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Development of a MeV ion beam lithography system in Jyväskylä

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Abstract

A lithographic facility for writing patterns with cyclotron beams is under development for the Jyväskylä cyclotron. Instead of focusing and deflecting the beam with electrostatic and magnetic fields a different approach is used. Here a small rectangular beam spot is defined by the shadow of a computer-controlled variable aperture in close proximity to the sample. This allows parallel exposure of rectangular pattern elements of 5–500 μm side with protons up to 6 MeV and heavy ions (^{20}Ne, ^{85}Kr) up to few 100 MeV. Here we present a short overview of the system under construction and development of the aperture design, which is a critical aspect for all ion beam lithography systems.

Key words: MeV ion beam lithography, cyclotron, proximity aperture, proton beam writing
PACS: 01.52.+r, 06.60.Ei, 29.20.Hm, 81.40.Wx, 85.40.Hp, 87.80.-y

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1 Introduction

MeV ion beam lithography is emerging as an advanced lithography tool for applications [1–7], which require extremely high line width to resist thickness aspect ratios [8,9]. Use of focused MeV proton beams from high-brightness

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electrostatic accelerators allows high spatial-density patterns to be written with line-widths on a few tens of nm scale. Cyclotron beams generally have higher energies, which enables pattern writing in thicker resists (up to 400 μm for 6 MeV protons in PMMA) [10]). However, even if large beam currents are available (up to 100's of μA), the divergence is often large (about 1 mrad) which implies it is not straightforward, to use a magnetic focusing or proximity aperture approaches.

For our biomedical research programmes at a cellular and sub-cellular level [11] we are interested in rapidly exposing patterns with a large number of pattern elements of 10–300 μm size over a large area in thick ($\leq$200 μm) resists and polymer films. For this purpose we are constructing an ion beam writing facility that is based on a computer-controlled aperture in close proximity to the sample. This allows entire rectangular pattern elements to be exposed in one step using proton beam lithography or single heavy-ion tracks.

2 Experimental set-up

The system is shown schematically in Fig. 1. The size and shape of the beam spot is defined by a computer-controlled aperture system that can be positioned in close proximity (0.3–20 mm) from the sample surface. The size and divergence ($<$0.7 mrad) of the beam impinging on the computer-controlled aperture is defined by a water-cooled 1 mm diameter Ta aperture located 1.78 m upstream close to the exit of the switching magnet. Focusing is carried out using a magnetic quadrupole pair further upstream. A fluorescent screen and Faraday cup as well as Si p-i-n diodes [12] are used for beam diagnostics and current measurement.

The principle of the aperture system is shown in Fig. 1. The sample is mounted on exchangeable sample holders that fit onto a computer-controlled x-y-z stage [13] that has 100 nm precision and approximately 1 μm accuracy (Fig. 1(b) and (c)). Two L-shaped aperture blades in close proximity to the sample surface cast a rectangular shadow on the sample that defines the shape of the beam spot on the surface. (Fig. 1(a)). Precise movement of each L-shaped blade in the X' and Y' directions using linear motion stages [13] defines the vertical and horizontal size of the aperture. One corner of the rectangular aperture remains in a fixed position, while the position of the other three corners depends on X' and Y'. Then combination of the sample position (x, y, z) and the computer-controlled aperture (X', Y') allows rectangular pattern elements to be written over a 20×20 mm field. The maximum side length of the rectangular pattern elements can be up to 500 μm while the minimum side length is determined by the resist contrast and penumbra broadening. The apertures, sample stage and beam blanking are controlled with a LabView-control program.

