Lawrence Berkeley Laboratory
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Accelerator & Fusion Research Division

LBL--16592
DE84 001875

To be presented at the Brookhaven Conference on Advances in Soft X-Ray Science and Technology, Brookhaven National Laboratory, Upton, NY, October 17-19, 1983

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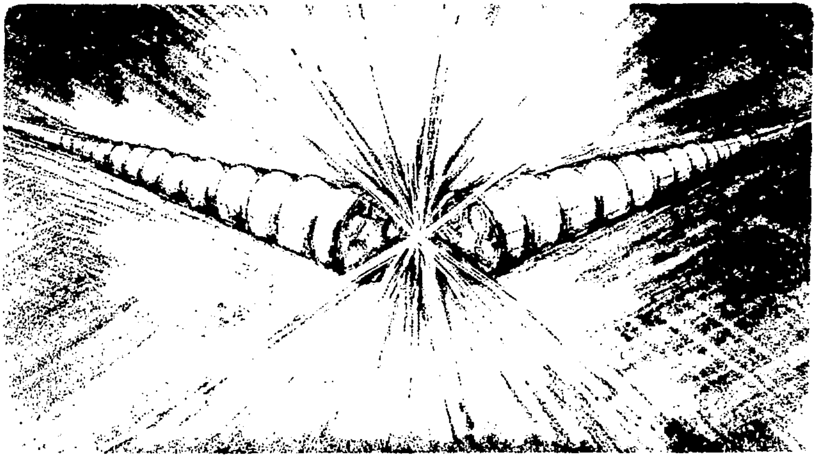
August 1983



Prepared for the U.S. Department of Energy under Contract DE-AC03-76SF00098

X-Ray Lithography using Wiggler and Undulator Synchrotron-Radiation Sources

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ABSTRACT

Wiggler and undulator insertion devices are very powerful sources which allow new approaches in the design of synchrotron x-ray lithography systems. The principal advantage of insertion devices is that they can be used as a narrow bandwidth high throughput lithography sources at any wavelength. For a wiggler the increased flux can be continuously traded off against beam current, horizontal beam angle and bandwidth. The undulator offers several watts of power in a narrow 1% bandwidth and has a very compact beam (0.05 mr) which must be scanned both horizontally and vertically. Insertion devices could thus be used in an evolutionary way with conventional x-ray tube technologies or in a revolutionary way at high contrast very soft x-ray wavelengths.

A systems design approach is used to identify feasible options for wiggler and undulator beam lines for x-ray lithography in the 0.5-0.2 μm linewidth region over 5 cm by 5 cm fields. Typical parameters from the Wiggler and Undulator in the Advanced Light Source designed at the Lawrence Berkeley Laboratory are used as examples. Moving from the conventional wavelengths of 4-9 A to very soft wavelengths around 15 A is shown to be very promising. The mask absorber thickness can be reduced a factor of three so that 0.2 μm features can be made with a 1:1 mask aspect ratio. The mask heating limited exposure time is also reduced a factor of three to 3 sec/cm^2. However, extremely thin beam line windows (1/4 mil Be) and mask supports (1 μm Si) must be used. A wiggler beam line design using a small slit window at a scanning mirror appears feasible. A unconventional, windowless differentially pumped beam line with dual deflecting mirrors could be used with an undulator source.

I. Introduction

X-ray lithography is one of the most promising approaches for high volume IC production. To follow the success of optical lithography the effective writing speed of x-ray systems must be on the order of 2 cm^2/sec at a net cost of about $2.00 per level. X-Ray systems are now commercially available[1,2] which use conventional electron beam x-ray tubes. They will likely be successful on special products down to 0.5 μm linewidths but will rely heavily on the use of very sensitive resists and multilayer pattern transfer techniques. Bending magnet synchrotron sources are being investigated[3] as much more powerful sources for use with robust single layer resists at linewidths down to 0.1 μ. Wiggler and undulator sources offer a two order of magnitude increase in flux[4,5] which allows flexible tradeoffs for improved performance.

