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# Optimization of a synchrotron based x-ray lithographic system

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Exposure time and mask contrast are two of the main parameters affecting the x-ray lithographic (XRL) process. In a synchrotron-based XRL system (SXRL), both parameters strongly depend on the source spectrum and beamline characteristics. Calculations have been done in order to optimize a SXRL system (source + beamline), taking also into account another important parameter like resolution. One of the main results is that a "cutoff" mirror, generally used in many beamlines, strongly increases exposure times without significantly improving contrast and resolution.

## INTRODUCTION

In the last few years, great importance has been given to x-ray lithography (XRL) as a promising tool to meet the resolution and throughput requirements of giant scale integration. Nevertheless, some problems, principally concerning x-ray masks and sources, still must be solved in order to reach an industrial application of this technique.

Concerning the source, storage rings appear to be very good x-ray sources for XRL, and work is being done to optimize these machines and the related beamlines to meet the requirements of XRL.

An ideal synchrotron based XRL system (SXRL) must give the maximum throughput at the minimum cost, and the best resolution and aspect ratio achievable; all these quantities depend on the whole source-beam line-mask-resist system. In this paper we report the results of calculations performed to obtain an "optimal" SXRL system, focusing our attention mainly on the source and beamline optics.

## I. STORAGE RING AND BEAMLINE PARAMETERS

Table I reports the energies of the machines considered in the calculations and the critical energies obtained with a 1.6 T magnetic field. Conventional magnet machines have been considered since at the moment their realization can be based on the existing technology, while problems related to superconducting sources seem to be not completely solved.[1] The highest energy machines ($E > 1.2$ GeV) have been introduced only for sake of completeness: their cost is probably too high and the radioprotection problems are too severe to be considered for an industrial application.

TABLE I. Energy and synchrotron radiation spectrum critical energy of the storage rings considered in the calculations.

| Machine number | Energy (GeV) | Critical energy (keV) |
|---|---|---|
| 1 | 0.84 | 0.75 |
| 2 | 0.97 | 1.00 |
| 3 | 1.10 | 1.25 |
| 4 | 1.19 | 1.50 |
| 5 | 1.37 | 2.00 |
| 6 | 1.50 | 2.40 |

As a comparison, some calculations have been also done for COSY, the lithography dedicated machine which is being completed in Berlin.[2]

Figure 1 shows the elements of a typical SXRL system; the optical elements of the beamline, considered here, are the mirror and the window (sometimes additional filters are used). The mirror is usually utilized as a high energy cutoff filter and, when necessary, to scan the beam in the vertical direction; the window separates the ultrahigh vacuum of the machine from the atmospheric pressure and acts as a low energy cutoff filter (high and low energy radiations are cutoff mainly since they degrade resolution).

The power incident on the resist—output power of the SXRL system—is given by

$$P_i = \int_{E_{\min}}^{E_{\max}} P(E) R(E) T_w(E) T_s(E) dE, \qquad (1)$$

where $P(E)$ is the spectral power of the machine, $R(E)$ is the mirror reflectivity, $T_w(E)$ and $T_s(E)$ are, respectively, the window and the mask substrate transmission. Figure 2 shows the action of these functions in a particular case.

The values of $P_i$ have been evaluated for three different beamline configurations (Fig. 3):

(1) 25 $\mu$m Be (window) + 2 $\mu$m Si (mask substrate);

(2) 12.5 $\mu$m Be + 2 $\mu$m Si;

(3) 12.5 $\mu$m Be + 2 $\mu$m Si + gold coated mirror [1.5° grazing angle; $s$ polarization; 10 Å (rms) roughness].

Due to its low absorption, low radiation damage, and good mechanical properties, Be seems to be the most suitable window material. The possible thickness values are limited by the window dimensions (of the order of some cm$^2$) necessary to accept several milliradians in the horizontal plane.

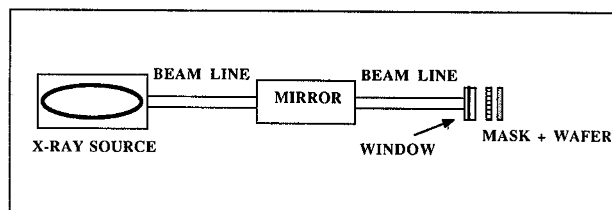


FIG. 1. Schematic layout of a typical SXRL system.

