AIP | Review of Scientific Instruments

The second generation Singapore high resolution proton beam writing facility

J. A. van Kan, P. Malar, and Armin Baysic de Vera

Citation: Rev. Sci. Instrum. **83**, 02B902 (2012); doi: 10.1063/1.3662205

View online: http://dx.doi.org/10.1063/1.3662205

View Table of Contents: http://rsi.aip.org/resource/1/RSINAK/v83/i2

Published by the American Institute of Physics.

Related Articles

Recent progress on the superconducting ion source VENUS
Rev. Sci. Instrum. 83, 02A311 (2012)

A very low energy compact electron beam ion trap for spectroscopic research in Shanghai
Rev. Sci. Instrum. 83, 013303 (2012)

Simulations of slow positron production using a low-energy electron accelerator
Rev. Sci. Instrum. 82, 063302 (2011)

Performance of the Argonne National Laboratory electron cyclotron resonance charge breeder
Rev. Sci. Instrum. 82, 053301 (2011)

Modal response of 4-rod type radio frequency quadrupole linac
Rev. Sci. Instrum. 80, 103303 (2009)

Additional information on Rev. Sci. Instrum.

Journal Homepage: http://rsi.aip.org

Journal Information: http://rsi.aip.org/about/about_the_journal

Top downloads: http://rsi.aip.org/features/most_downloaded

Information for Authors: http://rsi.aip.org/authors

ADVERTISEMENT

AIP Advances

Explore AIP's new open-access journal

- Article-level metrics now available
- Join the conversation! Rate & comment on articles

Submit Now

REVIEW OF SCIENTIFIC INSTRUMENTS **83**, 02B902 (2012)

The second generation Singapore high resolution proton beam writing facility[a)]

J. A. van Kan,[b)] P. Malar, and Armin Baysic de Vera
Centre for Ion Beam Applications, Department of Physics, National University of Singapore, Singapore 117542, Singapore

(Presented 12 September 2011; received 6 September 2011; accepted 4 October 2011; published online 6 February 2012)

A new proton beam focusing facility, designed for proton beam writing (PBW) applications has been tested. PBW allows for proximity free structuring of high aspect ratio, high-density 3D nanostructures. The new facility is designed around OM52 compact quadrupole lenses capable of operating in a variety of high demagnification configurations. Performance tests show that proton beams can be focused down to 19.0×29.9 nm^2 and single line scans show a beam width of 12.6 nm. The ultimate goal of sub 10 nm structuring with MeV protons will be discussed. © *2012 American Institute of Physics*. [doi:10.1063/1.3662205]

I. INTRODUCTION

Currently, industry is looking for replacement of 193 nm optical lithography. Due to the diffraction constraints of 193 nm optical lithography, the next generation lithographies (NGLs) will utilize any one or more of extreme ultraviolet,[1] x-ray, electron or ion beam technologies for circuits beyond the 22 nm generation. Electron beam lithography (EBL), a candidate for direct-write technology at nanodimensions has extensively been investigated for the last four decades. However, high resolution lines and spaces in single step exposures for EBL are challenging beyond the 22 nm generation due to proximity effects from high energetic secondary electrons initiating from adjacent and nearby features giving rise to structure broadening. Perhaps the most under-developed and under-rated is the utilization of ions for lithographic purposes. The three ion beam techniques, proton beam writing (PBW), focused ion beam (FIB), and ion projection lithography have the flexibility and potential to become leading contenders as NGLs.[2]

At the Centre for Ion Beam Applications (CIBA) in the Physics Department of the National University of Singapore, we have established sub 100 nm beam spot sizes for MeV protons.[3] This improved performance has opened up new ways of structuring of resist and Si as well as bio-imaging. The mass mismatch between proton and electron results in minimal energy transfer between an incoming proton and the substrate electrons. Therefore, the secondary electrons generated have limited range, resulting in minimal proximity effects. Low proximity effects coupled with the straight trajectory and high penetration of the proton beam have revolutionized applications for MeV proton beams in the area of:

- MeV proton beam writing allowing the production of high density and high aspect ratio 3D nanostructures with well-defined smooth sidewalls.[4]
- Sub 100 nm imaging of whole cells and of relatively thick tissue sections without any significant loss of resolution.[5]
- To achieve features below 10 nm using PBW three main technological challenges need to be met:
- First, the capability to focus MeV proton beams.
- Second, the low brightness for proton sources,[6,7] typically 6 orders of magnitude lower compared to electron sources[8] or FIB (Ref. 9) sources.
- Third, a suitable resist material and a development procedure[10,11] need to be employed to render the energy deposition profile of the protons in usable nanostructures.

