X-RAY LITHOGRAPHY SOURCES: A REVIEW*

James B. Murphy
National Synchrotron Light Source
Brookhaven National Laboratory
Upton, NY 11973

1. Abstract

Synchrotron radiation from dipole magnets in electron storage rings has emerged as a useful source of x-rays for lithography. To meet the need for these sources numerous groups around the world have embarked on projects to design and construct storage rings for x-ray lithography. Both conventional electromagnets as well as superconducting (SC) dipoles have been incorporated into the various designs. An overview of the worldwide effort to produce commercial x-ray sources will be presented. To better illustrate the elements involved in these sources a closer examination of the Superconducting X-ray Lithography Source Project (SXLS) at BNL will be presented.

2. Introduction

X-ray lithography[1-3] has emerged as a strong candidate to meet the demands of ever finer linewidths on integrated circuits, particularly for linewidths less than .25 microns. X-ray lithography makes use of soft x-rays to shadow print an image of a mask onto a semiconductor wafer to produce integrated circuits. To produce the required x-rays in sufficient quantities to make commercial production viable, electron storage rings have been proposed as the soft x-ray sources. Existing storage rings have been used to do the initial development work and the success of these efforts has led the lithographers to request that new rings be constructed that are dedicated to x-ray lithography.

As a result of a series of workshops held at BNL[4] which were attended by both semiconductor and accelerator scientists the following set of 'zeroth order specifications' on the light and electron beam of a storage ring for x-ray lithography were developed:

- critical wavelength: λ_c = 6 - 10 Å,
- white light power: P = .25 - 2.5 w/mrad,
- collection angle per port: θ = 10 - 50 mrad,
- electron beam sizes: $\sigma_x = \sigma_y \leqslant 1$ mm,
- vertical angular spread: $\sigma'_y \leqslant 1$ mrad.

It is certainly possible to design both conventional and superconducting magnet based rings to meet the above specifications but tradeoff questions such as "Would you accept a beam with $\sigma_x > 1$ mm in order to reduce the circumference of the ring?" can only be answered by the lithographers. Along with the above requirements came the desire to have as low an injection energy as is possible for a commercial storage ring.

3. Design of Storage Rings for X-ray Lithography

The gross parameters of an electron storage ring to meet the above requirements can be obtained from the following formulas where E and I are the energy and current of the electrons, B and ρ are the dipole field strength and bending radius and C is the circumference of the ring, respectively:

$$E\ [GeV] = .3\ B[T]\ \rho[m], \tag{1a}$$

$$\lambda_c\ [\AA] = \frac{18.64}{B\ [T]\ E^2\ [GeV]}, \tag{1b}$$

$$P\,[w/mrad] = \frac{.0787\ E\ [GeV]\ I\ [ma]}{\lambda_c\ [\AA]}, \tag{1c}$$

$$C = 2\pi\rho + L_{quad} + L_{drift} + L_{sext} \tag{1d}$$

Conventional electromagnets are limited to fields of about 1.5 Tesla whereupon the saturation of the iron yoke becomes a problem. Superconducting magnets can be used to produce much higher fields of about 4 Tesla at the price of a more complicated magnet. With these constraints on the magnetic field the possible storage rings bifurcate quite naturally into two classes, one based on conventional magnets, the other on superconducting magnets. Typical parameters of the two types of machines are given in Table 1.

Magnet	EM	SC
B [T]	1.5	4
E [GeV]	1.1	.68
λ_c [Å]	10	10
ρ [m]	2.4	.56
C [m]	25-50	8-15
I [ma]	200	300

Table 1: Typical parameters of conventional and superconducting magnet storage rings designed for x-ray lithography.

Conventional magnet rings have the advantage that they are based on well established technology which should provide high reliability and they could be made available in roughly the time it takes to build them (≈ 2 years).

