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Brightness measurement of an electron impact gas ion source for proton beam writing applications

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We are developing a high brightness nano-aperture electron impact gas ion source, which can create ion beams from a miniature ionization chamber with relatively small virtual source sizes, typically around 100 nm. A prototype source of this kind was designed and successively micro-fabricated using integrated circuit technology. Experiments to measure source brightness were performed inside a field emission scanning electron microscope. The total output current was measured to be between 200 and 300 pA. The highest estimated reduced brightness was found to be comparable to the injecting focused electron beam reduced brightness. This translates into an ion reduced brightness that is significantly better than that of conventional radio frequency ion sources, currently used in single-ended MeV accelerators. © *2015 AIP Publishing LLC.* [http://dx.doi.org/10.1063/1.4932005]

I. INTRODUCTION

Proton beam writing (PBW) is a direct-write lithographic technique for three-dimensional nanofabrication, capable of writing high aspect ratio (height/width) nanostructures in photo-resist like poly-methyl methacrylate (PMMA) and hydrogen silsesquioxane (HSQ).[1–3] For example, the energy transferred to the excited PMMA electrons from a 500 keV proton penetrating 500 nm deep is within 2.5 nm of the original proton track,[4] thus resulting in minimal proximity effects. We are recently progressing towards sub-10 nm lithography in nuclear microprobe experiments,[5,6] but further improvements in the beam resolution and writing speed are limited by the low brightness radio frequency (RF) ion source (10-30 A/m^2 sr V) currently used in single-ended MeV accelerators.[7,8]

We are developing a high brightness nano-aperture electron impact gas ion source (NAIS), based on the concept by the Charged Particle Optics group, Delft University of Technology (CPO-TUD).[9] The idea of this ion source is to create ion beams with small virtual source size of about 100 nm from a miniature ionization chamber with nano-sized double-aperture. Prototype NAIS chips have also been fabricated and demonstrated by Liu *et al.*[10] A total Ar ion output current of about 300 pA (Ar^+ 89%, rest is Ar^{n+}, n = 2-4)[11] has been demonstrated. In this paper, we experimentally measure the reduced brightness B_r, for this NAIS ion source, inside a Philips XL30 field emission Scanning Electron Microscope (SEM).

II. EXPERIMENTAL DESIGN

An ion source test column was designed to measure the source reduced brightness B_r, as shown in Fig. 1. The B_r measurements were performed inside the SEM chamber, with the test column mounted on the SEM stage. With injecting electrons (beam energy E_e) and gas (inlet pressure P_{in}) introduced into the ion source chip double-aperture, the source total output current I_t was recorded at the Faraday cup (FC, biased at −36 V). The extractor was biased at a negative potential (V_{Ext}) to extract ions from the source and deflect the injecting electrons. The suppressor was biased at the same negative potential as the extractor to create an electric field free region in between them and also to prevent secondary electrons from leaving the FC. A DC chip bias (V_{Cb}) was supplied to the top Cr + Au electrode of the ion source chip to assist ion extraction.

A silicon angular aperture was fabricated using similar processes as the ion source chip.[10] The angular aperture has a pyramid window opening size of ~95 μm × 95 μm. It was mounted below the extractor on a separate piezo-XY stage (SmarAct® SLC-1720-S-HV). The angular aperture was precisely positioned to capture the maximum axial ion beam current (I_a) which was recorded at the FC.

I_a was measured as a function of P_{in}, V_{Cb}, V_{Ext}, and E_e. The ion source reduced brightness B_r can be calculated using the following equation:[12,13]

$$B_r = \frac{I_a}{A_S \Omega V_{Ext}} \approx \frac{I_a}{A_S \frac{A_a}{L^2} V_{Ext}}, \qquad (1)$$

where A_S is the virtual ion source size, Ω is the ion beam solid angle, V_{Ext} is the ion beam potential at the angular aperture plane, A_a is the angular aperture size, and L is the distance from the virtual ion source to the angular aperture.

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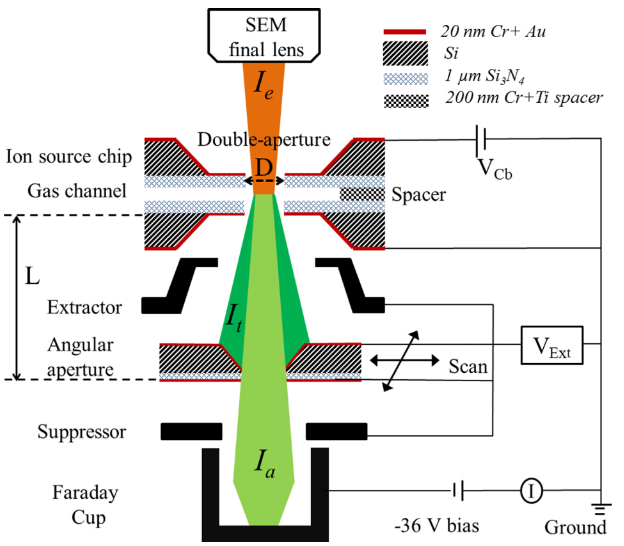

FIG. 1. Schematic setup of the ion source reduced brightness experiments inside a Philips XL30 SEM.

