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Research paper

Fabrication and development of high brightness nano-aperture ion source

Xinxin Xu [a], Rudy Pang [a,b], P. Santhana Raman [a,b], Rajasekaran Mariappan [a],
Anjam Khursheed [b], Jeroen A. van Kan [a,*]

[a] Centre for Ion Beam Applications, Department of Physics, National University of Singapore, 117542, Singapore
[b] Department of Electrical and Computer Engineering, National University of Singapore, 117583, Singapore

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ABSTRACT

Nano-aperture ion source (NAIS) is a potential candidate to be a part of a sub-10 nm proton beam writing (PBW) system. To improve the performance of our prototype NAIS, currently we have modified the fabrication process. Through integrating the ionization chamber into the silicon nitride membranes and reducing the size of double-aperture, we have improved the overall performance of NAIS. The reduced brightness from this modified NAIS was obtained to be 9.1×10^3 A/(m^{2}srV) for an Ar$^+$ beam. Limitations and further improvements of the current design are discussed in the paper.

1. Introduction

Proton beam writing (PBW) is a direct-write lithographic technique developed in the Centre for Ion Beam Applications, National University of Singapore (CIBA-NUS), which employs focused protons, for fabricating three-dimensional nano-structures [1–3]. Compared with electron beam lithography (EBL), the advantage of PBW is that a proton is ~1800 times heavier than an electron, which makes a proton to transfer less energy to secondary electrons and can penetrate straighter into the material, depositing a constant energy along its path in the resist [4]. With these unique features, PBW can fabricate nano-structures without proximity effects and having smooth sidewalls [3,5]. Currently, the performance of PBW in terms of spot size and throughput is limited by low brightness ~20 A/(m^{2}srV) of the radio frequency (RF) ion source, available in PBW systems [6,7]. Therefore a high brightness ion source is the key to further improve the performance of PBW system.

The reduced brightness is an important parameter to exemplify beam quality, like beam current density, beam angular spread, and beam energy spread [8,9]. Reducing the virtual source size is a practical way to obtain high brightness ion source [10]. High brightness ion sources, like liquid metal ion source (LMIS) and gas field ionization source (GFIS), have small virtual source sizes. LMIS is the most widely used high brightness ion source, which has a liquid metal reservoir on top of a sharp tip [11–13]. A strong electric field is used to pull the liquid metal to a sharp electrospray cone, known as Taylor cone [14]. Meanwhile this strong electric field also generates ions at the tip of the Taylor cone by field evaporation. The most common LMIS is Ga-LMIS but several other metals (e.g. Al, In, Sn, Cs, Bi, Au) as well as alloy metals (Au-Si, Au-Ge, Si-Be-Au, Ni-B-Pt) are also used [11]. The typical virtual source size of Ga-LMIS is about 50 nm and the reduced brightness is about 10^6 A/(m^{2}srV) with typical energy spread of around 5 eV [11,15,16]. However, the choice of ions from the LMIS is limited to metallic ions, and the energy spread results in high chromatic aberration. GFIS has recently emerged as a credible choice for high brightness ion source, which is based on the field ionization created by strong electric field [17–19]. A strong electric field is concentrated at the apex of a pyramidal tip, which terminates with three atoms. GFIS has been mostly used for generating He and Ne ions [19,20]. For He-GFIS, the reduced brightness can reach as high as 10^9 A/(m^{2}srV) with a 1 eV energy spread [21]. The small virtual source size (<1 nm), due to the three-atom terminated tip, results in having high brightness [22,23]. While the GFIS can deliver an extremely high brightness ion beam, it is limited by the variety of available ion species. Another approach to obtain high brightness ion source is to reduce the beam angular spread, which can be achieved by reducing the source operating temperature (<100 μK). Such ion sources, operating at low temperatures (usually achieved by laser cooling), are called cold atom ion source. These ion sources have a theoretical reduced brightness of around 10^7 A/(m^{2}srV), with <0.5 eV energy spread [24–27]. Using laser-cooled Cr atoms and Li atoms, beams with reduced brightness of 2.25×10^4 A/(m^{2}srV) [28] and 6×10^3 A/(m^{2}srV) [29] have been achieved respectfully. Although these ion sources can deliver high brightness ion beams, they are not designed to produce high brightness proton beams. A nano-aperture

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* Corresponding author.
E-mail address: phyjavk@nus.edu.sg (J.A. van Kan).