In contrast, the superconducting magnet ring while being a challenging physics and engineering problem, requires considerable research and development to perfect the dipole. At this time, while at least 2 machines are in the early stage of commissioning, no SC machine is yet operating at an acceptable level of performance.

The smaller 'footprint' of the SC machine, C ≈ 8-15 m, has proven seductive to several potential lithographers as at least 2 machines have been sold to industry; Hitachi participated in the design and manufacture of a machine that has been delivered to the Nippon Telephone and Telegraph Co. (NTT) and Oxford Instruments is producing a machine for IBM. The smaller C and ρ of the SC machine provides a smaller damping time, τ_i, for a fixed energy which should help with low energy injection, i.e.,

$$\tau_i\ [ms] = \frac{C\ [m]\ \rho\ [m]}{13.2\ J_i\ E^3\ [GeV]}, \qquad i = x, y, \varepsilon, \tag{2}$$

where the J_i are the damping partition numbers.

To insure that a storage ring source of soft x-rays will be available, both EM and SC rings are being built and a survey of these efforts is given in succeeding sections.

4. Existing Rings As Lithography Sources

The proof of principle of electron storage ring based x-ray lithography has been done on existing storage rings[1-3] within the past five years. Table 2 lists the existing conventional magnet storage rings that are known to the author to be used today for x-ray lithography. The author would like to caution the reader that this list may not be complete as other rings in the energy range .7-3 GeV are also suitable lithography sources. In general, the users of the beamlines are semiconductor manufacturers, e.g.,

* work performed under the auspices of the U.S. Department of Energy and funded by the U.S. Department of Defense

CH2669-0/89/0000-0757$01.00©1989 IEEE

at the NSLS, IBM has 2 beamlines and at the KEK Photon Factory, Fujitsu, Hitachi, NEC and NTT, each have 1 beamline.

Machine	Energy [MeV]	λ_c [Å]	Beamlines
NSLS VUV	750	25	2
BESSY	800	19.4	1-5
TERAS	800	21.8	2
ALADDIN	800	22.7	2-4
KEK PF	2500	3.1	4

Table 2: Existing conventional magnet rings being used for x-ray lithography.

5. New Conventional Magnet Rings

Since the number of beamlines on existing rings is limited and the development of superconducting magnet based rings will require additional work, new conventional magnet storage rings have been built to fill the gap. Table 3 lists the new conventional magnet storage rings that are being built for the purpose of x-ray lithography. Diversity probably best describes the numerous approaches as various lattice configurations and injectors are being tried.

The first four machines listed in Table 3 are located in Japan where to date the greatest effort to develop storage rings for x-ray lithography is taking place. All four of the Japanese machines will be fully assembled and begin commissioning by the middle of 1989.

NIJI-II, a four dipole racetrack type ring at the Electrotechnical Lab (ETL) in Tsukuba, is the smallest of the rings, C = 17 m, but with a critical wavelength of λ_c = 37 Å it is not optimized as a lithography source.

LUNA, a four dipole four superperiod machine, is being constructed by Ishikawajima-Harima Heavy Industries (IHI) in Tsukuba. It achieves its small circumference of C = 23.5 m by using only four dipoles but with so few dipoles it is difficult to meet the specification of σ_x < 1 mm in the dipole. LUNA has a 45 MeV linac built by IHI as an injector.

The four superperiod Chasman-Green ring at NTT in Atsugi was built by Toshiba as part of the NTT lithography effort and is already in the commissioning stage. This ring is accompanied by a 15 MeV linac injector that was delivered by Mitsubishi Electric. The NTT ring can operate as a stand alone storage ring or as a booster for NTT's superconducting ring, SUPER ALIS, about which more will be said in the next section.

The SORTEC corporation, which was established by the Ministry of International Trade and Industry in 1986, is a collaborative effort between thirteen Japanese companies to develop sources, beamlines and applications for x-ray lithography. To this end SORTEC has purchased a 40 MeV linac from Mitsubishi Electric to inject into a full energy booster ring provided by Toshiba which eventually stacks electrons in the 1 GeV storage ring supplied by Mitsubishi Electric.

