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Deep X-ray lithography with a tunable wavelength shifter at CAMD

C. Khan Malek,* V. Saile, H. Manohara and B. Craft

Center for Advanced Microstructures and Devices (CAMD), Louisiana State University, 3990 West Lakeshore Drive, Baton Rouge, LA 70803, USA. E-mail: chantal@lsu.edu

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An additional X-ray lithography facility is under construction at the Center for Advanced Microstructures and Devices. It will receive radiation from a 7.5 T superconducting three-pole wavelength shifter. The critical energy of the insertion device is tunable up to a maximum value of 11.2 keV, allowing for optimization of photon spectra to resist thickness. In particular, this hard X-ray source will allow investigation of X-ray lithography at very high energies for devices with thicknesses in excess of 1 mm, and study of low-cost mass-production concepts, using simultaneously exposed stacks of resist layers.

Keywords: X-ray lithography; LIGA; wavelength shifter.

1. Introduction

The Center for Advanced Microstructures and Devices (CAMD) operates a relatively compact and low-cost 1.5 GeV storage ring for the production of synchrotron radiation (Scott *et al.*, 1992). It was built by industry (Brobeck Division, Maxwell Laboratories Inc.) as the only US commercial storage ring. CAMD is a regional light source owned and supported by the State of Louisiana. Research and development efforts are focused on a limited number of special-purpose projects using synchrotron radiation. In particular, the facility operates four beamlines and exposure stations dedicated to X-ray microfabrication activities, one in X-ray lithography (XRL) and three beamlines for deep X-ray lithography (DXRL), as well as a 250 m^2 class-100 fully equipped cleanroom (Khan Malek *et al.*, 1996). The center supports one of the leading programs in synchrotron radiation microfabrication in the US, in particular in DXRL for high-aspect-ratio microsystems using LIGA (German acronym for lithography, galvanoplasty and molding [*Abformung* (Becker *et al.*, 1986)]. In the first step of this process an X-ray-sensitive polymer (resist layer) is patterned by deep X-ray lithography. The exposed areas of the resist are selectively removed in an appropriate solvent (developer), thereby transferring the latent resist image into a relief in the resist to provide thick electroplating templates for the production of metal parts or mold inserts. Mass production is possible in principle by two different approaches: using the molds produced with X-rays or by direct production of components with X-rays ('direct LIGA') (Guckel, 1996).

The infrastructure for LIGA manufacturing has been established at CAMD and is routinely available for government and industrial partners and customers, with resist thicknesses between 50 and 1000 μm (typically 300 μm) (Khan Malek *et al.*, 1997). 'Direct LIGA' for small to medium volume production of parts requires low exposure costs as well as efficient exposure strategies for throughput. Throughput can be increased by increasing the exposed area (width of the beam), using resist with higher sensitivity (Numazawa *et al.*, 1996), increasing the intensity of the X-ray beam, and by new concepts such as simultaneously exposing a stack of resist layers ('stacked exposure') with the same mask instead of serially exposing the resist/wafer layers one after the other. Stacked exposures require hard X-rays, as was first demonstrated at the NSLS X-ray ring (Siddons *et al.*, 1994) and SPEAR at SSRL (Brennen *et al.*, 1995). At CAMD, the concept of stacked exposures is currently being investigated theoretically and experimentally (Manohara *et al.*, 1997), in order to understand and optimize various parameters and finally demonstrate its viability for manufacturing. For hard X-ray exposures, photon energies well in excess of 10 keV are required. An upgrade of the CAMD facility for hard X-ray production is in progress. It includes the installation of a 7.5 T superconducting multipole wavelength shifter and a beamline for ultra-deep X-ray lithography (UDXRL). This paper discusses the status of hard X-ray lithography at CAMD as of August 1997.

2. X-ray lithography at various energies

In X-ray lithography, the absorber pattern on the mask is transferred utilizing synchrotron radiation by shadow casting. Table 1 shows respective characteristics of UDXRL compared with DXRL and XRL. An obvious requirement of such an exposure scheme is radiation energetic enough to penetrate through the resist depth and deposit sufficient dose at the bottom of it. The penetration depth of the X-rays in the resist [poly(methyl methacrylate) (PMMA)] as a function of photon energy is shown in Fig. 1. Resist requirements include a limited dose gradient. Thick PMMA resist requires long exposures because sufficient dose has to be absorbed in each volume element from the surface to the bottom of the resist layer. Exposure of PMMA resist is restricted by the following conditions:

(*a*) A threshold dose of approximately 2 kJ cm^{-3} is required at the bottom of the resist to allow development (sensitivity of the resist).

