Electron beam lithography tool for manufacture of X-ray masks

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An electron beam lithography system suitable for manufacturing X-ray masks with critical dimensions down to 0.35 μm is described. The system features a 50-kV variable shaped spot (VSS) electron column with a variable axis immersion lens (VAIL). This column is capable of maintaining 0.035-μm edge acuity of the focused spot over a 2.1-mm deflection field. These fields are stitched together over an 84 × 84-mm active pattern area via motion of an *xy* table. The table position is measured using a laser interferometer. The measurement data are fed back to the magnetic deflection to correct small errors. Maintaining positional accuracy of the beam relative to the writing surface relies on a strategy of measuring and correcting repeatable errors. This is described in detail. Pattern placement accuracy is 0.070 μm (3σ) and image size control is 0.025 μm (3σ), achieved over the entire 84 × 84-mm pattern area. This performance is achieved with yield better than 90%, as confirmed by routine measurements. The system is currently used to manufacture product X-ray masks with 0.35-μm critical dimensions. Typical measurement results on product masks are presented.

Introduction

Since the late 1970s electron beam lithography has been the method of choice for fabricating masks and reticles for optical lithography of integrated circuits in high-volume manufacturing, because electron beam systems provide the needed resolution, throughput, and automated pattern data processing capability. The use of electron beams for X-ray mask fabrication is a natural extension of this.

Lithography requirements are driven by the need to manufacture dynamic random access memory (DRAM) circuits. This application is the most demanding in the sense that small feature size or critical dimension (CD) must be maintained along with high pattern complexity. The latter drives large volumes of numerical control (NC) pattern data. DRAM therefore leads other technologies in critical requirements. The trend of CD for DRAM is shown in **Figure 1**. The pattern placement or overlay accuracy must be some reasonably small fraction of the CD, typically 20%. The trend in placement accuracy is included in the figure. Optical lithography at 4× to 5× reduction is relatively tolerant of errors in the mask, since these errors are demagnified on the wafer. It is anticipated that optical reduction steppers will be hard-pressed to print feature sizes of 0.20 μm or less in volume manufacturing. The burden shifts to X-ray lithography at 1×, where the errors in linewidth and placement on the mask become relatively more important. This represents a formidable challenge in

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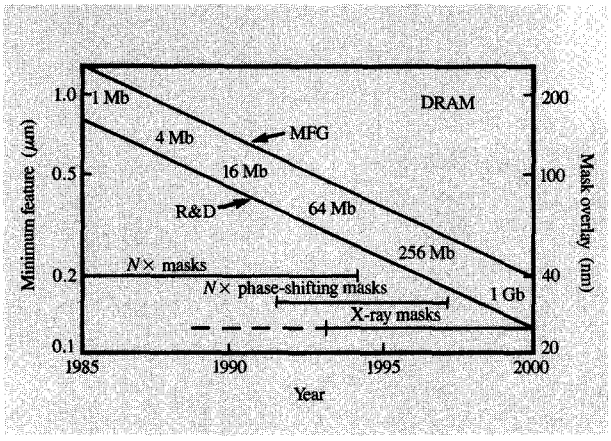


Figure 1

Trend of critical dimension (CD), or minimum feature size, with year, for dynamic random access memory (DRAM) integrated circuits [5]. This trend is driven by the desire to increase the density of these devices on a chip. This drives the accuracy of pattern placement, which must be maintained as some reasonably small fraction of the CD. The ability of lithography tools to meet the placement requirements is also shown in the figure. For optical masks, the term $N\times$ indicates that the mask feature is larger than the printed image by a factor N.

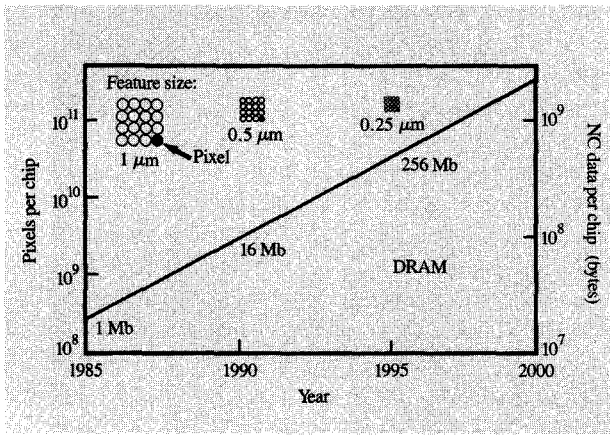


Figure 2

Trend of NC data volume as a function of year for DRAM circuits [5]. This trend is driven by the desire to increase the density of these devices. As a result, the number of written pixels per chip increases similarly. This trend, acting in concert with the trend toward decreasing CD and pattern placement tolerances, presents formidable challenges to mask making.

manufacturing [1–4]. The trend for NC data volume and corresponding pixels per chip is shown in **Figure 2**. While the CDs and placement tolerance decrease with time, the data volume increases rapidly. Acting in combination, these trends place severe requirements on the mask-writing tool [5].

