The Development of SOR Lithography Technology

Sunao ISHIHARA
NTT LSI Laboratories

Abstract

This paper reviews NTT Laboratories' research and development of x-ray lithography during the last ten years since the application of synchrotron orbital radiation(SOR). First, the historical background of x-ray lithography research, NTT's research programs on synchrotron x-ray lithography(SOR lithography), and the current status of NTT's SOR lithography system are overviewed. Then, the key elements of SOR lithography system are reviewed, including the electron storage ring, the x-ray stepper, and the x-ray mask. Finally the application of SOR lithography technology to device fabrication is reported.

I. Introduction

The ongoing trend towards smaller feature size and higher integration scale in LSI is bringing the era of system-on-chip ever closer to reality. The NTT LSI Laboratories have been engaged in the research and development of fundamental technologies in this field in order to realize high-performance LSIs for the telecommunication systems of tomorrow. Advancement in LSI performance largely depends on how small the feature size of circuit patterns can be. Up to now, ultraviolet-based optical lithography has effectively halved the minimum feature size every six years. Reductions in wavelength, increased numerical apertures in projection lenses, and other resolution enhancement techniques have been expanding the capability of optical lithography. Sooner or later, however, optical lithography will reach its resolution limit determined by the wavelength and depth of focus of the light. In 1972, Spears and Smith published papers proposing the use of soft x-rays for lithography,(1), (2) applying simple 1 : 1 proximity printing. The x-ray mask is made of a thin membrane transparent to x-rays, on which mask patterns are formed with a heavy metal that absorbs x-rays. Since x-ray lithography uses a much shorter wavelength than that used in optical lithography, it is almost free from resolution-degrading factors such as diffraction and interference. Thus it can, in principle, provide a deeper depth of focus and a higher resolution. The NTT Research Laboratories began research on x-ray lithography in 1974, and have been continuing this research as a fundamental technology for LSI development. The application of SOR to lithography has brought about technical innovation and made significant advances in x-ray lithography research.

This paper reviews, in outline form, the research projects undertaken by NTT, describing the historical background, the objectives of the projects, and technical results.

II. Historical background

1. Early research work

NTT Electrical Communication Laboratories (now the NTT LSI Laboratories) started x-ray lithography research in 1974, when NTT launched full-scale R&D of LSI technology. In the early stages, characteristic x-rays generated by an electron bombardment x-ray source were utilized for exposure. In other words, proximity printing was performed using divergent x-rays from a point source. Because the intensity of these x-rays was low, the x-ray power on the wafer was extremely low, less than 1 mW. Thus, each exposure process took hours. The initial masks broke easily because of their weak membrane, while mask flatness and x-ray absorber placement accuracy were also poor. These shortcomings meant that the exposure experiment was a time-consuming process, and it was difficult to analyze error factors in evaluating the accuracy of pattern overlays. The first-stage equipment employed full wafer exposure because the wafers were small. It was in about 1980 that the introduction of a step-and-repeat scheme provided the first breakthrough: an x-ray lithography system. This new method offered several benefits and improved the performance of the x-ray aligner.(3) These benefits included increased x-ray mask accuracy due to the smaller exposure fields, and stronger x-ray power resulting from the shorter source distance. However, the x-ray exposure time was still much longer than that of optical lithography, and pattern overlay accuracy was insufficient for the reproduction of fine patterns. Despite these drawbacks, x-ray lithography was applied to test device fabrication at that date.(4)

2. Movement to SOR lithography

The most innovative advance in x-ray lithography came at the beginning of the 1980s with the application of synchrotron orbital radiation(SOR). SOR offers such advantages as high brightness, excellent collimation, and good stability, while providing a choice of wavelength within a broad spectrum. By applying these features effectively in using SOR as an x-ray source, a dramatic improvement in the performance of x-ray lithography was achieved. The x-ray power intensity on the wafers was increased by as much as 100times over conventional electron bombardment x-rays. This combined with the development of more sensitive resist dramatically decreased the exposure time. In addition, using collimated light minimized blur and run-out, resulting in greatly enhanced resolution and exposure accuracy.

Synchrotron x-ray lithography research was carried out from an early stage using giant synchrotron radiation facilities.(5), (6) In the United States, IBM conducted a range of experiments using the National Synchrotron Light Source(NSLS) at the Brookhaven National Laboratory,(7), (8) and the Center for X-ray Lithography(CXrL) was established at the University of Wisconsin-Madison somewhat later based on use of the ALADDIN ring. In Europe, the Fraunhofer Institute carried out its own research programs using the Berlin Electron Storage Ring for Synchrotron Radiation (BESSY).(9) In Japan, the Photon Factory(PF) at the National Laboratory for High-Energy Physics(KEK) was made available for research use. NTT and several electronics firms constructed the beamlines for x-ray lithography research. These various research efforts confirmed the excellent resolution and exposure stability offered by synchrotron radiation, and underlined its potential as a commercial production technology once the size and cost of the electron storage rings could be minimized. At that point, the ultimate objective of the research shifted from pure research work to LSI manufacturing technology for industry. Japan established SORTEC, a joint institute dedicated to accelerating x-ray lithography R&D. Heavy industry led the way in developing compact electron storage rings suitable for commercial production. These efforts led to the development of electron storage rings that are currently in use.(10)~(12) R&D of a vertical x-ray stepper,(13)~(18) high-quality x-ray mask production,(19), (20) an electron-beam writer for x-ray masks,(21) defect inspection equipment for x-ray masks,(22) and x-ray mask repair equipment(23) was among the work being carried out, primarily in the United States and Japan. Both IBM and NTT completed integrated x-ray lithography facilities, including a compact ring and clean room, for use as an infrastructure for full-fledged research focused on device fabrication by x-ray lithography.(24)~(30)

