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Summary. — The design of a synchrotron radiation source dedicated to X-ray lithography is presented. The parameter optimization carried out is based on the lithography requirements, on the radiation spectrum and beam source sizes, and on the machine performances, such as long lifetime, absence of beam instabilities and reliable operation at design current. High-field conventional magnets are proposed for the radiation production.

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1. – Introduction.

X-ray lithography (XRL) is a promising tool to meet the resolution and throughput requirements of ultralarge-scale integration (ULSI). It overcomes the fundamental limitations of diffraction and depth in the field of optical lithography, allowing the replication of patterns in the submicrometric region. Moreover, as XRL is a parallel printing process, it can give a throughput of more than one order of magnitude, higher than that of e-beam lithography [1].

The principles of XRL are fairly simple: the patterns of an X-ray mask are repli-

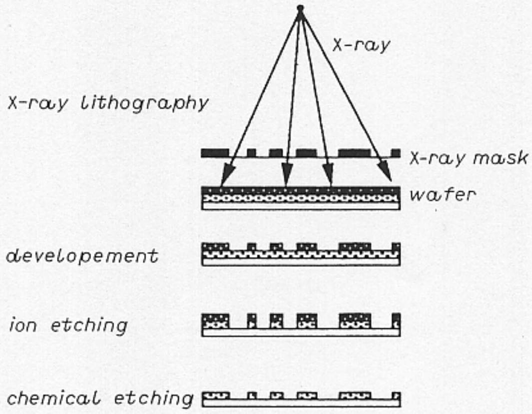

Fig. 1. – Typical steps of a device production process based on X-ray lithography.

cated in an X-ray resist deposited on a substratum (wafer); subsequent chemical and physical processes (ion etching, metallization, etc.) produce the desired structure in the wafer. In general, many exposures of the same wafer, using different masks, are necessary to realize a practical device. A typical step of the process is illustrated in fig. 1.

Storage rings appear to be ideal X-ray sources for this kind of application: the small dimensions of the electron bunch minimize structure blurring due to penumbral effects, the high collimation of the photon beam reduces geometrical

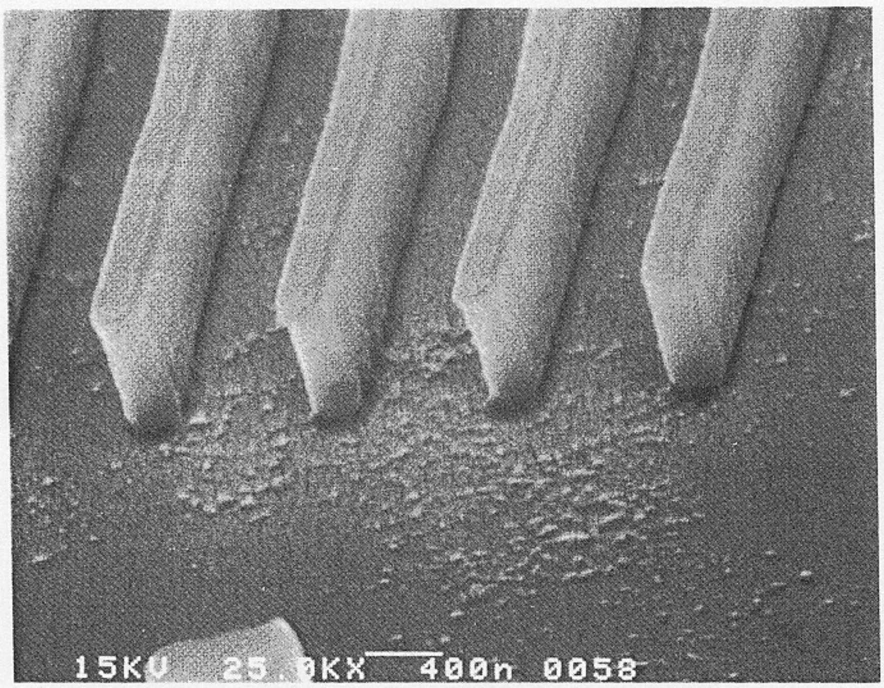

Fig. 2. – SEM photograph of 0.15 μm structures replicated on PMMA resist.

distortion (run out) and the high-intensity broadband spectrum allows very short exposure times [2, 3].

