Improvement in Brightness of Multicusp-Plasma Ion Source

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Abstract

The beam brightness of a multicusp-plasma ion source has been substantially improved by optimizing the source configuration and extractor geometry. The current density of a 2 keV He^+ beam extracted from a 7.5-cm-diameter source operating at 2.5 kW RF power is ~100 mA/cm^2, which is ~10 times larger than that of a beam extracted from a 5-cm-diameter source operating at 1 kW RF power. A smaller focused beam spot size is achieved with a counter-bored extractor instead of a conventional ("through-hole") extractor, resulting another order of magnitude improvement in beam current density. Measured brightness can be as high as 440 A/cm^{2}Sr, which represents a 30 times improvement over prior work.

I. Introduction

Maskless ion beam lithography is one of the "next-generation lithography" techniques for integrated-circuit manufacture at the 70 nm technology node and beyond. The use of ions is

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attractive for lithography, because resist sensitivity is almost two orders of magnitude higher for ions than for electrons[2], and higher resolution is achievable due to reduced proximity effects. A compact focused-ion-beam system incorporating a multicusp-plasma ion source has been under investigation at the Lawrence Berkeley National Laboratory.[1,3-5] Multicusp-plasma ion sources have been used for many applications, such as neutral-beam injectors for fusion devices, particle accelerators, ion-implantation systems, neutron tubes for oil-well logging, and proton therapy machines.[6,7] They can produce a uniform plasma over a large area[6]; therefore, a single source can be used to generate a large number of closely packed beamlets for parallel processing □ an advantage which cannot be provided by any other type of ion source.

The brightness of a multicusp-plasma ion source is a key issue for its application to maskless ion beam lithography. If an array of 100×100 independently controlled beamlets is used to expose a wafer, the brightness for each beamlet at the entrance of the objective lens needs to be ~1000 A/cm^{2}Sr, in order to achieve exposure throughput of sixty 300-mm-diameter wafers per hour.[1] Scott *et al.* recently reported the measured beam brightness of a 5-cm-diameter multicusp-plasma ion source to be less than 15 A/cm^{2}Sr, using 5-μm-diameter extraction apertures,[1] which falls far short of the brightness requirement.

In this paper, the brightness of a multicusp-plasma ion source has been substantially improved by optimizing the source configuration and extractor geometry. First, a larger source (7.5 cm in diameter) is employed to achieve higher source current density. Second, a counter-bored extraction aperture is used to achieve smaller focused beam spot size with much reduced

aberration. With increased RF power, the brightness of the multicusp-plasma ion source can be sufficiently high to make it suitable for application to high-throughput maskless lithography.

II. Approaches to Improving Brightness

The beam brightness B at a plane is defined as:

$$B = \frac{I_\Omega}{\pi r^2} = \frac{I}{\pi r^2 \cdot \Omega} = \frac{J}{\Omega} \tag{1}$$

where I_Ω is the angular current density, r is the radius of the beam spot at that plane, I is the total beam current, Ω is the solid angle of the beam, and J is the current density at that plane. For a fixed solid angle, higher current density at a given plane results in higher brightness. In this paper, two approaches have been taken to improve the brightness of a multicusp-plasma ion source: increasing the total beam current extracted from the source, and reducing the focused beam spot size.

A. Increasing total beam current

Figure 1(a) shows the cross-sectional view of a RF-driven multicusp-plasma ion source. An RF discharge is generated using an induction-coil antenna located inside the source. As shown in Figure 1(b), an azimuthal electric field is generated by the time-varying magnetic field inside the antenna loop. Electrons present in the gas volume are accelerated by the induced electric field, and quickly acquire enough kinetic energy to generate a high-density plasma by ionizing the background gas particles. This mode of operation is referred to as the inductively coupled mode, and it is desirable for achieving a high plasma density in the region from which the ion beams are extracted. If the antenna is too close to the wall, strong oscillating electric fields can easily be generated between the antenna and the source chamber, resulting in a capacitively coupled

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discharge in the source wall region. For this reason, it is difficult to operate a 5-cm-diam source with a 3-cm-diam antenna in the inductively coupled mode, as compared to a 7.5-cm-diam source with a 4.5-cm-diam antenna.

