Extended Abstracts of the 16th (1984 International) Conference on Solid State Devices and Materials, Kobe, 1984, pp. 11-14

Invited

X-Ray Lithography Using Synchrotron Radiation

Koichiro Hoh

Electrotechnical Laboratory

1-1-4 Umezono, Sakura-mura, Niihari-gun, Ibaraki 305, Japan

Present status of the research on the synchrotron radiation(SR) lithography is reviewed putting emphasis on the basic factors which determine the resolution and the throughput. These are electron energy, mask and resist materials, proximity gap etc. Recent advancements in the development of elementary technologies at principal SR lithography facilities in the world are introduced with the reference to the plan of the compact SR source.

1. Introduction

Synchrotron radiation (SR) is a promising candidate for the X-ray source in microlithography with its high brightness and collimation. The study of SR lithography (SRL) has been accelerated in these couple of years because the experiments have started at the newly built electron storage rings with the beam lines dedicated to the lithography experiments. These activities have been stimulated by the pioneering experiments made at the first-generation SR facilities, DESY(West Germany)¹⁾, ACO (France)²⁾ and INS-ES/SOR(Japan). The first experiments in Japan were made by Professor Namba's group of Osaka University.³⁾⁴

The present talk deals with the factors which determine the resolution and the throughput of SRL and the studies on the elements of the SRL system, referring to the idea of the compact SR source.

2. Elements of SR Exposure

As depicted in Fig.1, principal elements involved in SRL are radiation source, mask and resist. Besides, a thin window is often inserted to separate the exposure chamber from the storage ring. Mirrors are sometimes used to expand the exposure area or to cut-off the hard X-ray components. Table 1 shows variety of these elements utilized in the major SR facilities conducting the lithography experiment.

Because the SR source has a continuous spectrum, the spectral range utilized in lithography depends on the combination of these elements through the superposition of the spectra of the source power, reflectivity of mirrors, transmissivity of windows and mask membranes, and absorbance of the resist.⁵) Figure 2 shows an example of the calculated spectra of the power emitted from the 600 MeV storage ring, transmitted through Si₃N₄ membrane, and absorbed at the surface of PMMA resist. The spectrum of the absorbed power shows a peak around $\lambda_p = 15$ A. The spectal shape changes when the parameters of the source and the other elements are changed.

As will be stated below, the effective wavelength is related to the resolution through the diffraction effect and the absorbed power integrated with the wavelength determines the exposure time.

3. Resolution of SR Lithography

Because of high collimation of the SR beam, the penumbral and run-out errors are decreased to less than 1/30 of the divergent X-ray source.⁶⁾ Principal factors which determine the resolution are Fresnel diffraction and the range of secondary electrons. Figure 3 shows an example of the resist pattern when a finite gap existed between mask and wafer. Structures on the resist wall coincides semi-quantitatively with the calculation based on the Fresnel diffraction theory. Fresnel diffraction is characterized by a non-dimensional parameter $u = l\sqrt{2/(\lambda g)}$ where l is the linewidth, g is the gap between mask and wafer and λ is the wavelength of SR, respectively. Satisfactory replication without diffraction effecs is realized when u exceeds a certain critical value u_c , that is, $u \ge u_c$. This leads to the minimum linewidth $l_{min} = u_c \sqrt{\lambda g/2}$ when the gap is settled.

For PMMA, we obtained an empirical result that $u_c = 3$ if we demand high fidelity in the shape of the resist wall⁷⁾, or $u_c = 1.5$ if we only need the accuracy of the line width⁸⁾. In Fig.4, the relationship between l_{min} and λ , represented by the peak wavelength λ_p in the spectral absorption, is shown, gap g being a parameter.

The range of photoelectrons and Auger electrons in the resist, wafer, and, in some cases the mask, can be a limiting factor for the resolution when harder X-ray components are utilized. Also shown in Fig.4 is the estimated range R_g of these secondary electrons as a function of λ_p .⁸⁾ Fig.4 helps us in selecting λ when 1_{min} to be resolved and g are given.