The main parameters of an industrial storage ring dedicated to XRL have to be determined to obtain a certain throughput, taking into account the beam line transmission T and the resist sensitivity S. Assuming typical values of $T = 0.2$ and $S = 300$ mJ/cm^2, utilizing 50 mm diameter masks and 100 mm diameter wafers, and by means of a fast stepper, a throughput of about 50 wafer/hour per beam line is achievable with a machine generating a power of about 1 W/mrad. This throughput is about ten times higher than that of a very fast e-beam system.

A soft X-ray beam line is in operation at Frascati to perform research activity in the X-ray lithography field [4]. Recently, using different kinds of masks and different kinds of resists (low and high sensitivity), some interesting results have been obtained working in the fixed beam configuration [5]. The SEM photograph (fig. 2) realized after metallization of 200 Å of gold shows structures replicated using PMMA resists with a very good aspect ratio and an excellent resolution equal to 0.15 μm line/0.6 μm space.

2. – The X-ray beam line.

The layout of a typical beam line for XRL is shown in fig. 3. The main components of the beam line are the vacuum system, the fast valve, the Be window and the beam stopper, the optical elements (mirrors, slits, filters) and some detectors. The vacuum system must keep the pressure inside the pipe at about the same value present in the storage ring vacuum chamber—of the order of 1 nTorr or less. The Be window separates the vacuum from the atmospheric pressure and acts also as a filter for the low-energy photons ($E < 1$ keV), which can heat up the mask (causing pattern distortion) and are absorbed from the surface of the resist causing its nonuniform dissolution rate during its development.

Since the Be window is quite brittle, to protect the vacuum of the storage ring, a fast vacuum valve is installed at the end of the beam line, near the accelerator, and connected to a vacuum sensor close to the window. The beam stopper acts as a shutter to stop the X-ray beam when the safety requirements are not satisfied.

Sometimes—when the fraction of the power above $(5 \div 6)$ keV generated by the accelerator is not negligible—a grazing incidence mirror with a metallic coating must be utilized to remove high-energy photons from the beam because their presence lowers the mask contrast and degrades the resolution, producing long-range photoelectrons in the resist.

To evaluate the possibilities of the dedicated machine considered here, detailed calculations have been made for a particular beam line configuration. A 12.5 μm thick

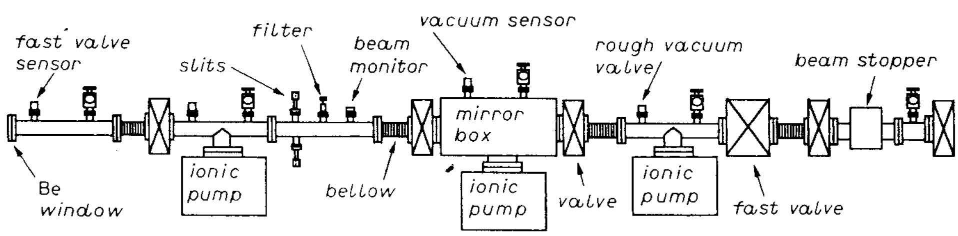

Fig. 3. – Layout of a typical beam line for X-ray lithography.

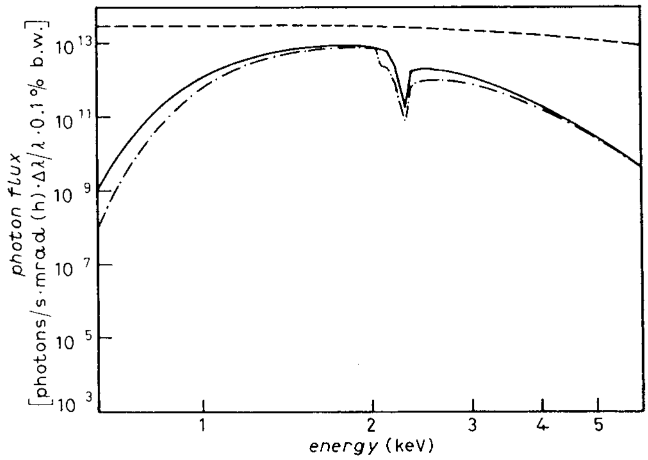

Fig. 4. – Effect of the beam line optical elements on the synchrotron radiation spectrum (dashed line): gold mirror reflection and Be window (continuous line); gold mirror reflection, Be window and Si mask substratum (dashed and dotted line).

