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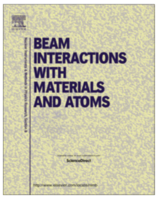

Development of ion sources: Towards high brightness for proton beam writing applications

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ABSTRACT

An Ion Source Test Bench (ISTB) has been designed and commissioned to facilitate the measurement of ion beam reduced brightness (B_r) obtained from different ion sources. Preliminary B_r measurements were carried out, with RF ion source, in the ISTB for He ions. Meanwhile we have also fabricated and tested a novel ion source called electron impact gas ion source, whose reduced brightness is expected to reach up to 10^7 pA/μm^2 mrad^2 MeV. Initial ion-current measurements from such electron impact gas ion source (tested inside an environmental SEM) has yielded about 300 pA of Ar ions. The areal ion current density from this electron impact gas ion source is found to be at least 380 times higher than the existing RF ion source. This novel ion source is promising for application in proton beam writing lithography with feature sizes smaller than 10 nm.

1. Introduction

In the recent past we have demonstrated the potential of proton beam writing (PBW) as a leading candidate for the next generation lithography technique [1–3], highlighted in the Japanese government's Nanotechnology Business Creation Initiative (NBCI) roadmap 2010 [4]. We are now progressing towards sub-10 nm lithography in nuclear microprobe experiments [5,6]. To achieve this goal, plans are being rolled out to improve the performance of the existing low brightness radio frequency (RF) ion source, used for the production of proton beams at Centre for Ion Beam Applications (CIBA), National University of Singapore (NUS). This RF ion source has potential to deliver higher brightness [7]. An Ion Source Test Bench (ISTB) set-up has been designed and commissioned in-house to extract the full potential of the existing RF ion source by improving its reduced brightness, as attempted by a few other researchers [8–12]. First brightness measurements obtained from RF ion source in this ISTB will be presented in this paper. In future the ISTB will be used to test novel high brightness ion source designs, which has the capability to form part of a compact PBW system.

In search of high brightness ion sources, we are developing a modified electron impact gas ion source, based on the design by the Charged Particle Optics group, Delft University of Technology. Their electron impact gas ion source is expected to have smaller virtual source size (~100 nm) and deliver higher reduced brightness, B_r (~10^7 pA/μm^2 mrad^2 MeV for Ar$^+$ beam) [13]. Prototypes of the miniaturized gas ionization chambers have been fabricated in CIBA, NUS. First experiments with a small gas ionization chamber were performed inside a field emission Scanning Electron Microscope (SEM) in NUS. The design of the current ionization chamber is equipped to admit different gases (e.g. helium, argon, and hydrogen) into the ion source. This paper presents preliminary results about the extracted ion currents (for air and argon) from this ion source.

2. Experimental procedures

2.1. Ion Source Test Bench (ISTB) set-up

Fig. 1 shows the schematic diagram of the ISTB set-up. The current version of ISTB is coupled with a RF ion source. An oscillating RF voltage (~100 MHz) is capacitatively coupled onto a quartz tube, which is filled with the gas of interest, that produces a stable plasma. The positively biased plasma is then extracted through a 2 mm diameter canal, with a variable extraction voltage of 0 to −3 kV. The extracted beam is accelerated by passing through an acceleration column, which consists of an array of metal electrodes (separated by insulators) acting as a potential divider across the high voltage to the ground terminal. The accelerated beam is collimated using a Ni object aperture before entering a Wien filter

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assembly, where ions of selected mass and charge state are transmitted un-deflected. The beam of interest will then pass through a Ni collimator aperture before reaching the target. The aperture assemblies will be used, in combination with the ion current measurements carried out on the target (where secondary electron suppression is taken care), to evaluate the reduced brightness of the ion beam (B_r).

2.2. The electron impact gas ion source concept

As mentioned early, we are developing a high brightness electron impact gas ion source, which will eventually be coupled to the ISTB. The idea of the electron impact gas ion source is to introduce an electron beam into a gas chamber through a small double aperture (100 nm to 1 μm diameter) as shown in Fig. 2. The gas chamber is miniaturized to provide a small spacing between two apertures (100 nm–1 μm). Once ions are produced inside the gas chamber by electron impact, they can be extracted through the double aperture by applying an electric field up to 10^6 V/m across the double aperture and followed by an extractor. The DC bias electric field (as shown in Fig. 2) corresponds to a small bias voltage of 1–9 V for the present system. Depending on the position where the ionization occurs along this electric field axis, the ions may have different initial energy (ranging from 1 to 9 eV) which translates to the ion source energy spread.