In this paper, we discuss the performance of the new proton nano probe facility capable of focusing proton beams down to 12.6 nm and an outlook on what needs to be done to achieve PBW below 10 nm.

II. INSTRUMENT DESIGN

The next generation PBW line is designed based on the existing CIBA PBW line[6] and the fact that protons have several advantages in structuring resist materials over other lithographic techniques. In PBW proximity effects are greatly reduced,[12,13] which allow the fabrication of high-density high aspect ratio nanostructures,[4] a second advantage is the fact that PBW has typically a 100 fold higher sensitivity compared with electron beam writing in the same resist material.[14]

The new PBW line is attached to a 3.5 MV high brightness High Voltage Engineering Europa Singletron™ ion accelerator. This beamline is designed for low proton currents. The beam optics follows a normal layout of a nuclear microscope, following the beam after the accelerator it features:

- Object apertures (Oxford Microbeams OM10).
- Collimator apertures to control the beam aberrations (home built[15]) both apertures have 1 μm accuracy.

[a)] Contributed paper, published as part of the Proceedings of the 14th International Conference on Ion Sources, Giardini Naxos, Italy, September 2011.

[b)] Author to whom correspondence should be addressed. Electronic mail: phyjavk@nus.edu.sg.

© 2012 American Institute of Physics

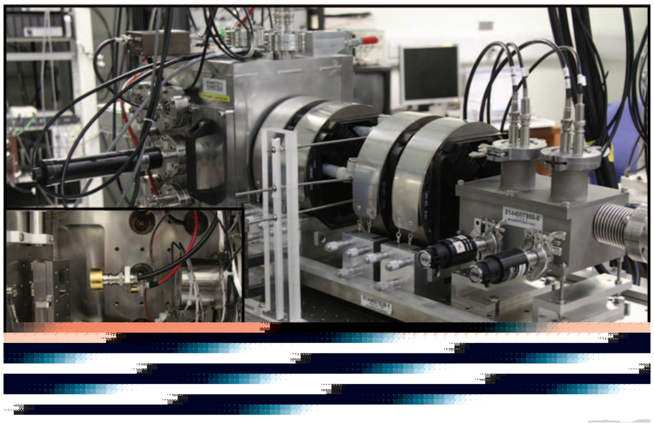

FIG. 1. (Color online) Layout of the new proton beam writing facility. Coming from the right we see the electrostatic scanning system, four quadrupole lenses and endstation, the inset shows the inside of the endstation.

- Electrostatic scanning system with X and Y scanning plates which can be accurately aligned (see Fig. 1). Two electrostatic amplifiers power the scan system (7224 AE Techron, 75 μV noise level).
- Four magnetic quadrupole lenses (Oxford Microbeams OM52). These lenses can be quickly repositioned in order to test different lens configurations (see Fig. 1). The lenses are powered using Bruker power supplies, which have a stability of 1 ppm/°C.
- PBW endstation (see Fig. 1).

The inside of the target chamber is shown in Fig. 1 (inset). It houses an electron detector to collect secondary electrons, a conventional surface barrier RBS detector to measure forward scattered beam, a simple optical zoom lens (back viewing) to setup PBW experiments. The samples are mounted on a precision controlled XYZ stage with 4 nm closed loop in X and Y and open loop in Z. The system is capable of 20 mm movement in each of the XYZ directions (PI N-310K059), controlled by the stage controller: E-861 NEXACT®. The PBW facility is supported by an optical table to reduce vibrations.