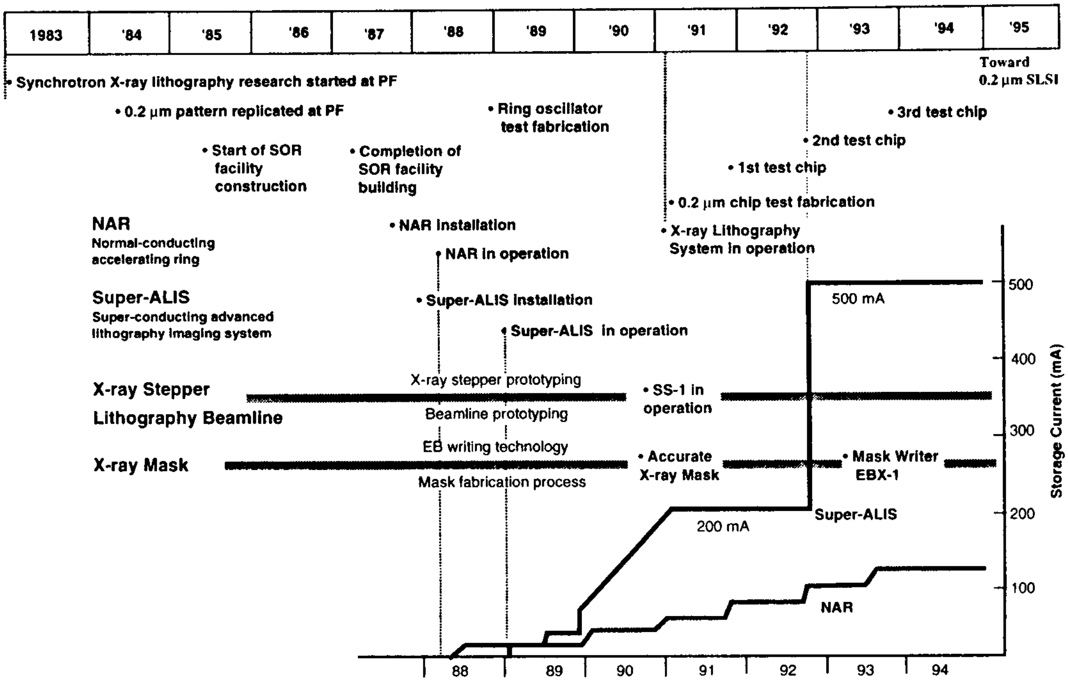
3. Full-scale research on SOR lithography

In early 1984, NTT decided to start full-scale R&D of SOR lithography based on the research results obtained at the PF. Projects included the development of a compact electron storage ring and the construction of an SOR facility at the Atsugi Electrical Communications Laboratories(now the NTT LSI Laboratories). It was clear that the fundamental technology for advanced LSI was lithography. It was also recognized that SOR lithography had the potential to break through the resolution limit of optical lithography. The initial plan was set to establish facilities for LSI R&D by 1990, anticipating commercial introduction into manufacturing in the second half of the 1990s. R&D programs were started to develop a compact electron storage ring, beam lines, x-ray steppers, an electron-beam mask writer, and x-ray masks. The compact storage ring was the initial development target. While development of a ring was uncharted territory for the NTT Labs, the design work was executed based on the electron beam technology obtained through experience in developing electron-beam exposure systems. The labs also worked to significantly enhance the x-ray mask and x-ray stepper techinologies that had been developed over the previous ten years. Figure 1 outlines the progress of NTT's R&D after launching its SOR lithography research project. An SOR system was designed, manufactured, and installed, as well as the facility building. In 1988, SOR was successfully extracted from the NAR(normal-conducting accelerating ring).(31) In the next year, the first ring oscillator circuits was fabricated using the NAR, x-ray masks, and an x-ray stepper prototype.(26) In early 1989, SOR was extracted from the Super-ALIS(super-conducting advanced lithography imaging system),(10) which is the first time ever that SOR had been derived from a super-conducting compact ring. Since then, the storage current has been steadily increasing. Combined with a in-house developed x-ray mask and x-ray stepper, an advanced SOR lithography system became available in an integrated manner(32) in 1991. Following that, a series of test device fabrications was carried out.(26)~(29) The SOR lithography system has continued to be enhanced and further stabilized based on feedback from process engineers, the main users of this system.