The LSU-CAMD ring[5] is also a four superperiod Chasman-Green machine to be constructed on the Louisiana State University campus by Maxwell-Brobeck Inc. The project began in December 1988 and the machine is scheduled for operation in early 1992 with 1 LSU sponsored lithography beamline to start with and plans for more later on.

6. New Superconducting Magnet Rings

In parallel with the construction of conventional magnet rings at least six SC magnet rings are currently under construction (see Table 4), with two of these already in the commissioning stage. For these machines the diversity of approaches exceeds that in the conventional magnet machines. There are one, two and four dipole machines with a broad range of magnet types and injectors.

AURORA[6], which is being built by Sumitomo Heavy Industries (SHI), is in a class by itself as it is constructed as a single 360° dipole weak focusing storage ring along the lines of the existing SURF II machine at NIST and the previously proposed KLEIN ERNA[7] machine. This design gives the smallest possible circumference, $2\pi\rho$ = 3.14 m, and there are no fringe field regions to worry about but the machine itself is a monolith of iron weighing 120 tons (3 m OD and height of 2.2 m), although the large mass of iron will reduce the amount of required external shielding. The injection system for AURORA is a 25 turn, 150 MeV racetrack microtron built by SHI. AURORA will make use of a novel half integer resonance injection scheme[8].

For a weak focusing machine of the AURORA type an analytic expression for the electron beam sizes can be given in terms of the field index, n, the bending radius, ρ and the electron energy,

$$\sigma_x\ [mm] = 2.1\ E\ [GeV] \left[\frac{\rho\ [m]}{n(3-4n)}\right]^{1/2} . \qquad (3)$$

For typical values of the field index, 0 < n < .75, this leads to horizontal electron beam sizes in the range of 1-2 mm. To lower the beam size the dipole magnets must be split into more pieces and quadrupoles must be added to reduce both the emittance and the dispersion. Split the magnet into more pieces also makes it easier to include the other necessary hardware such as the RF cavity, injection kickers, etc. The next four machines in Table 4 are machines making use of two 180° dipole magnets.

The COSY ring at BESSY makes use of a 50 MeV racetrack microtron as an injector. While the superconducting magnets were being fabricated the machine was fitted with conventional magnets to study low energy injection. During that time up to 100 ma were stored. The SC magnets, constructed by Interatom, have since been delivered and the machine is currently undergoing commissioning.

NTT's SUPER ALIS[9] ring was designed and constructed in collaboration with Hitachi Corporation. A unique feature of this machine is that it has two injection septum magnets to accommodate very low energy injection (15 MeV) directly from a linac or full energy injection (600 MeV) from their conventional magnet booster/storage ring. It is also the only two dipole machine to have a magnet with an iron yoke. So-called 'wobbler' magnets

Machine	C [m]	E [MeV]	λ_c [Å]	Location	E_{inj} [MeV]	B [T]	ρ [m]
NIJI II	17	600	37	ETL	200 L	1.4	1.4
LUNA	23.5	800	22	IHI	45 L	1.33	2.0
NTT	52	800	20	Atsugi	15 L	1.46	1.83
SORTEC	46	1000	15.5	Tsukuba	1000 LB	1.2	2.77
CAMD	52.8	1200	9.5	LSU	150 L	1.37	2.93

Table 3: New conventional magnet rings being built for x-ray lithography (L = linac & B = booster).