The goal of this paper is to examine how wigglers and undulators might best be utilized in an x-ray lithography system. Here a high throughput system for linewidths in the 0.5-0.2 μ range over a 5 cm by 5 cm field is envisioned. Large wafers could be handled with this system by making a number of steps depending on wafer distortion and mask runout. The real advantage of the insertion devices over a bending magnet is that they have sufficient power for narrow band operation. This would allow the mask and resist technologies developed for conventional x-ray tube sources to be adapted to synchrotron sources in an evolutionary manner. With true wavelength flexibility the use of absorption edges in resists and windows can be more fully exploited. More importantly, for the first time it is feasible in high throughput systems to move into the very soft x-ray region 13-16 A where very high contrast is available[6].

The characteristics of wigglers and undulators are first discussed in Section II. Section III presents the case for using very soft 15 A x-rays. Wiggler and undulator beam line design strategies are given in Sections IV and V for the challenging case of 15 A operation.

II. Characteristics of insertion devices

Wiggler and undulator devices consist of arrays of alternating magnetic field polarity which laterally deflect the electron beam. A sketch of a wiggler structure is shown in Figure 1. The essential feature is the periodic array of magnet pairs which form the array pole pairs. The development by Halbach[7] of insertion devices which use rare earth permanent magnets has made possible very powerful x-ray sources. An undulator is basically similar in appearance. Suitable examples of insertion devices for lithography can be found in the wiggler E and undulator D specifications in the Advanced Light Source machine design[5]. Wiggler E has 25, 10 cm periods for a total length of 2.5 m. Undulator D has 142, 3.5 cm long periods and a total length of 5 M. The wiggler requires a higher magnetic field (1.6T) than is used with the undulator (0.57T).

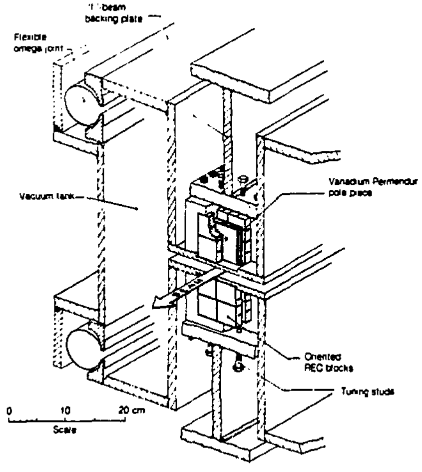

Figure 1. Physical structure of a wiggler showing the periodic array of alternating magnetic field polarities. The undulator physical structure is similar.

The wiggler utilizes N pole pairs to achieve a 2N increase in flux over a limited horizontal angle (±4 mr) for wiggler E). The spectrum of the wiggler is basically a 2N upward shift of the bending magnet spectrum. This can be seen in the spectra shown in Figure 2. The higher flux could be used to address other system problems such as beam current, horizontal beam angle or bandwidth. Undulators utilize coherent addition of signals from the arrayed pole pairs to produce an N^2 flux increase. However, the coherent interaction produces a narrow bandwidth (1%) and a narrow horizontal beam angle (0.5 mr). The undulator typically has extremely high brilliance over a narrow bandwidth as shown in Figure 2. Note the presence of harmonics as well. The desired 5th harmonic at 827 ev (15 A) is accompanied by undesired radiation at the 3rd (25 A) and 7th (10.7 A) harmonics.

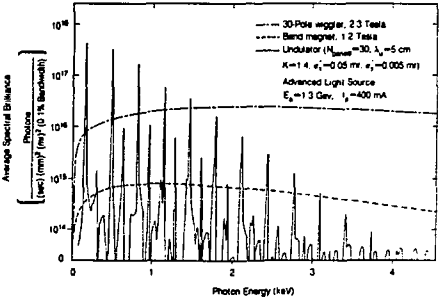

Figure 2. Example of the spectral brilliance characteristic of a bending magnet, wiggler and undulator.

A basic comparison of typical beam line parameters and writing speeds is shown in Figure 3. As a point of reference the two optimized bending magnet sources described by Grobman[3] are shown. The use of a non-optimized source, SPEAR[8], is also included. The bending magnet sources all operate in a broadband mode (4-14 A) centered around 8-9 A. They use a 1 mil Be window with 3.0 μm silicon and 2.0 μm of polymer. The sequence of bending magnet cases shows the need for simultaneous high beam current, large horizontal angle and broad spectrum.