III. SOR Lithography System

1. Design of the x-ray lithography system

Table 1 shows the main specifications of the SOR lithography system. The system is designed to achieve a resolution with critical dimension control of $0.2 \pm 0.02 \mu m$ and an over-



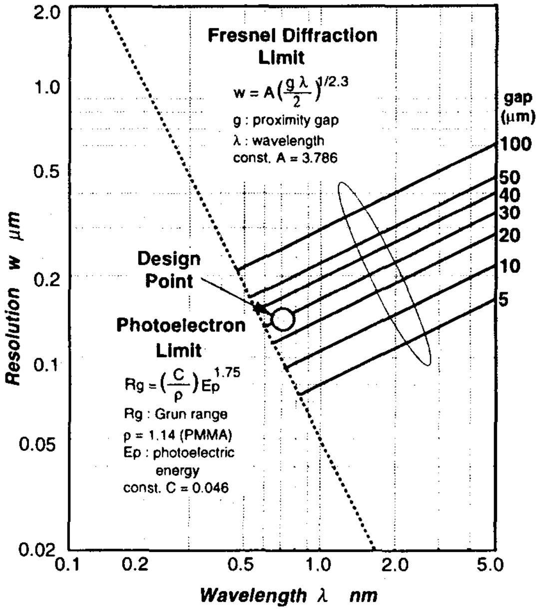
〈Fig. 1〉 R&D of synchrotron x-ray lithography at NTT Labs.

lay accuracy of ±0.1μm using an exposure wavelength of 0.7-1nm and an exposure gap of 30μm. In designing the resolution capability of an x-ray lithography system, the following factors should be taken into account; penumbral blur, Fresnel diffraction at the edge of the mask absorber, secondary electrons emitted from the resist and underlying substrate as a result of x-ray radiation, and the contrast of the mask to the x-rays. SOR minimizes the effect of penumbral blur but increases the influence of Fresnel diffraction. This is because SOR is coherent light with strong directivity. Since the Fresnel diffraction increases in proportion to the square of the product of the proximity gap and the wavelength, a higher resolution can be achieved by using a shorter wavelength and a narrower gap for exposure. However, short-wavelength x-rays have high radiation energy and, therefore, increase the volume of secondary electrons emitted from the substrate, which in turn degrades resolution.(33), (34) Figure 2 illustrates the relations between the resolution-limiting factors. The estimated resolution limit is 0.2μm with an exposure gap of 50μm, and 0.15μm with a 30μm gap, given an exposure wavelength of 0.7-1nm. The circle in the figure shows the design point of the SOR lithography system. Although x-ray lithography offers excellent critical-dimension control, the extremely small target feature size involved makes it necessary to maintain uniformity in the x-ray radiation intensity.

〈**Table 1**〉 Main specifications of the SOR lithography system.

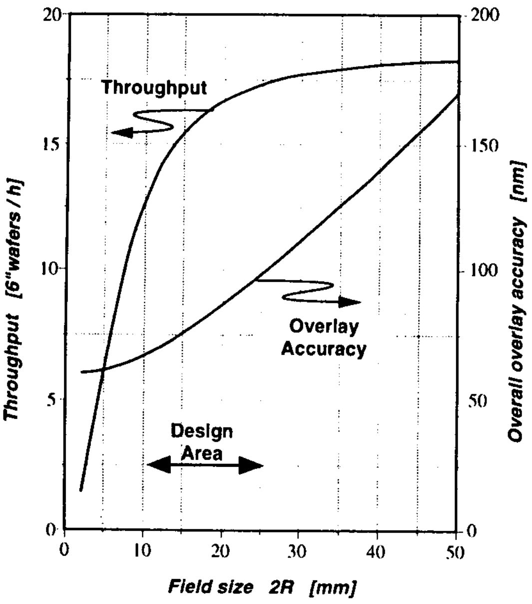
Resolution/Accuracy Overlay Accuracy	0.2±0.02μm ±0.1μm
Wavelength	0.7-1nm
Exposure gap	20-40μm(typ. 30μm)
Field size	up ;to 25×25mm mirror scanning
Exposure Environment	in air
Wafer size	6 inches

The trade-off between pattern overlay accuracy and throughput, both of which are affected by field size(see Figure 3), should also be taken into account. In the pattern overlay process, run-out and rotational errors, as well as physical errors in x-ray masks, are functions of the exposure-field size, which means that overlay accuracy decreases as field size increases. On the other hand, a reduction in field size sharply increases the number of wafer step-positioning and alignment, thus decreasing throughput. Throughput improves with in-



〈**Fig. 2**〉 Resolution capability of SOR lithography system.

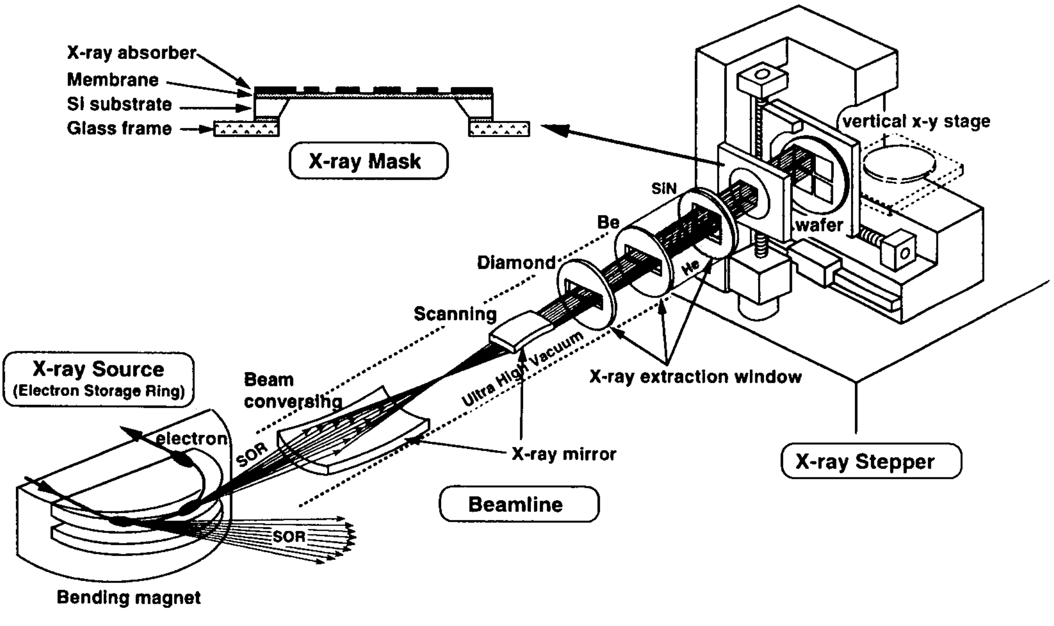
creases in field size, although the improvement gradually saturates with exposure time. The SOR lithography system is designed to achieve an overlay accuracy of ±0.1μm for, at most, 1-inch-square exposure field. Components of the system are designed to deliver performance that maximizes throughput under these conditions.



