CONF-961086--8

ANL/XFD/CP--89571

BEAMLINE AND EXPOSURE STATION FOR DEEP X-RAY LITHOGRAPHY
AT THE ADVANCED PHOTON SOURCE

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NOV 05 1996

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Abstract

The Advanced Photon Source (APS) is a third-generation synchrotron radiation source. With a characteristic x-ray energy of 19.5 keV and highly collimated beam (< 0.1 mrad), the APS is well suited for producing high-aspect-ratio microstructures in thick resist films (> 1 mm) using deep x-ray lithography (DXRL). The 2-BM beamline has been constructed and will be used for DXRL at the APS. Selection of the appropriate x-ray energy range is accomplished by a variable-angle mirror and various filters installed in the beamline. At the exposure station, the beam size will be $100(H) \times 5(V)$ mm². Uniform exposure will be achieved by a high-speed (100 mm/sec) vertical scanner. The scanner allows precise angular (~ 0.1 mrad) and positional (< 1 μ m) control of the sample, allowing full use of the highly collimated beam for lateral accuracy and control of sidewall slopes during exposure of thick resists, as well as the generation of conicals and other profiles. For 1-mm-thick PMMA, a 100×25 mm² area can be fully exposed in about 1/2 hour, while even 10-mm-thick PMMA will require only 2-3 hours.

Keyword: x-ray lithography, micromachining, LIGA, high-aspect-ratio microstructures, x-ray scanner.

Introduction

MASTER

To produce high-aspect-ratio microstructures with submicron precision, intense synchrotron radiation sources in the hard x-ray regime are necessary.¹ A commonly used photoresist is poly methyl methacrylate (PMMA), and the x-ray absorption length in PMMA is shown in Fig. 1. For 7 keV x-rays, the $1/e$ absorption length is about 1 mm, which will result in an absorbed dose ratio of 3 to 1 between the surface of the resist and at a depth of 1 mm. The absorption length increases to 10 mm for 15 keV x-rays. In practice, even higher energy x-rays are desired in order to achieve a wider process latitude. At the APS, the high critical energy (19.5 keV) of the bending magnet radiation² makes possible the fabrication of very thick structures and allows for wider process latitude. The high flux available even at

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energies above 10 keV will greatly reduce the exposure time for thick resists. Another important factor is the higher resolution with which the structure can be replicated by the deep-etch lithography process. The resolution of a feature can be degraded due to finite source size or collimation of the x-ray beam. At the APS, because of the large source distance and small source size involved, the penumbral blur on the sidewall straightness is reduced. These factors strongly suggest that the APS should be exploited as a source for deep x-ray lithography.

Source Characteristics

The APS is a high-brilliance third-generation synchrotron radiation source for the hard x-ray regime. The bending magnet radiation (BM) has a critical energy of 19.5 keV, which provides very high flux ($>10^{12}$ ph/s/0.1%BW/mrad-horizontal) even up to 80 keV and beyond. The source size is $\sigma_x = \sigma_y = 0.11$ mm, small compared with most other synchrotron radiation sources, which have 3-10 times larger horizontal source size. The angular intensity is similar to Gaussian in the vertical direction. In the case of the APS, because of the high particle beam energy (7 GeV), the characteristic opening angle is $1/\gamma = 73$ μ rad in the vertical and is highly collimated. In the horizontal direction, the intensity is uniform and the angular divergence is defined by the acceptance of the beamline.

These geometric source parameters affect the penumbral blur and runout error generated during exposure.³ The small source size, together with the long distance from the source (25-50 m), ensure the penumbral blur in the horizontal direction will be less than 0.1 μ m on resist structures up to 1 cm thick. In the vertical direction, the mask and resist are scanned together through the beam in order to achieve a uniform dose over a large area. In that case, the penumbral blur is limited by the $1/\gamma$ opening angle to about 0.7 μ m for a 1-cm-thick resist. If only a small area needs to be exposed (< 3 mm vertically), the mask and resist can be stationary in the beam (with proper cooling provided) and the penumbral blur will be limited to less than 0.1 μ m, identical to that in the horizontal direction. The runout error mainly occurs in the horizontal direction because a fan of radiation is accepted. For the 2-BM beamline, a total of 2 mrad is accepted, and thus the runout on a 1-mm-thick resist increases linearly from zero at the center to 1 μ m at the two ends of the exposure field, which is about 10 cm wide for an exposure station located 50 m from the source. In the future, collimating optics may be considered to further reduce the penumbral blur and runout error.

