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Design considerations for a compact proton beam writing system aiming for fast sub-10 nm direct write lithography

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ABSTRACT

In order to realize sub-10 nm feature size by proton beam writing (PBW) with writing speed comparable to electron beam lithography (EBL), a 200 kV compact PBW system is proposed here. In this system, a new nano-aperture electron impact ion source with a potential reduced brightness of 10^6 A/(m^2 srV) will be employed. To achieve sub-10 nm spot sizes with pA beam current, two different focusing lens configurations were evaluated. Both of these configurations were found to be theoretically capable of achieving sub-10 nm beam spot size.

1. Introduction

Proton beam writing (PBW) is a direct 3D writing lithographic technique that utilizes fast and focused MeV proton beam to pattern photoresists (e.g. hydrogen silsesquioxane (HSQ), SU-8, AR-P, and polymethyl methacrylate (PMMA)) and form sub-100 nm features [1,2]. This technique has been optimized at the Centre for Ion Beam Applications (CIBA), National University of Singapore [3,4], and has also been used at a few other ion microprobe laboratories worldwide (Leipzig [5], Lund [6], Ljubljana [7], Debrecen [8], Guildford [9], Rez [10], Takasaki [11], Tokyo [12], etc.). PBW is analogous to electron beam lithography (EBL), but employs protons with MeV energy. Fast protons traveling into materials mainly lose energy through proton-electron interactions. Due to the higher mass of the proton, when compared to the electron (~1800 times), MeV protons mainly transfer less than 100 eV energy to each secondary electron. As a result, there is limited scattering of protons and minimal lateral spread of secondary electrons in photoresists (e.g. less than 2 nm within 5 μm thick PMMA [13]), resulting in a minimized proximity effect coupled with a straight and deep proton trajectory. These features make PBW uniquely capable of fabricating high aspect ratio (height/width) sub 100 nm structures (~160 aspect ratio in SU-8 [3,14]) compared with other direct write lithographic techniques. Since the depth of proton penetration in resist materials can be precisely controlled by varying the incoming beam energy, PBW can be used to fabricate multilevel structures in a single layer of resist [15,16]. Due to these prime features, PBW serves as a powerful tool in many applications, such as waveguide fabrication [17], micro and nano-fluidic device fabrication [18] and X-ray mask fabrication [19]. The PBW setup is also useful for 3D whole cell imaging and analysis [20]. Currently, the smallest structure that has been written with PBW is 19 nm lines in 100 nm thick HSQ using a 2 MeV proton beam [21]. Additionally, proton beam spot size down to 9.3×32 nm^2 has been achieved at CIBA [22]. The current PBW system in CIBA employs a radio frequency (RF) ion source [23] within a 3.5 MV High Voltage Engineering Europa Singletron™ accelerator [24]. Prior to entering the focusing system, the high energy proton beam is collimated using collimator slits. The focusing system consists of three magnetic quadrupole lenses (Oxford Microbeams OM52) operated in a spaced Oxford triplet configuration [25]. The RF ion source in the current PBW system has a reduced source brightness, B_r, of 20–30 A/(m^2 srV) [25], which is approximately 5 orders lower than a gallium liquid metal ion source [26] and 6 orders lower than an EBL system [27]. This lower brightness limits the writing speed, throughput, and the capability to further reduce the beam spot size in the current PBW system. To improve the writing speed and throughput of PBW, a 200 kV compact PBW (c-PBW) system aiming for single digit nanometer resolution, with comparable writing

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speed to that of EBL system, is being built in CIBA. This paper evaluates the performance of the upcoming c-PBW system.

2. Requirements for c-PBW

2.1. Proposed proton energy for c-PBW

The objective of the proposed c-PBW system is to fabricate sub-10 nm structures in 200 nm thick photoresists. For finer patterns, the response of resists is very important and hence the choice of resists becomes critical, for example, 10 nm lines have been achieved in 60 nm thick HSQ using EBL [28]. In an another example, sub-5 nm lines have been fabricated in 25 nm thick HSQ with EBL [29]. As well as for PMMA, 5–7 nm grating lines were successfully patterned at a pitch of 30 nm in a 40 nm thick resist layer [30]. However, for EBL, a thicker resist layer introduces higher electron beam forward scattering and therefore generates more secondary electrons in the resist, resulting in a broadening effect of the structures [31]. In PBW, 19 nm wide lines with a spacing of 80 nm in a 100 nm thick HSQ layer have been demonstrated by a focused 2 MeV proton beam [21].