(*b*) The degradation of the resist induced by the absorption of the radiation in the bulk of the resist is accompanied by the

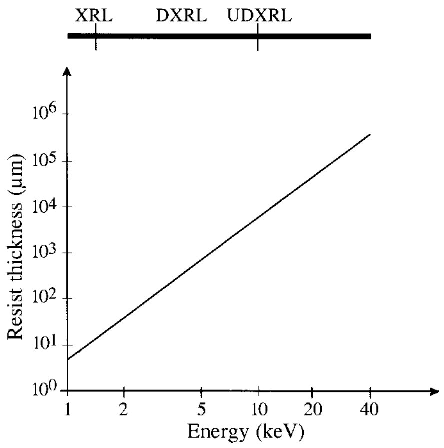

Figure 1

PMMA resist thickness as a function of photon energy. The ratio of top to bottom dose within the resist was assumed to be 5. The values were calculated from mass attenuation coefficients tabulated by the National Institute of Standards and Technology (NIST) (http://physics.nist.gov/PhysRefData/X-rayMassCoef/).

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Table 1
Comparison of various X-ray lithographic methods using proximity printing.

	XRL	DXRL	UDXRL
Technology	Microelectronics	High-aspect-ratio MEMS	Precision machining
Process	Planar patterning	Three-dimensional microstructures	Three-dimensional microstructures
Production method	Direct exposure	Moulds for replication or direct exposure	Stacked exposure, direct exposure
Applications	DRAM, processor (optoelectronics) (nanolithography)	Sensors, actuators, optics	Mechanical parts, gears
Typical wavelength (nm)	0.8–1.4	0.2–0.4	0.07
Typical resolution (μm)	High ≤ 0.25	Medium ≥ 1	Low ≥ 10
Typical thickness (μm)/resist	1/various	$\leq 10^3$/PMMA	$\leq 10^5$/PMMA
Aspect ratio	Low ≤ 10	High ≤ 100	High ≤ 100
X-ray source	Synchrotron or point source	Synchrotron	Synchrotron
Synchrotron energy (GeV)	0.6–1.2	1.0–2.0	≥ 2.5
Wavelength shifter		≥ 0.8	≥ 1.3
Beamline	Collimating mirrors	Filters, no/plane mirrors	Filters, no mirrors

formation of gaseous species in the polymer. If the gas production rate is too high, the gas cannot diffuse fast enough out of the resist, bubbles are formed within the resist and the resist 'swells'. This swelling presents the most severe restriction for reducing exposure times because it limits the rate of dose deposition within the resist.

(*c*) If the surface dose is too high, the resist will decompose ('foam and burn'). This maximum dose depends on the photon energy.

One of the major problems of commercialization of LIGA is cost and throughput. Direct production of LIGA parts is limited by the maximum dose rate tolerated by the resist. This limits the benefits of higher synchrotron radiation power by increasing the stored current in the ring. One concept to increase throughput is to distribute a high dose rate over several resist layers. Each layer would be exposed with a tolerable dose rate but the overall throughput would be increased by *N* times, if *N* is the number of resist layers. Stacking of *N* resist layers requires photon energies with a penetration depth large enough to expose the bottom of the last layer. For this reason, the use of hard X-rays for LIGA will be investigated at CAMD.

The CAMD storage ring operates with an electron energy of 1.3 or 1.5 GeV, which yields a critical photon energy of 2.5 keV (4.8 A) at 1.5 GeV from a bending-magnet source. The DXRL beamline with its 125 μm-thick Be window functions as a high-pass filter transmitting the spectrum for photon energies above 1.5–2 keV. The transmitted spectral distribution can be shifted towards harder X-rays with filters attenuating lower-energy photons but at the expense of the overall power on the resist, and in practice, exposure times become longer. For example, in a typical exposure scenario with optimized conditions (filters, energy), the exposure time is approximately a factor of 4 longer for 1 mm-thick resist exposed as compared to 300 μm resist. For thick resist or multiple resist layers, this calls for exposures at higher photon energies and flux than currently available at CAMD.

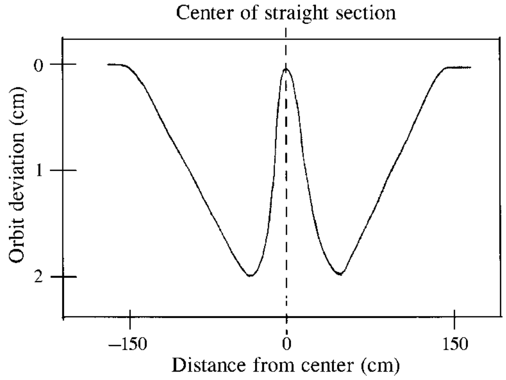

Figure 2
Electron trajectory in the wavelength shifter at 7 T magnetic field.