Beamline Design

The 2-BM beamline was designed to take advantage of the source characteristics and to provide flexible spectral tuning. This is necessary for DXRL because the x-ray energies should be optimized

depending on the resist thickness. This is accomplished by using x-ray filters to adjust the low-energy cutoff and mirrors for the high-energy cutoff.

The beamline consists of two stations (Fig. 2): the first optics enclosure (FOE) at about 26 m from the source, and the experimental station at about 52 m, connected by 15 m of beam transport between them. Although the experimental station will be used primarily for exposure, the FOE can also be used, depending on the requirements. Most of the optics are located inside the FOE, including the filter assembly and the first mirror. The filter assembly (F2) consists of two actuators; each can accommodate four filter materials (Table 1). With various combinations, the low-energy cutoff may be adjusted between 2 to 15 keV (Fig. 3). The first mirror (Y3-30) is a flat vertically deflecting mirror 1.2m long. It has two adjacent reflective surfaces: a polished silicon surface and a platinum-coated surface. The grazing angle of incidence is fixed at 0.15° , which eliminates all high energy x-rays above 35 keV when reflected by the Pt-coated section of the mirror (Fig. 3). This should be sufficient for exposing photoresists with thicknesses up to several centimeters. For thinner resists, the polished silicon surface on the mirror may be used, which reduces the high-energy cutoff to 12 keV. Although high energy x-rays may improve the exposure latitude, they also increase the absorber thickness requirement on the mask in order to maintain adequate contrast. The first mirror serves two other purposes: 1) to separate the x-rays from the bremsstrahlung radiation that affects the exposure process in a manner that is not well characterized, 2) to reduce thermal load on the x-ray mask. For instance, the total incident power on a downstream mask may be reduced from 125 W to 72 W when the Pt part of the mirror is used and is further reduced to 27 W if the silicon part is used. Other beamline components in the FOE include an upstream 500- μm -thick Be window (which will be replaced by the differential pumping section (V1) after the initial commissioning period), a slit assembly, a photon shutter, bremsstrahlung collimator and stop. A multilayer monochromator and a crystal monochromator will also reside in the FOE, which will be used for other purposes, such as optics characterization, instrumentation development, as well as energy-dependent studies of resist exposure or chemistry.

Either the mirror-reflected (pink) beam or the monochromatic beam can be transported to the experimental station. A beam position monitor is provided to establish the stability of the x-ray beam from the FOE. A second slit assembly may be used to provide better collimation if necessary or to limit the horizontal beam size. Because the first mirror in the FOE operates at a fixed angle, a second mirror (Y3-20) with adjustable angle of incidence is installed in the experimental station, just before the scanner, for more flexible tuning of the high-energy cutoff. A spectrally tuned x-ray beam with a size of 100(H) x 5(V) mm^2 is thus available for DXRL exposure.

Scanner Design

The x-ray scanner consists of four precision motion stages—two translations and two rotations (Table 2). There is a θ rotation in the horizontal plane at the base, which allows precision setting of the angle of inclination of the x-rays to the substrate for inclined, trapezoidal, and conical exposures. The horizontal X travel is mounted on the θ rotation and provides accurate positioning in the horizontal direction to allow field stitching and general alignment. The vertical Z travel is mounted on the X travel and is used to scan the mask and substrate through the x-rays repeatedly during exposure. The ϕ rotation is mounted on the Z travel and can be used for generating pyramidal and conical structures. Total absolute worst case angular error due to the sum of the stage motions, including θ axis wobble, X axis pitch, yaw, and roll, and Z axis pitch, yaw, and roll should be 100 μ rad. The entire scanner is mounted on a precision optical table that can be aligned to within 5 μ m in position and 5 μ rad in angle with a full 6 degrees of freedom.

The motion stages are driven by stepping motors for positioning and DC servo motors for the vertical Z scan and include encoder feedback. The motors are controlled using the APS standard EPICS distributed control system.⁴ All of the other beamline components and the optical table are also controlled by EPICS, and this allows the complete integration of the operation of the scanning stage with the optical table, filters, slits, mirrors, and shutters, to provide the user with full control of the exposure from a program running on a computer workstation.

