Design Study of a Synchrotron Radiation Source for X-ray Lithography

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Abstract

The design of an electron storage ring for Industrial X-ray Lithography is presented. The parameter optimization is based on the requirements set by lithography on the radiation spectrum and on beam source sizes, and on general specifications for the machine perfomance such as long life time, beam stability, and reliable operation at the design current. High field conventional magnets are used in the storage ring.

Introduction

X ray lithography (XRL) is a promising tool to meet the resolution and throughput requirements of giant scale integration.
It overcomes the fundamental limitations of diffraction and depth of field of the optical lithography, allowing the replication of patterns in the submicrometric region. Moreover, because XRL is a parallel printing process, a throughput more than one order of magnitude higher than that of the e-beam lithography process can be achieved. The principles of XRL are simple: the pattern of an X ray mask is replicated on an x ray resist deposited on a substrate (wafer); subsequent chemical and physical processes (ion etching, metallization, etc.) produce the desired final structure on the wafer . In general, several exposures of the same wafer with different masks are necessary to realize a practical device. Fig. 1 shows a typical step of the process.

Storage rings appear to be ideal X ray sources for this kind of application: the small dimension of the electron bunch minimizes the blurring due to penumbra effects, the high collimation of the photon beam reduces the geometrical distortion (run out) and the high intensity broadband spectrum allows for very short exposure times.

The main parameters of an industrial storage ring dedicated to XRL have to be determined so as to obtain a given throughput, having considered the beam line transmission coefficient T and the sensitivity S of the resist .
For typical values such as : T = 0.2 and S= 300 mj/cm^2, 50 mm mask diameter , and 200 mm wafer diameter, a throughput of about 50 wafers/hour per beam line - about ten times higher than that of a very fast e-beam system - is obtained, using a fast stepper, with a source that produces only about 1W/mrad of synchrotron radiation.

Storage ring parameters

Reliability : It is of primary importance for a machine intended for industry. It has to be accompanied by simplicity of construction and ease of maintenance so as to ensure a high efficiency of the production process.
It is mainly because of these requirements that we believe that conventional magnet technology has is the correct choice in the design of the first generation of lithography sources.

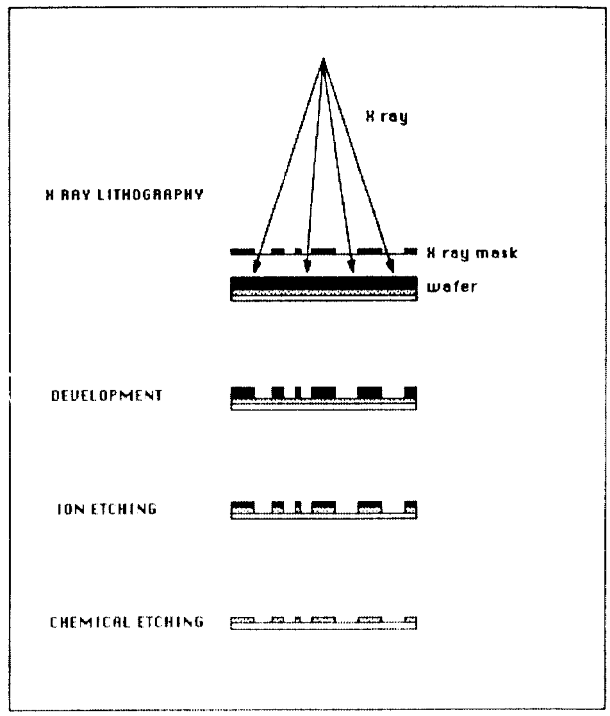

Fig.1 Typical step of a device production process based on X-ray lithography.

Critical Wavelength : The analysis of the transmission and absorption of spectral components through the beam line and the mask-wafer system shows that a critical wavelength of 10 Å is the best choice. The critical wavelength divides the power spectrum into two equal halves and is determined by the radius of curvature of the bending magnet ,ρ , and by the electron energy, E, through equation :

$$\lambda_c(\text{Å}) = 5.59\ \rho(m)/E^3(GeV) \qquad (1)$$

with :

$$\rho(m) = 3.33\ E(GeV)/B(T) \qquad (2)$$

Once the wavelength and the magnetic field are given, the magnet bending radius ρ and the energy E are uniquely determined. Since a high magnetic field leads to a shorter machine and has other advantages in terms of power consumption and injection time, a magnetic field B=1.6T, easily achievable with conventional technology, has been chosen, yielding a bending radius ρ = 2.3 m and a maximum energy of 1.1 GeV.

Power : The requirement of 200 mW/cm^2 on a chip which is tipically 10 meters away from the source leads to a source power emission of about 1 W/mrad when a reasonable transmission efficiency of 20% is assumed. This power level corresponds, for a 1.1 GeV storage ring, to an average stored current I_0 = 110 mA .

Machine Lattice : The machine lattice consists of four 90° bending magnets with a field index n= .5 , and of six horizontally focusing quadrupoles. It is a hybrid lattice providing strong focusing in the horizontal plane and weak focusing in the vertical one.
The list of the ring main parameters is given in Table I ; the lattice optical functions are plotted in fig. 2.