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ion source (NAIS) with an estimated brightness of 10^6 A/(m^{2}srV) has been reported by the Charged Particle Optics group at Delft University of Technology [30]. This NAIS is expected to generate high brightness proton beams. Thus NAIS is a prospective candidate for a sub-10 nm PBW system, which can deliver high throughput. This system is expected to achieve writing speed comparable to those in EBL without the unwanted proximity effect [31].

2. NAIS concept and fabrication process

The mechanism of NAIS is to extract ions from electron-gas collision, which creates ionization, in a sub-micron ionization chamber, as shown in Fig. 1. This is a simple and reliable ionization approach to generate various types of ions. The superiority of NAIS is to reduce the virtual source size to sub-micrometer while maintaining a strong electric field (~10^7 V/m) with a small chip bias (~1 V), resulting in an ion energy spread of <1 eV [30]. Furthermore, the versatility of NAIS makes it convenient to select different ion species spanning from low Z to heavy Z gaseous elements, catering to different applications. All these virtues require a critical ionization chamber to deliver high brightness ions. We have shown a brightness of about 750 A/m^{2}srV for Ar$^+$ with the NAIS in our preliminary experiments [32]. These experiments were performed in a scanning electron microscope (SEM), which serves as a source to supply the electron beam for gas ionization. The ion brightness of this prototype NAIS was mainly limited by the poor brightness of the injected electron beam, large dimension (600 nm height) of the ionization chamber, thick silicon nitride membranes (1 μm), and a large double-aperture (1.5 μm) [32,33]. Therefore, a modified ionization chamber is fabricated to further improve the performance of NAIS.

A 7 mm × 1 mm × 300 nm NAIS ionization chamber has been fabricated by gluing two silicon nitride membranes, as shown in Fig. 1, using a microelectromechanical system (MEMS) technique. The step-by-step fabrication procedure is shown in Fig. 2. The ionization chamber was formed from the top and bottom chips of a 400 μm thick <100> silicon wafer. The silicon wafer was double-side-polished with a 280 nm low-pressure chemical vapor deposited (LPCVD) silicon nitride on both sides. To enable batch production, the top and bottom chips were designed to be identical to each other. In order to create the gas inlet, electron beam inlet, and ion beam outlet (referred as double-aperture) windows, the front side of the wafer was spin-coated with 2.5 μm thick AZ 1518 photoresist followed with 50 s soft bake at 100 °C. Subsequently, the photoresist was exposed with a 405 nm laser to pattern the windows. The exposed windows were developed in AZ 400k developer diluted to 1:4 with DI water for 1 min. The patterned windows were then transferred to silicon nitride through deep reactive ion etching (DRIE) with process parameters of 48 sccm CHF_3, 5 sccm O_2, 15 Pa pressure, and 250 W RF power, as shown in Fig. 2(a). This is followed by stripping of the residual AZ 1518 resist in acetone, opening up access holes by etching the exposed Si in KOH (Fig. 2(b)) and creating a freestanding silicon nitride membrane, and electrode formation by depositing a conductive layer (10 nm Cr and 20 nm Au) via magnetron sputtering on the processed side of the wafers (Fig. 2(c)). On completing the process steps at the front side of the wafer, the fabrication process was carried out at the back side of the wafer to create the ionization chamber. For the back side, the wafer was spin-coated with 5 μm thick AR-P 3250 photoresist followed by 2 min soft bake at 95 °C. The ionization channel pattern was exposed using a 365 nm ultraviolet (UV) and developed in AR 300-26 developer diluted to 3:2 in DI water for 1.5 min. The back side of silicon nitride membrane was dry-etched down to 150 nm depth in a selected window (see Fig. 2(d)). The two chips were then bonded face to face (see Fig. 2(e)) to create an ionization chamber with a dimension of 7 mm × 1 mm × 300 nm. The gas inlet aperture and the double-aperture were created with the aid of gallium FIB milling (FEI Quanta Dual Beam). The double-aperture size was set to be 500 nm. Finally, the larger opening at the bottom side of the