A temperature-controlled fixture is mounted on the ϕ rotation, and the mask and substrate to be exposed are held by this fixture. A small housing with a Kapton window mounts onto the fixture to enclose the mask and substrate in a controlled helium environment during exposure.

Thermal Management

It was recognized that the thermal loading on the x-ray mask would be a concern. The total power incident on the mask can be as high as 72 W. Higher power density would result when the exposure is carried out in the FOE rather than in the experimental station. Preliminary thermal analysis of such a case had been carried out using finite element analysis. For the purpose of the study, a 10x10 cm² beryllium mask 0.5 mm thick with a gold absorber of 50 μ m thickness had been assumed. The horizontal beam size is 6 cm in the FOE, and the mask was assumed to be scanned 6 cm vertically. The mask was in contact with cooling blocks along the four edges and was also cooled with helium gas on one side. The other side of the mask would be in proximity to the photoresist and thus cannot be provided with usable convection cooling by helium. With this geometry, the maximum temperature rise

in the mask reaches 30°C. This temperature rise and the resulting thermal expansion, though high, are acceptable for applications with relaxed tolerance and could be reduced by adapting more advanced cooling geometries or mask materials. Further studies are being performed in this direction.

Conclusion

The Advanced Photon Source offers unique capabilities in deep x-ray lithography, particularly for fabrication of high-aspect-ratio microstructures. The 2-BM beamline was designed to exploit these source characteristics and to provide optics that are necessary for optimization of the process. Flexible spectral tuning is available, and exposure can take place at two stations. A high precision scanner was designed to allow full use of the highly collimated beam for lateral accuracy and also generation of 3-dimensional profiles. Both the beamline and a prototype scanner are being commissioned, and initial exposures are being carried out to confirm their characteristics.

Acknowledgment. The authors wish to thank A. Khounsary for the thermal analysis. This work is supported in part by the Dept. of Energy, BES-Materials Science, under contract no. W-31-109-ENG-38.

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Fig. 1 Absorption length in PMMA in the hard x-ray regime.

Fig. 2 Layout of the 2-BM beamline at the APS. There are two stations: (a) the FOE, and (b) the experimental station. The following components are in the FOE: fixed mask MB, differential pump V1, filter assembly F2, slit L3, collimator K4, first mirror Y3-30 at 0.15° , multilayer monochromator DMM1, crystal monochromator OCM2, and integral shutter P6. In the experimental station, there are: beam position monitor B6, slit L4, second mirror Y3-20 with variable angle, and Be window W4.

Table 1. X-ray filter materials used in the filter assembly.

<i>Actuator A</i>	<i>Actuator B</i>
25 μm graphite	50 μm graphite
150 μm graphite	300 μm graphite
1 mm graphite	150 μm aluminum
300 μm aluminum	600 μm aluminum

Fig. 3 Spectral selection available with the 2-BM beamline. The low-energy cutoff is provided by various filter combinations. The high-energy cutoff is provided by the first mirror, using the Pt-coated surface in this case. The high energy cutoff can be further reduced by using either the Si surface on the first mirror or the second adjustable angle mirror.

Table 2. Specification of the x-ray scanner.

<u>θ Rotation</u>		<u>ϕ Rotation</u>	
Range	± 180 degrees	Range	360 deg. continuous
Resolution	20 μ radians	Resolution	100 μ radians
Accuracy	20 μ radians	Accuracy	100 μ radians
Repeatability	20 μ radians	Repeatability	100 μ radians
<u>X Travel</u>		<u>Z Travel</u>	
Range	300 mm	Range	300 mm
Resolution	0.1 μ m bidirectional	Resolution	1.0 μ m bidirectional
Accuracy	± 0.5 μ m	Accuracy	± 0.5 μ m
Repeatability	bidirectional ± 0.5 μ m	Repeatability	bidirectional ± 0.5 μ m
Velocity	bidirectional to 10 mm/sec	Velocity	bidirectional to 100 mm/sec
Veloc. Regulation	$\pm 5\%$ RMS	Veloc. Regulation	$\pm 1\%$ RMS