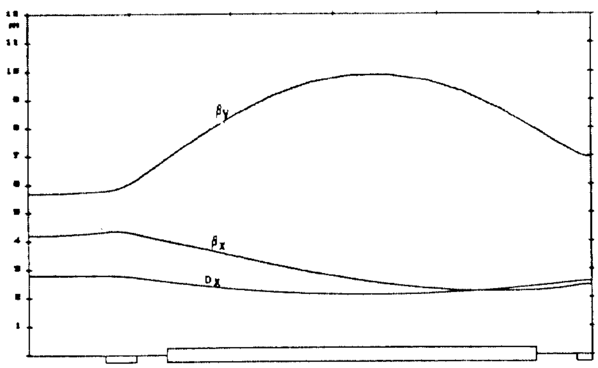

Fig.2 Storage ring optical functions (half period)

The beam size at one standard deviation is determined by the beam emittance and the machine optical functions.
The resulting beam dimensions satisfy everywhere the conditions :

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

that are necessary to obtain an acceptable resolution and that minimize run-out effects. It is worth noting that they stay approximately constant over the portion of trajectory from which the radiation originates, thus ensuring that the various extracted beams have practically identical characteristics.

Beam Stability

The main concern are single-bunch destructive transverse instabilities. The limits set to the storable current by the transverse "microwave" instability is particularly severe at the design injection energy of E_i =100 MeV since the threshold current is given by:

$$I_{th} = \frac{4\sqrt{\pi}\, \nu_s h\ E\ \sigma_l}{e \langle\beta\rangle R \left| Z_\perp \right|_0}$$

where ν_s is the synchrotron tune, h is the RF harmonic number, σ_l the bunch-length, E the energy, R the average machine radius, $<\beta>$ the average beta function in the machine, and $|Z_\perp|_0$ the transverse impedance, related to the longitudinal one by

$$|Z_\perp|_0 = \frac{2R}{b^2}\left(\frac{Z}{n}\right)_0$$

However, because of the large momentum compaction coefficient, for a beam pipe radius b=3 cm and a longitudinal impedance $|Z/n|_0$=5 Ω, the "microwave" instabily threshold current is higher than the nominal operating current.
The head-tail instability at injection energy has also been studied. A simple expression for the rise time of this instability is given by:

$$\tau_{ht} = \frac{4\sqrt{2}\ h\ \alpha_c E\ \omega_r \sigma_l}{e\ c^2 \left| Z_\perp \right|_0 \xi\ I_0}$$

Table I : Storage ring parameters

Energy	E	1.1	GeV
Length	L	22	m
Natural Emittance	ε_0	1.5 10^{-6}	m
Momentum spread	σ_p	6.2 10^{-4}	
Momentum compaction	α_c	.63	
Horizontal betatron number	Q_x	1.2	
Vertical betatron number	Q_y	0.6	
Horizontal cromaticity	ξ_x	-1.2	
Vertical cromaticity	ξ_y	-.52	
Horizontal damping time	τ_x	2.9 10^{-3}	s
Vertical damping time	τ_y	2.9 10^{-3}	s
Bending radius	ρ	2.3	m
Bending Field	B	1.6	T
Quad. max. gradient	G_{max}	1.3	T/m
Stored Current	I	110	mA
r.f. Frequency	f_{rf}	200	MHz
Harmonic number	h	15	

where ω_r is the resonant frequency of the equivalent broad band resonator describing the short-range wakefield interaction. At the operating energy this instability is damped by radiation damping, but it leads to very low thresholds at the injection energy. In order to suppress it, the ring natural chromaticity should be corrected. However experience with electron machine shows that normally the beam is strongly Landau-damped by the octupole terms in the magnetic field and by nonlinearities introduce by the fields of the residual-ion cloud. The results from a simple computation are therefore rather pessimistic and a full chromaticity correction could be unnecessary.
On the other hand a low, corrected chromaticity ensures that betatron frequencies will always lie within the working space of the Q-diagram.

Beam life-time

The beam life-time is determined by the combined effect of two processes: Touschek scattering and elastic-gas scattering The lifetimess scale with E^2/I so that it is preferable to operate at high energy and low current. Calculations show that, at injection energy, the loss rate due to the gas scattering produces a beam half life τ_{gas} = 6 min, still acceptable for injection. The Touschek half life, computed at the nominal current, taking into account the beam size enlargement produced by the longitudinal microwave instabilty (bunch lengthening and increased energy spread) and by multiple scattering, is five times larger.
At the operation energy both effects are strongly reduced and the overall life time, determined by elastic gas scattering, becomes 18 hrs.

Injection

In general it can be stated that, to ease injection and make it as efficient as possible, the injector beam should have low emittance, small energy spread, and an energy as close to the operating energy as affordable.
The 100 MeV recirculated microtron considered in the present design is characterized by a very small energy spread ($\sigma_p \cong 10^{-3}$) and rather low emittance. A 4 µs macropulse, carrying a total charge of 400 nC, is recirculated 18 times. The energy gain per passage, in an 8-cell SW accelerating section, is 5.5 MeV. At the end of the acceleration cycle the bunch is deflected and injected in the storage ring using a septum magnet and a fast kicker.