The two L-shaped aperture blades are each made from two 100 μm thick 8×15 mm Ta sheets. Each aperture blade must be sufficiently thick to completely stop the incident ions. Taking this thickness to be $R_p + 2\sigma_p$, where R_p and σ_p is the projected range and projected range straggling, respectively, allows patterning with our system up to $\sim$ 6 MeV protons and a few hundred MeV heavy ions such as ^{20}Ne, ^{85}Kr (see Fig. 2). Comparison of the aperture thickness for stopping the beam and the range in PMMA (a typical resist material) in Fig. 2) shows that up to 400 μm thick resist can be written with protons and $\sim$150 μm for heavy ions. This is well-matched to the capabilities of the Jyväskylä cyclotron which can deliver ions up to 130A/q^2 MeV. Ta was chosen as the aperture material because of the ease of working and its high Z, which

presents a high Coulomb barrier to most ions (11 MeV for protons, 21 MeV for ^{4}He, 87 MeV for ^{20}Ne, 262 MeV for ^{85}Kr [14]). This is important in order to minimize spurious exposure of the resist by charged reaction products formed on the aperture edges, as well as undesirable neutron production as well as activation of the resist itself. Proton irradiation of polymers with energies of 6 MeV, or lower, can result in production of short-lived ^{13}N with a 9.96 minutes half-life. The cross-section at 6 MeV for fusion reaction ^{12}C(p,γ)^{13}N well below the Coulomb barrier (11 MeV) was estimated to be 6 μb based on a quantum mechanical calculation using the parabolic potential approximation with a 5 MeV curvature parameter [15].

Experiment showed edge-polishing of the Ta blades clamped in a metal polishing jig with 2000 grove SiC paper followed by diamond paste [16], resulted in an edge with better than 80 nm peak to valley deviation from straightness [17] over 3.6 mm, measured with a profiler(Fig. 3). Presumably, this can be further improved using finer diamond paste or sputtering.

The penumbra broadening is presented in Fig. 4(b) for different aperture - sample distances. Note that because of the aperture construction, the minimum separation, when the sample and last aperture blade are in contact, is 3 times the aperture thickness (300 μm). Taking a realistic minimum gap of 600 μm gives an edge penumbra broadening of 340 nm. This value represents an upper limit and the actual broadening is expected to be smaller because of concentration of the beam along paraxial directions. Thermal heating of the computer controlled aperture is an important issue because thermal expansion limits the rate of pattern writing. The fluence required to expose PMMA corresponds to about 10^{14} of 2 MeV H^{+} ions per cm^{-2} [18]. An exposure rate of one pattern element in 30 s requires 0.6 μA of protons into a 1 cm^{2} area onto

1 the first aperture and correspondingly a maximum heat load of 9.2 mW on
2 the second aperture. For zero thermal resistance between the L-shaped blades
3 and the mounting blocks, which are assumed to be cooled only by radiation,
4 the corresponding linear change in aperture size is 14 nm for 10 mm between
5 blade-tip and fixing point. The overall absolute accuracy of the patterns is
6 then set by the combined accuracy of the (x and X') and (y and Y') linear
7 motion slides and corresponds to 1.4 μm over 20 mm with a precision of better
8 than 140 nm. It should be noted that parallel exposure of an entire pattern
9 element rather than exposing pixel by pixel dramatically reduces the problem
10 of thermal drifts because the much faster writing speed, allows a significant
11 reduction in beam current. At these exposure rates the beam is adequately
12 blanked within 1.5–2 μs by a TTL signal sent to the accelerator injection
13 system [19].

14 Secondary and scattered particles from the aperture blade edges may to have
15 degrade the pattern edge sharpness. No theoretical analysis was performed,
16 however, pattern broadening due to the particles scattered by the aperture is
17 believed on the basis of ref. [20] to be relatively small.

18 3 Conclusions

19 The new MeV ion beam lithography system being constructed at the Jyväskylä
20 Cyclotron Laboratory is described. This system is based on a computer con-
21 trolled aperture system that can simultaneously expose rectangular pattern
22 elements up to 500 μm side length over a 20×20 mm^2 field with low energy
23 (6 MeV) protons for proton beam writing or up to a few hundred MeV heavy
24 ions (Ne, Ar) for ion track patterning. The minimum exposed feature size set

by penumbra broadening is $\sim$ 400 nm for a 600 μm proximity gap. The energy (2–1300 MeV) and ion range (from hydrogen to gold) available from Jyväskylä K130 cyclotron make the presented lithography setup a very versatile system.