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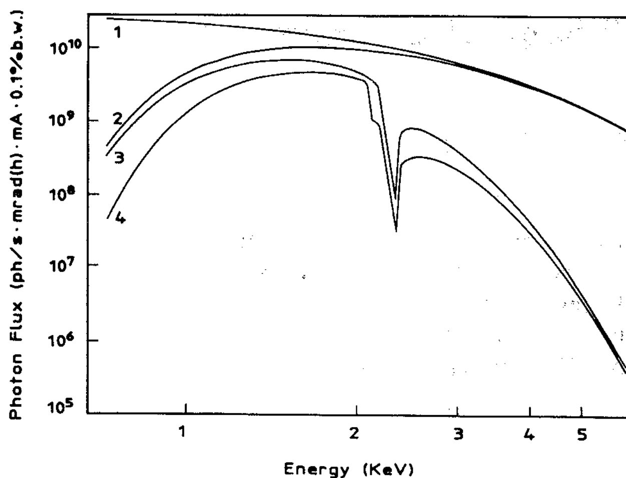


FIG. 2. Effects of the beamline optical elements on the spectral flux of the 1.1 GeV storage ring: (1) machine spectral flux; (2) 1 + 12.5 $\mu$m Be window; (3) 2 + gold coated mirror, 1.5° grazing angle, $s$ polarization, 10 Å rms roughness; (4) 3 + 2 $\mu$m Si mask substrate.

Gold-coated mirrors are commonly used in x-ray optics; they have good optical properties and are commercially available. The 1.5° grazing angle has been chosen to have a cutoff energy of the order of 3 keV, which is the highest energy value generally used in XRL[3]. The mirror reflectivity has been calculated by using the scattering factors reported by Henke *et al.*[4], extrapolating the real part of the scattering factor in all the energy range considered by means of the Kramers–Kronig integral.

Since recent mask technology seems to be oriented towards silicon substrates, for their mechanical properties in supporting metallic patterns,[5] the mask used in our calculations is a 2 $\mu$m Si substrate with 0.5 $\mu$m Au patterns.

The values of $E_{min}$ and $E_{max}$ used in evaluating $P_i$ are 0.65 and 6.0 keV, respectively; this gives $P_i$ with a quite good approximation since, in all the cases considered, the transmission of the Be window is negligible below 0.65 keV, and above 6.0 keV the residual fraction of power generated by the machines is of the order of few percent for the 0.84, 0.97, and 1.1 GeV machines, less than 10% for the 1.19 and 1.37 GeV machines, and less than 20% for the 1.5 GeV one.

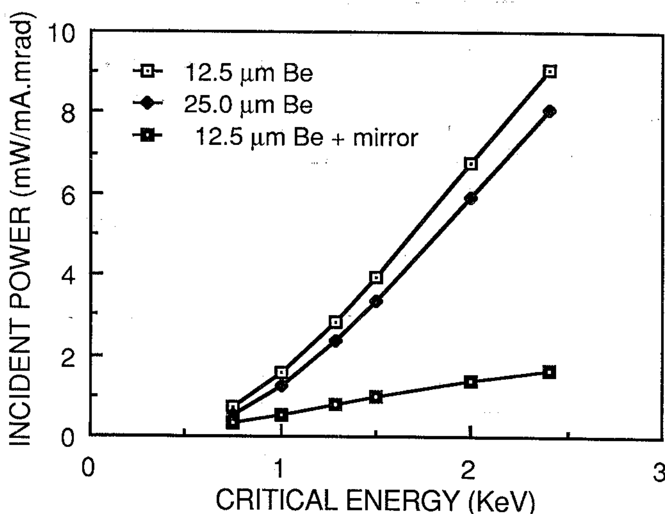


FIG. 3. Power incident on the resist as a function of critical energy for three different beamline configurations.

From Fig. 3 it appears that the mirror strongly affects the incident power giving, in the best case (lowest critical energy), a 50% reduction.

## II. EXPOSURE TIME AND CONTRAST

The exposure time $T_{exp}$ (defined here as the time, per milliamp of circulating current, necessary to expose 1 cm of resist in the vertical direction), is one of the main parameters of the XRL process, since it directly affects the throughput.