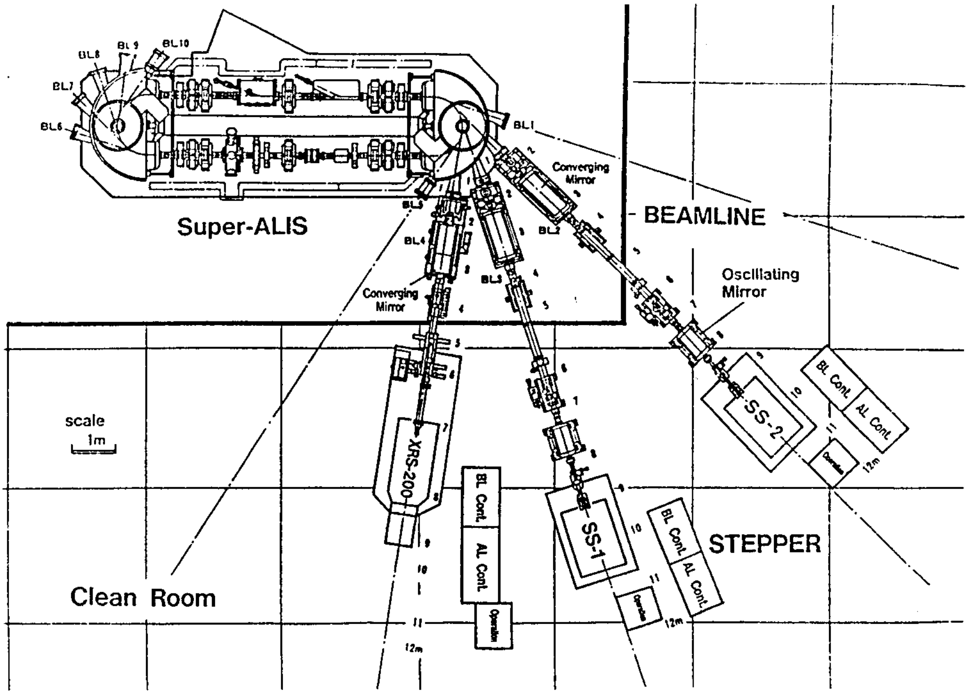
〈Fig. 3〉 Trade-off between accuracy and throughput in SOR lithography system.

2. Key elements

Figure 4 gives a schematic view of the SOR lithography system. Figure 5 shows the layout of the SOR lithography facility. A compact electron storage ring is used as the x-ray source, from which a beamline extends into a clean room. At the other end of the beamline is an x-ray stepper, in which an x-ray mask is held vertically and wafers are exposed in succession. This paper outlines the main features



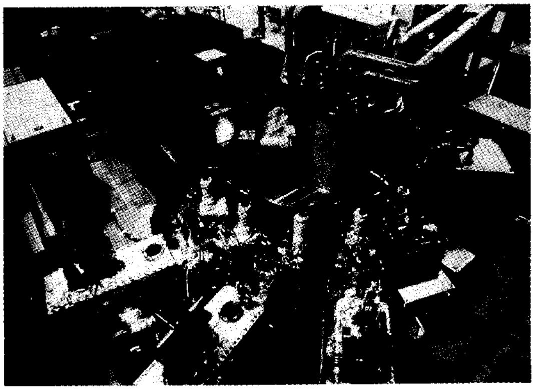
〈Fig. 4〉 Schematic of the SOR lithography system.



〈Fig. 5〉 Equipment layout at the NTT SOR lithography facility.

of these various elements and discusses the current status of research.