III. INSTRUMENT PERFORMANCE

In the current performance tests, the system is operated in a spaced Oxford triplet configuration (using lens 1, 3, and 4). Each lens is 55 mm wide, the spacing between lens 1 and 3 is 185 mm and the distance between lens 3 and 4 is 25 mm. To allow for high system demagnification the distance from the last lens to the image plane is set at 30 mm, this results in a system demagnification of 857 × 130 in X and Y, respectively. In future we will also test the Russian quadruplet in spaced double-crossover mode, which has equal demagnifications of 300 or more in the X and Y directions.[16]

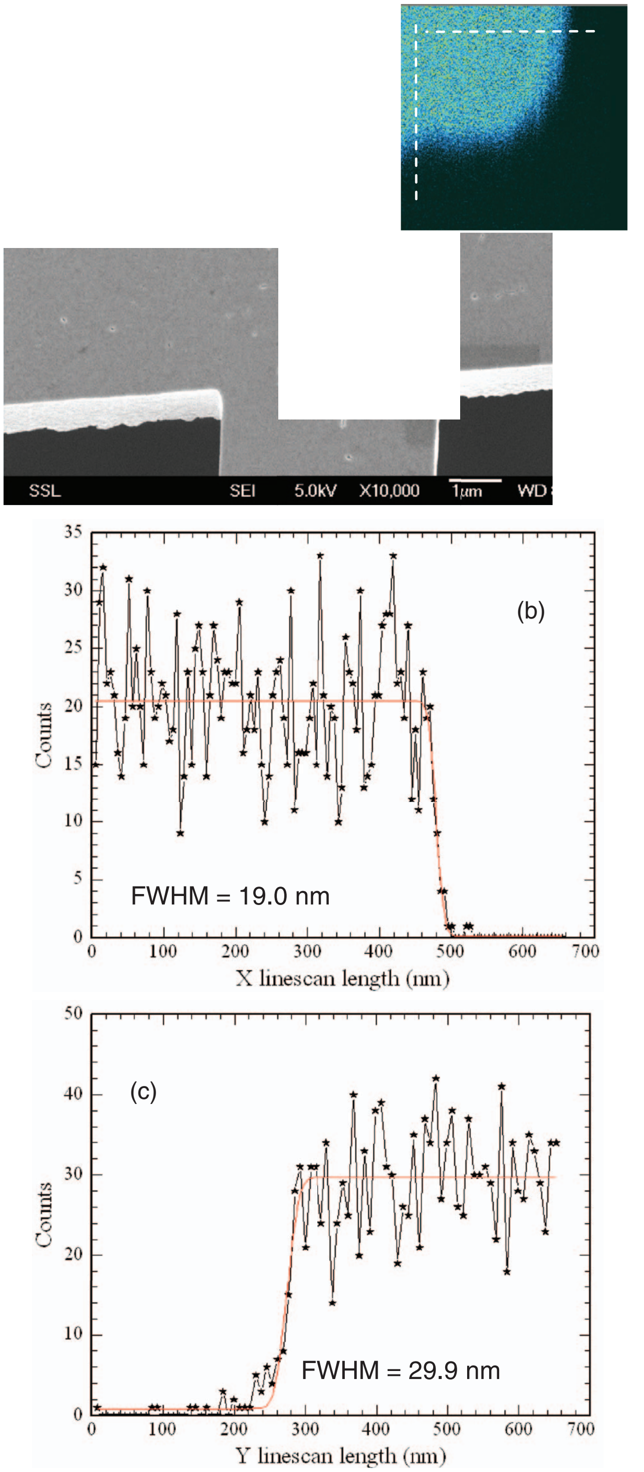

FIG. 2. (Color online) (a) SEM image of the Ni grid used in focusing of the proton beam (15° tilt angle), inset shows the on-axis STIM scan of the Ni grid using 2.0 MeV H_2^+ (scan size 655 nm). (b and c) Extracted line profiles indicating a resolution of 19.0 × 29.9 nm^2 in X and Y, respectively.

