Superconducting Compact SR Source AURORA for X-ray Lithography

Hiromitsu NAKABUSHI

Quantum Equipment Division
Sumitomo Heavy Industries, Ltd.
2-1-1 Yato-cho, Tanashi-city, Tokyo 188, Japan

Abstract- Synchrotron X-ray lithography meets sub-half-μm semiconductor device requirements. Sumitomo Heavy Industries is now developing X-ray lithography system, which consists of a compact SR source, X-ray beam lines and X-ray steppers. This SR source, called AURORA, is composed of a 150-MeV racetrack microtron injector and a 650-MeV electron storage ring. The ring is only a superconducting weak-focusing single-magnet of 1-m orbital diameter. The critical wavelength is 1.02 nm. Sixteen beam ports are available for X-ray lithography from the ring. The construction of the prototype machine has been completed in our Tanashi Works, Tokyo. The specified performances have been almost attained recently. The evaluation study of X-ray lithography system is now being performed, in which is used a newly-developed X-ray stepper incorporated with chromatic bifocus alignment technique.

1. INTRODUCTION

Optical lithography, the present production technology of LSI circuits, continues to extend its ability to critical dimensions below 0.5 μm. Some promising innovations, such as phase shifting mask [1], planarizing resist layer and multilayer resist methods, may be able to extend its limiting linewidths as low as 0.25 μm, narrow enough to produce the next two generations of circuits (16-Mbit and 64-Mbit DRAM chips). But, these gains are being achieved with increased process complexity and low process latitude, and the chip production costs may become beyond permissible levels.

To raise further integration to 256 Mbits or more will probably require wavelengths typical of soft X-rays rather than ultraviolet light. X-ray lithography [2] has a variety of technical advantages over optical lithography, that is, high resolution with large depth of focus, simple resist scheme, good linewidth control, transparency of defects and large exposure field. The leading contender among X-ray sources is the synchrotron radiation (SR) from electron storage rings, as it is the only source that delivers the high flux needed for productive throughputs.

2. DEVELOPMENT OF COMPACT SUPERCONDUCTING SR RINGS

The desirable X-ray wavelengths for the exposure seem to be in the range 0.7 - 1.2 nm, which results from a compromise in which the photoelectron range and the diffraction blurring are both within allowable limits [3]. Accordingly, SR sources developed for industrial X-ray lithography are so-called soft X-ray rings having critical wavelengths around 1 nm and will have to fit into industrial settings, where floor space is at a premium. Conventional SR sources are too large for installation in semiconductor factories. Superconducting SR sources can be relatively compact and are now being extensively developed in several companies in the world [4].

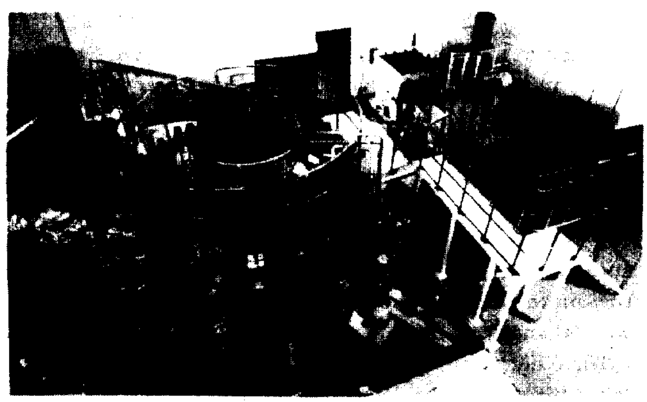

Fig.1. Layout of the superconducting compact SR source AURORA, consisting of a 150-MeV racetrack microtron, a 650-MeV electron storage ring and X-ray beam lines.

The accelerator technologies developed so far in conventional synchrotrons and storage rings can mostly be applied to superconducting rings with separate sector magnets linked by straight sections. Most of compact superconducting rings under development or operation are of separate sector configurations. The two-sector racetrack configuration has been adopted by COSY [5], SXLS [6], Helios [7] and Super-ALIS [8].