Hardening the synchrotron radiation spectrum of a storage ring using a superconducting wavelength shifter and a multiple-pole wiggler is a well proven concept. For example, a wavelength shifter in the 800 MeV BESSY I ring (Gerner *et al.*, 1996) shifts the critical energy from 0.65 keV at a bending magnet to 1.7 or 2.6 keV at 4 and 6 T, respectively. This insertion device allows for deep X-ray lithography at a low-energy storage ring and furthermore for optimization of the exposure conditions with resist thicknesses through the choice of critical energy. At CAMD a similar concept is employed to produce hard and very hard X-rays with a very compact, medium-energy machine. This will allow, among other applications, exposure of both very thick resist for precision machining with X-rays and for stacked exposures.

An upgrade of the storage ring to include a source of high-energy X-rays is underway. It consists of a superconducting wavelength shifter (Borovikov *et al.*, 1998) and two normal conducting magnets in a 3 m-long straight section of the ring. The wavelength shifter is composed of three superconducting magnets, a central pole with a maximum field of 7.5 T and two side poles (1.55 T). The two side poles along with the additional two normal conductivity magnets are arranged and excited in such a way that the position of the X-ray source in the storage ring is independent of the magnetic field strength of the central pole and remains fixed even when tuning the spectrum emitted by the wavelength shifter. Adding two additional side poles to a classical wavelength shifter allows for a fixed electron beam position in the central pole when changing the magnetic field strength (Fig. 2) and keeps the X-ray source on-axis in the straight section of the storage ring. The latter allows the maximum horizontal width emitted by the wavelength shifter (26 mrad at the port) to be accepted with minimum change of critical energy and power over the width of the emitted radiation fan (see Fig. 3). The one-pole fixed-source concept provides major advantages in particular when installing multiple beamlines at the same insertion device because it provides a single source, a large angle of radiation and tunability of the spectrum. This wavelength shifter has been built by the Budker Institute of Nuclear Physics in Novosibirsk and will be installed at CAMD at the end of 1997. In addition to the installation of the insertion device, an upgrade of the RF system is underway, including a second 500 MHz cavity powered by a 65 kW amplifier.

The wavelength shifter at 7.5 T provides a gain in power per horizontal angle of 4.4 at 1.5 GeV and 5.1 at 1.3 GeV compared with a CAMD bending magnet [power P (W mrad^{-1}) = $4.33E^3BI$, where E and I are the electron energy and current, respectively, and B is the magnetic field]. At 7.5 T, the critical energy of the spectrum is 11.2 keV (0.11 nm), which allows applications requiring photon energies of 30 keV and above. For comparison, Brookhaven's NSLS X-ray ring provides a fixed critical energy of 5.6 keV from a bending-magnet source with the ring operating at 2.56 GeV. Important design criteria for the insertion device were homogeneity of power for lithographic applications over a large horizontal distance of up to 150 mm (8″ wafer), and no 'multiple source' effects for additional beamlines using the remaining beam width from the port. The variation of the critical energies from the central pole and the two side poles with observation angle in the horizontal plane is shown in Fig. 3. For the central pole it is less than 1% over the central 15 mrad radiation fan dedicated to lithography. The critical energy of radiation emitted by the side poles is 2.5 keV at 1.5 GeV, and thus comparable to those of a bending magnet of the storage ring. As a result, an observer will see three light sources separated horizontally by approximately 2 cm and having critical energies of 11.2 and 2.5 keV. In particular in applications where the source is imaged or the angular resolution of synchrotron radiation is important, such as in crystallography, one well defined source point is essential. The additional sources originating from the side poles can be then eliminated by sufficient thickness of beryllium window or additional metal filters, which allows work at energies higher than approximately 5 keV, with a single source. The tunability of the radiation spectrum from soft to very hard X-rays will enable research, prototyping and production under optimal conditions. In particular, it will allow optimization of the penetration depth of the X-ray spectrum within the resist layer to match the resist thickness of the microstructures to be fabricated.

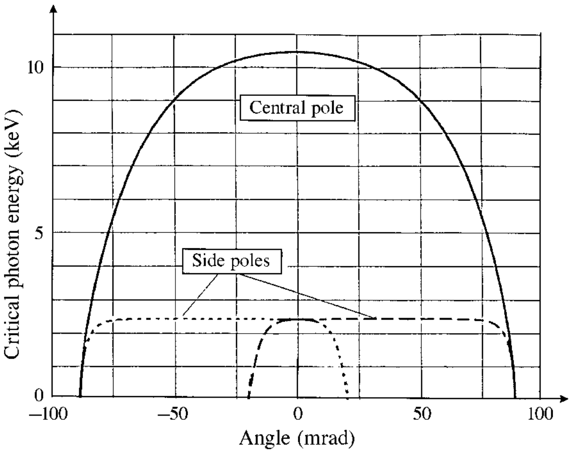

Figure 3
Critical photon energy *versus* horizontal angle at electron energy of 1.5 GeV (courtesy N. Mezentsev, Budker Institute for Nuclear Physics, Novosibirsk).

