma increases abruptly, and the extractable current is also greatly increased. This corresponds to the mode change from capacitive discharge to inductive discharge. Due to the higher power efficiency in inductively coupled discharge, the plasma density is much enhanced. Consequently, higher ion current can be extracted. After the source is operating in inductively coupled mode, the matching network needs to be adjusted in order to obtain zero reflected power. The RF input power can then be decreased and the inductive discharge can be maintained at much lower power than the threshold. This kind of source operation has been extensively investigated by several authors [13-16].

An alternative approach to reach inductive discharge is to increase the gas pressure while maintaining the RFpower at a relatively low value. For argon and krypton, the threshold RF power for inductive discharge can be lowered by increasing the neutral gas pressure inside the plasma chamber. The gas pressure is not an important issue in mini source. In order to produce nano ion beams, the extraction hole will be less than 100 μm in diameter. The neutral gas pressure in the accelerating and focusing column is still low when modest pumping speed is applied in the vacuum chamber. High voltage can be sustained even as the gas pressure inside the plasma chamber is over 1 Torr. When inductive coupling is reached, the pressure is optimized to give the highest current density. This optimized gas pressure inside the plasma generator is dependent on forward RF power; the higher the rf power, the lower the optimized gas pressure. If the forward RF power is lower than 100 watts, the optimized neutral gas pressure is usually around several hundred milli-torr for argon and is slightly lower for krypton because the ionization energy of krypton is lower than argon.

The second method cannot be used for hydrogen. If hydrogen is used for the discharge, the bright and red plasma (an indication of high atomic H^+ ion concentration) can only exist when the neutral gas pressure inside the plasma chamber is lower than several hundred milli-torr at 200 watts of RF forward power. In order to start the inductively coupled hydrogen plasma, the initial forward RF power is usually kept at 200 watts and the initial neutral gas pressure is usually above 1 Torr. The plasma tends to be white at this pressure. As the neutral gas pressure is decreased to about 500 milli-torr, a mode change is observed. The color of the hydrogen plasma changes to red, while the light intensity and the extracted beam current are greatly increased. This corresponds to the inductively coupled discharge with high percentage of atomic ions inside the plasma.

The upper gas pressure threshold for inductively coupled hydrogen plasma is correlated with the molecular nature of hydrogen gas. The cross section for the dissociation of H_2 molecule is in the order of several 10^{-17} cm^2 when the energy of the electrons is just above 10 eV. At this energy region, the cross sections for the ionization of H atom and H_2 molecule are on the order of 10^{-19} cm^2 just above the ionization threshold. All these data indicate that most of the electron will lose the energy to dissociate the H_2 molecule and only small portion of the electron will be used to ionize the H atom or H_2 molecule. As a result, a relatively higher rf power is needed to generate inductively coupled hydrogen plasma compared with argon and krypton. The threshold electron energy for the ionization of H_2 is 2 eV higher than that for H atom, and the cross section for ionization of H atom is much higher than that of H_2 molecule. The H atom is much more easier to be ionized compared with H_2 molecule. These means that the lower the neutral gas pressure, the more electrons are used in ionization, and also that the higher the portion of H atom in neutral gas, the higher the efficiency of ionization. A relatively high H atom portion in low neutral gas pressure can be expected, thus the ionization efficiency will be higher at relatively low neutral gas pressure. Therefore, the inductively coupled hydrogen plasma with lots of atomic ions exists at lower neutral gas pressure.

The plasma potential in inductive discharge is much lower than capacitive discharge, and the higher the pressure in the source, the lower the plasma potential[9]. The optimized neutral gas pressure for the highest current density is usually in the order of several hundred milli-torr, which is rather high and helps to reduce the plasma potential. When the source is working in inductively coupled mode, no perceptible sputtering from the molybdenum electrode has been observed. This means that the potential of the plasma is lower than the sputtering threshold of argon or krypton ions on molybdenum. Usually, the energy spread of the extracted ion beams is reduced at lower plasma potential. This will help to reduce the chromatic aberration in ion beam focusing optics.

Single and double layer antenna coils have been used in the experiments. The double layer coils spread out less than the single layer coils. The volume surrounded by the double layer coils is decreased, thus the power density is higher with double layer coils at the same RF power. Capacitive discharge is induced by the voltage difference between the two ends of the coils. The voltage is approximately lowered by one half when the coils are wrapped in series in double layers. The capacitive discharge is minimized when double layer coils are used to generate the plasma. Because of the higher power efficiency in an inductive discharge, the double layer antenna coils can generate the discharge at rather low RF power consumption.