TABLE I. – *Throughput (wafer/hour) per beam line and power incident on the resist for two beam line configurations.*

Beam line parameters	Beam line transmission	Power on the resist (W/mrad)	Throughput
12.5 μm Be + + 2 μm Si	28%	0.3	55
12.5 μm Be + + 2 μm Si + Au mirror	8%	0.09	20

Be window, a gold-coated mirror (1.5° grazing angle, *s* polarization, 10 Å r.m.s roughness) and a 2 μm thick Si mask substratum have been considered. Figure 4 shows the effect on the spectrum of the optical elements of the beam line: the upper curve shows the machine spectrum, and the lower ones show the transmitted one in several different configurations. Table I reports the values of the beam line transmission, power incident on the resist and estimated throughput with and without mirror. A 10 m long beam line, a stepper working time of 20s per wafer, a resist sensitivity of 300 mJ/cm^2, a 50 mm diameter mask and 100 mm wafers have been assumed in estimating the throughput.

3. – Storage ring parameters.

3·1. *General considerations.* – The optimum choice of storage ring parameters is basically related to the features of the X-ray beam necessary to the lithography process. Further considerations are the absence of instabilities, long lifetime, low cost and, particularly for a storage ring addressed to industry, reliability, ease of construction and maintenance, such as to ensure high efficiency of the production process.

A large number of dedicated storage rings have been designed and several prototypes developed, which adopt either conventional or superconducting magnets [6]. The main advantages of the superconducting sources are their compactness and relatively low operating energy, which implies significant reduction of the r.f. power supplied to the beam, low injection time and less shielding problems. However, the overall instrumentation size is mainly dominated by the X-ray beam lines (typically 10 m long), while the saving in power consumption is partly reduced by the cryogenic system. In addition, the cost/beam line and the operating cost show little differences in the two cases, while the conventional solution compares favourably from the point of view of simplicity, ease of construction and maintenance. Thus, at present, conventional magnet technology seems to be the most suitable to develop a first generation X-ray synchrotron radiation source dedicated to industrial lithography. The main argument on behalf of the superconducting solution is considerable development potential, which could lead to technological improvements and cost reduction in the future.

3·2. *Radiation and power requirements.* – The analysis of the transmission and absorption of the spectrum components through the beam line and mask-wafer system shows that a wavelength of 10 Å is desirable. In order to obtain a high photon flux we design the radiation sources such as to produce a power spectrum distribution characterized by a critical wavelength of 10 Å. This wavelength, which divides the spectrum in two regions with equal radiated power, can be determined by the radius of curvature of the bending magnet ρ and by the electron energy E, following the relation

$$\lambda_c\,(\text{Å}) = 5.59\,\rho(\text{m})/E^3\,(\text{GeV})$$

with

$$\rho(\text{m}) = 3.33\,E\,(\text{GeV})/B\,(\text{T})\,.$$

Once the wavelength and magnetic field are given, ρ and E are fixed. Since a high magnetic field leads to a more compact machine and to several advantages concerning the consuming power and injection time, a magnetic field $B = 1.6\,\text{T}$ has been chosen, which is easily achievable with conventional technology, giving a bending radius $\rho = 2.3\,\text{m}$, at the energy $E = 1.1\,\text{GeV}$.

The density power required on a chip with an exposure time of roughly 5 s is $200\,\text{mW/cm}^2$. Assuming the chip to be 10 m from the source and a beam line transmission efficiency of 20%, the source must provide a density power emission of about 1 W/mrad. Such radiated power, at the energy of 1.1 GeV, is obtained with an average injected current equal to 110 mA, according to the relation

$$\frac{\Delta P(\text{W})}{\Delta\theta(\text{mrad})} = 18.04\,\frac{I(\text{mA})\,E^4(\text{GeV})}{\rho(\text{m})}\,.$$

It is worth noting that, once the critical wavelength and power density are fixed, a conventional source operates at higher energy and lower current, becoming less critical with respect to the instability phenomena.