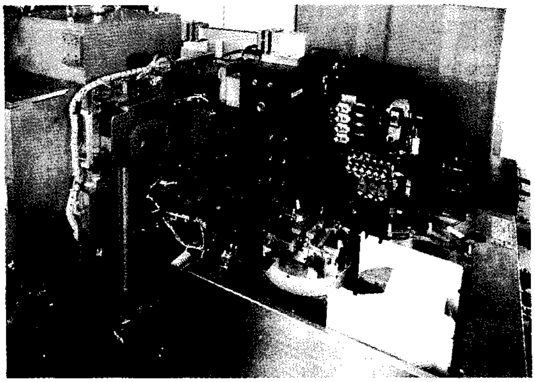
The NTT SOR facility consists of a linear accelerator(Linac), two electron storage rings (Super-ALIS and NAR), and beam transport systems linking these systems. Super-ALIS is a dedicated x-ray source used for lithography.(10) Figure 6 shows a photograph of the Super-ALIS with three beamlines. A racetrack-shaped compact ring with super conducting bending magnets on both ends, Super-ALIS is designed to emit a peak wavelength of about 0.7nm, which is appropriate for lithography, at a final energy of 600MeV. This system has a low-energy injection mode in which 15-MeV electrons are injected directly from the Linac to Super-ALIS, and a high-energy injection mode which uses NAR as a booster synchrotron. The low-energy injection mode achieves a stored current of 200mA, while the high-energy injection mode achieves a stored current of 500mA. Super-ALIS now offers users SOR with an initial stored current of 500 mA.



〈Fig. 6〉 Superconducting compact electron storage ring Super-ALIS.

The role of the beamline is to transmit x-rays onto the entire exposure field with minimum loss and a maximum degree of uniformity. The beamline is also capable of selecting the exposure wavelength. In order to satisfy function and performance requirements, the beamline uses two x-ray mirrors : one for horizontal convergence to increase x-ray intensity (the vacuum chambers of the 1st mirror are seen in Fig. 6) and the other for both x-ray beam collimation and vertical scanning of the exposure beams by mirror vibration. The 0.7-1nm beams are selectively extracted by filtering out shorter wavelength beams by x-ray mirror reflection and longer-wavelength beams by beryllium window absorption. In an attempt to maximize x-ray intensity loss in reflection, an ion-assisted evaporation method has been developed for coating the x-ray mirror with platinum thin film. This has succeeded in increasing the x-ray mirror's reflectivity at an incidence angle of 1.8 to over 50%, close to its theoretical value.

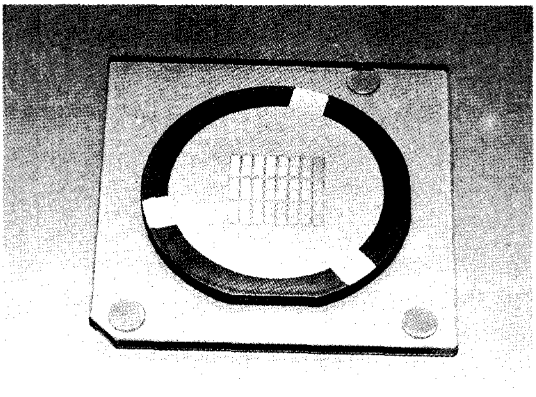
The principal requirements for an x-ray stepper are a small exposure gap and high alignment accuracy. In order to satisfy these requirements, an x-ray stepper called SS-1 has been developed by combining novel friction-free xy stage technology and an optical- heterodyne alignment method. The main part of the SS-1 is shown in Fig. 7. The xy stage fully utilizes air lubrication, including air-bearing lead screws, and achieves both nanometer-level step positioning and long stroke drive. This contributes to making the stage compact and lightweight, offering high operating speed and positioning accuracy. The positioning control is executed with a precision of 5nm. Optical-heterodyne alignment is achieved through the use of two incident laser beams with slightly different wavelengths. The beams illuminate the gratings on an x-ray mask and a wafer, and the beams diffracted by the gratings interfere with each other. The phase of the resulting beat signals is then detected. The phase difference between the signals from the x-ray mask and those from the wafer corresponds to the lateral displacement between them. This method plays a vital role in achieving high alignment accuracy because it has a nanometer level detection sensitivity and is less sensitive to accuracy-degrading factors such as changes in wafer surface reflection and atmospheric fluctuation. From many exposure experiments designed to evaluate the alignment capability, the x-ray stepper SS-1 has achieved an alignment repeatability of ± 25nm. In addition. the size of the x-ray stepper has been reduced by adopting a mechanism for loading wafers from the back of the stepper, and the wafer exposure process has fully computerized. The x-ray stepper SS-1 is already being used in the fabrication of many test devices.



〈Fig. 7〉 Main part of the x-ray stepper SS-1.

3. X-ray masks(20)

For the x-ray mask fabrication process, techniques were selected to be similar to the LSI process techniques already developed in the laboratory. A photograph of an x-ray mask fabricated in the NTT Labs is shown in Fig. 8. The membrane is SiN and the x-ray absorber is Ta. The mask patterns are formed through an etching process. The major issues in x-ray mask development are reducing absorber pattern feature size, improving flatness, and enhancing the accuracy of absorber pattern placement. The last issue is particularly important because mask accuracy is a decisive factor in determining the viability of x-ray lithography, which remains, in essence, a 1 : 1 exposure process. As is clear from the x-ray mask structure and the method of fabrication, the major error factors affecting the mask pattern position accuracy are pattern placement error generated in the electron-beam writing process and distortion generated in the mask fabrication process. The distortion can be classified into two types: position shifts generated by absorber and membrane stress during the back-etching process, and those produced when the silicon substrate is mounted onto a glass frame.