The high-resolution capability of e-beam writers has been used to advantage throughout the early development of X-ray mask technology with the vector scan generation of tools at the IBM Thomas J. Watson Research Center [6]. Using this capability, a robust process was developed by which X-ray masks could be patterned with high fidelity. Independent of this, the EL-3 generation of direct-write and mask-making tools provided IBM with experience in manufacturing, where high resolution must be combined with the ability to process large data volumes at reasonable throughput [7]. This latter development led to the EL-3+ tool described here. This tool is installed and operational in the IBM Advanced Mask Facility in Burlington, Vermont. It is currently being used to fabricate production X-ray masks with ground rules down to 0.35 μm. The purpose of this paper is to describe the EL-3+ system, along with the performance requirements and measured performance data. This discussion logically begins with the lithography requirements, the subject of the next section.

Lithography requirements

The lithography requirements are determined by the nature of the X-ray mask, and by the specifications governing the final product wafers. Most masks written to date consist of a boron-doped silicon wafer, back-etched to form the thin X-ray window, with the wafer anodically bonded to a round Pyrex™ ring. The entire structure, including wafer and Pyrex ring, is 10 mm thick. This thickness dimension governs the stiffness and the resulting bending distortions. The X-ray membrane window consists of multiple layers, to be described in the section on test results. The resist forms a negative mask for electroplating of a patterned gold X-ray absorber. The plated area is opaque to soft X-rays, while the unplated area is transparent.

The pattern specifications on the mask are governed by the need to make the variations in linewidth and pattern placement a small fraction of the CD for the final printed image on the wafer. Pattern errors originate from both the tool and the processing. Lithography tools inevitably suffer from noise, drift, and distortion, while the process tends to distort the mask thermally and mechanically. The metrology, by which these errors are characterized, contributes errors which are not entirely distinguishable from those of the tool and process. Consequently, the tool, process, and metrology are each apportioned a fraction of the overall error budget.

The key tool specifications are shown in **Table 1**. These values are verified by measuring written test masks. They implicitly include those errors in metrology and process which are indistinguishable from those of the lithography

tool itself. A key requirement not explicitly included in the specifications is that the tool be suitable for use in a manufacturing environment. This necessitates a high level of automation. A description of the tool features needed to meet these requirements is given in the next section.

Enhanced features

The general architecture of the EL-3 systems has been described previously [8]. The system features a variably shaped spot with two-level hierarchical deflection. Magnetic deflection is used to step through a 2.1-mm field in a serpentine fashion. This field is tiled with stitched 37.5-μm subfields, within which fast electrostatic deflection in vector mode is used. Both deflections are implemented in a way which preserves normal incidence of the beam on the writing surface over the entire written area. The placement of pattern features thus becomes insensitive to variations in the height of the writing surface. Writing begins once the stage has reached the target destination within 10 μm. The stage position is measured using a laser interferometer, with the e-beam locked to the table position electronically via a feedback loop which includes the magnetic deflection.

Direct-write tools accurately place their fields on the substrate by using the e-beam to register to previously generated marks. This is necessary in order to position the beam accurately relative to layers previously written on the wafer. In mask writing, each level of a mask set has only one layer. This mask must overlay all of the other layers of the set, each of which is written independently, often using different writing tools. In practice this requires that each mask must be referenced to an external, absolute standard. All masks in this study are measured using a Leica-Leitz LMS-2000 metrology tool.[1] This tool is, in turn, calibrated using a standard traceable to a linear, absolute standard at the National Institute for Standards Technology.

Although some type of registration is usually employed, it is only to remove tool drift at intervals during the writing process. This kind of blind writing, called "dead reckoning," requires stability of the writing tool over the writing time, and to the level indicated by the specifications in Table 1. Indeed, achieving accurate pattern placement represents the central problem in present-day mask making, and a leading technical challenge for the system described here.