A 2 μm thick Ni grid produced using proton beam writing[17] was used to determine the beam size through energy loss measurements of forward scattered protons, see Fig. 2(a). A 2.0 MeV H_2^+ beam was focused down using on-axis scanning transmission ion microscopy (STIM). The scan size was varied from 100 μm down to 300 nm and the object slits were set at 11 × 5.5 μm^2. The STIM image of the Ni grid (Fig. 2(a), inset) was taken at 655 nm scan size using 23 200 protons per second and recorded at 256 × 256 pixels, defining a pixel resolutions of 2.56 nm. Figures 2(b) and 2(c) show examples of horizontal and vertical line profiles extracted from the STIM image in Fig. 2(a). These line profiles indicate a beam spot size of 19.0 × 29.9 nm^2 in the horizontal and vertical directions, respectively. To increase statistics neighbouring pixels

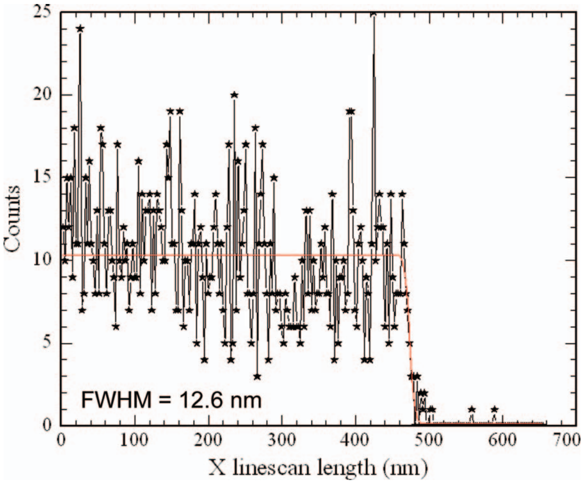

FIG. 3. (Color online) Extracted line profile in X direction from Fig. 2(a) indicating a beam width of 12.6 nm.

were added in these lines scans. In a separately extracted linescan in X direction a beam width of 12.6 nm was observed (see Fig. 3), exactly matching the geometrical demagnification. The fits to the line profiles are measured using the error function.

IV. DISCUSSION AND CONCLUDING REMARKS

A new facility has been constructed in CIBA, designed specifically for lithography with protons. The design specifications include the provision of STIM and secondary electron imaging. A spatial resolution of 19.0 × 29.0 nm^2 and a beam width of 12.6 nm has been demonstrated using a high demagnification quadrupole lens system in a spaced Oxford triplet configuration. Several points for improvement have been identified.

Due to the small spot sizes the particle detector gets locally damaged relatively quickly. To make this system cost effective for PBW, an alternative way to focus down the proton beam will be implemented through detection of proton-induced secondary electrons.

A challenge in performing PBW experiments in the current system is the lack of a closed loop in the Z axis. Due to the divergence angle of the beam, the spot size will increase if the sample plane is not known accurately with respect to the Ni grid; 1–2 μm accuracy is required to allow for PBW at the 10 nm level. Therefore, an interferometer system will be implemented to control the Z axis. The nickel grid manufactured in CIBA using PBW and Ni electroplating has a thickness of 2 μm and a sidewall angle of 89.4°,[17] this will also add significantly to the spot size measurement. Experiments are ongoing in CIBA to fabricate thinner resolution standards which will be integrated in a Si wafer.

Thermal stability of the lens system is currently another challenge in achieving smaller spot sizes. Due to thermal fluctuations the lens system moves mainly up and down, limiting the focusing performance in the Y direction. This prevents reliable PBW at the 10 nm level. Efforts are ongoing to address this issue.