Several cases of wiggler and undulator sources for x-ray lithography are given in Figure 3. These devices are evaluated in systems operating near 15 A where it is difficult to get high delivery efficiency. Results at other wavelengths would however be roughly similar. The wiggler narrowband (1%) system shows the same writing speed as the small optimized bending magnet. Yet this speed is accomplished with one 50th the bandwidth and one tenth the horizontal beam angle. The narrow bandwidth is assumed to be made possible by a multilayer mirror with a 40% reflectivity. As an alternative to this mirror a small partial pressure of Ne gas along the

Synchrotron X-Ray Lithography Systems

Type	Example	λ (A)	Mask μm	BW (%)	Angle (mr)	Power (w)	Efficiency (%)	Writing Speed (cm²/s)
Bending Magnet	SPEAR 1.5 GeV 100 mA	8.4	0.8	50	2.5	0.24	17	0.05
Bending Magnet	0.8 GeV 400 mA 1.91m	8.7	0.85	57	25	4.3	13	0.88
Bending Magnet	1.0 GeV 400 mA 1.91m	8.4	0.6	40	25	14.0	17	3.0
Wiggler (Multilayer)	1.3 GeV 400 mA 1.8T, N=25	15	0.2	1	2.5	1.7	9	0.6
Wiggler (No Filter)	1.3 GeV, 400 mA 1.8T,N=25	15	0.2	15	2.5	25.0	8	11.0
Undulator (Diff Pump)	1.3 GeV 400 mA N=100	15	0.2	1	0.5	2.6	17	1.8

Figure 3. Lithography system beam line parameters and writing speed typical of bending magnet, wiggler and undulator source systems.

beam line from the mirror could be used to filter out wavelengths harder than 14.3 A. This would produce about a 15% band pass filter and give an order of magnitude increase in writing speed. For true narrow band operation (1%) the undulator is the best as its spectrum is prefiltered. The undulator radiation pattern is sufficiently compact that a windowless differentially pumped beam line is possible. The writing speed is a respectable 1.8 cm^2/sec.

III. Use of very soft 15 A x-rays

X-Ray lithography faces many technology problems other than source power which must be simultaneously advanced. These include mask fabrication, alignment, pattern transfer and defect density. The flexibility of wiggler and undulator devices can be used to impact some of these technology problems. One promising approach is to shift the wavelength of operation to the very soft 15 A region. Such a change would allow a reduction in mask absorber thickness which would benefit mask fabrication, detection of alignment marks, and possibly defect density. Resist loading with fluorine[9] would also be possible.

The gold thickness required to adequately mask is shown in Figure 4 as a function of wavelength. Here the traditional optical lithography definition of contrast as (max-min)/(max+min) is used. The calculation is based on the data of Viegle[10]. A contrast of 0.85 is viewed as just adequate for lithography and corresponds to a factor of 12 attenuation by the absorber. The required absorber thickness decreases rapidly as the wavelength increases. By moving from 8-9 A to 15 A the absorber thickness can be reduced a factor of 3 to 0.2 μ. Thus the mask pattern height to linewidth aspect ratio can be reduced at 0.2 μm resolution from 3 to 1. This reduction is not possible even with bending magnet sources as additional thickness is needed to mask the short wavelengths in the broadband spectrum.

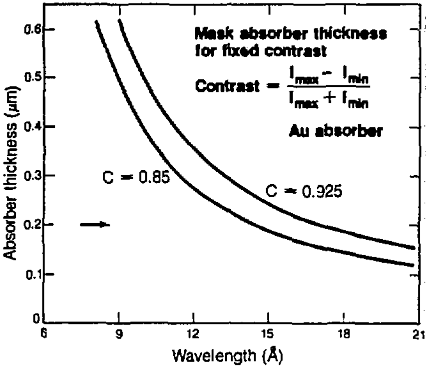

Figure 4. Mask absorber thickness required for a fixed contrast as a function of wavelength.

There are several other issues which must be considered in moving the exposing wavelength to 15 A. To compensate for the effect of the resist absorption in lowering the contrast between the bottom of the exposed resist and the top of the masked resist, the mask thickness must be increased slightly (from 0.185 to 2.3 μm). The diffraction of the x-rays passing through the mask limits the mask to wafer spacing to 17 μm for 0.2 μm features at 15 A[11,12]. Mask heating and the resulting distortion will likely limit the flux density to 100 mW/cm^2[13]. For exposure of PMMA at 1000J/cm3 this results in a writing time of 10 sec at 9 A which reduces to a more favorable 3 sec at 15 A.