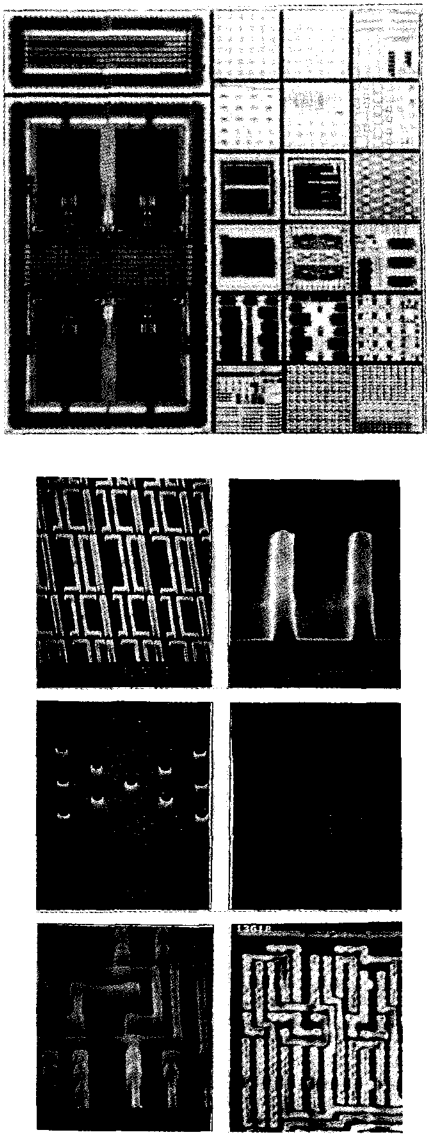
〈**Fig. 8**〉 Photograph of an NTT x-ray mask.

Electron-beam writing accuracy has been further improved through the development of an advanced writing system. The newly-developed EBX-1 is a dedicated x-ray mask writing system. It features an improved electron-beam edge sharpness(50nm) for higher resolution, an improved beam-positioning resolution(5nm) to correct deflection distortion, and improved wafer flatening capability with an electrostatic wafer chuck. The EBX-1 achieves an overall pattern placement accuracy of 50nm in 3σ. The electron-beam system uses a variable-shaped beam, and has a throughput significantly higher than that of the vector-scanning system. With regard to the electron-beam writing process, a multiple writing procedure has been developed that improves accuracy by writing the same pattern using various pattern data in a multiplexed fashion. The accuracy is improved by averaging the EB system's beam drifts, charge-up, and beam current fluctuations. A quadruple writing scheme has been shown to achieve twice the accuracy of the previous single-writing scheme in terms of line width, pattern placement, and stitching.

To minimize distortion generated during mask fabrication, processing conditions have been optimized to control the stress in films. The extent of the position shifts generated during back-etching depends largely on the ability to control the stress on both the membrane and absorber thin film. At present, stress-control conditions are less than 5×10^8dyn/cm^2 for the SiN membrane and less than 1×10^8dyn/cm^2 for the Ta absorber. Furthermore, to minimize distortion due to adhesion during the process of mounting the x-ray mask substrate on a glass frame, an effective technique for one-point adhesion has been developed.

4. Application to test-device fabrication(26)~(29)

In terms of the resist process, the advantages of x-ray lithography include high resolution, good depth of focus, and high process latitude. To take advantage of these benefits, we have developed a 0.2μm LSI x-ray lithography resist process using EXP and CANI positive resist developed in-house, and commercially available SAL601 negative resist. The resist process achieves an isolated pattern(gate layer) resolution of 0.1μm, a line-and-space pattern(wiring layer) resolution of 0.15 μm, and a hole pattern(contact hole layer) resolution of 0.1μm. Experimental study shows that the exposure-dose margin allowed for 0.2μm patterns is ±20% to restrict variations in line width to less than ±10% of the design size. The capability for linewidth control in the test-device fabrication processes was evaluated to be less than ±20nm in 3σ. The SOR lithography system and the resist process technology have been applied to the fabrication of various test devices in order to confirm their feasibility. To fully exploit the high resolution of x-ray lithography, the technology has been applied to fabricate devices with pattern sizes of less than 0.2μm, and the integration scale of devices has gradually increased. In particular, the installation of the Super-ALIS super-conducting ring, the SS-1 x-ray stepper, and the availability of high-accuracy x-ray masks has greatly accelerated SOR lithography application to full-scale LSI device development. Figure 9 shows an example of the test devices fabricated by SOR lithography. In addition to confirming the feasibility of SOR lithography, test-device fabrication has been very effective in improving x-ray masks and other lithography system elements, and in overcoming a number of technical obstacles. As a result, the SOR lithography technology is becoming more practical for LSI fabrication.



〈Fig. 9〉 SEM photographs of a LSI test chip fabricated by SOR lithography.

IV. Summary

This paper has outlined the background of x-ray lithography, and presented an overview of NTT's R&D of SOR lithography technology up to the present. The breadth of research and development projects has resulted in SOR lithography systems able to test-fabricate LSIs, and the technologies involved are now close to practical feasibility. It should, of course, be remembered that NTT does not manufacture semiconductors or LSI production equipment on a commercial basis, and that its research on key LSIs for telecommunication systems is not intended to lead to volume production of general use LSIs. Rather, the principal objective of this research on x-ray lithography is to provide industry with the most advanced manufacturing technologies for both telecommunication-use LSIs and LSIs for other applications. NTT will further its research and development of communications-use LSIs in the ongoing advancement of technology, and hopes that its R&D activities will continue its contribute to industry.