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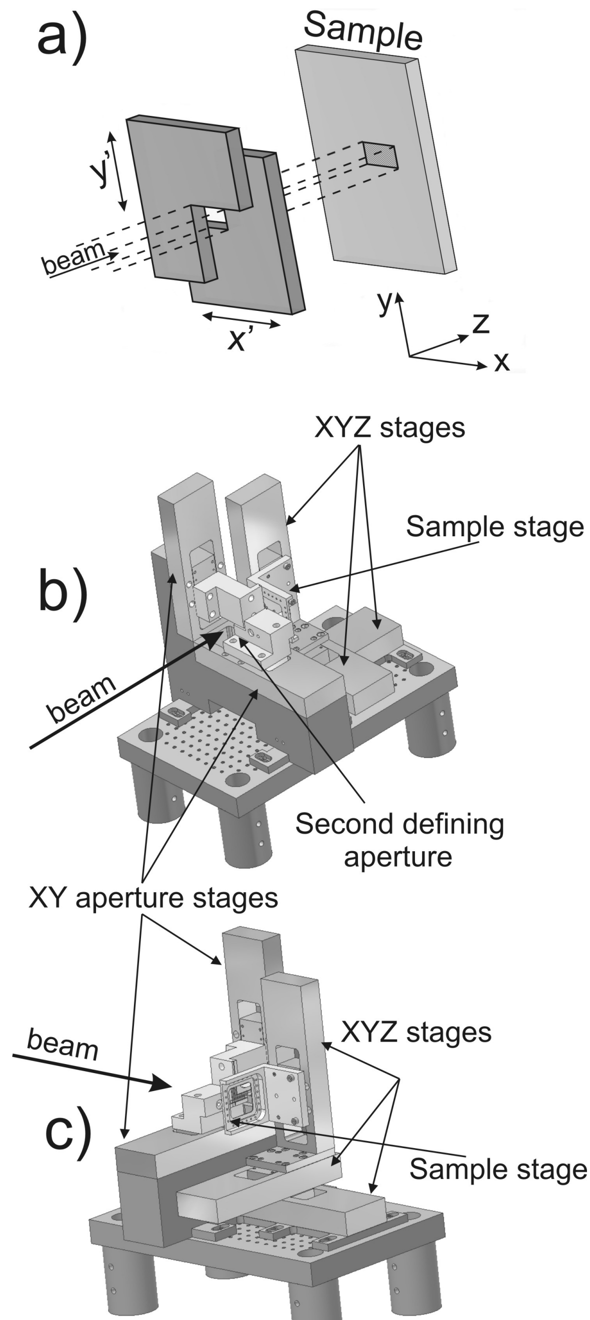

Fig. 1. Schematic layout of the ion beam lithography setup: The defining aperture. The opening of the aperture is controlled by relative motion of two tantalum L-shape plates. b) Aperture and sample are mounted on motorised stages. c) View from behind.