To calculate $T_{exp}$ from the incident power, it is necessary to fix the distance source-wafer ($D$) and to know the absorption coefficient of the resist as a function of the energy [$\mu_r(E)$], its thickness ($t$) and sensitivity ($S$) in J/cm$^3$ (also knowing only the sensitivity in mJ/cm$^2$ it is possible to estimate the exposure time).

In our calculations the values $t = 1$ $\mu$m and $D = 10$ m have been assumed, and two kinds of positive resists, polymethyl-methacrylate (PMMA) and a Thomson resist[6] have been considered.

PMMA is a well-known resist with a very good resolution ($<0.1$ $\mu$m) and low sensitivity ($S = 1000$ J/cm$^3$); the Thomson resist is a high sensitivity resist (280 mJ/cm$^2$) with an average resolution ($<0.4$ $\mu$m).

Table II reports the exposure times for both resist as a function of the critical energy and beamline parameters. It can be useful to give a practical meaning to this parameter estimating the throughput (wafer/hour).

The throughput depends on the exposure time per wafer (which is a function of the circulating current and of the wafer and mask size) and on the "stepper working time" (necessary for loading, unloading, and alignment operations) which depends on the kind of stepper utilized; using a fixed beam configuration, the stepper is generally used to make a vertical scan, necessary to expose the whole mask field.

Table III shows the throughput per beamline of three different machines, with various beamline configurations, for the two resists considered. The throughput has been evaluated for two different working times: 60 s (commercially available x-ray stepper) and 20 s (very "aggressive" stepper)[7] and assuming a 200 mm wafer diameter and a 50 mm

TABLE II. Exposure times [1000× (s mA/cm(vertical))] for two different resists (P = PMMA, T = Thomson) and various beamline configurations: A = 12.5 $\mu$m Be; B = 25.0 $\mu$m Be; C = A + mirror; D = B + mirror. The absorption of 2 $\mu$m of Si has been included.

| Machine number | P | | | | T | | |
|---|---|---|---|---|---|---|---|
| | A | B | C | D | A | B | C |
| 1 | 1.49 | 2.63 | 2.63 | 4.17 | 0.38 | 0.52 | 0.91 |
| 2 | ··· | 1.47 | ··· | 2.44 | 0.18 | 0.23 | ··· |
| 3 | 0.59 | 1.00 | 1.14 | 1.66 | 0.10 | 0.12 | 0.36 |
| 4 | ··· | 0.76 | ··· | 1.32 | 0.07 | 0.08 | ··· |
| 5 | ··· | 0.52 | ··· | 0.97 | 0.04 | 0.05 | ··· |
| 6 | 0.28 | 0.43 | 0.60 | 0.81 | 0.03 | 0.03 | ··· |
| COSY | 1.43 | 2.50 | 2.70 | 5.00 | 0.28 | 0.36 | 0.91 |

TABLE III. Comparison of the estimated throughput (wafer/hour) of three different machines, considering two different resists (P = PMMA, T = Thomson), two different stepper working times ($T_1 = 60$ s, $T_2 = 20$ s) and three different beamline configurations (A = 12.5 $\mu$m Be, B = 25.0 $\mu$m Be, C = A + mirror).

| Machine number | Current (mA) | P | | | | | | T | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | A | | B | | C | | A | | B | | C | |
| | | $T_1$ | $T_2$ | $T_1$ | $T_2$ | $T_1$ | $T_2$ | $T_1$ | $T_2$ | $T_1$ | $T_2$ | $T_1$ | $T_2$ |
| 1 | 300 | 12 | 13 | 7 | 8 | 7 | 8 | 29 | 43 | 25 | 34 | 7 | 21 |
| 3 | 110 | 12 | 14 | 8 | 8 | 7 | 8 | 34 | 54 | 30 | 45 | 17 | 21 |
| COSY | 300 | 11 | 12 | 7 | 8 | 6 | 7 | 34 | 55 | 31 | 48 | 16 | 20 |

mask diameter. It appears that the mirror strongly increases the exposure times decreasing the throughput: its presence can be justified only if it gives an appreciable contrast enhancement.