The edge acuity of the focused spot is limited by the Coulomb interaction of electrons along the beam path, and by spherical aberration of the final projection lens. In EL-3+ the beam energy is 50 keV, compared with 25 keV for earlier mask makers. This provides improvement in resolution as a result of lower Coulomb interaction. This remains true despite the increased current needed to compensate for reduced resist sensitivity at the higher voltage [9]. The higher voltage also provides added immunity against stray fields. The noise immunity has been further improved through addition of highly efficient passive shielding in the column, and modifications to the electronics which greatly decrease the sensitivity to ambient 60-Hz noise.

Table 1 Specifications for the EL-3+ lithography system.

Critical dimension (CD)	0.350 μm
Pattern placement accuracy (absolute)	0.070 μm
Image size control	0.025 μm
Writing area size	84 × 84 mm
Field stitching accuracy	0.060 μm
Subfield stitching accuracy	0.040 μm
Beam voltage	50 kV
Current density	20 A/cm^2

The variable axis immersion lens (VAIL) provides advantages in both image quality and overlay over the earlier EL-3 in-lens deflection design [10]. At the design current density of 20 A/cm^2, the spot edge acuity was determined by simulation to be less than 0.035 μm over the entire 2.1-mm field. This corresponds to 60 000 lines of resolution, about two orders of magnitude larger than a high-resolution electron microscope. The VAIL concept relies on dynamically moving the magnetic symmetry axis of the final projection lens in synchronism with the field position [11]. The subfield deflection employs two electrostatic dodecapoles separated axially. All deflection is configured such that aberrations through third order, along with transverse chromatic aberration, are zero. It is essential to achieving the required 0.025-μm image size control (see Table 1).

A number of pattern placement error sources must be addressed. In addition to repeatable, correctable, systematic distortions, they include time-dependent errors which span the frequency spectrum from 0–20 MHz. Central to our writing strategy is the concept of detection and correction of these error sources. Calibration of the system with respect to the repeatable, systematic errors is the subject of the next section.

System calibration

The repeatable errors include, primarily, distortions of the deflection system and the *xy* table. The deflection distortions are corrected by a procedure called Learn. A patterned reference grid is permanently mounted in the system. The grid consists of tungsten lines 3 μm wide, patterned on a planar silicon substrate. The grid period is 18.75 μm, exactly half the subfield size. This target provides good contrast as the beam is scanned across the

[1] Leica-Leitz, Inc., 24 Link Drive, Rockleigh, NJ 05647.

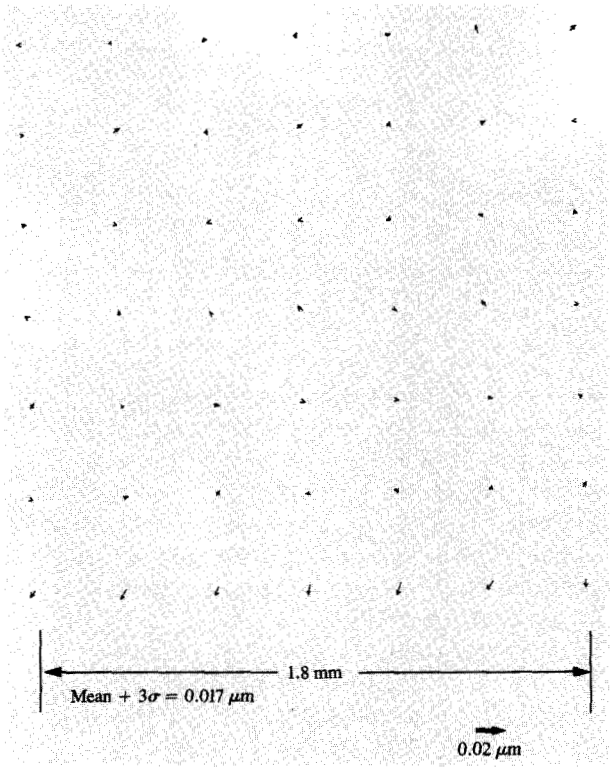


Figure 3

Results of the Learn procedure, plotted at various locations within the 2.1-mm major deflection field. This error represents the position of the electron beam relative to the Learn grid, obtained using the registration capability of the e-beam tool. These results were obtained after removal of the systematic deflection distortions, based on prior application of the Learn and Gridcal procedures (see text for description). In this sense, the Learn calibration may be described as self-consistent. The errors shown here are 0.017 μm (3σ), and are due to residual noise and drift in the deflection system. They represent a lower limit on pattern placement errors encountered in writing.

tungsten lines, with backscattered electrons collected. This provides a registration signal by which the beam position can be measured relative to the xy table.