II) Beam current density measurement

The first mini RF driven ion source in the current experiment consists of 15 turns of single layer copper coils and a quartz tube with 1.7 cm diameter. The measured 7 keV ion current density j versus RF power is plotted in Fig. 2. Current density is the current collected by Faraday cup divided by the area of the extraction aperture. At higher RF power, the extracted current density from krypton plasma is generally lower than that of argon ions when 7 kV extraction voltage is applied. The maximum current density calculated by the Child-Langmuir equation is:

$$j = \frac{4 \cdot e_0}{9} \sqrt{\frac{2 \cdot q}{m}} \cdot \frac{f^{\frac{3}{2}}}{d^2}$$

Where e_0, m, q, f and d are the permittivity of free space, mass of ion, charge of ion, extraction potential and extraction distance respectively. The current density is inversely proportional to the square root of mass. Since the mass of krypton is larger than that of argon, the extracted current density should be lower for krypton when the density of the plasma is the same. At lower RF power, the difference of the current densities is decreased; eventually, the krypton ion current density exceeds the argon ion current density at 20 Watts. This is reasonable, because krypton is easier to ionize than argon, the plasma density of krypton at low rf power can be higher than that argon. The saturation value of ion current density that can be extracted from a plasma of certain density is given by:[17]

$$j_s = 0.6 \cdot n_i \cdot q \cdot \sqrt{\frac{kT_e}{m}}$$

Where n_i and T_e are plasma density and electron temperature. This saturated current is proportional to plasma density, though the mass of krypton is heavier than argon, a higher current density for krypton at low rf power can be extracted from the plasma due to higher plasma density. The measured current densities level off at high RF power. When the plasma density is too high, the plasma meniscus will protrude out, and the extracted ion beam will have larger angular divergence. Some of the ions will be blocked by the second electrode and lost. This means that higher electric field is needed to extract more current from higher density plasma.

Compared with single layer coils, the extracted current density is increased by 30% if the 15 turns of copper coils are wrapped in double layers (Fig. 3), with 8 turns in the first layer and 7 turns in the second layer. As has been pointed out, the double layer antenna has a higher power density compared with single layer antenna at the same RF power. As a result, the extracted ion current density is higher when double layer antenna coils are used. The double layer coils can be wrapped in parallel or in series. But the extracted current densities are about the same within experimental error.

A smaller ion source with 1.2cm inner diameter and 13 turns of double layer copper coils (7 turns underneath and 6 turns in the outer layer) has been tested for argon and krypton. For argon, the extracted current density (Fig. 4) is increased by 25% at 70 watts and 75% at 20 watts compared with the results shown in Fig. 3. The lower the RF power, the bigger is the increase. Since the volume of the plasma chamber is smaller in the small source, the power density should increase. As a result, it is capable of providing higher current density at lower RF power. The plot of current density versus extraction voltage for this source is shown in Fig.5. The extracted current density is far from saturation even when only 40 watts RF power is used. More current can be extracted if the extraction voltage is increased or extraction distance is decreased.

It has been pointed out in the beginning of this section that more RF power is needed to produce inductively coupled hydrogen plasma. For the sake of cooling the antenna at high RF power, the copper tubing with cooling water was used as the antenna of the hydrogen ion source. 18 turns of water-cooling coils were used. This arrangement has 10 turns in the bottom layer and 8 turns in the second layer. The measured current density for 6 keV hydrogen ion beam is plot in Fig.6. At 220 watts RF power, 100 mA/cm^2 current was obtained.

These mini rf driven sources can also be used to generate electron beams. Generally, the extracted current density for electron beams will be about 40 times higher than ion beams when argon is used to generate the plasma. This means that electron beams with current density 9 A/cm^2 can be extracted with 70 watts RF power in the 1.2 cm diameter mini source using the double layer antenna.

The mini RF-driven ion source will be combined with electrostatic focusing column to produce focused nano ion beams in future experiments. These gaseous ion beams have many superior advantages over the liquid metal ion source. They will greatly improve the performance of the FIB systems, in which the LMIS is currently used.