Pattern dimensions are determined by the response of resist, the beam lateral spread, the beam spot size, and the energy transferred to secondary electrons. Protons are more suitable for fabricating nanostructures in thicker resists. The lateral spread radii of the proton beam for different beam energies within PMMA were simulated using Monte Carlo simulation program SRIM [32], and are shown in Fig. 1. Plots in Fig. 1 were obtained by accounting for 90% of the total incoming protons. As seen from Fig. 1, for 100 keV protons, beam spot size is broadened to 10 nm after passing through 200 nm of PMMA. However, the lateral beam diameter broadening within 200 nm of PMMA is 5 nm for 200 keV protons and 2 nm for 500 keV protons. Taking secondary electrons into account, for 500 keV protons, 90% of energy deposited due to secondary electrons is within 1 nm radial distance from the original proton track [13]. Furthermore, for lower energy protons, secondary electrons will travel even shorter distance due to the reduced energy transferred from protons. Therefore, from a system design perspective, 200 keV protons with a sub-5 nm beam spot size are better suited to fabricate sub-10 nm structures in 200 nm thick PMMA. For thinner PMMA, beam lateral spread and secondary electrons play a less crucial role in beam broadening, and hence the pattern dimensions are dominated by the beam spot size. Therefore, for the c-PBW, a sub-10 nm beam spot size is sufficient to meet the objective of achieving sub-10 nm structures in 100 nm thick photoresists.

Although a sub-10 nm spot size in one direction has been achieved with the current PBW system [22], the primary limitation of this system is its low reduced brightness resulting in a slow writing speed. This restricts the sub-10 nm focusing capability and also ends up having a low beam current (~0.01 fA) resulting in a low throughput [22]. For EBL, the typical beam current at the image plane is around tens of pA [27], which is 6 orders of magnitude higher than the current PBW system. But the typical dose required for protons in PMMA is 80–150 nC/mm^2 [33], which is 100 times lower than in EBL [34]. Thus in order to make the proposed c-PBW comparable to the EBL in its performance, a high brightness ion source is required that can deliver >0.2 pA of beam current at the image plane.

2.2. Nano-aperture ion source (NAIS)

A nano-aperture ion source (NAIS) [35] has been reported by the Charged Particle Optics group at Delft University of Technology that has the potential to become part of our proposed c-PBW system, to achieve a sub-10 nm beam spot size and faster writing capability. The concept of this NAIS is to extract ions from a small aperture (~100 nm) generated by electron-gas collisions within a sub-micron ionization chamber, as shown schematically in Fig. 2. This dramatically reduces the source size from mm range (as is the case with current PBW system) to the sub-micron range (~100 nm). Once ions are produced inside the ionization chamber, a strong electric field (~10^7 V/m) is applied to extract these ions. Since the ionization chamber spacer is only 100 nm, a small bias voltage (~1 V) is sufficient to generate such a strong electric field, resulting in a minimal ion energy spread (~1 eV).

From the electron-gas collision, the resulting proton beam current density J_p is described as

$$J_p = \sigma J_e N l \quad (1)$$

where J_p and J_e are current densities of protons and injected electron beam respectively, N is the gas density (corresponding to inlet gas pressure P) inside the ionization chamber, l is the spacer length between the two membranes, and σ is the electron impact gas ionization cross section. The energy of the injected electrons was chosen to be 1 keV, a trade-off between currently available electron beam systems and ionization cross section [35,36]. For hydrogen: the electron impact ionization cross section, σ (with 1 keV electrons) to generate H_2^+ and H^+ is 2.02×10^{-17} cm^2 and 1.19×10^{-18} cm^2 respectively [36].

For a planar ion source emitter, reduced brightness B_r is given as [37]

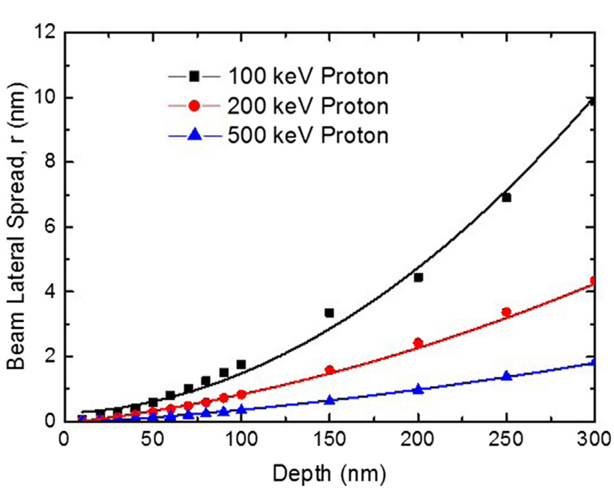

Fig. 1. Proton beam lateral spread radii in PMMA for 100 keV, 200 keV and 500 keV calculated from SRIM. These plots were obtained by accounting for 90% of the total incoming protons.

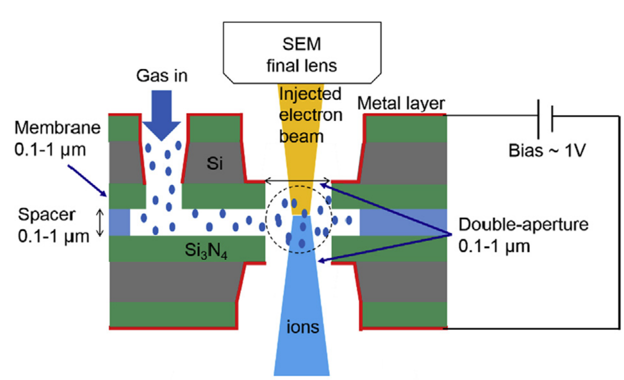

Fig. 2. Schematic of NAIS configuration and its dimensions.

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