3·3. *Machine layout.* – In order to achieve high beam current in the storage ring, it can be stated in general that the injector should provide the beam qualities necess-

TABLE II. – *Machine parameters.*

Energy	E	1.1 GeV
Length	L	22 m
Natural emittance	ε_0	$1.5\cdot10^{-6}$ m·rad
Momentum spread	σ_p	$6.2\cdot10^{-4}$
Momentun compaction	α_c	0.63
Horizontal betatron number	Q_x	1.2
Vertical betatron number	Q_y	0.6
Horizontal chromaticity	ξ_x	− 1.2
Vertical chromaticity	ξ_y	− 0.52
Horizontal damping time	τ_x	$2.9\cdot10^{-3}$ s
Vertical damping time	τ_y	$2.9\cdot10^{-3}$ s
Bending radius	ρ	2.3 m
Bending field	B	1.6 T
Quad. maximum gradient	G_{max}	1.3 T/m
Average current	I	110 mA
Radiofrequency	$f_{r.f.}$	200 MHz
Harmonic number	h	15

ary for easy and high-efficiency injection, and its energy should be as high as possible, commensurately with a reasonable cost of the injection system. An on-energy injector allows continuous recovery of the particle lost in the storage ring which, operating at its maximum energy, avoids the undesired magnet field cycle and is less critical with respect to the instability phenomena. Therefore, an on-energy injector is strongly advised, since it is the main tool responsible for the duty cycle of the overall system.

In the present work, a 100 MeV microtron [7] has been considered for comparison as a possible injector at low energy. Its energy turns out to be the lowest possible and the limitations induced by low-energy injection weakly depend, in general, on the lattice chosen for the storage ring, as will be shown.

The machine lattice considered here is composed of four bending magnets, each deflecting the particle trajectory at an angle of 90°, with a field index $n = 0.5$, and 6

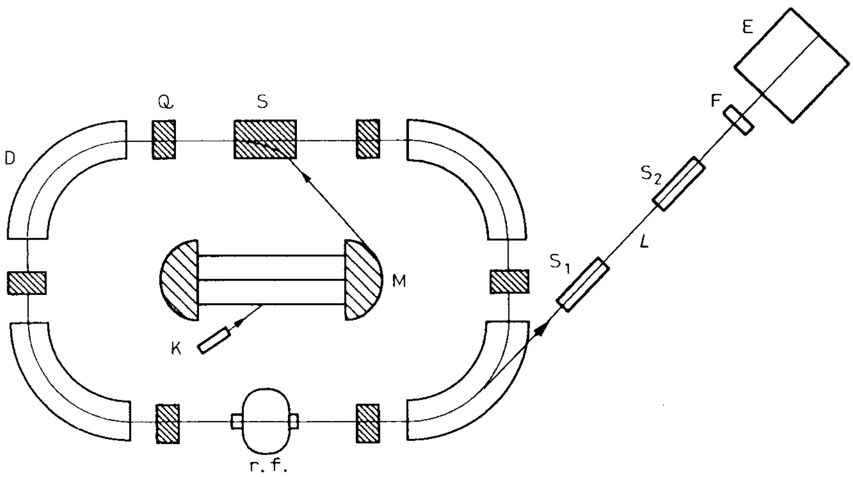

Fig. 5. – Machine schematic layout.

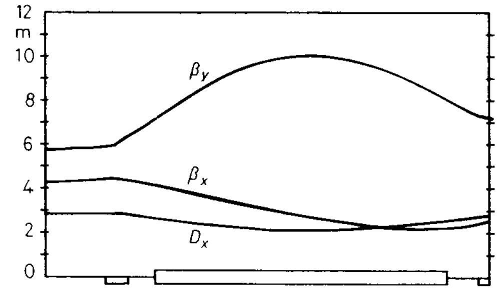

Fig. 6. – Machine optical functions (half period).

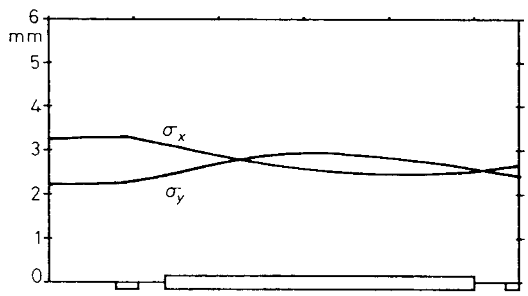

Fig. 7. – Transverse r.m.s. beam size.

quadrupoles focusing in the horizontal plane. It is a hybrid lattice focusing strongly in the horizontal plane and weakly in the vertical one.