The most likely limitation in going to 15 A is the absorption of the intermediate windows, mask support and atmosphere on the way to the resist. This is illustrated in Figure 5 where the effective writing speed for exposing the top of a PMMA resist to 1000J/cm3 is shown. The only intervening materials are a Be window of various thicknesses and a 1 μm Si mask support. The initial reduction in effective writing speed due to increased resist absorption is quickly over powered by the increase due to window absorption. For operation at 15 A, a 1/4 mil Be window produces almost a 3 fold decrease in the writing speed. Thicker windows are unacceptable. Thus the capability to build beam lines with extremely thin windows is probably the most critical issue for operation at 15 A.

IV. Wiggler beam line strategies

Conceptual designs for lithography beam lines will now be considered in detail to establish the feasibility of operating at 15 A. The intent here is to put forward several new approaches which have been created to handle the characteristics of the wiggler and undulator devices. These designs are

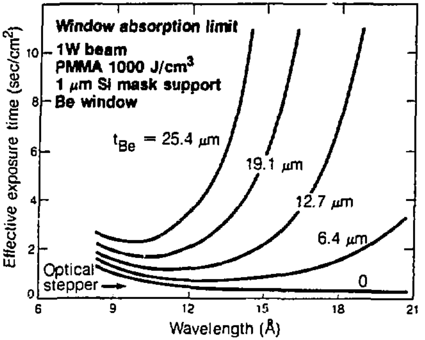

Figure 5. Effective exposure time per cm^2 as a function of wavelength for different Be window thickness with a 1 μm Si mask.

merely plausible approaches from which more useful designs will hopefully evolve.

A possible beam line design for a wiggler at 15 A is shown in Figure 6. The primary design considerations are the cooling gas, reducing the window size, minimizing the flux attenuation, scanning the beam vertically and constructing a narrow bandwidth filter. For cooling a small pressure of 50 Torr of He should suffice[14]. The He could extend back up the beam line to the mirror chamber to allow a very small window to be used. A valve is used to isolate the exposure chamber. The window could be 3 mm high which could handle a load of 5 W in a 1 mm high beam. For writing speed the window could at most be 1/4 mil thick. To produce a 5 cm wide field 20 m from the source the window would need to be 3 cm long. The relatively small beam size would also allow the window to be replaced by a differentially pumped section similar to those which will be described for use with undulators. Scanning could be accomplished by rotating a grazing incidence mirror ±2.5 mr to cover a 5 cm high field 10 m away at the wafer location.

The most difficult problem is high throughput, narrow bandwidth filtering. Multilayer mirrors as developed by Barbee[15] appear promising. For a 1% bandwidth an efficiency of 20% has been obtained and up to 40% efficiency is theoretically possible[16]. A single multilayer mirror would deflect the beam at a net angle of about 45°. Two such mirrors could be used to compensate each other as shown in Figure 7. A pair of these mirrors could also deflect the beam 90° and conventional horizontal mask and wafer stages might be used. The design of a high throughput, narrow bendwith filter presents an interesting challenge to multilayer mirror technology.

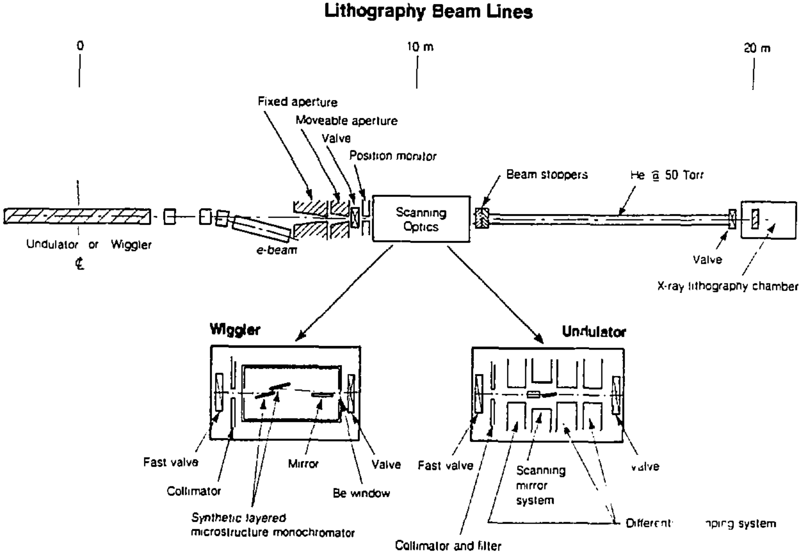

Figure 6. Lithography beam line design for a wiggler and an undulator source.