Reference

〔1〕 D. L. Spears and H. 1. Smith : High Precision Pattern Replication Using Soft X-rays, Electron. Lett., 8, No.4, 102, 1972.

〔2〕 D. L. Spears and H. I. Smith : X-Ray Lithography - A New High Resolution Replication Process. Solid State Technol., 15. No. 7, 21, 1972.

〔3〕 T. Hayasaka, S. Ishihara, H. Kinoshita and N. Takeuchi : A step-and-repeat x-ray exposure system for 0.51μm pattern replication, J. Vac. Sci. Technol., B(3), 6, 1581, 1985.

〔4〕 K. Deguchi, K. Komatsu, H. Namatsu, M. Sekimoto, M. Miyake and K. Hirata : Step-and-Repeat X ray/Photo Hybrid Lithography for 0.3μm MOS Devices, IEEE Trans. ED-34, 4, 759, 1987.

〔5〕 E. Spiller, D. E. Eastman, R. Feder, W. D. Grobman, W. Gudat and J. Topalian : Application of Synchrotron Radiation to X-rayLithography,J.Appl.Phys.,47,5450,1976.

〔6〕 H. Aritome, T. Nishimura, H. Kotani, S. Matsui, O. Nakagawa and S. Namba : X-ray lithography by synchrotron radiation of INS-ES, J. Vac. Sci. Technol., 15(3), May/Jun., 992, 1978.

〔7〕 R. P. Haelobich, J. P. Silverman, W. G. Grobman, J. R. Maldonaldo and J. M. Warlaumont : Design and performance of an x-ray lithography beamline at a storage ring, J. Vac. Sci. Technol., B1(4), 1262, 1983.

〔8〕 J. P. Silverman, W. G. Grobman, J. R. Maldonaldo and J. M. Warlaumont : X-ray Lithography Exposures Using Synchrotron Radiation, SPIE, 393, No.99, 1983.

〔9〕 A. Heuberger : X-ray lithography, J. Vac. Sci. Technol., B6(1), Jan./Feb., 107, 1988.

〔10〕 T. Hosokawa, T. Kitayama, T. Hayasaka, S. Ido, A. Uno, A. Shibayama, J. Nakata, K. Nishimura and M. Nakaijma : NTT Super-conducting Storage Ring, Super-ALIS, Rev. Sci. Instrum., 60, No.7, Jul., 1783, 1989.

〔11〕 H. Yamada : Commissioning of aurora : The smallest synchrotron light source, J. Vac. Sci. Technol., B8(6). Nov. /Dec., 1628, 1990.

〔12〕 M. M. Wilson, A. C. I. Smith, V. C. Kempson, A. L. Purvis, R. J. Anderson, M. C. Townsend, A. R. Jorden, A. D. Anotews, V. P. Suller and M. W. Poole : Update on the Compact Synchrotron X Ray Source Helois, JJAP, 29, No.

11, 2620, 1990.

〔13〕 E. Cullmann, K. A. Cooper and W. Vach : An x-ray stepper for production lithography, SPIE, 773, No.2, 1987.

〔14〕 S. Ishihara, M. Kanai, A. Une and M. Suzuki : A vertical stepper for synchrotron x-ray lithography, J. Vac. Sci. Technol., B7(6), Nov./Dec., 1652, 1989.

〔15〕 S. Ishihara, A. Une, M. Kanai, M. Suzuki, M. Fukuda, and F. Omata : A Vertical Stepper for SOR Lithography, JSPE, [in Japanese], 57, 3, 459, 1991.

〔16〕 K. Koga, J. Nomura, J. Yasui, Y. Temi, H. Nagano, K. Fujita, K. Kusumoto, K. Nakano, S. Nakanishi, S. Mizuguchi, S. Aoki, S. Yamamoto, K. Yamaguchi, T. Sato, K. Matsuo and K. Yanagida : High-performance synchrotron x-ray stepper, J. Vac. Sci. Technol., B8(6), Nov./Dec., 1633, 1990.

〔17〕 S. Ishihara, M. Kanai, M. Suzuki and M. Fukuda : An Advanced X-ray Stepper for 1/5μm SR Lithography, Microelectronic Engineering, 14, 141, 1992.

〔18〕 N. Uchida, O. Kuwabara, Y. Ishibashi, N. Kikuiri, R. Hirano, J. Nishida, T. Nishizawa, Y. Kikuchi and H. Yoshino : X-ray stepper aiming at 0.2μm synchrotron orbital radiation lithography, J. Vac. Sci. Technol., B11(6), Nov./Dec., 2997, 1993.

〔19〕 R. Viswanathan, R. E. Acosta, D. Seeger, H. Voelker, A. Wilson, I. Babich, J. Maldonado, J. Warlaumont, O. Vladimirsky, F. Hohn, D. Crockatt and R. Fair : Fully scaled 0.5μm metal-oxide semiconductor circuits by synchrotron x-ray lithography : Mask fabrication and characteristics, J. Vac. Sci. Technol., B6 (6), Nov./Dec., 2196, 1988.

〔20〕 for example, S. Ohki and H. Yoshihara : High-Precision X-ray Mask Technology. JJAP. 29, No.11, 2600, 1990.