SUMMARY

Mini RF-driven ion sources for focused ion beam systems have been successfully developed which can generate many kinds of gaseous ion beams at very low RF power. The operating condition has been discussed in detail. The extraction of high current density argon, krypton and hydrogen ion beams has been demonstrated in the present experiment. Compared with our previous work[4], the current density has been increased about 47 times for krypton ion beam, image-side brightness of 8×10^4 A/cm sr^2 at 35 keV can be predicted based on the work of Scipioni and coworkers[2]. The extracted ion current from the mini RF-driven ion source is far from saturation. As a result, it is possible to obtain the image-side brightness of over 10^5 A/cm sr^2. This value is close to the brightness of LMIS, which is usually on the order of 10^6 A/cm sr^2. But plasma ion sources have much higher current yield than LMIS. The mini ion sources can be operated for a long time without visible sputtering damage of the chamber. Since they are small and work at low RF power, it is possible to build very compact higher current density ion sources for FIB systems. These advantages also make it easy to integrate these sources into commercially available FIB systems.

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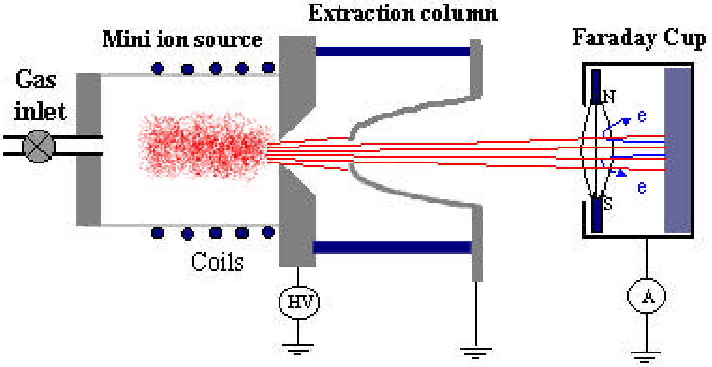

Fig. 1. Schematic diagram of the current density measurement for mini rf driven ion source.

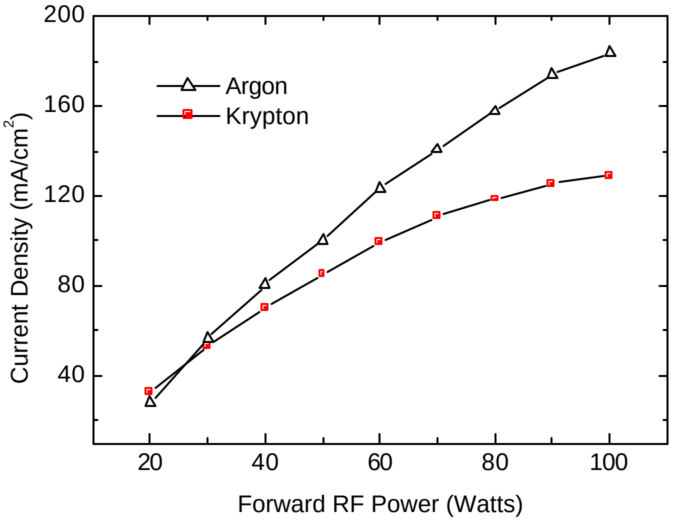

Fig. 2. Extracted ion current density versus forward rf power for 1.5 cm inner diameter mini ion source with 7 kV extraction voltage when 15 turns of single layer cooper coils are used.

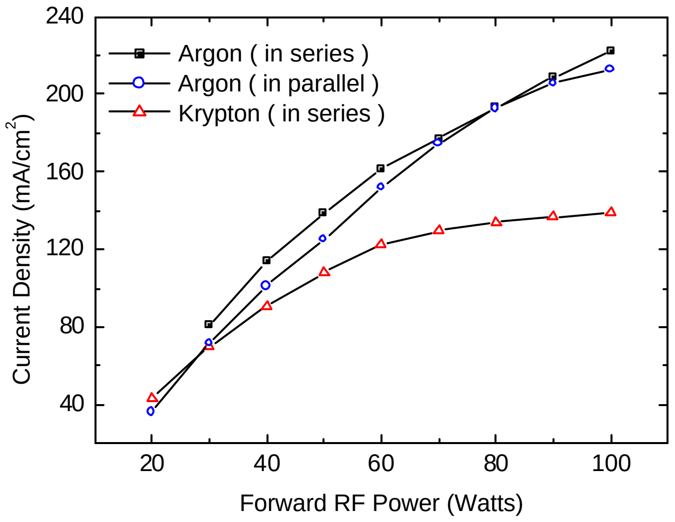

Fig. 3. Extracted ion current density versus forward rf power for 1.5 cm inner diameter mini ion source. 15 turns of cooper wire is used to wrap the double layer antenna. The coils are wrapped in series or in parallel. 7 kV extraction voltage was used in the experiment. There are 8 turns in the first layer and 7 turns in the second layer.

