Preface

Lithography, the printing of patterns on surfaces, is one of the key elements of semiconductor manufacturing. Lithography determines the minimum feature size in the semiconductor chip, thereby gating the speed of operation of the circuit and controlling the number of circuit elements that can be placed on the chip. This relationship among lithography, circuit complexity, and performance has closely tied the evolution of integrated circuits to the evolution of lithographic technology. Lithography is also a key element of the cost of semiconductor manufacturing—it is the single most expensive step in the integrated circuit fabrication process, accounting for more than 30% of the manufacturing cost.

IBM, as a major semiconductor manufacturer, has always recognized the importance of lithography, and has maintained a strong program of research and development in lithography. While optical lithography is today almost exclusively used for semiconductor fabrication, IBM has been a major developer of alternative technologies. For more than twenty years IBM has had a program in proximity X-ray lithography (XRL), maintaining a position as one of the world's leaders in this technology. Today, IBM has in place an X-ray lithography system capable of patterning the world's most complex circuits. This system is ready for adoption by the semiconductor establishment when optical lithography has reached its limit. This issue of the *IBM Journal of Research and Development* chronicles the twenty years of X-ray lithography development at IBM, discusses the potential of X-ray lithography, and describes many of the elements of the present IBM system.

Proximity X-ray lithography is conceptually the simple shadow printing of a mask onto the semiconductor wafer. It is a one-to-one printing process which does not use an imaging lens, possesses a relatively large depth of focus, and makes possible large chip sizes.

As described in the paper by Smith and Schattenburg, the optimal wavelength for proximity printing is around 1 nm. However, because the production of 1-nm X-rays and of X-ray masks for use at 1 nm is difficult, proximity printing for semiconductor fabrication was initially done optically, using near-visible photons with wavelengths near 400 nm. Proximity printing at 400 nm leads to feature sizes no smaller than a few microns, feature sizes which were common twenty years ago. Simply decreasing the wavelength below 200 nm is not possible, since there are no transparent mask substrate materials for use between 200 nm and 1 nm. As a result, twenty years ago optical lithographers (optical lithography is defined as printing using near-visible photons) moved on to the use of imaging lenses for increased resolution, and those wishing to extend proximity printing began to study printing at soft X-ray wavelengths of a few nm and below. The potential of XRL, detailed in the papers by Smith and Schattenburg and by Guo and Cerrina, is the fabrication of sub-100-nm features.

The work at IBM in soft X-ray proximity printing can be divided historically into three periods. Eberhard Spiller describes in his paper the work done in the first period, the 1970's, when Ralph Feder and Spiller concentrated on building an X-ray exposure system using conventional electron-bombardment X-ray sources. During the 1970's there were significant X-ray programs at Lincoln Laboratories (led by Henry Smith) and at Bell Laboratories.

Unfortunately, conventional electron-bombardment X-ray sources do not produce sufficient X-rays for economical manufacturing, so in the 1980's the IBM X-ray program focused on the use of electron storage rings as X-ray sources. As described in the paper by Alan Wilson, a complete prototype storage-ring-based X-ray lithography system was demonstrated during the 1980's by IBM; this system is the basis for the X-ray system now in place. The work in the 1980's culminated in the use of X-ray lithography for the successful fabrication of 0.5-μm ground rule integrated circuits. In 1990, a 1Mb DRAM with one million 1-μm gate transistors was fabricated in the Burlington Laboratory. Four levels of lithography were employed, and the bit yield on the best chip was 45%. During the 1980's, several other storage ring X-ray lithography programs existed at other institutions worldwide, but the IBM program was one of the most comprehensive and was the first to produce submicron integrated circuits. By the end of the decade, the IBM program had clearly established a path for constructing a high-volume X-ray lithography system. In 1992, a 512Kb static RAM with 0.25-μm features, using a repaired mask, was built at the Watson Research Center, with a 99.882% bit yield on the best chip.

The third, or current, phase of the IBM X-ray program is focused on bringing into operation a complete X-ray lithography system capable of producing the most complex, highest-performance integrated circuits, with minimum feature sizes below 250 nm. The planning for this system took place during the 1980's, as described by Alan Wilson, and by 1990 the final development and acquisition of all the components of this system was under way. Today, in 1993, the system is nearly complete, and the prototyping of 350-nm chips has been demonstrated. It is expected that in the next few years the system will be completed, and the fabrication of 250-nm (and smaller) ground rule chips will be routine.