The smallest electron storage ring should consist of a single superconducting magnet of axial symmetry, giving a circular electron orbit. In addition, a circular type superconducting magnet has advantages in both the design and fabrication. Sumitomo Heavy Industries (SHI) has developed a compact SR source AURORA [9], composed of a single circular superconducting weak-focusing magnet with an electron storage orbit of 1-m diameter. To realize this type of the ring, we have intro-

Table 1. Main design parameters of the injector for AURORA

Type	Racetrack type microtron	
Energy	150	MeV
Peak current	5	mA
Pulse width	1.0	μsec
Energy resolution	0.1	%
Repetition rate	10-180	Hz
Beam emittance	1π	mm-mrad

duced a half-integer resonance injection method [10], and have developed unique technical components for superconducting magnet, beam-injection, RF-acceleration and ultrahigh-vacuum systems.

3. DESCRIPTION OF AURORA

AURORA includes a 150-MeV racetrack microtron as an injector, a 650-MeV superconducting single-magnet electron storage ring and X-ray beam lines. The construction of the prototype machine has been completed in our facility in Tanashi, Tokyo, as is shown in Fig. 1.

3.1. Injector Microtron

A racetrack microtron is of recirculating type of accelerator and has advantages of good beam quality and small machine size. There is a 108-MeV racetrack microtron used as the injector of Aladdin in SRC, University of Wisconsin [11]. We have adopted the similar concept as this machine

In the racetrack microtron, electrons produced in an electron gun are boosted up to an energy of 120 keV, and are injected into an acceleration column. The electrons gain an energy of 6 MeV in passing through the column, and return after the flight in two main 180° bending magnets. The electron beam of 150-MeV energy is finally extracted after 25 laps. The main design parameters of the injector microtron are shown in Table 1.

In April of 1989, we succeeded in the first beam acceleration of the microtron [12]. But, the output beam current was far less than the designed value and insufficient for the storage ring to accumulate the designed current. Therefore the improvement program of the microtron started soon and the remodeling was finished in late 1990 [13]. The improvements were quite successful and now the revised microtron has achieved the design specifications with ease. The operation has proved its reliablity and stability.

3.2. Superconducting Electron Storage Ring

The storage ring is a superconducting weak-focusing, single-magnet one, having an outside diameter of 3 m and height of 2.2 m. 150-MeV electrons are injected into the ring under a magnetic field of 1.0 T. The injected electrons are accelerated to an energy of 650 MeV and then stored on a circular orbit of 1-m diameter in a magnetic field of 4.3 T. The designed maximum storage current is 300 mA, which corresponds to 2×10^{10} stored electrons, because the circulating frequency of the stored electrons is about 100 MHz. The main design parameters of the electron storage ring are shown in Table 2.

Table 2. Main design parameters of the electron storage ring for AURORA.

Type	Superconducting weak-focusing single magnet	
Energy	650	MeV
Beam current	300	mA
Critical wavelength	1.02	nm
Magnetic field	4.34	T
Bending radius	0.5	m
Field index	0.25	
RF frequency	190.86	MHz
Harmonic number	2	
RF voltage	120	kV

The ring is mainly divided into a superconducting magnet, a beam injection system, an RF acceleration cavity and an ultrahigh vacuum chamber. The magnet consists of superconducting coils, iorn poles and yokes. The coils need 1.9×10^6 A-turn to generate a field of 4.3 T. The yokes reduce not only the required A-turn but also the electromagnetic force between the coils, and furthermore work as magnetic and radiation shieldings. The beam injection system includes magnetic channels, electrostatic inflectors and a perturbator. The perturbator generates an octupole magnetic field, and the half-integer resonance orbit is generated by superimposing the field on the main weak-focusing field (field index n = 0.72). The injected beam is captured by the stable equilibrium orbit through a decay process of the perturbing field. The RF cavity consists of two $\lambda/4$ coaxial resonators which are curved along the central orbit. The built-in cryosorption pump evacuates the vacuum chamber to less than 1×10^{-9} Torr. The components located along the circular orbit, such as the beam duct and the RF cavity, have slits to release SR from stored electrons.