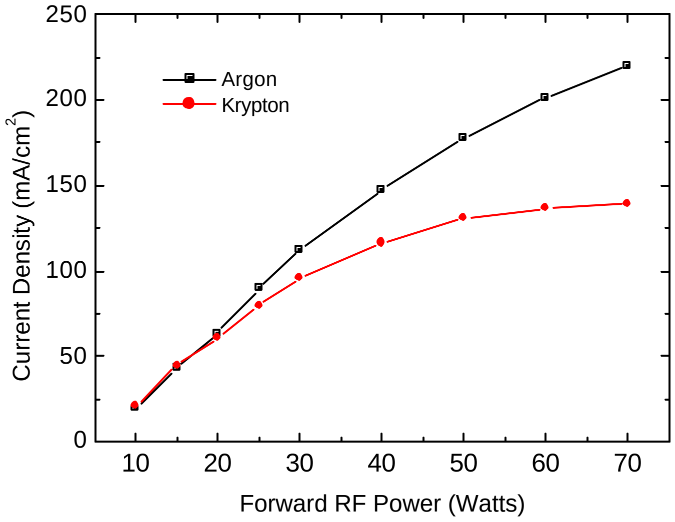

Fig. 4. Extracted ion current density from 1.2cm inner diameter mini ion source. 13 turns of cooper wire (7 turns in the first layer and 6 turns in the second layer) is used to wrap the double layer antenna. The double layer coils are wrapped in series. 7 kV extraction voltage was used in the experiment.

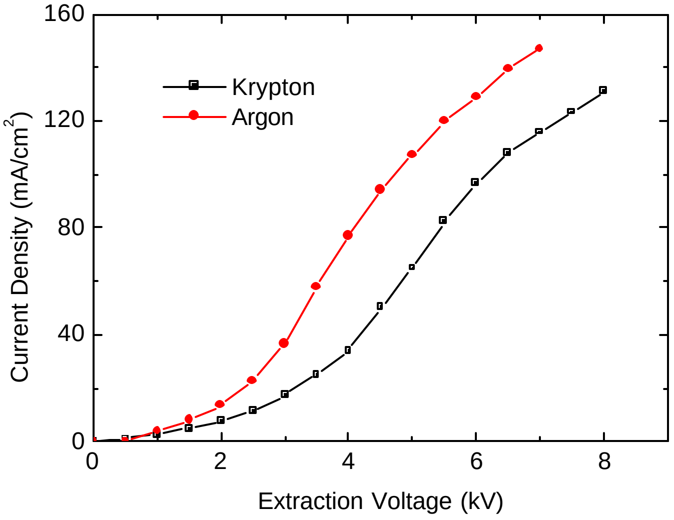

Fig. 5. Extracted ion current density as a function of the extraction voltage. 40 watts rf power was used in the experiment. Source setup is the same as that of fig. 4.

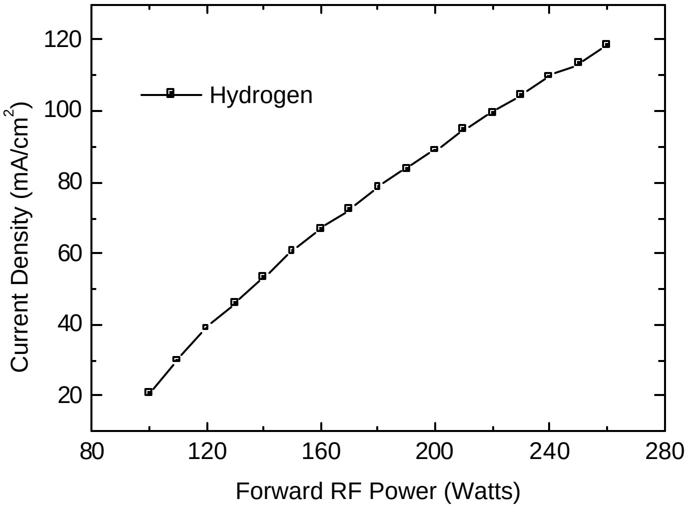

Fig. 6. Extracted hydrogen ion current density from 1.5cm inner diameter mini ion source. 18 turns of water-cooling antenna was used, which had 10 turns in the first layer and 8 turns in the second layer. The double layer antenna was wrapped in series. 6 kV extraction voltage was used in the experiment.