The present IBM XRL system is actually made up of two facilities: the Advanced Lithography Facility (ALF)—a storage-ring-based exposure facility attached to the Advanced Semiconductor Technology Center (ASTC) in East Fishkill, New York, and the Advanced Mask Facility

(AMF)—an X-ray mask fabrication facility which is part of IBM's mask house in Burlington, Vermont.

Wafers are exposed in the ALF facility using X-rays generated by the Oxford Instruments storage ring Helios 1. Its design and construction are described in the paper by M. N. Wilson et al., and its performance in the paper by Archie. The X-rays are transported from the ring to the mask–wafer aligner/stepper using custom X-ray beamlines, as described in the paper by Silverman et al. The beamline converts the fan-shaped X-ray beam from the storage ring into a uniform X-ray beam which covers the entire exposure field of the stepper. The mask and wafer are aligned with each other in steppers originally fabricated by Karl Suss, which have been designed to meet 350-nm ground rules. A program with SVGL Incorporated, in conjunction with ARPA (the Advanced Research Projects Agency), is in place to develop and test in ALF a new-generation stepper, designed for 250 nm. Completion of the first prototype of this stepper is expected by the end of 1995.

ALF, described in the paper by Leavey and Lesoine, is a novel facility in the semiconductor industry, since it is the first storage-ring XRL facility designed for compatibility with high-volume semiconductor manufacturing. ALF also contains a facility for processing X-ray resists. The paper by Seeger discusses the resist processes currently used in ALF; excellent process latitude for features down to 100 nm has been demonstrated.

The Advanced Mask Facility, or AMF, located in the IBM Technology Products semiconductor plant in Burlington, Vermont, is the world's first complete X-ray mask facility capable of fabricating manufacturing-grade VLSI X-ray masks. Mask fabrication begins with the mask blank, and the AMF currently fabricates thin (3 μm thick) silicon membranes for mask blanks. The blanks are patterned with an IBM EL-3 e-beam system, described in the paper by Groves et al., capable of producing 350-nm ground rule masks. The installation of an IBM EL-4 e-beam system, to pattern features of 250 nm and below, is planned.

The X-ray absorber on the mask is gold, electroplated into the e-beam resist stencil. Unfortunately, defects are a fact of life in mask manufacturing, but another fact of life is that the finished semiconductor chip must be defect-free. Thus, defect inspection and repair are necessary. Two significant accomplishments of the IBM X-ray program are the development of an SEM-based inspection system with KLA Inc., and the development of focused ion-beam processes and tooling for both opaque and clear repair, as described in the paper by Blauner and Mauer. The repair technology has been licensed to Micrion Corporation and is being incorporated into Micrion's commercial mask repair tool.

The ALF and AMF facilities have both recently become fully operational, and the first demonstrations of their capabilities have been completed. In conjunction with ARPA's National Lithography Program and with IBM Federal Systems Company's VLSI semiconductor fabrication facility in Manassas, Virginia, a complete, perfect (100% yield), fully functional 512Kb SRAM has been fabricated. This is a key demonstration, since it requires a defect-free mask, a defect-free X-ray exposure process, and the full function of both the ALF and AMF.

The design, development, and implementation of the IBM storage-ring-based XRL system is nearly complete. This program, which was based on the pioneering work of the 1970's and the prototyping of the 1980's, is the first X-ray lithography facility capable of high-volume semiconductor prototyping and eventual manufacturing. This program has also established, in conjunction with ARPA's national X-ray program, a commercial X-ray infrastructure, with a commercially available exposure system (including the X-ray source and mask/wafer aligner) and a manufacturing-grade mask house, including commercially available tooling for patterning, inspection, and repair. Efforts are now under way to broaden the availability of this system to other semiconductor manufacturers.

The IBM X-ray program has been developed by many of the world's finest lithographers; the contributions of many of these individuals are described in the papers in this issue of the *IBM Journal of Research and Development*. Financial support has come from IBM, from semiconductor vendors, from the Department of Energy at Brookhaven National Laboratory, and from ARPA's Defense Advanced Lithography Program.

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