Learn proceeds in two stages: First, the center of every subfield is addressed using the magnetic deflection. The appropriate tungsten bar is scanned with the e-beam, and the expected position compared with the actual position. The error is stored and applied to the deflection address to remove the distortion. In the second stage of Learn, the center of every subfield is addressed using the magnetic deflection, and the four corners are addressed using the electrostatic deflection. The errors are measured, stored, and applied to the electrostatic deflection to remove the linear distortions of the subfield. The time required to measure the entire 56 × 56 array of subfields is about one minute, making it feasible to repeat this process at intervals during the writing of a mask without significant loss of throughput.

The procedure thus far causes the system to replicate the character of the Learn grid. Any residual errors of the grid would then be replicated in every written pattern. To compensate for this, a fine correction is needed. In this procedure, called Gridcal, the system is calibrated normally using Learn. A test pattern is then written and measured to an external standard using a Leica-Leitz LMS-2000 tool. These errors are fed back to the e-beam tool and are used to provide a fine correction to the deflection. Using a written pattern for this has the advantage that errors peculiar to the writing process, which are not detected by Learn, are removed. The deflection is thus calibrated relative to an external, absolute standard. Data from a typical Learn scan after Gridcal are plotted in **Figure 3**. The results show mean plus 3σ error of 0.017 μm over 1.8 mm. This is a measure of the repeatability of the deflection system. With the

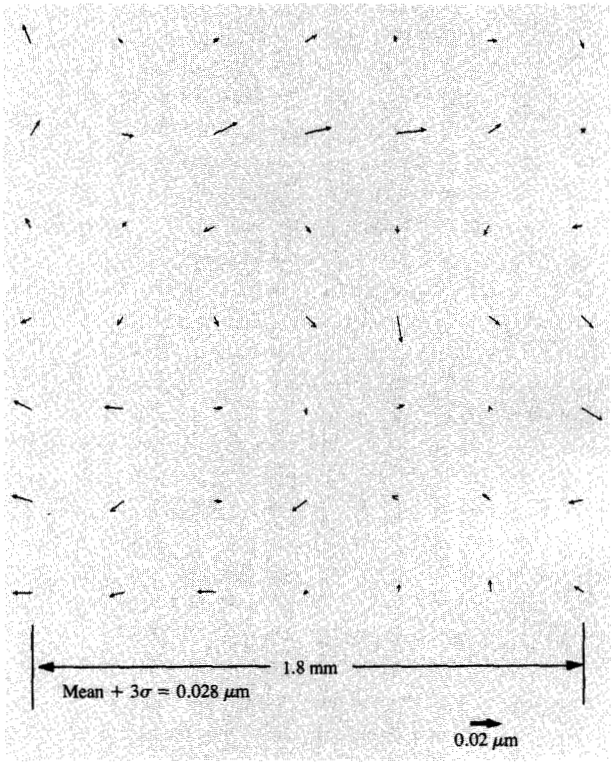


Figure 4

Pattern placement error measured for a written test pattern within the 2.1-mm major deflection. The measurements show 0.028 μm (3σ) error after the Learn procedure is applied (see Figure 3). These measurements were obtained using a Leica-Leitz LMS-2000 tool; they thus represent absolute calibration to an external, traceable standard.

system calibrated using Learn, the measurements on the Gridcal written test pattern are shown in **Figure 4**. The error is seen here to be 0.028 μm (3σ). This represents the accuracy of the deflection system, measured relative to an external standard.

The time required to write the most complex pattern levels is of the order of one hour. Pattern placement errors arising from drift are corrected by a procedure called Autolearn. In this procedure, Learn is executed at intervals during the writing process. First-order errors in the deflection are thus removed, including displacement of the beam relative to the writing surface. The procedure is adaptive in the sense that the frequency with which Autolearn is invoked depends on the size of the measured errors.