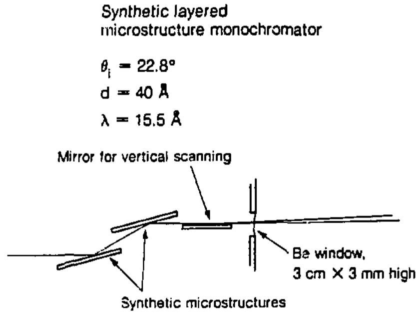

Figure 7. Monochromater design for the wiggler beam line.

The throughput of the wiggler system just described can be calculated as follows. Wiggler E produces $5X10^{14}$ photons/(sec mr 0.1%BW) which corresponds to 1.85 W over a 2.5 mr angle in a 1% bandwidth at 15 A. Assuming a single multilayer mirror which would deflect the beam about 45° the combined filter and scanning mirror efficiency of 0.32 would be typical. Using a window window efficiency of 0.39 only 15% of the power will reach the mask. The mask transmission is 0.56 so 9% or 0.14 W is incident on the resist. The effective writing speed of PMMA at a dose of 1000J/cm3 is about 0.8 cm^2/sec. An increased horizontal beam angle up to 8 mr could be used to boost the throughput. This may not be necessary as other robust resists which are up to 10 times faster than PMMA might be used.

As an alternative to a narrow bandwith filter, a small partial pressure of Ne gas in the beam line could be used to filter out radiation harder than 14.3 A. The silicon in the mask support would also help eliminate radiation harder than 6.7 A. The long wavelengths would naturally be eliminated by the increase in the Be, He, Ne, and Si absorption constants as the third power of wavelength. A proper design would weigh the tradeoffs carefully and might require a slight modification of the wiggler parameters to more rapidly roll off the hard radiation. The remaining natural bandwidth is about 15%. This would give an order of magnitude increase in writing speed as in the 15% wiggler example indicated in Figure 3.

V. Undulator beam line strategies

A possible beam line for an undulator source is shown in Figure 6. The key design issues are cooling the mask, elimination of windows, a dual scanning system, and filtering out the undesired undulator harmonics. Again 50 Torr of He is used for cooling which allows the optical components to be located 10 m from the wafer which is 20 m from the source. The natural choice for the undulator energy is the 5th harmonic which is in the vicinity of 827 ev corresponding to 15 A. The power in the 1% bandwidth of this harmonic is about 2 W. At 10 m from the source the beam size is an ellipse 0.5 mm by 0.2 mm. The flux is so high that even a 3 mm diameter window would not have adequate strength at the resulting operating temperature. However, the beam is sufficiently compact that a differential pumping system could be used to eliminate the need for a high vacuum window.

A possible windowless differential pumping system is shown in Figure 8. The system is based on using several 100:1 length diameter sections each of which can drop about three orders of magnitude in pressure. A 3mm diameter section is used between the machine vacuum and the scanning optics chamber. An identical section is used down line from the chamber. A third 5 mm diameter section is used to reach the 50 Torr He atmosphere. The He consumption will be tollerable as one cylinder would last three days. It is also possible to recycle the He from the turbomolecular pump. A similar windowless differential pumping system could be designed for use with the wiggler but would require five rather than three sections and the He consumption would be more than 10 times higher.

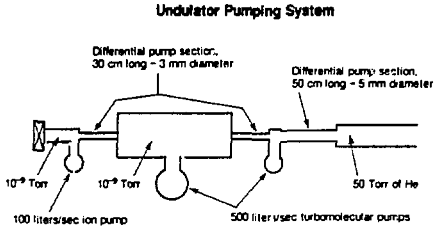

Figure 8. Windowless differential pumping system for the undulator lithography beam line.

