X-ray lithography station at MAX-Lab: First results

Alexei L. Bogdanov[*], Serguei Peredkov

MAX-Lab, University of Lund,

Box 118, S-221 00, Lund, Sweden

Abstract

Design, operation, and first lithography results of an X-ray exposure station for micromachining and nano-fabrication are presented. The station is built on a dedicated bending magnet beamline and provides exposures in a wide range of x-ray photon energies. Both deep x-ray lithography and soft x-ray lithography modes of operation are available. The scanner permits scanning velocities of up to 200 mm/s, which helps to avoid uneven heating of mask/substrate by the beam. Test exposures of negative photoresist SU-8 were performed for resist thickness 100-500 μm. SU-8 structures with aspect ratios as high as 100:1 (H:W) are demonstrated.

Introduction

Although proximity x-ray lithography (PXRL) is a very established technology with almost 30 years of development background, it has not so far found recognition as a lithography method for IC production. One of the main reasons for this is the absence of compact and low-cost source of x-rays in 0.5-2 keV spectral region. From the point of view of radiation suitability for lithographic use the best source is by far the synchrotron radiation (SR) with its continuos spectrum, easy collimation, and very high intensity in the spectral region of interest. The obvious drawbacks of synchrotron are its high purchase and ownership costs, and need in daily highly skilled and qualified technical support, which eventually results in even higher costs. Another reason for rejection of synchrotrons by the semiconductor industry is the fact that a semiconductor manufacturer willing to use SR based PXRL has to invest not only in synchrotron source itself but as well in as many as 16-20 exposure stations to make the synchrotron well used. These huge investments would rise commercial risks to a dangerous level. However in those cases when synchrotron sources are already built and in use for scientific or other purposes it is always worth to dedicate one or two beamlines to PXRL. Rather simple and inexpensive exposure station based on such an "academic" synchrotron source can be a valuable addition to vector scan e-beam lithography systems used for research and small-scale production of micro- and nanostructures. MAX-Lab is Swedish national synchrotron radiation facility. Two SR sources MAX-I and MAX-II are currently in operation. MAX-I synchrotron can accelerate and store electrons at the energy of 0.45 GeV. Partly these electrons are used to inject the MAX-II storage ring. MAX-II stores electrons with the energy of 1.5 GeV. X-ray lithography beamline BLD-811 uses radiation emitted at one of the MAX II bending magnets. Originally, the idea to build a PXRL facility at MAX-II was based on the interest to deep PXRL for LIGA process[1]. However already on the first stages of the project it became clear that possibility to carry out soft PXRL tasks with sub-micrometer resolution was of equal if not higher importance. The purpose of PXRL station at MAX-Lab is to provide access to PXRL technology for researchers and companies from Sweden and whole Scandinavia working in the field of nano-/microfabrication. Assembly and adjustment of the PXRL station on the beamline BLD-811 have been completed in the end of 1998 and the first lithography results were obtained in February 1999. The facility is steadily upgraded and in its final configuration it should allow x-ray exposures and in-house resist processing for small-