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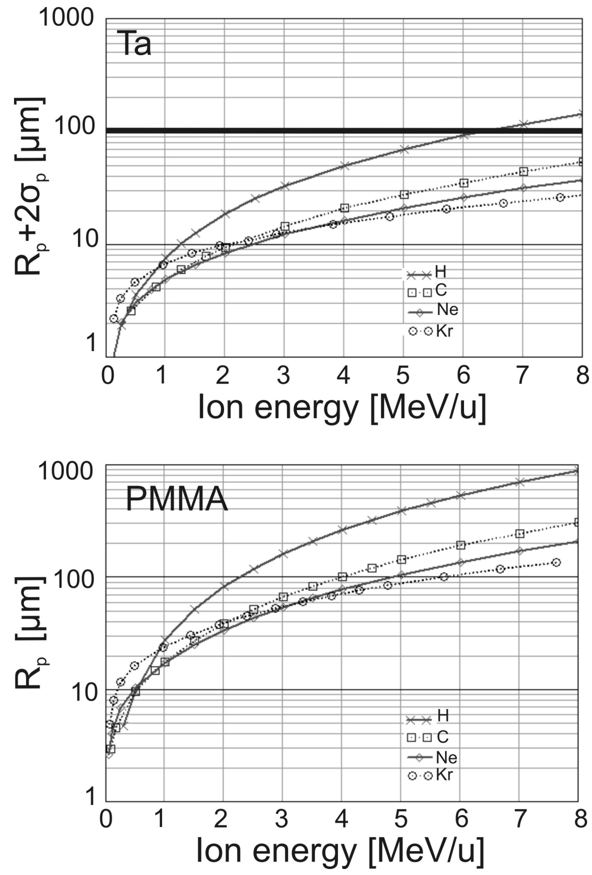

Fig. 2. $R_p + 2\sigma_p$ of different ions in Ta vs. ion energy (top), range for different ions in PMMA vs. ion energy (bottom) [10].

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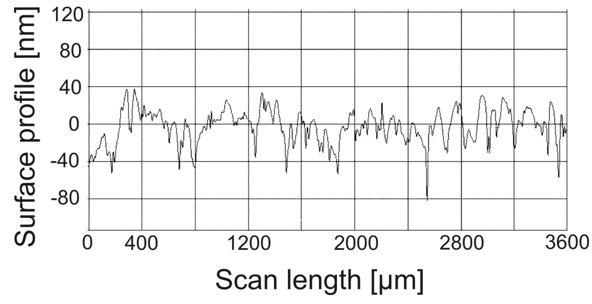

Fig. 3. Edge roughness of Ta aperture blade measured with a profiler after polishing with diamond paste.

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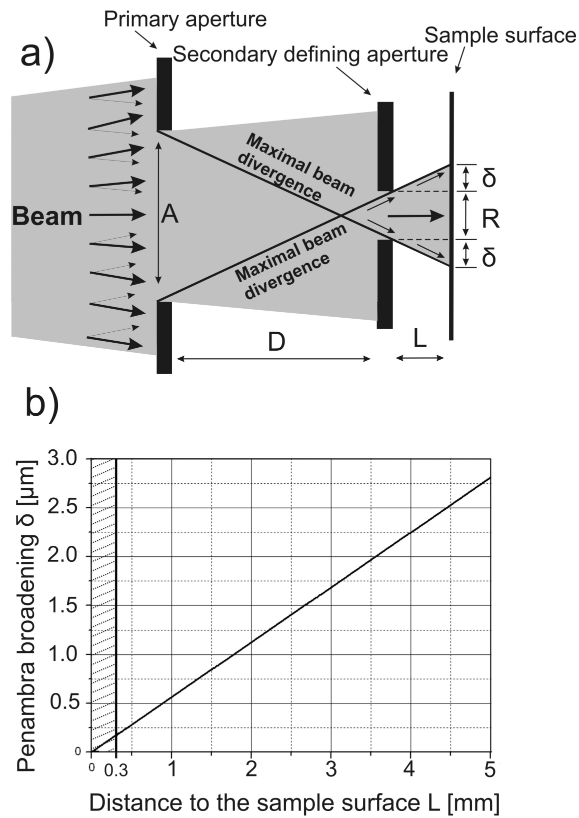

Fig. 4. a) Schematic of the collimation system. The primary aperture opening, A, is 1 mm in diameter, distance between the primary and the defining aperture, D, is 1.78 m, L is a distance between the sample surface the the defining aperture, and R is the opening of the defining aperture. b) Penumbra broadening, δ, for different proximity of the defining aperture to the sample surface. The shaded area denotes the forbidden distances resulting from the finite aperture blade thickness.

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