A dual mirror scanning system for the undulator line is shown in Figure 9. By itself the undulator beam would form an elliptical spot 1mm wide by 0.4 mm high on the wafer 20 m from the source. Deflection ±2.5 mr in both the vertical and horizontal directions would be necessary to illuminate a 5 cm by 5 cm area. The first mirror deflects the beam horizontally and the second deflects vertically. This can be carried out using 5 cm long mirrors at 1° grazing incidence. The maximum scanning deflection angle is only about half of the acceptance angle of the differentially pumped sections.

The writing speed for this undulator system can be calculated as follows. The spectral brilliance of the 5th harmonic of undulator D tuned to 15 A would be $1.5x10^{15}$ photons/(sec 0.1%BW). Thus the available flux in a 1% bandwidth peak is about 2 W of power. Assuming a scanning mirror efficiency of 75% and a 39% transmission through the He atmo-

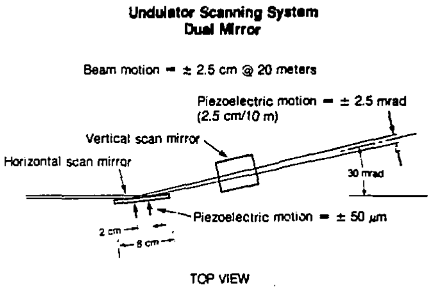

Figure 9. Dual horizontal and vertical scanning system for the undulator lithography beam line.

sphere almost 600 mW reaches the mask. With the 1 μm Si mask support over 300 mW is incident on the resist the effective writing speed is 1.8 cm^2/sec. This flux level at the mask would necessitate rapid scanning over at least a 8 cm^2 area.

To make a useable lithography system it is necessary to develop ways of eliminating the undesired 3rd and 7th harmonic exposure contributions. The third harmonic contribution at 25 A can easily be eliminated with the He gas atmosphere. The 7th harmonic contribution can be eliminated with a Ne environment but it is best if this filtering function could be folded into the scanning mirror design instead. The ability of a mirror at grazing incidence to rapidly cutoff depends critically on the optical constants of the mirror material. An example of the transmission of both Cu and Mg mirrors as a function of angle of incidence is shown in Figure 10 for both the 5th and 7th harmonics. The values show are the product of the s and p reflectivities as would occur in a dual scanning system. It has been calculated using the Fresnel formulas (see Rehn[17]) using the data of Hagmann et al.[18]. With Cu (and Au as well) the roll off of the 7th harmonic transmission is not very rapid due to a large k/δ value. Thus at 75% transmission of the 5th harmonic the relative suppression of th 7th harmonic is only a factor of 4. For Mg which has a small k/δ the roll off gives excellent rejection of a factor of over 1000. Multilayer scanning mirror materials are a third possibility in addition to Cu and Mg.

Three undulator beam line approaches can be based on the three options for mirror materials mentioned above. To evaluate each of these designs an exposure index is defined as the product of the flux transmission times the effectiveness of the exposure in PMMA relative to an exposure at the 5th harmonic (15 A). An exposure index of 1.0 corresponds to a writing speed of 11 cm^2/sec. The goal is to reduce the exposure contributions of the two unwanted harmonics to about 1% each without trading off too much throughput. The most conservative design is to simply assume Cu mirrors are used and eliminate the unwanted harmonics with Ne and He. An attractive alternative is to use Mg mirrors which eliminate the 7th harmonic and then use a He atmosphere to absorb the 3rd harmonic. Finally, a single multilayer mirror together with a Cu mirror might be used to filter out both the 3rd and 7th harmonic.

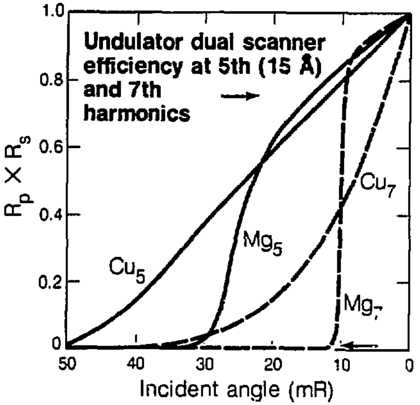

Figure 10. Dual scanning mirror transmission as a function of the grazing incidence angle for Cu and Mg at the 5th (15 A) and 7th (10.7 A) harmonics.