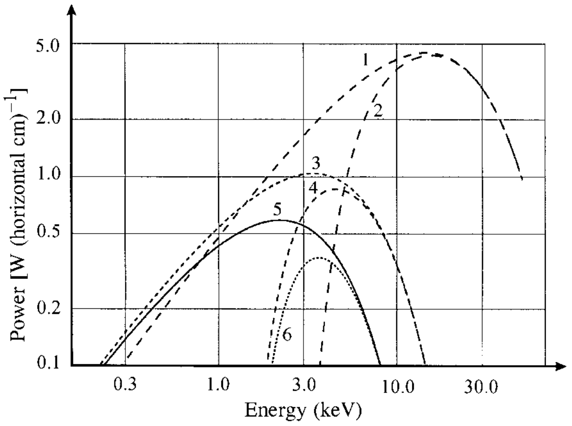

Figure 4
Synchrotron radiation power from a bending magnet and wavelength shifter at 7.5 T (curve 1). Parameters in the calculation were: storage ring operated at 1.3 GeV (curve 5) and 1.5 GeV (curve 3) electron energies with a current of 100 mA. Power available for lithographic applications: at the bending-magnet beamline, distance to X-ray source 10 m, no optical element, 125 µm Be window (1.3 GeV, curve 4, and 1.5 GeV, curve 6); at the wavelength shifter beamline, distance to X-ray source 10 m, no optical element, total of 150 µm graphite filters and 250 µm Be window (curve 2).

A beamline and an exposure station have been designed and are currently under construction. Initially, the beamline will use 5 mrad of the 16 mrad dedicated for microfabrication of a total fan of 26 mrad available for beamlines at this insertion device. A stack of graphite filters, with increasing thickness, amounting to a total thickness of 100 µm, reduces the heat load on the window by absorbing low-energy photons. It precedes a 250 µm-thick Be window followed by a 50 µm graphite foil. The exposures will take place in helium at atmospheric pressure. Fig. 4 shows the incident X-ray power downstream of the Be window with the wavelength shifter at 7.5 T in comparison to a bending-magnet source at CAMD.

3. Conclusions

A superconducting tunable wavelength shifter will enhance the capabilities of the relatively compact and medium energy CAMD ring by providing a source of hard X-rays at minimum cost compared to higher-energy facilities. This new X-ray source will allow investigation of deep X-ray lithography with high photon energy to meet requirements such as production of devices with thicknesses in excess of 1 mm and low-cost mass production with high throughput using stacks of resists to be exposed simultaneously. The tunable wavelength shifter in combination with CAMD extensive microfabrication infrastructure will open up new opportunities in LIGA-type applications.

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References

Becker, E. W., Ehrfeld, W., Hagmann, P., Maner, A. & Münchmeyer, D. (1986). *Microelectron. Eng.* **4**, 35–56.

Borovikov, V. M., Craft, B., Fedurin, M., Jurba, V., Khlestov, V., Kulipanov, G., Li, O., Mezentsev, N., Saile, V. & Shkaruba, V. (1998). *J. Synchrotron Rad.* **5**, 440–442.

Brennen, R. A., Hecht, M., Wiberg, D. V., Manion, S. J., Bonivert, W. D., Hruby, J. M., Scholz, M. L., Stowe, T. D., Kenny, T. W., Jackson, K. H. & Khan Malek, C. (1995). *SPIE J.* **2640**, 214–225.

Gerner, M., Kührich, H., Martin, M., Petersen, H., Scheer, M., Wüstefeld, G., Huber, H. L., Oertel, H. K. & Scheunemann, H. U. (1996). *Synchrotron Radiat. News*, **9**(3), 17–23.

Guckel, H. (1996). *Rev. Sci. Instrum.* **67**(9), 1–5.

Khan Malek, C., Manohara, H. & Saile, V. (1997). *Microsystem Technol.* **4**(1), 2–6.

Khan Malek, C., Vladimirsky, Y., Vladimirsky, O., Scott, J., Craft, B. & Saile, V. (1996). *Rev. Sci. Instrum.* **67**(9), 1–6.

Manohara, H., Khan Malek, C., Dewa, A. S. & Deng K. (1997). *Microsystem Technol.* **4**(1), 17–20.

Numazawa, T., Hirata, Y. & Takada, H. (1996). *Microsyst. Technol.* **2**, 46–49.

Scott, J. D., Bluem, H. P., Craft, B. C., Marceau-Day, L., Mihill, A., Morikawa, E., Saile, V., Vladimirsky, Y. & Vladimirsky, O. (1992). *SPIE J.* **1736**, 117–128.

Siddons, D. P., Johnson, E. D. & Guckel, H. (1994). *Synchrotron Radiat. News*, **7**(2), 16–18.