3.3. SR Source Characteristics

Figure 2 shows the calculated radiation spectra of SR from the ring. The ordinate gives the irradiation powers in mW per a stored current of 1 mA per a horizontal divergence angle of 1 mrad per 10^{-3} of the wavelength considered. The critical wavelength λ_c is 1.02 nm at a storage energy of 650 MeV, and the irradiation power is 1.5 W per a horizontal divergence angle of 1 mrad at a stored current of 300 mA.

The beam size of the stored electrons is uniform throughout the circumference, because the ring is of

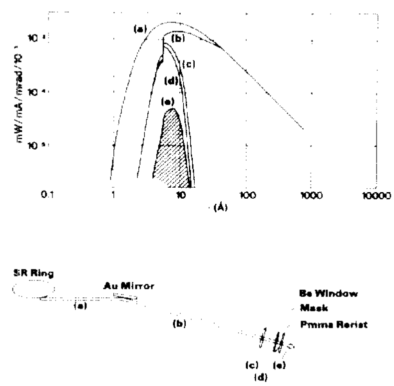

Fig.2. The calculated power spectra of SR in a X-ray lithographic system including the compact SR source AURORA;
(a) direct SR from the stored electrons,
(b) after reflection by a mirror,
(c) after passing through a thin Be window,
(d) after passing through a mask, and
(e) absorbed SR into a resist(PMMA 1μm).

weak-focusing circular type. The spatial widths of the stored electron beam are estimated to be σ_r = 1.4 mm in the radial direction and σ_z = 0.17 mm in the vertical direction, and the angular widths $\sigma_{r'}$ = 2.2 mrad and $\sigma_{z'}$ = 0.17 mrad, assuming Gaussian distributions. The angular distribution of SR emission from a single electron is assumed to be a Gaussian form of σ_R = 0.38 mrad. The source size of the SR light emitted from the ring is the same as the electron beam cross section, while the divergence angles are obtained by the square root of the sum of the electron beam angular width and the SR emission angle, squared respectively.

3.4. X-ray Beam Line

The X-ray beam line modifies and carries the X-rays emitted from the ring, to a clean room where the lithographic exposure takes place on a stepper. The wafer exposure position is located at a distance of 7 m from the source. A Pt-coated reflecting mirror is incorporated at a distance of 3 m from the source. The mirror bends down the X-ray beam by 2.4°. The vertical expansion of SR is made by rotating the mirror vertically. The stepper end of the beam line terminates in a Be window (25-μm thickness) which separates the beam line vacuum from the ambient pressure of the stepper. In case that the thin window could break from stress, safty and control instruments are installed. A sensor near the window detects the vacuum change and signals an actuator to close a fast closing valve upstream the mirror chamber, while an acoustic delay line slows the shock wave. As shown in curve c in Fig. 2, the desirable wavelength region is selected by the reflecting mirror and the Be window.

A maximum of sixteen beam lines can be utilized from the ring, while in the prototype ring only three lines are planned to be incorporated.

4. MACHINE AND APPLICATION STUDIES

AURORA's SR was first observed at the end of 1989. This success has proved that the half-integer resonance injection method works well. But, the storage current was limited by the injected current from the microtron. The machine study has been continued including the improvement program of the microtron. We have recently succeeded in the current storage of more than 300 mA at full energy. The beam lifetime is 3 hr at 300 mA, still increasing. Through these two years of operation, the optimization of operations has successfully made and the sequential operations of injection, ramping and storage can be automatically made.

The evaluation study of X-ray lithography system is now being performed, for which a new X-ray proximity stepper has been developed [14]. The X-ray stepper using SR, emitted in a horizontal direction, is of vertically moving type. A noble technique using a chromatic bifocus optics has been introduced for the fine alignment between mask and wafer, by which the overlay accuracy has been confirmed to be less than 80 nm.

5. REFERENCES

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