〔21〕 H. C. Pfiffer and T. R. Grones : Progress in E-Beam Maskmaking for Optical and X-Ray Lithography, Microelectronic Engineering, 13, 141 , 1991.

〔22〕 P. Sandland, W. D. Meisburger, D. J. Clark, D. D. Simmons, D. E. A. Smith, L. H. Veneklasen, B. G. Becker, A. D. Brodie, C. H. Chadwick, Z. W. Chen, L. S. Chuu, D. G. Emge, A. A. Desai, H. J. Dohose, A. Dutta, J. D. Greene, L. A. Honfi, J. Y. Jau, S. G.Lele, M. Y. Ling, J. E. McMurtry, R. E. Paul, C. -S. Pan. M. Robinson, J. K. H. Rough, J. Taylor, P. A. Wieczorek and S. C. Wong : An electron-beam inspection system for x-ray mask production, J. Vac. Sci. Technol., B9(6), Nov./Dec., 3005, 1991.

〔23〕 A. Wagner, T. P. Levin, J. L. Mauer, P. G. Blauner, S. J. Kirich and P. Longo : X-ray mask repair with focused ion beams, J. Vac. Sci. Technol., B8(6), Nov./Dec., 1557, 1990.

〔24〕 J. P. Silverman, V. DiMilia, D. Katkoff, K. Kwietniak, D. Seeger, L. K. Wang, J. M. Warlaumont. A. D. Wilson, D. Crockatt, R. Devenuto, B. Hill, L. C. Hsia and R. Rippstain : Fabrication of fully scaled 0.5μm n-type metal-oxide semiconductor test devices using synchrotron x-ray lithography : Ovarlay, resist processes, and device fabrication, J. Vac. Sci. Technol., B6(6). Nov./Dec, 2147,1988.

〔25〕 J. Warlaumont : X-ray lithography - On the path to manufacturing, J. Vac. Sci. Technol., B7(6), Nov./Dec., 163, 1989.

〔26〕 A. Yoshikawa, T. Horiuchi, K. Deguchi, M. Miyake, Y. Yamamoto, Y. Sakakibara and T. Kitayama : Synchrotron radiation lithography applied to fabrication of deep-submicron NMOS devices at all exposure levels, Microelectronic Eng., 11, No.233, 1990.

〔27〕 K. Deguchi, K. Miyoshi, H. Ban, H. Kyuragi, S. Konaka and T. Matsuda : Application of x-ray lithography with a single-layer resist process to subquartermicron LSI fabrication, J. Vac. Sci. Technol., B10(6), Nov./Dec., 3145, 1992.

〔28〕 H. Kyuragi, S. Konaka, T. Kobayashi, K. Deguchi, E. Yamamoto, S. Ohki and Y. Yamamoto : Deep subhalf-micron BiCMOS technology using synchrotron x-ray lithography and its application to 58ps 2V CMOS gate array, Digest of Technical Papers, 1992 Symp. on VLSI Technol., 4, No.1, 26, 1992.

〔29〕 Y. Kado, T. Ohno, M. Harada, K. Deguchi and T. Tsuchiya : Enhanced performance of Multi-GHz PLL LSIS using sub-1/4-micron gate ultrathin film CMOS/SIMOX technology with synchrotron x ray lithography, IEDM Tech. Digest, 243, 1993.

〔30〕 R. Viswanathan, D. Seeger, A. Bright, T. Bucelot, A. Pomerene, K. Petrillo, P. Blauner, P. Angello, J. Warlaumont, J. Conway and J. Patel : Fabrication of high performance 512K static-random access memories in 0.25μm complementary metal-oxide semiconductor technology using x-ray lithography, J. Vac. Sci. Technol., B11(6), Nov./Dec., 2910, 1993.

〔31〕 A. Shibayama, T. Kitayama, T. Hayasaka, S. Ido, Y. Uno, T. Hosokawa, J. Nakata, K. NiShimura and M. Nakaijma : NTT Normal-conducting accelerating ring, Rev. Sci. Instrum., 60, No.7, 1779, 1989.

32〕 T. Kitayama, T. Hayasaka, H. Yoshihara and S. Ishihara : Synchrotron X-ray Lithography System Using a Compact Source, SPIE, No.1089, 159, 1989.

〔33〕 N. Atoda, H. Kawakatsu, H. Tanini, S. Ichimure, M. Hirata and K. Hoh : Diffraction effects on pattern replication with synchrotron radiation, J. Vac. Sci. Technol., B1(4), Nov./Dec., 1267, 1983.

〔34〕 M. Suzuki, T. Kaneko and Y. Saitoh : Replicated resist pattern resolution with synchrotron orbital radiation, J. Vac. Sci. Technol., B7(1), Jan./Feb., 47, 1989.

저 자 소 개

Sunao Ishihara

received the B.E. and M.E. degrees from the University of Tokyo in 1971 and 1973, respectively. He joined the Electrical Communication Laboratory, NTT, in 1973. Since 1975 he has been engaged in the research on X-ray lithography. He worked mainly on the alignment technology, x-ray stepper, and x-ray lithography system. He received the doctor degree of engineering from the University of Tokyo in 1992. At present, he is the Executive Manager of Microfabrication Technology Laboratory, NTT LSI Laboratories.

Address : NTT LSI Laboratories 3-1, Morinosato Wakamiya,
Atsugi, Kanagawa 243-01, Japan.