The *xy* table has the property that the position, as reported by the laser interferometers, does not reflect the true position of the beam relative to the writing surface. The largest error of this kind is due to lack of orthogonality of the laser mirrors. Repeatable table errors of this kind are removed by using a process called Emulation. A test pattern is written with measurement targets covering the entire area addressed by the *xy* table. This pattern is again measured using the Leica-Leitz LMS-2000 tool. The results are shown in **Figure 5**, where the measurements are made at the center of each 2.1-mm field over the entire writing area traversed by the table. These results represent the average of four different written masks. They show a definite systematic character. In the Emulation procedure, these errors are stored and applied to the magnetic deflection to compensate for the repeatable table error. Measurement results with Emulation applied are shown in **Figure 6** for a representative mask. They show a residual error of 0.055 μm (3σ) with Emulation applied.

These procedures depend critically on the accuracy of the metrology tool. The repeatability of the Leica-Leitz tool has been shown to be better than 0.020 μm (3σ). It

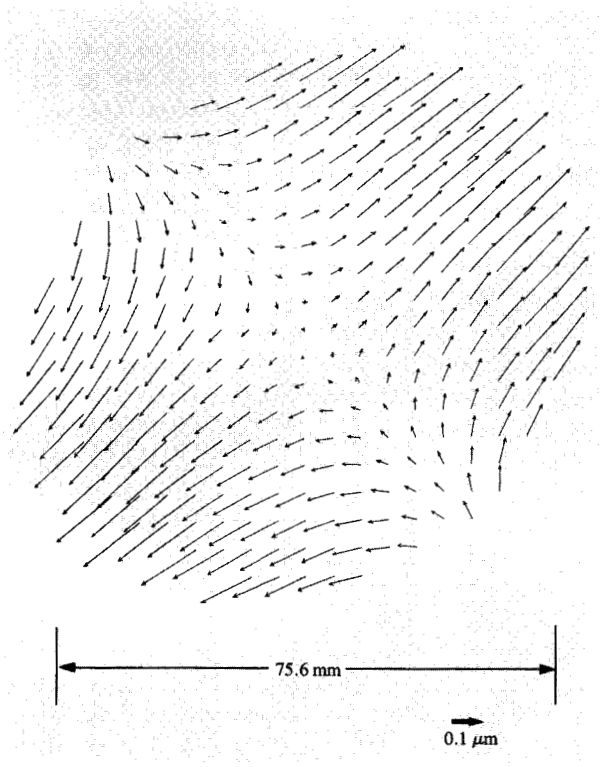


Figure 5

Pattern placement error measured for a written test pattern within a 76 × 76-mm range of the *xy* table travel. These errors represent the average of four written masks, and show a repeatable, systematic character for the table travel. These measurements form the basis of the Emulation table correction procedure, in which the errors are stored and later fed back to the magnetic deflection for removal. The measurements are taken at the center of each 2.1-mm deflection field.

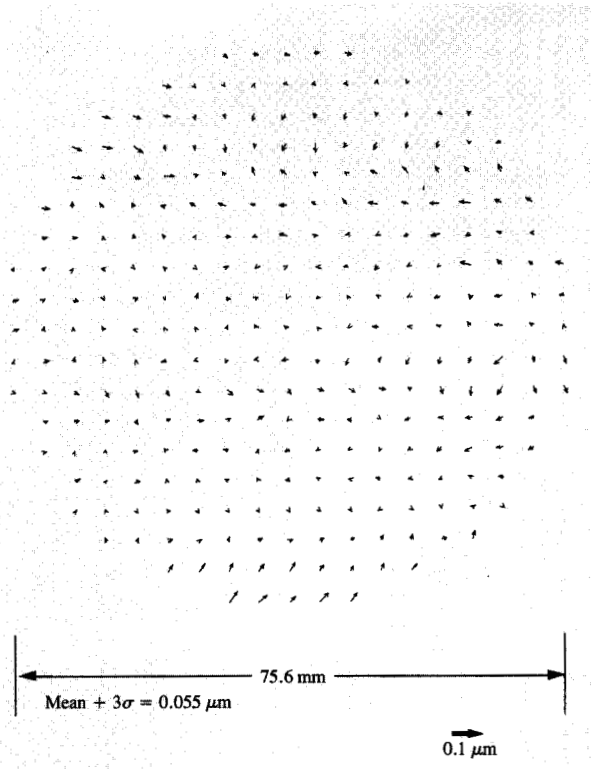


Figure 6

Pattern placement error measured for a written test pattern over the 76 × 76-mm range of table travel, with the Emulation procedure applied (see Figure 5). The measurements are taken at the center of each 2.1-mm deflection field, and show 0.055 μm (3σ) residual error.