The 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; usually some optical element (mirrors, slits, filters) and appropriate detectors are also present.
The beam line vacuum must be kept at about the storage ring value, namely in the order of 1 nTorr.
The Be window separates the vacuum from the atmospheric pressure and also acts as a filter for the low energy photons (E<1KeV) that would otherwise heat up the mask and distort the image and also, by being absorbed on the surface of the resist possibly produce a non-uniform dissolution rate during the development process.

Since the Be window is quite brittle, a fast vacuum valve is installed, to protect the storage vacuum in case of window failure. The valve is located at the accelerator end of the beam line and is actuated by a a pressure sensor installed right next to the window.
A beam stopper prevents the X rays from entering the line when the latter is not in use or whenever an unsafe condition is detected.
A metal coated grazing incidence mirror is also foreseen to remove from the beam the high energy end of the photon beam that, by producing long ranged photoelectrons in the resist, would lower the contrast and degrade the resolution.

To evaluate the end performance of the system, detailed calculations of the photon spectrum and intensity have been carried out for a particular beam line configuration. The line includes a 12.5 µm thick Be window, a 1.5° grazing angle gold-coated mirror with s polarization and a 10 Å rms roughness. A 2 µm thick Si mask substrate has also been assumed.
Fig.4 shows various photon spectra along the beam line. The uppermost curve shows the spectrum after the 12.5 µm Berillium window; the next curve corresponds to a point downstream from the gold coated mirror (1.5° grazing angle, s polarization, 10 Å rms roughness) and the last to the end point, after the 2 µm of Silicon mask substrate. The values of the beam line transmission, the power incident on the resist and the estimated throughput with and without mirror are listed in Table II. The throughput has been estimated assuming a beam line length of 10 m, a wafer processing time by the stepper of 20", a resist sensitivity of 300 mJ/cm^2, a 50 mm diameter mask and wafer dimensions of 200 x 200 mm^2.

Table II: 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

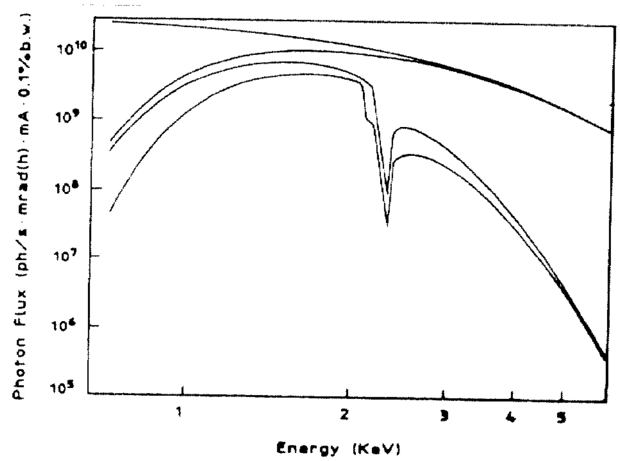

Fig.4 Effect of the beam line optical elements on the synchrotron radiation spectrum.

Conclusions

A design study of a storage ring synchrotron radiation source dedicated to X-ray industrial lithography is presented. The parameter optimization has been carried out for a machine with conventional bending magnets, to obtain a throughput per beam line of 20 to 55 wafer/hour, with special enphasis on reliability and ease of construction and mantainance, of primary importance for a source to be used in an industrial environement.

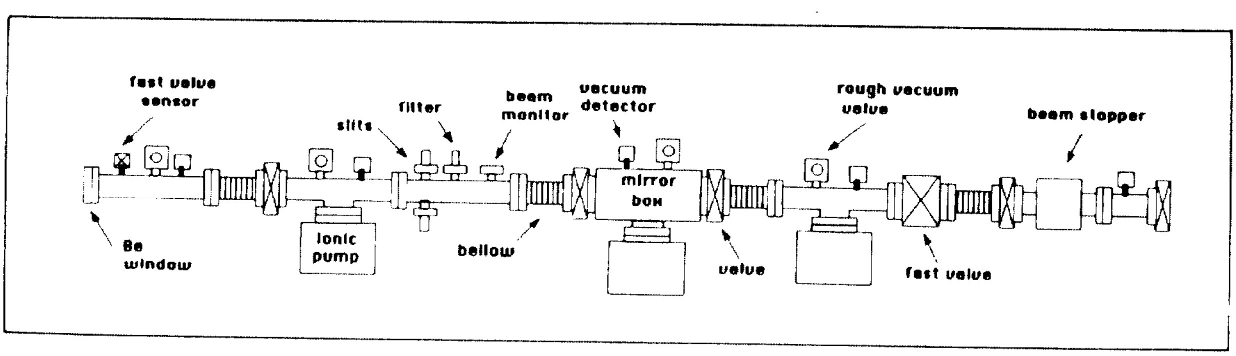

Fig.3 Layout of a typical beam line for X-ray lithography.