Figure 2 compares the extracted He^+ beam current densities for 7.5-cm-diam and 5-cm-diam sources. The current density of the extracted beam increases with RF power for both sources. At 1 kW of RF input power, corresponding to the source operation condition in Ref. 1, the 7.5-cm-source provides ~3 times higher current density than the 5-cm-source. This difference may be attributed to the different modes of source operation as discussed in the previous section. The current density for the 7.5-cm-diam source is over 100 mA/cm^2 at 2.5 kW of RF power, which is ~10 times larger than that of the 5-cm-diam source operating at 1 kW of RF power.

B. Reducing focused beam spot size

The effect of the two different extractor geometries on beam aberrations has been investigated: "through-hole" and counter-bored hole. As shown in Figure 3, the through-hole consists of a uniform-diameter (50 μm) aperture, 250 μm deep; the diameter of the counter-bored hole changes from 50 μm (for the first 250 μm of depth) to 300 μm (for the second 250 μm of depth) facing downstream.

Simulations were performed using the Munro code[8] and the results are summarized in Table 1. The aberration for the through-hole aperture is much larger than the focused Gaussian beam spot size. For an image 1 mm away from the extraction aperture, both geometries provide ~ 4 times reduction in image size. The through-hole generates almost one order of magnitude higher aberrations (spherical, coma, field curvature, astigmatism, and distortion) than the counter-bored

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hole. Thus, the counter-bored-hole geometry can substantially reduce the beam aberrations and hence the focused beam spot size.

A simple exposure experiment was performed to verify the simulation results (Figure 3). A 2 keV Ar^+ beam generated by a multicusp ion source operating at 500 W RF power was used to sputter a thin metal foil coated with dry erase ink for about 90s. The target was located at 1 mm away from the extraction aperture. With a through-hole extraction aperture, a feature size of 56 μm was obtained. In contrast, a feature size of 12.5 μm was achieved with a counter-bored aperture. These results agree with the simulation results very well. With a counter-bored extractor, the focused beam spot size is about four times smaller, yielding another factor of ten increase in focused beam current density.

III. Brightness Measurement

A. Experimental setup

The setup for the brightness measurement is shown in Figure 4. A helium plasma, generated by a 7.5-cm-diameter source, was used to illuminate a 50-μm-diameter counter-bored extraction aperture, which was at the same potential as the source chamber. The same brightness analyzer used in Ref. 1 was positioned 1 mm away from the extraction apertures to measure the beam profile. By scanning the voltages applied to deflector plates, the beam was swept over a 100 μm slit located beyond the electrodes. Any current passing the slit was measured by a Faraday cup.

The experimental setup was the same as for the prior work in Ref. 1, except for the following:

1. A 7.5-cm-diameter source was used instead of a 5-cm–diameter source. As mentioned above, the larger source is more easily operated in the inductively coupled mode, which provides a higher plasma density.

2. A 50 μm counter-bored aperture was used to extract the ion beam instead of a 5 μm through-hole aperture. The focused beam spot size is smaller, due to reduced aberrations.

3. The beam energy was 2 keV instead of 3 keV. No bias voltage was applied between the source and the extractor.

4. The RF and extraction high-voltage power supplies were pulsed at a duty cycle of 2%, to prevent the secondary 5 μm aperture from being damaged by the beam.

B. Results and Discussion

The beam profiles at the 100 μm slit for RF power of 1.0, 1.5, and 2.5 kW are shown in Figure 5. The beam semi-angles are all ~27 mrad for the different power levels. The total beam current passing the secondary 5 μm aperture can be calculated by integrating the beam profile. Thus, the current density at the secondary aperture can be easily obtained. The beam brightness was determined using Eqn. (1), and the results are shown in Figure 6. It can be seen that the beam brightness increases with RF power, reaching 440 A/cm^{2}Sr at 2.5 kW. Compared to the previous results[1], a factor of 30 improvement in brightness is achieved.

IV. SUMMARY

The brightness of a multicusp ion source can be high if it is operated in the inductively coupled mode and if the beam extraction system is optimized to reduce aberrations. For a 7.5-cm-diameter source with a 50-μm counter-bored extraction aperture, the measured brightness (440

A/cm^{2}Sr) is significantly higher than in previously reported work. Additional increases in RF power as well as improved source design are being investigated to further improve the brightness in order to meet the requirement of 1000 A/cm^{2}Sr for high-throughput maskless lithography.