2.3. Fabrication of the ion source chamber

In the miniature gas chamber by Delft, two 100 nm thick alloy metal layers were used as the double aperture membranes and two 100 nm thick silicon nitride layers were bonded as spacer [13]. The fabrication of our modified ion source chamber, carried out in CIBA, NUS, was based on bonding two 1 μm thick silicon nitride membranes (supported by 530 μm thick Si) together (Fig. 3), with a 200 nm Ti layer as spacer.

Free-standing silicon nitride windows (300 × 300 μm and 50 × 50 μm) were created on the top chip (as shown in Fig. 3), using a sequential procedure of photolithography, reactive ion etching (for removal of top Si_3N_4 layer) followed by potassium hydroxide solution etching (for removal of Si layer). A reservoir (of dimension 6 mm × 1 mm × 200 nm), to hold the gas, was created at the interface between top and bottom chip. This is achieved by 200 nm Ti metal lift off, which serves as a spacer. A thin Cr + Au metal layer (<20 nm) was deposited at the chip's top and bottom sides for applying a bias voltage across the chip. The two chips were then glued together at the edges. An opening of about 20 × 20 μm on the free standing Si_3N_4 of the top chip (for gas inlet) and another opening of about 1.5 μm (for double aperture, as shown in Fig. 4) were created by focused ion beam milling (FEI Quanta Dual Beam), with a 30 keV Gallium ion beam current of 1–2 nA.

2.4. The electron impact gas ion source current measurement setup inside a SEM

The experimental ion source test setup was established inside a Schottky emission SEM (Philips XL30) system in NUS (Fig. 5). The SEM provides an electron beam with 300 eV to 1 keV beam energy and an injecting electron beam current up to 30 nA. The gas inlet pressure can be varied from 1 mbar to 2 bar, using a gas regulating valve. The bias voltage across the double aperture can be applied up to 9 V. An ion-extraction voltage, ranging between −1 and −5 kV, was applied onto the extractor plate (having 1 mm diameter opening) for an injection of 1 keV electron beam. This extractor plate is placed at the mid-point, with a spacing of 1.5 mm, between the double aperture (above) and Faraday cup (below). The extracted ion current is collected and measured using a Faraday cup (biased at −30 V). The extraction voltage was always set to a higher negative value than the incident electron beam acceleration voltage, to prevent the incident electrons from reaching the Faraday cup. Moreover this negative potential also effectively suppresses the secondary electron emission from the Faraday cup. This secondary electron suppression is confirmed by simulation using Lorentz software [14]. Lorentz simulation also predicts that, for ions exiting the 1 μm diameter double aperture, their trajectories have a lateral spread within 100 μm when passing through the extraction plane. Therefore all ions reach the Faraday cup.

3. Results and discussion

3.1. B_r measurement of the RF ion source in the ISTB

After a few trial experiments in the ISTB, the RF ion source produces He^+, N^+ and Ar^+ ions with different energies varying from 1 to 15 keV, yielding a maximum ion current of about 20–25 μA at the exit of the accelerating column. Here we will describe the results, and brightness measurements obtained with 1 keV He^+ ions.

It is to be noted that, since most of the ion source components and its power supplies were at high voltage terminal, they need to be operated remotely. This is achieved in our ISTB using a wireless communication system, which was developed in-house using National Instruments (NI) Compact Real-Time Input/Output (cRIO) hardware. This reconfigurable embedded control and acquisition

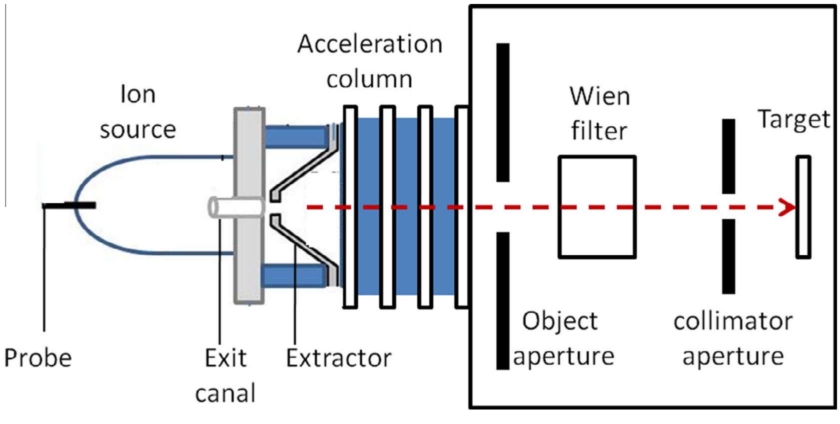

Fig. 1. Schematic of Ion Source Test Bench set-up, with a few ion beam diagnostics components. Dotted arrow represents the ion beam trajectory.