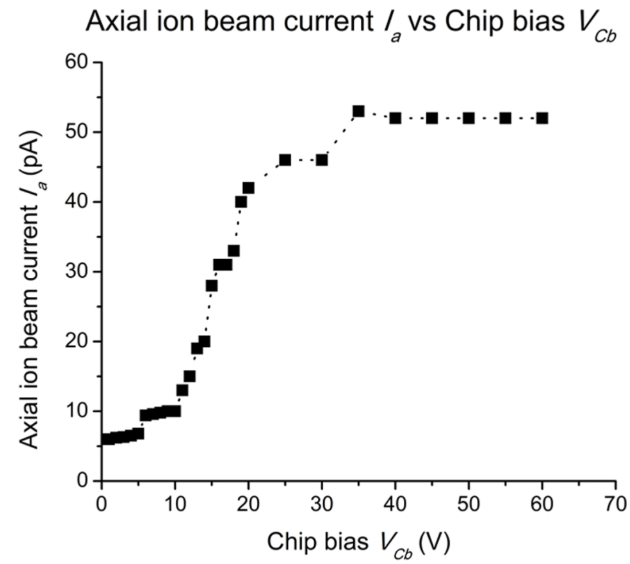

FIG. 2. The measured axial ion beam current I_a as a function of the chip bias V_{Cb}, with 1 keV injecting electron beam (about −4 nA beam current). The Ar gas inlet pressure is 700 mbar and extraction voltage is $V_{Ext} = -1550$ V. The measured ion source total output current I_t is about 200 pA. The error in the measured data is about ±1 pA as a result of the current integrator's accuracy. Dotted connecting lines are just for visualization assistance.

III. RESULTS AND DISCUSSION

The axial ion beam current I_a was observed generally to be increasing with increasing Ar gas inlet pressure. For the following results presented, Ar P_{in} = 700 mbar was used. An inlet pressure of more than 700 mbar resulted in a lower I_a due to ion/gas molecule scattering[9] as well as too high pressure levels inside the SEM vacuum chamber.

I_a was also studied by varying the extraction V_{Ext} (−1050 V to −5050 V). It was observed that I_a increased first with V_{Ext} up to −2050 V (equivalent extraction electric field E_{Ext} of about 1×10^6 V/m), then dropped with higher V_{Ext}, most likely due to axial alignment error (∼100 μm) between the ion source chip and extractor. The axial ion beam current is expected to increase further with better alignment.

The injecting SEM electron beam energy has also been varied to study its effect on I_a. However, the SEM electron beam resolution was found to be poor, with a beam full width at half maximum (FWHM) of about 1.5 μm–0.7 μm for beam energies E_e from 0.7 keV to 1.5 keV, respectively. The electron beam reduced brightness B_{r-e} was measured using the setup in Fig. 1, following the two-diaphragm method.[12] Setting V_{Ext} = 0 V, FC bias = +36 V and employing a single Si_3N_4 membrane chip with different aperture sizes (D = 0.5-1 μm), the electron beam was focused to a crossover at an aperture, which cuts (∼50%) the electron beam and defines an electron beam crossover size equivalent to A_S for Eq. (1). B_{r-e} was calculated using Eq. (1) and was found to be 850-4300 A/m^2 sr V for E_e from 500 eV to 1500 eV, about 1000 times lower than in a conventional field emission SEM.[12,14] The low B_{r-e} is probably due to its poor column conditions.

With 1 keV injecting electron beam and $V_{Ext} = -1550$ V, I_a was measured as a function of chip bias V_{Cb} from 0 to 60 V, using a double-aperture (D = 2 μm).[10] The captured axial ion beam current by the angular aperture increased with chip bias up to V_{Cb} = ∼35 V (Fig. 2). This indicates that the chip bias significantly helps to extract ions from the source. The distance between the two 20 nm Cr + Au layers is about 2.5 μm (two 1 μm Si_3N_4 + 200-500 nm gas channel spacing as in Fig. 1), which gives an electric field strength $E_{Cb} = 1.4 \times 10^7$ V/m. Due to thermal energy at room temperature (298.15 K), ions will have initial energy of ∼0.0385 eV with a Maxwell-Boltzmann distribution with random initial velocity direction.[15] The chip bias assists guiding ions with thermal energy throughout the ion source chip and increases I_a. This ion current enhancement effect is only insignificant for $V_{Cb} < 5$ V (Fig. 2), in which case I_a is not sensitive to E_{Cb} changes ($E_{Cb} < 2 \times 10^6$ V/m), as the ion extraction is dominated by the extractor ($E_{Ext} = 7.5 \times 10^5$ V/m). The angular aperture at 10 mm below the ion source defines a small beam divergence of about 5 mrad for the axial ion beam. This corresponds to an ion beam current angular density J_Ω of ∼6.6×10^5 A/sr.