To verify this, the average mask contrast (Fig. 4), with and without mirror, has been calculated by using the expression

$$\langle C \rangle = \int_{E_{\min}}^{E_{\max}} P(E) T_w(E) R(E) e(E) C(E) dE \times \left( \int_{E_{\min}}^{E_{\max}} P(E) T_w(E) R(E) e(E) dE \right)^{-1}, \quad (2)$$

where $C(E) = T_{\mathrm{Au}}(E)^{-1}$ is the mask contrast, $e(E) = T_s(E) \mu_r(E)$ the efficiency per unit depth of energy absorption and $T_{\mathrm{Au}}(E)$ and $T_s(E)$ the gold absorber and the mask substrate transmission, respectively .

It is very interesting to observe in Fig. 4 the lack of great difference between the two curves and to note that also in the worst case, without the mirror, $\langle C \rangle$ is bigger than 10, which is the value that gives a quite good aspect ratio (ratio of the height and width of the structures) also for small amount of absorbed dose.

## III. RESOLUTION

An SXRL process must be able to reproduce mask features having linewidths of the order of 0.2–0.3 $\mu$m (and anyhow lower than 0.5 $\mu$m, which is claimed to be the ultimate resolution limit of the UV lithography).

The linewidth depends on several factors:

(a) resist/developer resolution; (b) diffraction blurring; (c) penumbral blurring; (d) photoelectron range.

In our case, the penumbral and diffraction contributions being negligible and assuming a high resolution resist, the photoelectron range is the only factor to be considered.

Detailed calculations[2] demonstrated that using a broad band synchrotron spectrum up to about 4 keV, the dose released by 800 Å range photoelectrons is negligible; this means that this problem has to be considered only in the case of high energy machines without a cutoff mirror.

In our case, except for the machines of higher energy ($E > 1.2$ GeV), the fraction of the power above 4 keV is small, thus, also without a mirror, we can assume that the contribution of the photoelectrons to the structures blurring is not bigger than 0.1 $\mu$m. For the machines with energy higher than 1.2 GeV, a mirror is necessary to obtain good resolution.

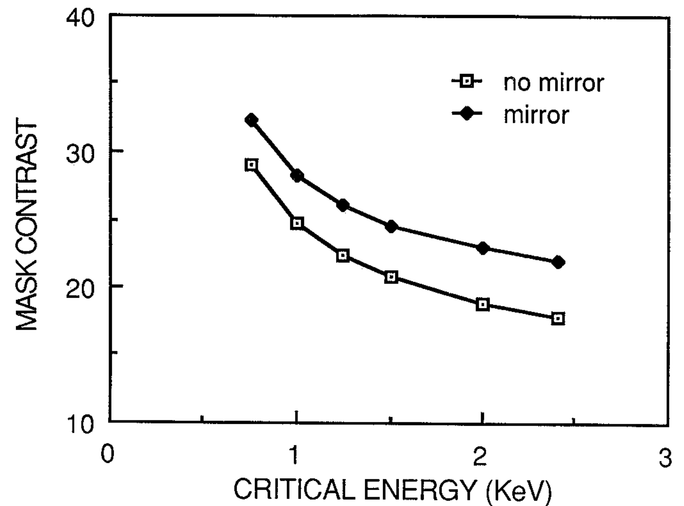


FIG. 4. Average mask contrast calculated as a function of critical energy, with and without mirror.

## IV. CONCLUSIONS

One of the main results of this paper is that generally a mirror is not useful in a SXRL system: it increases strongly the exposure time without significantly improving the contrast. Its application can be justified only in the case of high energy machines ($E > 1.2$ GeV) to reduce the structures blurring due to the photoelectrons; in the other cases, the absence of this optical element does not affect the linewidth achievable down to 0.1 $\mu$m.

To have a reasonable throughput, a beamline equipped only with a 12.5 $\mu$m Be window—and with a stepper for the vertical scan of the mask—seems to be the best choice.

With this beamline configuration, the 0.84 GeV conventional magnets machine, with 300 mA of circulating current, gives almost the same throughput per beamline as COSY. A similar throughput with less current (110 mA) is given by the 1.1 GeV machine.

Up to 20 beamlines can be easily connected to both these conventional magnets machines, giving, with a very sensitive resist and a very aggressive stepper, a throughput of about 50 wafer/hour.


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