A list of the main parameters of the ring is given in table II. The machine layout and the lattice optical functions are reported in fig. 5 and 6.

The beam size at one standard deviation is determined by the beam emittance and the machine optical functions. The resulting beam dimensions (horizontal with no coupling and vertical with full coupling) are shown in fig. 7 and satisfy everywhere the conditions

$$\sigma_x, \sigma_y \leq 2\,\text{mm}, \qquad \sigma_{y'} \leq 1\,\text{mrad},$$

which are necessary to obtain an acceptable resolution, minimize the run-out effects, keep the beam approximately constant in the region where radiation is delivered and ensure the extraction of almost identical light beams.

3·4. *Beam stability.* – The main concern in terms of beam stability is that of the destructive transverse instabilities arising in the single bunch dynamics, particularly the transverse «microwave» instability, whose threshold current is given by [8]

$$I_{\text{th}} = \frac{4\sqrt{\pi}\,\nu_{\text{s}}\,hE\sigma_{\text{l}}}{e\langle\beta\rangle R|Z_{\perp}|_0},$$

where ν_{s} is the synchrotron tune, h is the harmonic number, σ_{l} the bunch length, E the energy, R the average machine radius, $\langle\beta\rangle$ the average beta-function in the machine, and $|Z_\perp|_0$ the transverse impedance which is related to the longitudinal one by

$$|Z_\perp|_0 = \frac{2R}{b^2}\left[\frac{Z}{n}\right]_0 .$$

These limits on the storable current may be particularly severe for low injection energy. However, owing to the high momentum compaction, and assuming a beam pipe radius $b = 3\,\text{cm}$ and a longitudinal impedance $|Z_\perp/n|_0 = 5\,\Omega$ the «microwave» threshold is higher than the nominal current, even at an energy of 100 MeV. The head-tail instability may become dominant at this energy. A simple rise time expression of this instability is given by

$$\tau_{\text{ht}} = \frac{4\sqrt{2}\,h\alpha_c E\omega_r\sigma_l}{ec^2|Z_\perp|_0\,\xi I_0} ,$$

where ω_r is the resonant frequency of the equivalent broad-band resonator describing the short-range wake field interaction. This threshold is proportional to the ratio α_c/ξ, which assumes quite high natural values in our machines and means that this instability is damped by the synchrotron radiation damping at the operating energy. Since the low natural chromaticity ensures that the betatron frequencies lie within the stable working space of the Q-diagram, chromaticity correction could be unnecessary, with all the advantages related to the absence of nonlinearities (missing sextupoles) on the dynamical aperture of the storage ring and, therefore, on the beam lifetime.

At lower energies, the instability rise time is faster and balanced by a much weaker radiation damping so that the threshold dramatically drops to a quite low current. This makes chromaticity corrections necessary, although experience with electron machines shows that, due to Landau damping induced by octupole terms in the magnetic field and to interaction with residual ions in the vacuum chamber, the threshold estimation is rather pessimistic.

3·5. *Beam lifetime.* – The beam lifetime is determined by the combined effect of two processes: Touschek and elastic-gas scattering. These effects scale with E^2/I, so for a good lifetime it is preferable to operate at high beam energy and low current. At the operation energy, both effects are strongly reduced and the overall lifetime is limited to 18 h by elastic gas scattering.

Calculations performed at 100 MeV, the lowest possible injection energy, show that the loss rate due to elastic gas scattering halves the bunch population in a time $\tau_{\text{gas}} = 6\,\text{min}$, which is just acceptable for injection operation. The Touschek lifetime, calculated with the beam sizes enlarged by bunch-lengthening and multiple scattering, for the nominal current is five times larger.

4. – Conclusions.

We have analyzed the possibility of specifying a storage ring synchrotron radiation source dedicated to X-ray industrial lithography. The parameter optimizazion carried out shows that it is easy to obtain a throughput per beam line of 20-55 wafer/hour with a conventional bending magnet machine characterized by high reliability, ease of construction and maintenance, which are of primary importance for a source addressed to industrial purposes.

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