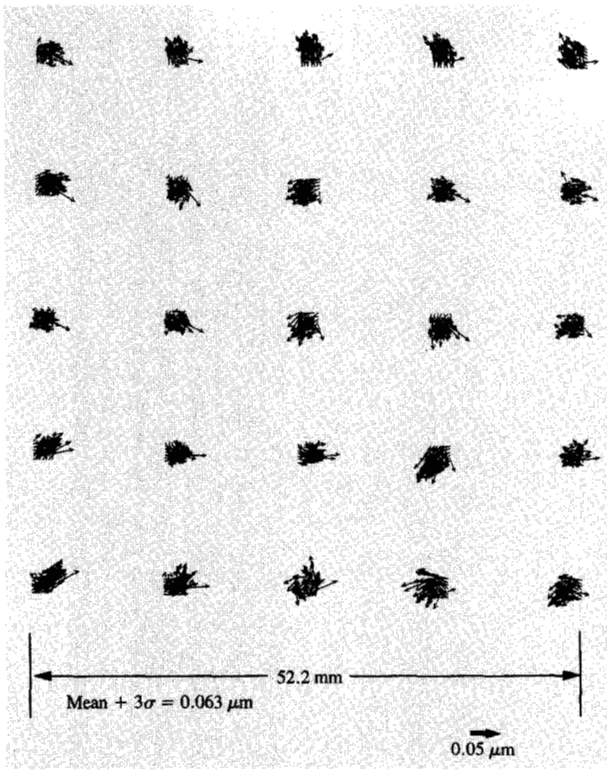


Figure 7

Pattern placement error for a written test pattern, with Emulation and Gridcal procedures applied. An array of 5×5 fields, 2.1 mm wide, and with 12.6-mm spacing, is measured. Within each field 7×7 targets are measured, for a total of 1225 measurements in each axis. Various positions within the deflection area and table travel area are thus sampled. The results show 0.063 μm (3σ) error. This represents the capability of the EL-3+ tool to place patterns accurately on written product masks.

is calibrated internally by measuring a test plate in four rotations, which removes most of the distortions of the test plate.

With the repeatable, systematic errors thus removed, the remaining errors consist mainly of noise and drift in the e-beam system. Although a considerable effort goes into ensuring that these error sources are as small as possible, some residual inevitably remains. A potential source of drift is thermal expansion resulting from temperature variations of the written mask. A temperature increase of 0.1°C results in 0.030-μm expansion of a silicon X-ray mask over the 84 × 84-mm writing area, representing a large fraction of the total 0.070-μm budget for pattern placement error. For this reason, great care is taken to maintain the mask at a constant and well-defined temperature during both the writing and the metrology.

The X-ray mask is kinematically mounted in a carrier. This carrier is, in turn, kinematically mounted to the *xy* table. This form of clamping ensures that no stress is transmitted to the mask, while uniquely determining its position relative to the *xy* table [12]. The clamping of the mask thus adds no distortion to the mask or written pattern. A slight out-of-plane distortion results from gravity, but it turns out to be insignificant for the pattern placement accuracy required here.

System calibration consists of an iterative procedure of writing, measuring, and adjusting, using test patterns which mimic the product. Measurement results at the end of this procedure indicate the capability of the system. These results are described in the next section.