Despite reaching a creditable proton beam resolution of 19.0 × 29.9 nm^2, the main factor in the quest for sub 10 nm proton spot sizes is undoubtedly the ion source brightness. A typical beam current of 1 pA is obtained using object and collimator slits set at opening sizes of 30 × 30 μm^2, corresponding to a system brightness of 20–30 $\text{A}/(\text{m}^2\ \text{rad}^2\ \text{V})$ and emittance of 4×10^{-7} mm^2 mrad^2. Our RF ion source is based on a 60 year old design,[18] operates inside a 1–2 MV terminal and has an exit canal of 2 mm diameter. To further optimize the performance of the new PBW system research is planned to develop and test high brightness ion sources. An improved brightness of 3–6 orders of magnitude is aimed for with an exit canal of 0.1–1.0 μm diameter,[19] an emittance of 10^{-8} mm^2 mrad^2, and a beam current of 1–100 pA on target.

ACKNOWLEDGMENTS

The authors acknowledge the support from A-Star (R-144-000-261-305), MOE Singapore (R-144-000-265-112), and the US Air Force.

[1] C. Tarrio, S. Grantham, S. B. Hill, N. S. Faradzhev, L. J. Richter, C. S. Knurek, and T. B. Lucatorto, Rev. Sci. Instrum. **82**, 073102 (2011).
[2] F. Watt, A. A. Bettiol, J. A. van Kan, E. J. Teo, and M. B. H. Breese, Int. J. Nanosci. **4**, 269 (2005).
[3] J. A. van Kan, A. A. Bettiol, and F. Watt, Appl. Phys. Lett. **83**, 1629 (2003).
[4] J. A. van Kan, A. A. Bettiol, and F. Watt, Nano Lett. **6**, 579 (2006).
[5] F. Watt, A. A. Bettiol, J. A. van Kan, M. D. Ynsa, R. Minqin, R. Rajendran, C. Huifang, S. Fwu-Shen, and A. M. Jenner, Nucl. Instrum. Methods Phys. Res. **B 267**, 2113 (2009).
[6] F. Watt, J. A. van Kan, I. Rajta, A. A. Bettiol, T. F. Choo, M. B. H. Breese, and T. Osipowicz, Nucl. Instrum. Methods Phys. Res. **B210**, 14 (2003).
[7] R. Szymanski and D. N. Jamieson, Nucl. Instrum. Methods Phys. Res. **B130**, 80 (1997).
[8] L. W. Swanson and G. A. Schwind, *Charge Particle Optics*, 2nd (CRC Press, Boca Raton, FL, USA, 2009), Vol. 1.
[9] C. W. Hagen, E. Fokkema, and P. Kruit, J. Vac. Sci. Technol. **B26**, 2091 (2008).
[10] S. Bolhuis, J. A. van Kan, and F. Watt Nucl. Instrum. Methods Phys. Res. **B267**, 2302 (2009).
[11] A. Han, J. Chervinsky, D. Branton, and J. A. Golovchenko, Rev. Sci. Instrum. **82**, 065110 (2011).
[12] H. J. Whitlow, M. L. Ng, V. Aŭzelyté, I. Maximov, L. Montelius, J. A. van Kan, A. A. Bettiol, and F. Watt, Nanotechnology **15**, 223 (2004).
[13] C. N. B. Udalagama, A. A. Bettiol, and F. Watt, Nucl. Instrum. Methods Phys. Res. **B260**, 384 (2007).
[14] J. A. van Kan, A. A. Bettiol, S. Y. Chiam, M. S. M. Saifullah, K. R. V. Subramanian, M. E. Welland, and F. Watt, Nucl. Instrum. Methods Phys. Res. **B260**, 460 (2007).
[15] J. A. van Kan, P. Malar, A. B. de Vera, X. Chen, A. A. Bettiol, and F. Watt, Nucl. Instrum. Methods Phys. Res. **A645**, 113 (2011).
[16] G. W. Grime and F. Watt, *Beam Optics of Quardupole Probe Forming Systems* (Hilger, Bristol, 1984), pp. 126–246.
[17] F. Zhang, J. A. van Kan, S. Y. Chiam, and F. Watt, Nucl. Instrum. Methods Phys. Res. **B260**, 474 (2007).
[18] C. D. Moak, H. Reese, and W. M. Good, Nucleonics **9**, 18 (1951).
[19] D. S. Jun, V. G. Kutchoukov, and P. Kruit, *MNE2011* (MNE, Berlin, 2011), pp. 202–202.