[*] E-mail: *Alexei.Bogdanov@maxlab.lu.se*

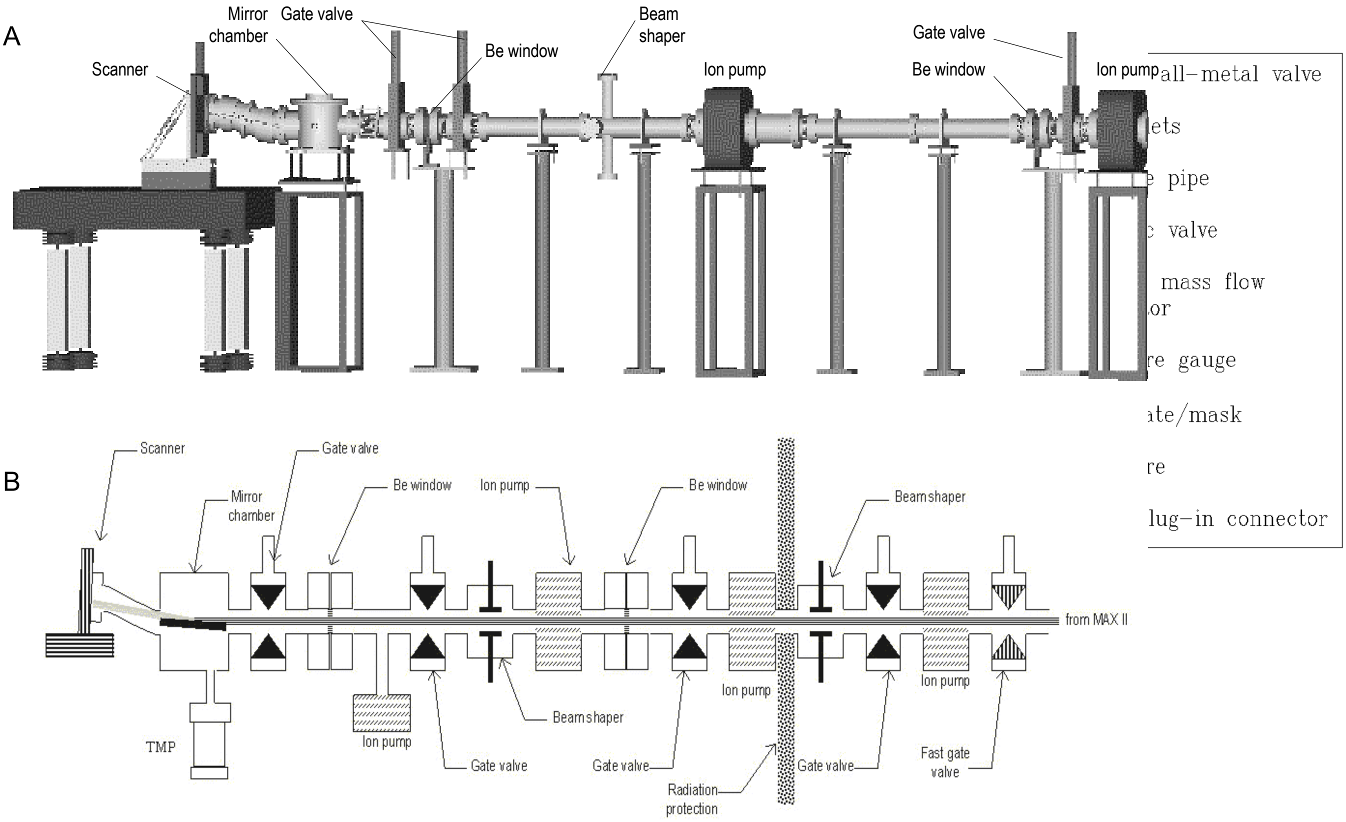

Fig. 1: A) 3D solid model of the part of the beamline outside radiation protection wall.
B) Vacuum scheme of the beamline and the x-ray exposure station..

scale fabrication of micro- and nonostructures. In parallel with the exposure tool development possibilities for x-ray masks fabrication are thoroughly studied in order to provide the users with a reliable source of inexpensive custom made masks.

Beamline design and parameters

The beamline (Fig.1) has two beryllium windows 15 and 20 um thick for vacuum insulation, two sets of motorised beam-shaping baffles, and usual equipment for pumping and pressure monitoring. The beamline has automatic vacuum control and automatic vacuum alarm function, which in the case of pressure rise above 10^{-7} torr closes the fast gate valve and all other gates downstream. Approximate distance from the radiation source to the exposure chamber is 20 meters.

Exposure station

Exposure station consists of three connected vacuum chambers (Fig. 2). The first chamber contains filtering Si mirror. The second chamber is flexible and is used as an x-ray duct between the mirror chamber and movable exposure chamber. During exposure mirror and exposure chambers are filled with helium. Mass flow regulators in the gas system allow controllable flow of **He** for cooling and flushing of gaseous contaminants released from resists during exposure. Small amount of oxygen can be let in for the mirror self-cleaning. Pure nitrogen is used for venting of the system. Some amount of the nitrogen can be added to increase absorption of soft x-rays undesirable at the resist in the case of very deep lithography.

Scanner

Design of the scanner is presented in Fig.3. A servodrive linear stage has 150 mm travel. Under the present loading conditions the stage provides acceleration to a maximum velocity of 200 mm/s in less than 10 mm from the starting point, thus leaving maximum 130 mm of the travel for uniform scanning. The exposure chamber is attached to the vertical linear stage. The face of the exposure chamber confronting the beamline is made compatible with CF DN160 flange connection. Different types of mask/substrate holders are designed and made in the same standard to stack them. Maximum exposed area is 76 x 76 mm.

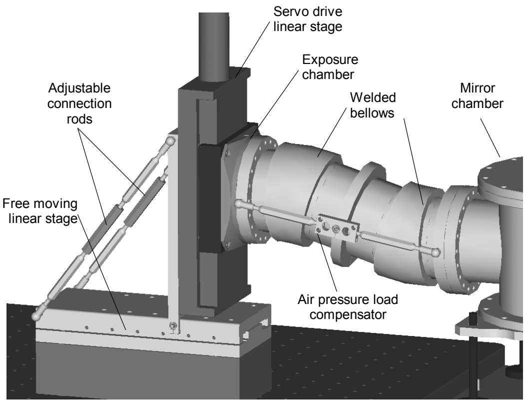

Fig. 3: The scanner. 3D solid model

Mirror chamber

Flat chromium coated silicon mono-crystal mirror is used as low-pass filter for soft x-ray nanofabrication experiments. The mirror chamber (Fig. 4) design allows to change the mirror working angle and to remove the mirror out of the beam without infringement of vacuum. The axis of the mirror rotation is placed so that when the mirror is lower than its horizontal position the SR beam can go through the mirror chamber freely. Minimum deflection angle for the mirror is defined by its length and the beam height. In our case usable length of the mirror is L = 190 mm and the beam is baffled to a rectangle 2.5×80 mm ($H \times W$). Minimum deflection angle in this case is