IV. VIRTUAL ION SOURCE AND BRIGHTNESS

The virtual ion source size A_S was studied using ion optics simulation software Lorentz[16] ray tracing. The ion source test column setup was simulated in Lorentz, with a trajectory tracing accuracy of about 10 nm, following the approach of Khursheed *et al.*[17] The virtual ion source position and size were obtained by back tracing the ion trajectories from the angular aperture plane. The FW50 (full width containing 50% of the beam current) virtual ion source diameter D_S obtained using optics simulation is presented in Fig. 3, as a function of the chip bias V_{Cb}. In contrast with I_a study, $V_{Cb} < 5$ V helps to reduce D_S, while $V_{Cb} > 5$ V significantly increases D_S from 200 (40) nm to 1050 (20) nm, as higher V_{Cb} will extract more ions with large initial transverse velocity, which contribute as off-axis ions. The effects of Coulomb ion-ion interactions on D_S for small $I_t < 2$ nA can be neglected.[9,14]

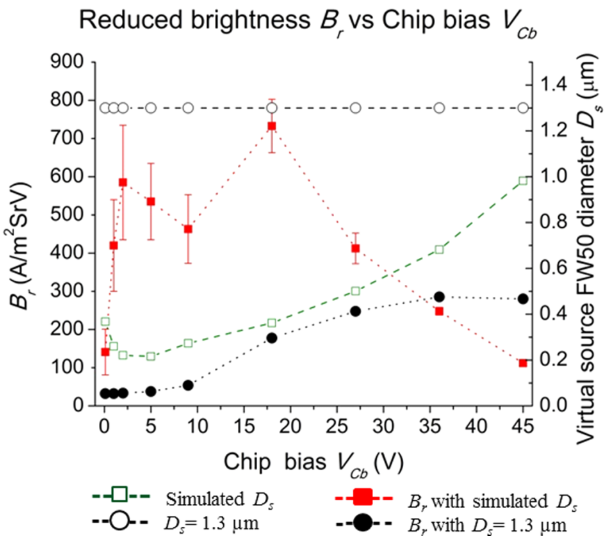

FIG. 3. The virtual ion source FW50 diameter D_S and B_r as a function of the chip bias V_{Cb}, with 1 keV (beam FWHM 1.3 μm) injecting electron beam (about −4 nA beam current). The Ar gas inlet pressure is 700 mbar and extraction voltage is $V_{Ext} = -1550$ V. Dotted connecting lines are just for visualization assistance.

Considering the competing effects of E_{Cb} and E_{Ext} on I_a and D_S, the ion source reduced brightness B_r is calculated using Eq. (1), see Fig. 3. If the ion source diameter is assumed to be the same as the 1 keV injecting electron beam FWHM (1.3 μm), then the ion source B_r reaches a maximum of 280 A/m^2 sr V. With simulated trajectory back tracing, a smaller virtual source size is obtained and FW50 B_r reaches a maximum of ∼750 A/m^2 sr V with V_{Cb} = 18 V (Fig. 3). The corresponding E_{Cb} inside the chip is optimum at $\sim 7 \times 10^6$ V/m for a fixed E_{Ext} ($\sim 7.5 \times 10^5$ V/m). A possible 100 μm axial ion test column misalignment was also considered in the B_r results presented in Fig. 3. Generally, this misalignment has limited effects on the ion source brightness, contributing to an error of <±20% in the calculated B_r value. The ion source B_r measured is limited by the injecting 1 keV electron beam brightness (880 A/m^2 sr V), due to its large beam size.

V. CONCLUSION

The NAIS B_r has been experimentally examined, together with ion optic simulation software Lorentz to study its virtual ion source size. Axial Ar ion beam current of about 53 pA has been achieved with an angular beam current density of 6.6×10^5 A/sr. The highest B_r was reported as 750 A/m^2 sr V, with a chip bias of 18 V. This chip bias can be greatly reduced to be ∼1 V with the same electric field strength maintained inside the ion source chip in future source designs, with 100-200 nm spacing between the two (100 and 200 nm) metal membranes. Therefore, the ion source energy spread, determined by the chip bias,[9] is expected to be small (∼1 eV), which is a critical requirement for sub-10 nm ion beam probe formation.[5]

Currently, the NAIS reduced brightness B_r is limited by the low SEM electron beam resolution and brightness. With a conventional field emission SEM column, the electron beam resolution can be improved to be <100 nm with a few 100 nA electron beam current, thereby greatly reducing the virtual ion source size and increasing B_r by at least four orders of magnitude.

The existing PBW is approaching sub-10 nm H_2^+/H^+ ion lithography,[5,6] but limited by the low RF ion source B_r. The electron impact gas ionization cross section for H_2^+ is about 3.5 times lower than Ar, for E_e = 500 eV–1000 eV.[11,18] Therefore, the NAIS H_2^+ B_r is expected to be about 10^4–10^5 A/m^2 sr V (emittance $\sim 2 \times 10^{-4}$ π mm mrad), ∼2 orders higher in magnitude than the RF ion source.

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