The efficiency budgets for these three designs are shown in Figures 11-13. In all cases the minimal amount of Ne and He has been used. The resulting writing speeds are all in the 1.5-2.0 cm^2/sec and the Mg mirror case was selected as the undulator example in Figure 3. The specifications chosen for the multilayer mirror case represent the minimal undulator harmonic rejection ratio (30) and reflectivity (0.4) which would be required to be comparable to the other two approaches. A careful consideration of design tradeoffs possible with multilayer mirrors is needed.

Undulator Lithography Beam Line
Design I: Cu Mirrors and Ne Filter
Efficiency Budget

Harmonic	3	5	7
Cu Mirrors 10mr	0.884	0.781	0.406
He	0.050	0.390	0.819
Ne	0.100	0.546	0.017
Si$_{1\mu m}$	0.127	0.561	0.780
PMMA Response	4.24	1.0	0.381
Exposure Index	0.002	0.141	0.002
Relative Index	0.017	1.0	0.012

Delivery Efficiency to Mask = 25.2%

Figure 11. Beam line efficiency budget and relative exposure index for the 3rd, 5th and 7th undulator harmonics using a Cu mirror and a Ne absorption edge filter.

Undulator Lithography Beam Line
Design III: Multilayer Mirrors
Efficiency Budget

Harmonic	3	5	7
Multilayer Mirror System	0.010	0.32	0.010
Si$_{1\mu m}$	0.127	0.561	0.780
PMMA Response	4.24	1.0	0.386
Exposure Index	0.005	0.18	0.003
Relative Index	0.030	1.0	0.016

Delivery Efficiency to Mask = 32%

Figure 13. Beam line efficiency budget using a multilayer mirror to attenuate both the 3rd and 7th harmonics.

Undulator Lithography Beam Line
Design II: Mg Mirrors
Efficiency Budget

Harmonic	3	5	7
Mg Mirrors 15 mr	0.751	0.748	4.5×10^{-4}
He	0.005	0.393	0.702
Si/μm	0.127	0.561	0.780
PMMA Response	4.24	1.0	0.386
Exposure Index	0.002	0.165	10^{-4}
Relative Index	0.012	1.0	0.001

Delivery Efficiency to Mask = 29.4%

Figure 12. Beam line efficiency budget using Mg mirrors to attenuate the 7th harmonic.

VI. Conclusion

Insertion devices in synchrotrons offer a two order of magnitude increase in available flux for lithography. In the case of the wiggler the increased flux can be continuously traded off against beam current, horizontal beam angle and bandwidth. Undulators offer several watts of power in a narrow bandwidth (1%) and have a very compact beam (0.05 mr) which must be scanned both horizontally and vertically.

The beam line designs for wigglers are similar to those for bending magnets with more attention paid to selecting a desired portion of the spectrum. Multilayer mirrors or absorption edge filters might be used for this purpose. Undulator beam lines require unconventional approaches such as differential pumping and dual scanning mirrors. It is preferable to use mirror materials such as Mg which give a sharp rejection of the 7th harmonic but absorption edge filters could also be used.

The possibility of narrow bandwidth exposure with insertion devices offers significant advantages in lithography. Mask and resist technologies developed for conventional x-ray tubes could be directly utilized in an evolutionary manner. Further optimization of materials properties could be made with a flexible wavelength choice. Moving from conventional wavelengths 4-9 A to very soft wavelengths around 15 A appears very promising. The mask absorber thickness can be reduced a factor of three so that 0.2 μm features can be made with a 1:1 mask aspect ratio. The mask heating limited exposure time is also decreased a factor of three to 3 sec/cm^2. However, extremely thin beam line windows (1/4 mil Be) and mask supports (1 μm Si) must be used. This could be accomplished in a wiggler system by using a very small slit window at the scanning mirror. For the undulator system windowless differential pumping has been shown to be feasible.

VII. Acknowledgment

This work was supported in part by a National Science Foundation Grant ECS-8106324 and by the Director Office of Basic Energy Sciences. Office of Energy Research, U.S. Department of Energy, under Contract No. DE-AC03-76SF00098.

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