$$\phi_{\min} = 2 \arcsin \frac{H}{L} = 1.51^\circ$$

Maximum deflection of ~5° can be achieved when the mirror is in its highest position (see *Side view* in Fig. 4). The ambient helium-oxygen mixture cools the mirror during exposure. If the mirror is in the beam soft plasma-chemical cleaning of the mirror surface takes place. The cleaning is done by oxygen atoms, O_2, and O_3 molecules excited and ionised by x-rays. To ensure minimum twisting and bending of the mirror due to the uneven heating by the incident flux the mono-crystal mirror base is fixed on the sides coinciding with the crystal planes so that in the process of thermal expansion the base will not be deformed and the uniformity of the reflected beam will not be spoiled (*Top view* in Fig. 4).

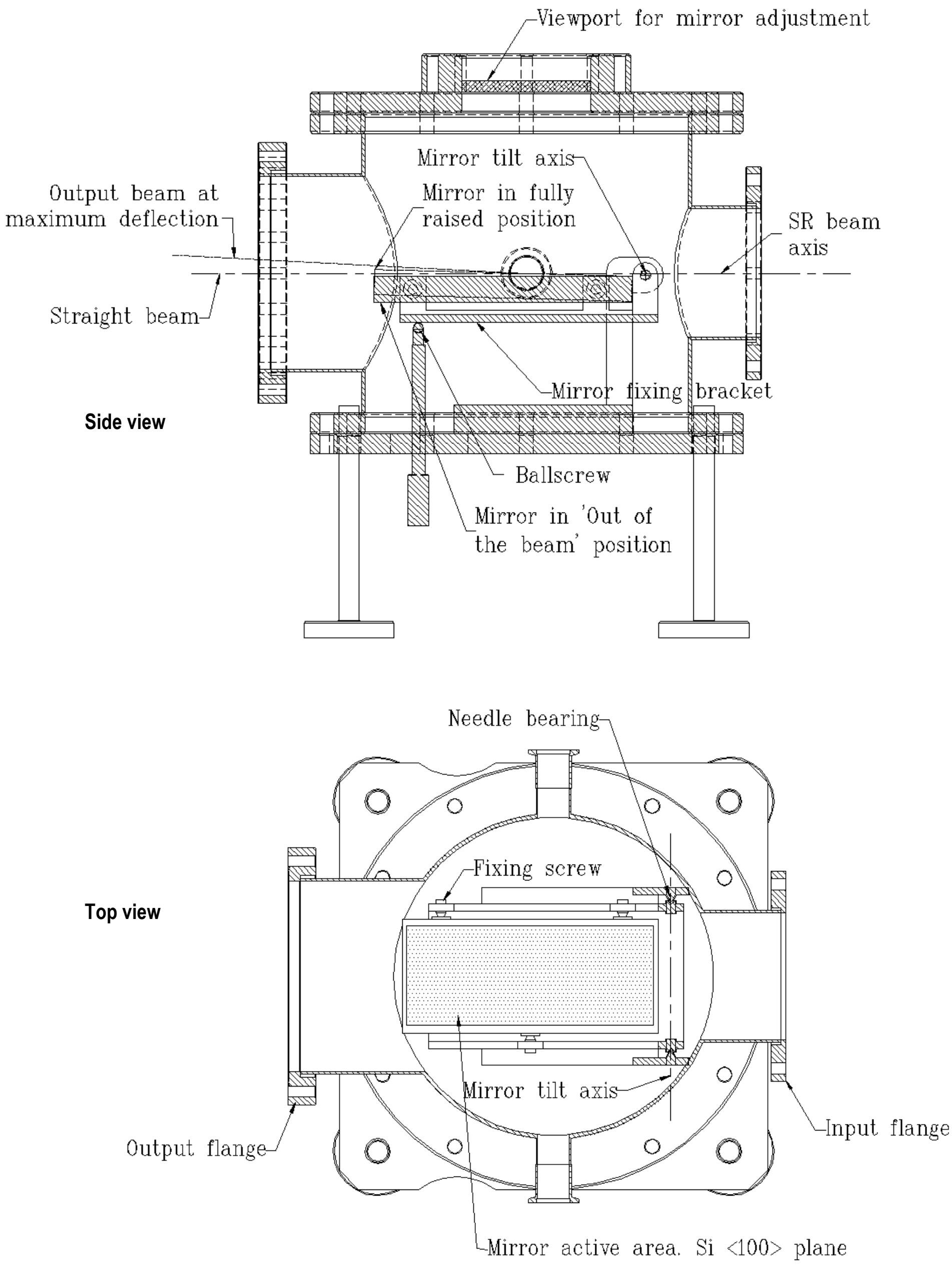

Fig.4: Exposure station gas and vacuum system.