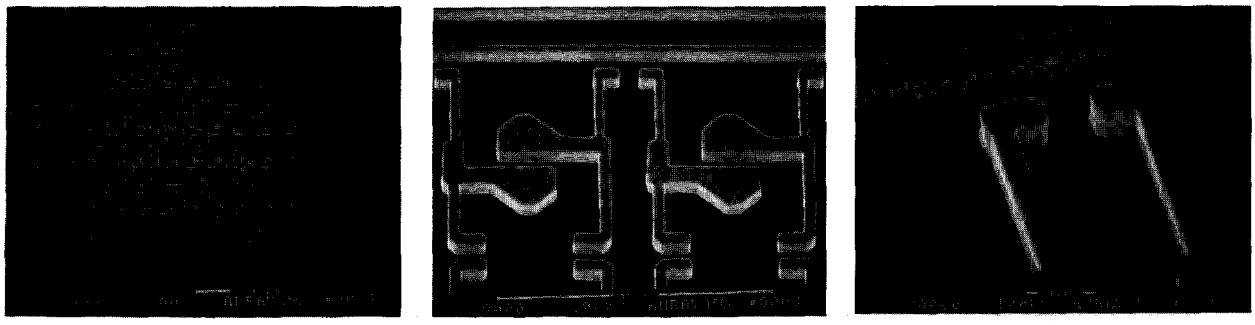
Test results

The critical tool parameters are image size, stitch, and pattern placement accuracy. Image size is monitored on a daily basis. A test pattern is exposed on a substrate which mimics the X-ray mask, except that the bulk silicon is not etched away to form the membrane. The mask is a multilayer structure consisting of 3 μm Si, 1.7 μm polyimide, 0.005 μm Cr, 0.03 μm Au plating base, and 0.78 μm novolak resist. The resist is patterned using the e-beam tool, and electroplated with 0.65 μm Au, forming the gold pattern. The fact that the bulk silicon is present for the test patterns means that a class of process-related problems arising from in-plane membrane distortions is not present. In this way the assessment of tool performance becomes less dependent on process variations.

An array of test sites is generated within each 2.1-mm field, consisting of nine horizontal and nine vertical bars 0.35 μm wide. The bar width is measured at each site using an Amray 1500 scanning electron microscope (SEM).[2] Each site is contained within a single subfield. The measured variation of linewidth is typically under 0.025 μm (3σ) across the array of fields. Within a single 2.1-mm field the variation is typically under 0.020 μm (3σ). The repeatability of the measurement is 0.008 μm, as determined by repeated measurement of a single substrate. The linewidth measurement is done periodically as needed. If necessary, the focus and astigmatism corrections are updated on the basis of measurements of written patterns. Our experience has shown that the corrections are stable over a period of at least a month, as long as the tool is kept clean and free of charging.

Stitching accuracy is measured at the edges of both the 37.5-μm subfields and the 2.1-mm fields. The calibration of stitch is contained within the Learn algorithm. In general the Learn grid has a slight rotation and scale error relative to the written pattern grid. Since this error is constant, it is removed by a linear correction of the magnetic deflection, where the correction is derived from stitch measurements on written test patterns. A similar linear transformation is

[2] Amray, Inc., 160 Middlesex Turnpike, Bedford, MA 01730.



(a) (b) (c)

Figure 8

(a) Finished product X-ray mask suitable for fabrication of a critical 0.35-μm static random access memory (SRAM) level. Masks such as this are fabricated and delivered to customers on a routine basis. Electron micrograph was taken at 1000× using an Amray 1500 scanning electron microscope. The patterned, electroplated gold X-ray absorber is 0.65 μm thick. The critical dimension (CD) or minimum feature size is 0.35 μm. (b) Finished product X-ray mask, same as (a) but at 8000× magnification. (c) Finished product X-ray mask, same as (a) but at 20 000× magnification.

derived to correct the electrostatic deflection for subfield stitch. This correction is automatically applied on the basis of Learn. The measurement results show field stitch which is under 0.040 μm (3σ). The measurements show subfield stitch under 0.030 μm (3σ) over the active area.

Pattern placement accuracy is measured both on product X-ray masks and on control masks using a collection of test sites. Image placement error can be regarded as the vector sum of individual components from the stage and deflectors. The stage contribution is studied by measuring targets at the field and subfield centers (zero deflection). Similarly, the magnetic deflection component is studied by measuring at subfield centers. Each test target has the shape of a block "L," allowing separate measurements in x and y with the Leica-Leitz LMS-2000.

Typical pattern placement measurement data are shown in **Figure 7**. The test pattern contains a mixture of high- and low-density written areas, intended to mimic the variations in pattern density seen on product. The exposure time was approximately one hour, comparable with the most dense product levels at 0.35-μm ground rules. The exposure was made on a silicon wafer bonded to a Pyrex ring. It is identical with the product X-ray masks in all respects, except that the wafer is not back-etched to form the membrane. An array of 5 × 5 fields, 2.1 mm on a side, with 12.6-mm spacing and spanning a 52.2-mm-square area, was measured. Within each field 7 × 7 targets were measured, for a total of 1225 measurements in each axis. Emulation and Gridcal were in use while this test pattern was written. The results show mean plus 3σ absolute placement error of 0.063 μm (3σ), consistent with the 0.070-μm absolute placement specification in Table 1. With the ability of the system to meet the test specifications in Table 1 established, some results on product X-ray masks are discussed in the next section.