Machine	C [m]	E [MeV]	λ_c [Å]	Location	E_{inj} [MeV]	B [T]	ρ [m]	Beam Tube	Magnet Core
AURORA	3.14	650	10	SHI	150 M	4.34	.5	warm	iron
COSY	9.6	590	12	BESSY	50 M	4.47	.44	cold	air
SUPER ALIS	16.8	600	17.3	NTT	15 L, 600 B	3.0	.66	warm	iron
HELIOS	9.6	700	8.5	OXFORD	<200 L	4.5	.52	cold	air
SXLS	8.5	700	10	BNL	<200 L	3.85	.6	warm	air
NIJI III	16	620	11.7	SEI	<200 L	4.13	.5	cold	air

Table 4: New superconducting magnet rings being built for x-ray lithography, (L = linac, B = booster & M = racetrack microtron).

are included in the machine to move the closed orbit vertically by ± 1.5 cm to scan the light beam on the silicon wafer. The machine is presently undergoing commissioning and to date is the only SC ring that has ramped some electrons to full energy.

HELIOS[10] is Oxford Instruments compact ring based on two 180° dipole magnets. A 200 MeV linac from CGR MeV in France has been purchased as an injector. The machine is scheduled to begin commissioning in late 1989.

The last of the two 180° dipole rings, the SXLS ring at Brookhaven National Laboratory, will be described in some detail in the next section.

NIJI-III, which makes use of four 90° dipoles, is being built by Sumitomo Electric Industries in collaboration with ETL. The machine is located at ETL in Tsukuba and will make use of the existing linac as an injector. The two phase project makes use of low field iron dipoles to facilitate machine studies pending delivery of the superconducting dipoles. A unique feature of this machine is that superconducting dipoles are textbook cos(θ) magnets in the sense that there is no break in the outside of the coils to extract the light. The light is extracted from the end of the dipole magnets only thereby limiting the number of ports per dipole to 2-3. Like the rest of the NIJI series of rings, NIJI-III will wobble the beam vertically to scan the light over the wafer[11].

7. Superconducting X-Ray Lithography Source (SXLS)

In March 1988 the Superconducting X-Ray Lithography Source (SXLS) project at the National Synchrotron Light Source at Brookhaven was initiated with funding from the Defense Advanced Research Projects Administration (DARPA). The goals of the project are to design and construct a superconducting magnet based storage ring as an x-ray lithography source and to transfer the technology of how to build the machine to US industry. The Grumman Aerospace Corporation and General Dynamics were selected as the industrial participants. The initial projected funding for the project was twenty one million dollars spread over a five year period.

As the design and fabrication of the superconducting dipole requires a minimum of two years of work, the project is being executed in two phases. In Phase I the machine will be constructed with low field iron dipole magnets, B_{max} = 1.1 T, with the same bending radius as the superconducting magnet. With this low field dipole the energy of the machine will be limited to E_{max} = 200 MeV. The parameters of the storage ring can be seen in Table 5 and the betatron and dispersion functions are displayed in Figure 1.

At present the design of the Phase I machine has been completed and all of the parts are on order. The parts will be delivered during the Spring and Summer of 1989 with magnet measurements following in the Fall. The completed Phase I machine is scheduled for commissioning in November 1989. The Phase I ring will be sited inside the existing 2.5 GeV x-ray

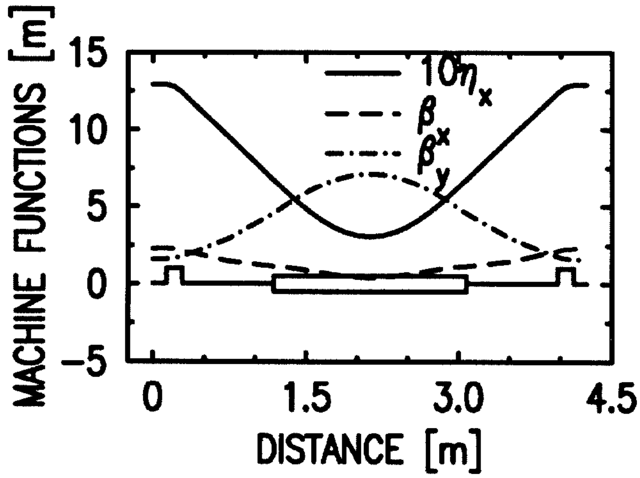

Figure 1: SXLS Betatron & Dispersion Functions

ring at the NSLS and the existing linac and booster will serve as the injector. The goals of Phase I will be to study the accelerator physics issues associated with low energy injection (E < 200 MeV) with an eye toward lowering the injection energy if possible.