4. Enlargement of the Exposure Area

High collimation of the SR beam, though favorable for high source brightness and small geometrical errors, results in the deficiency of the vertical width of the exposure area even for a single field in the step-and-repeat exposure.

In Fig.5, the vertical distributions of the SR energy absorbed in the resist are shown, represented as the thickness of the resist removed by the development.⁹⁾ Broken line shows the distribution obtained by a usual exposure at the distance 10 m from the 500 MeV ring with the magnetic radius R= 2m. The width of the uniformly exposed area within the variation 10 % is 5 mm.

For the enlargement of the vertical width, oscillation of cylindrical or plane mirror has been adopted. 10)11 We proposed simpler methods with a fixed toroidal mirror or with fixed,

planar side mirrors in which we can expect the maximum square area 15 x 15 mm^2 .¹²)

Another method is tried which does not use mirrors. It is to steer the electron orbit in the ring vertically by a horizontal magnetic field. $^{9)13}$ SR beam is vertically deflected and scan the sample surface. Solid line in Fig.5 shows the result of beam scanning. The vertical width of the uniformly exposed area is expanded by 3 times and it can moreover be 30 mm when the height of the slit in the beam line is properly chosen.⁹)

Discussions about merits and demerits of these methods have been made.¹²⁾ The choice among these methods depends on the situation of the beam line and affects the throughput.

5. Throughput Considerations

Exposure time with SR is approximately determined by the total energy absorbed in the resist Q, which is obtained by integrating the spectral energy absorbed in the resist with the wavelength. It has been found that the dissolution rate S of the positive resist depends on Q as $S \propto Q^{1.5}$ for $Q(J/cm^3) < 960$, $S \propto Q^{2.1}$ for $960 \leq Q \leq 2400$ and $S \propto Q^4$ for Q > 2400, respectively.¹⁴) In the last regime, considerable amount of the resist is vaporized by SR irradiation and direct formation of patterns is exhibited.¹⁵)

In Figure 6, the exposure time $T_{\rm ex}$ with 1 μm thick PMMA is shown for various mask membranes as a function of the electron energy E_{\bullet}^{5} When 20 µm-thick Be window is inserted, T_{ex} increases by a factor of 3 - 5.⁸⁾ Figure 6 shows that T_{ex} is reduced according to the increase of E. The increase of E, however, results in the increase of the range of secondary electrons as shown in Fig.4 together with the degradation of the mask contrast and the increase of the machine- and running cost of the storage ring. As far as the present style of the ring(R= 2m) is concerned, optimum E could be searched in the range 0.6-1 GeV, in which the throughput far exceeds that of the divergent X-ray source and possibly be comparable to the optical lithography.

6. Compact Storage Ring and Other Novel Sources

To realize a compact storage ring maintaining the intensity of soft X-ray components suitable for lithography, we must use stronger field B of bending magnets . The effort of constructing compact ring is announced by BESSY, which utilizes superconducting magnets with B = 5T, R= 29-38 cm, E= 430-560 MeV, outer diameter 2-0.8 m, and with a compact accelerator for the electron injection.¹⁶)17)

In the SR application to solid state study, new types of radiation sources, wigglers and undulators are tested for the enhancement of hard X-ray components or to increase the beam intensity. They emit intense but small-size beams and are not readily applicable to the lithography. Modification of a multipole wiggler and an undulator with enlarged exposure field for the lithographic purpose have been proposed.¹⁸)

7. Concluding Remarks

SR has great potential as a source for highresolution volume production of microcircuit patterns. With the advancements in the system elements including mask fabrication,¹⁹⁾ highsensitivity resists, alignment method and mechanisms etc., which are not mentioned here because of the limited space but not less important, the SR lithography will make more rapid progress than we have expected at the start.

Table 1.	Major	SR	beam	lines	dedicated	to	
----------	-------	----	------	-------	-----------	----	--

The author is indebted to H. Tanino, N. Atoda, M. Hirata, S. Ichimura and I. H. Suzuki for their collaboration and stimulating discussions. He is also grateful to T. Tomimasu, T. Noguchi and the staffs of the High Energy Radiation Section for the operation of the SR facility.