Lithography results

Proximity printing experiments with two negative resists were conducted. Negative resists SAL-601 (thickness 2-10 µm) and SU-8 (thickness 60-120 µm) were tested in hard x-ray mode (no mirror filtering). A mask was provided by *IMM Mainz.* The mask was made as 500 µm thick **Be** membrane with 14 µm thick **Au** patterned absorber on it.

SAL-601 was chosen for its known fine resolution [2]. First lithography results were obtained in 2 µm thick SAL-601. The scale of the features on the used mask (minimum feature size was 5µm) did not allow us to investigate the resist resolution limits. Unfortunately, getting of thick resist layers (more than few micrometers) of SAL-601 appeared to be a very tedious and labour consuming process involving multiple spin coatings. So for the kind of mask we used we decided to choose another negative resist.

Epoxy based negative photo resist SU-8 is easy to spin up to 120-150 μm thickness in a single spin[3].

High aspect ratio (**~30:1**) structures in 120 **μm** thick resist were obtained (Fig. 5). Typical exposure time for 76×76 mm² area was 1-2 min. In our experiments we used both spinning and casting of SU-8_5 resist. Spining better suited for 10-50 μm thick films, whilst casting could be used for 100-

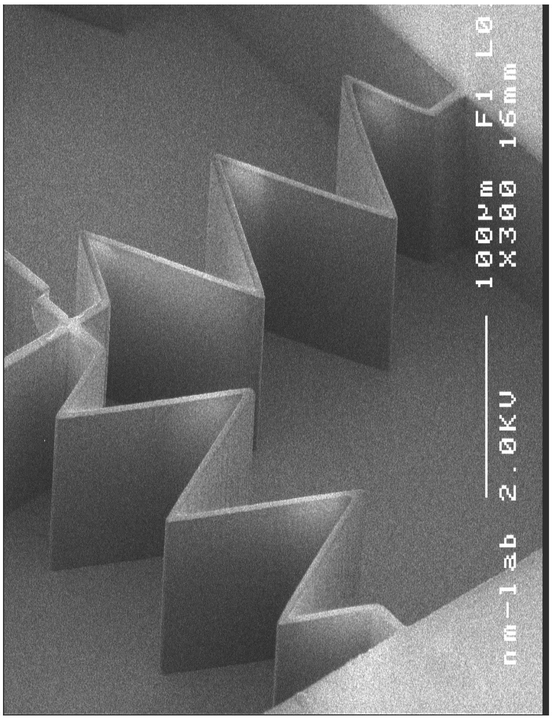

Fig. 5: SEM micrograph of 4 μm thick and 120 μm high fences. Material SU-8. Image was taken at 45° tilt.

500 μm thick resist. Resist was developed in GBL thinner in an ultrasonic bath at room temperature.

Influence of post-exposure bake conditions on XPSU-8 resist mask quality was investigated. It was found that slow ramping (e.g. in 45 min from 50°C to 90°C) of the post-bake temperature is essential to avoid resist cracking on large exposed areas. It was also found that resist becomes more prone to cracking if even slight (~10%) underexposure occurred. The sensitivity of SU-8 appeared to be 20-30 times higher than that of PMMA. The structures obtained in SU-8 demonstrated excellent thermal stability. No flowing or feature shape change was observed upon heating the substrate to 190°C. Simulations of dose distribution in the resist indicated that **1 mm** thick resist could be exposed under present exposure conditions in less than **30 min**.

Conclusion

X-ray lithography station at MAX-Lab is now commissioned and operational. Deep x-ray lithography works can be successfully carried out. High resolution lithography with soft x-rays can be conducted with a help of grazing incidence mirror. It was shown that SU-8 resist can be used for high aspect ratio PXRL.

Acknowledgement

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[1] E. Becker et al., Microelectronic Engineering **4**, 35 (1986)

[2] L. Malmqvist, A.L. Bogdanov, L. Montelius, H.M. Herz, Nanometer table-top proximity x-ray lithography with liquid-target laser plasma source, J. Vac. Sci. Technol. B15(4), pp. 814-817, (1997)

[3] US Patent 5304457, Day, Gelorme, Russell, Wih, "Composition for photoimaging" April 1994, IBM.