Results for product X-ray masks

The IBM Advanced Mask Facility in Essex Junction, Vermont fabricates X-ray masks for internal IBM customers and for the U.S. Government.[3] These masks consist of various 0.35-μm CD test sites and product memory chips covering a wide range of sizes and complexities. Membrane sizes range from 13 mm × 26 mm to 30 mm × 32 mm. Design constraints and X-ray stepper requirements often result in these membranes being offset from the center of the substrate. The standard IBM X-ray substrate consists of the multilayer membrane structure described in the preceding section.

Before writing the pattern, it is necessary to convert the design data into NC data format usable by the tool. This is achieved using a custom IBM program called the Post Processor. Design shapes are broken up into rectangles and are then corrected for proximity effect. Depending on the complexity of the pattern, this can result in significant data volumes and processing times. The program exploits the highly repetitive nature of DRAM patterns using the large array macro (LAM) capability developed at IBM Haifa, Israel. This greatly reduces the computation time needed to process these patterns.

The standard photoresist consists of a positive-tone novolak resist 0.78 μm thick. The base dose required is 42.5 $\mu C/cm^2$. After developing, the patterned resist image is used as a mask for deposition of the gold absorber layer

[3] Defense Advanced Lithography Program, Phase II X-ray Contract N00019-91-C-0207, sponsored by DARPA, administered by NAVAIR.

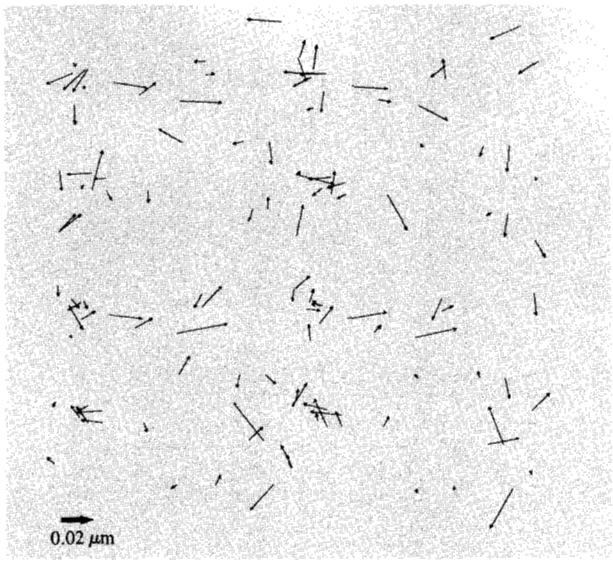


Figure 9

Pattern placement errors for a product X-ray mask, measured using a Leica-Leitz LMS-2000 metrology tool. The measurement utilizes test targets which are distributed around the periphery of the active device array. The results show pattern placement accuracy of 0.067 μm (3σ).

by electroplating. After the electroplating step, both the resist and the gold plating base under the resist are removed. The chromium is removed from the optical alignment windows to ensure proper optical transmission for registration in the X-ray stepper. The mean plus 3σ linewidth, relative to nominal linewidth, is controlled to under 0.050 μm for most products. As an option, a negative-tone, chemically amplified resist is also used; it has a base dose requirement of 4.5 $\mu C/cm^2$.

As mentioned previously, image placement control depends on a variety of factors, including the exposure tool, the measurement tool, the mask processing, and the distribution of the measurement locations across the mask. Product specifications depend on the design. Current product specifications range from 0.070 to 0.120 μm for 3σ image placement control.

A piece of the pattern from a finished X-ray mask written using the EL-3+ tool is shown in **Figure 8**. The images were taken in a SEM at three different magnifications, thus revealing the coarse and fine structure in the mask. They show the plated structure for a critical product static random access memory (SRAM) level with 0.35-μm ground rules. The gold X-ray absorber layer is 0.65 μm thick. Masks such as this are routinely fabricated and delivered to customers.

Pattern placement accuracy for a finished, critical-level X-ray mask is shown in **Figure 9**. The measurements were taken using the Leica-Leitz LMS-2000 tool. The measurement technique utilizes test targets positioned around the periphery of the active device array. The error is seen to be 0.067 μm (3σ).

Conclusion

An e-beam lithography tool called EL-3+ has been developed for the purpose of manufacturing 1× masks for X-ray lithography. The tool has been shown capable of fabricating 0.35-μm lines with 3σ image size control of 0.025 μm. Pattern placement accuracy in blind-write mode has been demonstrated as 0.070 μm (3σ), achieved on a routine basis. Product X-ray masks fabricated using this system have been used to make working devices.

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Pyrex is a trademark of Corning Glass Corporation.

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