References

- 1) E.Spiller et al.: J.Appl. Phys. 47(1976)5450.
- 2) B.Fay et al.: Appl. Phys. Lett. 29(1976)370.
- 3) T.Nishimura et al.: Jpn.J.Appl.Phys. <u>17</u>(1978) Suppl.17-1, p.13.
- 4) H.Aritome et al.: J.Vac.Sci. & Tech. <u>15</u>(1978) 992.
- 5) H.Tanino et al.:Tech. Repts of IECE Japan, SSD 82-179(1983).[J]
- 6) K.Hoh:Oyo Buturi <u>53(1984)17[J]</u>; Proc.SEMI Tech.Symp.(Dec. <u>1983</u>, Tokyo) 1-41.
 7) N.Atoda et al.:J.Vac.Sci. & Tech. <u>B1(1983)</u>
- /) N.Atoda et al.: J.Vac. Sci. & Tech. <u>B1(1983)</u> 1267.
- 8) N.Atoda: Meeting of Soc. Polym. Sci. Japan, June 14, 1984.[J]
- 9) H.Tanino et al.: Jpn.J.Appl.Phys. 22(1983)L677
- 10)R.P.Haelbich et al.:J.Vac.Sci. & Tech. B1 (1983)1262.
- 11)M.Bieber et al.: ibid. 1271.
- 12)H.Tanino et al.:J.Vac.Sci & Tech. <u>B2</u>(1984) Symposium issue, to be published; Tech.Digest of 1984 Spring Meeting of Jpn. Soc. Appl.Phys pp.282-283[J].
- 13)H.Betz and G.Mülhaupt:SPIE Proc. 448(1983).
- 14)N.Atoda et al.:Proc.24th Symp. Semicond. & ICs (Electrochem. Soc. Japan, 1983) p.24.[J]
- 15)S.Ichimura et al.: J.Vac.Sci. & Tech. <u>B1</u>(1983) 1067.
- 16)A.Heuberger and H.Betz:Solid State Devices 1982(ed. A.Goetzberger and M.Zerbst, Verlag Chemie, Weinheim, 1983) p.121.
- 17)G.Mülhaupt:Proc.Symp.X-Ray Microscopy(Springer Verlag, 1983).
- 18)H.Tanino and K.Hoh:Jpn.J.Appl.Phys. <u>22</u>(1983) L718, <u>23</u>(1984)131.
- 19)T.Kanayama et al.: This Conference, A-2(4).

Location	Res. Group	Source E(GeV)	R(m)	I(A)	$\lambda_p(A)$	Mirror	Window	Mask Membrane	Resist
ETL	ETL	0.6	2	0.1	17.8	Pt/SiO (fixed ² side mirror) (removable)		polyimide(3µm) Si ₃ N ₄ (1µm)	PMMA EBR-9 PGMA CMS-EX
NSLS ^{a)}	IBM	0.75	1.9	1.0	8.6	Au/Cr/SiO (oscillat ² ing)	Be (18µm)	Si(3µm)	PMMA AZ1400 AZ4110 XR1-3
BESSY ^b)	IFT ^C)	0.8	1.8	0.5	6.9	SiO (osĉ.)	Si (3µm)	Si(2µm)	PMMA
Photon Factory	ECL	2.5	8.7	0.5	1.1	SiC (high-cut)	Ве	Si ₃ N ₄ (2µm)	PMMA,FPM CMS,∳MAC

a) National Synchrotron Light Source (Brookhaven Nat. Lab., USA)

b) Berliner-Elektronenspeicherring-Ges. für Synchrotronstrahlung mbH (West Berlin)

c) Fraunhofer-Institut für Festkörpertechnologie (Fed.Rep.Germany)

the lithography experiments ([J] denotes the papers in Japanese)



Fig. 1 Elements of SR Lithography



Fig. 3 Resist Pattern Fabricated by SR (pitch 1.5 μm, height 3 μm, polyimide mask, E= 600 MeV)



Fig. 5 Vertical Distribution of SR Energy

Fig. 6 Exposure Time of SR Lithography (fitted to the experiments at E= 500-600 MeV)







Fig. 4 Diffraction-limited minimum linewidth (1) and Range of Secondary Electrons (R_g)