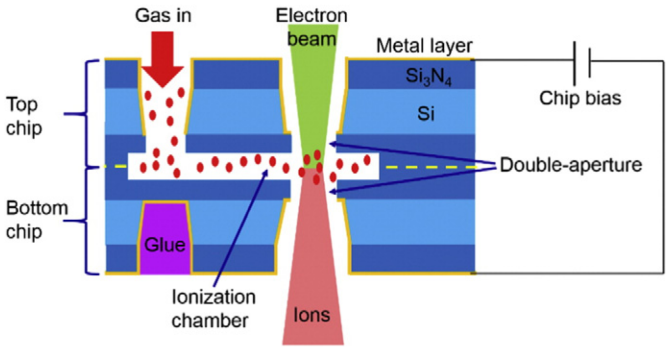

Fig. 1. Schematic of modified NAIS.

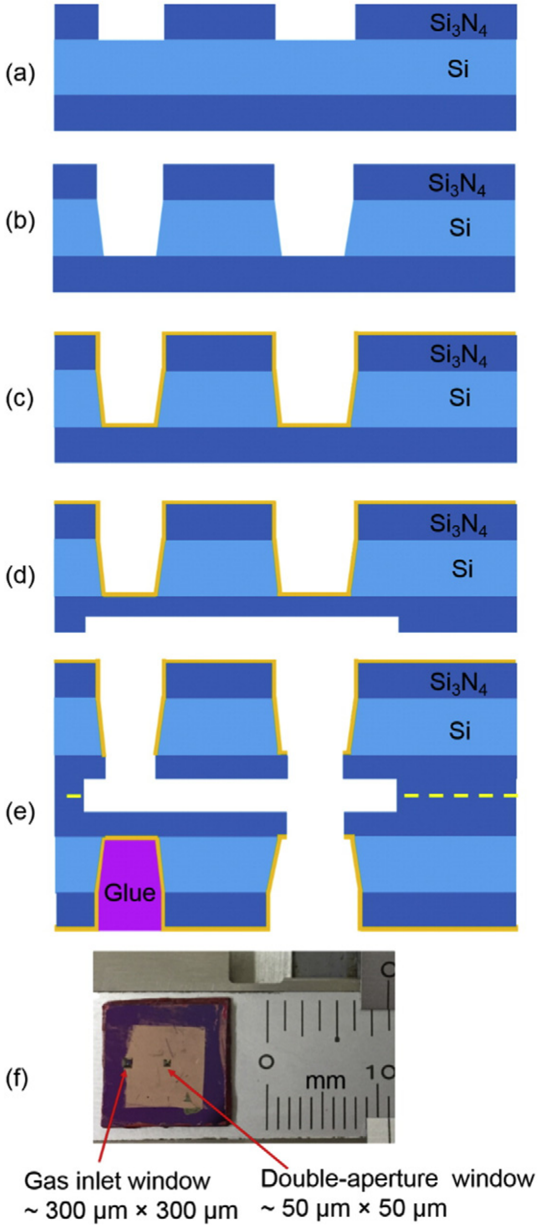

Fig. 2. Depiction of the NAIS chip fabrication process: (a) DRIE to create gas inlet and double-aperture windows on silicon nitride. (b) KOH etching to reach the bottom side of silicon nitride membrane. (c) 10 nm Cr + 20 nm Au deposited by magnetron sputtering for electrode. (d) 150 nm depth ionization spacer created by DRIE. (e) NAIS chip bonded with two individual chips and FIB-milled for creating gas inlet aperture and double-aperture. The diameter of the double-aperture is 500 nm. (f) A fabricated NAIS chip with a 300 μm × 300 μm gas inlet and 50 μm × 50 μm double-aperture windows.