Machine Phase	Phase I	Phase II
Energy, E [MeV]	200	696
Dipole Magnet Type	EM	SC
Dipole Field, B_0 [T]	1.1	3.85
Bending Radius, ρ [m]	.6037	
Superperiods, N_s	2	
Circumference, C [m]	8.503	
Critical Wavelength, λ_c [Å]	423	10
Number of Superperiods	2	
Horizontal Betatron Tune, ν_x	1.415	
Vertical Betatron Tune, ν_y	.415	
Energy Loss Per Turn, U_0 [KeV]	.234	34.4

Table 5: SXLS Storage Ring Parameters

Phase II of the project actually proceeds in parallel as the design of the superconducting dipole magnets is ongoing and nearly all of the hardware from Phase I simply carries over to Phase II. Although for Phase II the RF system will be upgraded to operate at full power since the Phase I RF system makes uses of an existing 211 MHz cavity that is only suitable for low power operation. The final realization of the superconducting dipoles is about 2.5 years away. After magnetic measurements the dipoles will be installed and the entire machine will be relocated, with a new dedicated injector, and the machine will be commissioned.

8. Conclusions

With at least four new conventional magnet machines and three new superconducting rings joining the ranks of operating or commissioning machines, the next 12 months should prove very exciting for the lithographers and the accelerator physicists working on the rings. Valuable information on the design and fabrication of small bending radius superconducting magnets and low energy injection into a storage ring should be forthcoming.

9. Acknowledgments

The collaboration of my colleagues in the SXLS group at the NSLS is gratefully acknowledged. This paper was made possible by the generous exchange of information with the groups at the aforementioned facilities. In particular I would like to acknowledge discussions with the following individuals: F. Cerrina, B. Craft, Y. Hoshi, T. Hosokawa, T. Keishi, T. Kitayama, S. Mandai, Y. Nagatoro, N. Takahashi, T. Tomimasu, E. Toyota, G. Vignola, E. Weihreter, & M. Wilson.

10. References

[1] A. Heuberger, "X-Ray Lithography", J. Vac. Sci. Tech. B, Vol. 6, No. 1, p. 107, (1988).

[2] A. Wilson, "X-Ray Lithography: Can It Be Justified?", Solid State Technology, p. 249, (1986).

[3] J.P. Silverman, et. al., "Fabrication of Fully Scaled 0.5 μm n-type Metal-Oxide Semiconductor Test Devices Using Synchrotron X-Ray Lithography: Overlay, Resist Processes and Device Fabrication", J. Vac. Sci. Tech. B Vol. 6, No. 6, p. 2147, (1988).

[4] "BNL Lithography Workshop Proceedings", BNL Reports 38764, 38789, 52005, 52046 (1986), 52096 (1987).

[5] B. Craft, these proceedings, (1989).

[6] N. Takahashi, "Compact Superconducting SR Ring for X-Ray Lithography", NIM B24/25, p. 425, (1987).

[7] U. Trinks, et. al., NIM 200, p. 475, (1982).

[8] T. Takayama, "Resonance Injection Method for the Compact Superconducting SR-RING", NIM B24/25, p. 420, (1987).

[9] T. Hosokawa, et. al., "Injector Linac for Super Alis", these proceedings, (1989).

[10] D.E. Andrews, et. al., "A Compact Synchrotron X-Ray Source for X-Ray Lithography", AIP Conf. Proc. No. 171, eds. H.J. Halama, J.C. Schuchman and P.M. Stefan, p. 135, (1988).

[11] T. Tomimasu, "An Electron Undulating Ring Dedicated to VLSI Lithography", Jap. J. Apl. Phys., Vol. 26, No. 5, p. 741, (1987).