V. ACKNOWLEDGMENTS

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Figure and Table Captions:

Figure 1. (a) Cross-sectional view of a RF-driven multicusp-plasma ion source. (b) Top view of the source. Two modes of plasma generation: capacitively coupled and inductively coupled.

Figure 2. Comparison of extracted beam current densities for different size multicusp-plasma ion sources.

Figure 3. Comparison of exposure results using (a) counter-bored hole and (b) through hole as extraction aperture. 2 keV Ar^+ beams generated by a multicusp source at 500 W RF power were used to sputter a thin metal foil for about 90sec. The target was located 1 mm away from the extraction aperture.

Figure 4. Experimental set-up for brightness measurement.

Figure 5. Beam profile at the 100 μm slit, for 1.0, 1.5, and 2.5 kW RF power.

Figure 6. Brightness of 2 keV He^+ beams as a function of RF power.

Table 1. Comparison of simulation results for a 50 μm through-hole and counter-bored extraction aperture. The image is 1 mm away from the extraction aperture.

Gas Inlet
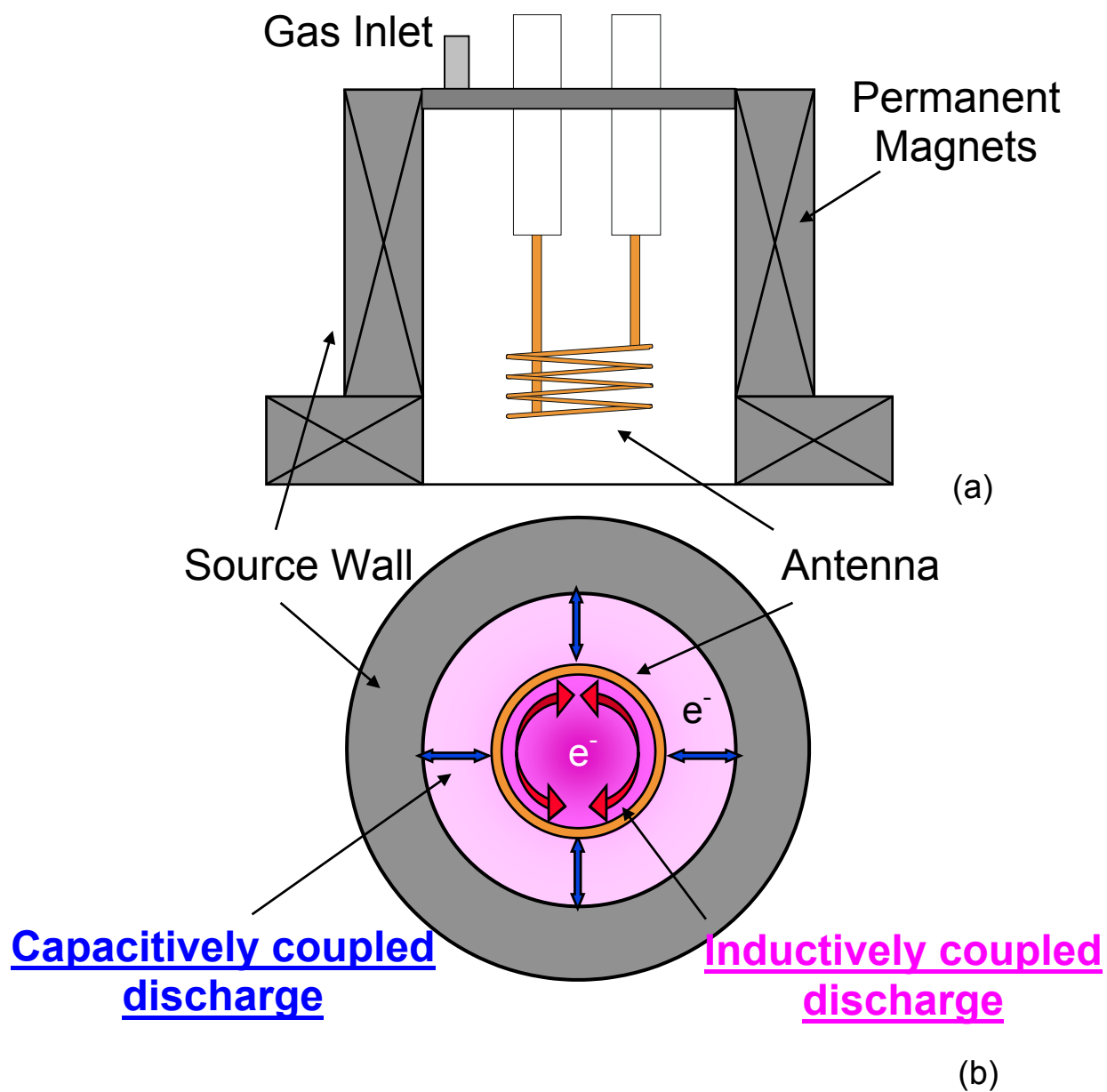
Permanent
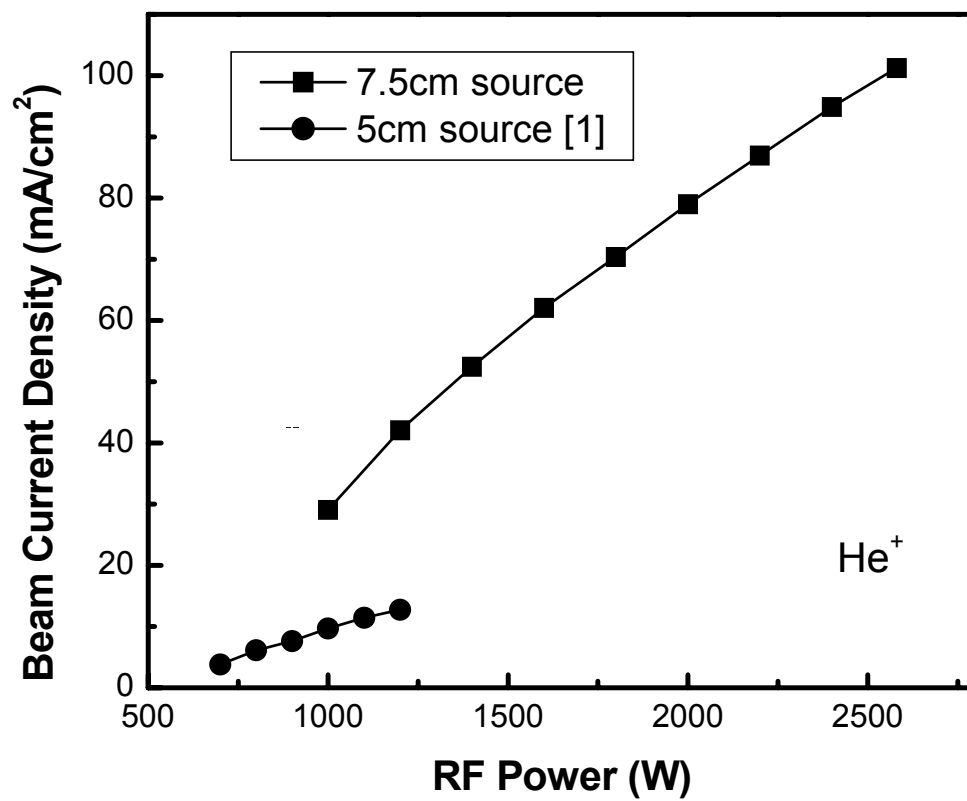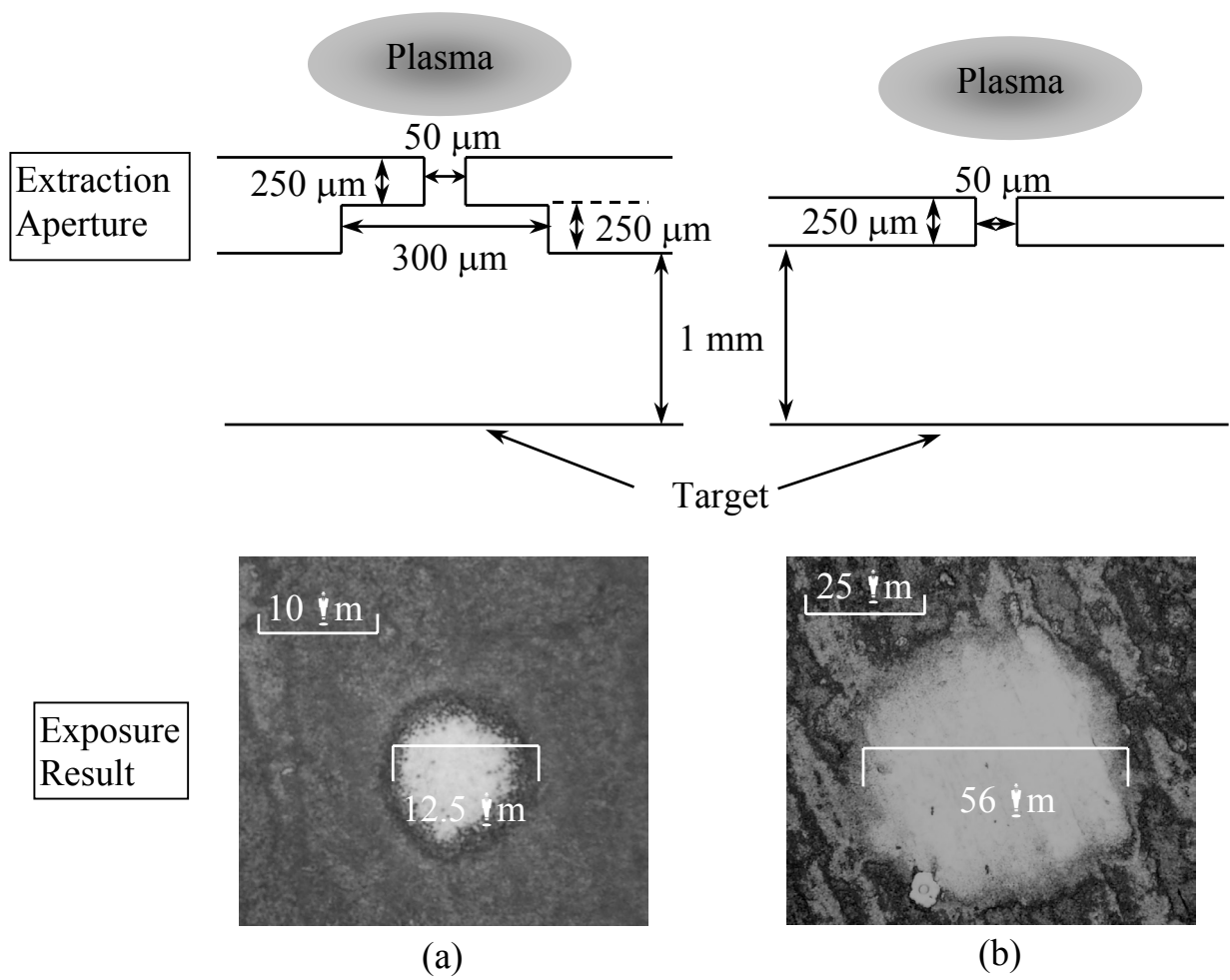Magnets

Source Wall

Antenna

(a)

e⁻

e⁻

Capacitively coupled discharge

Inductively coupled discharge

(b)

Figure 1

Figure 2

Plasma

Plasma

Extraction
Aperture

50 μm

250 μm

250 μm

300 μm

50 μm

250 μm

1 mm

Target

Exposure
Result

10 μm

12.5 μm

25 μm

56 μm

(a)

(b)

Figure 3

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Multicusp Plasma Ion Source

He Plasma

2 kV

1 mm

GND

50 μm counter-bored Aperture

5 μm Secondary Aperture

Deflector

5 cm

6.6 cm

100 μm Slit

Faraday Cup

Figure 4

Figure 5

Figure 6

Table 1

Extraction geometry	Beam size (μm)	Total blur (μm)	Aberration (μm)					
			Spherical	Coma	Field curvature	Astigmatism	Distortion	Chromatic
Through hole	16.4	46.4	14.3	31.4	27.6	16.8	3.39	2.19
Counter-bored hole	13.1	4.51	1.58	2.99	2.31	1.13	0.24	1.49