# The Electron Beam Pattern Generator

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*An electron beam pattern generator is being developed to write directly on photographic plates with a 4-μm diameter beam over a 5-cm by 5-cm field with an address structure of 25,000 by 25,000. Two unique features of this pattern generator are random-access computer control of the beam and a 15-bit digital-to-analog converter stable to better than ±1 part in $10^6$. Capability for drawing 4-μm lines having an edge gradient less than 0.5 μm and an optical density greater than three has been demonstrated. Stability of better than ±1 μm in 24 hours over a 4-mm by 4-mm field has been achieved. Experiments still in progress have demonstrated ±1-μm stability over the entire 5-cm by 5-cm field for shorter time periods. Reticles of typical complexity are drawn routinely in less than five minutes.*

## I. INTRODUCTION

The demand for integrated circuits is increasing rapidly, and projections indicate that the existing mask-making facilities will be severely overloaded in the near future. The major portion of the time required to make a mask is taken in producing the reticle. The electron beam pattern generator was originally conceived to assist the mask-making shop by producing reticles rapidly.

The use of a computer-controlled electron beam also holds promise for solving other problems. As integrated circuits become more complex, it is increasingly difficult to meet the line-width and field-size requirements of the final masks. The fundamental limits set by diffraction effects are currently being approached; moreover, the depth of focus of the lens system producing these masks is so small that severe requirements are made on material tolerances. Due to the extremely short wavelength of kilovolt electrons, diffraction effects are negligible and it is possible to write with beams a few tenths of a micron in width over small fields. A. N. Broers et al.[1] have succeeded in producing interdigital surface-wave transducers of 0.3-μm width and 0.7-μm spacing using a modified form of scanning electron microscope. With electron beams it is possible to use very high *f* numbers to give a large depth of focus; this relieves the problem of extreme materials tolerances.

This paper describes an experimental machine built to prove the feasibility of drawing reticles on photographic plates. The requirements to be met are as follows. The address structure should be greater than 25,000 by 25,000 over a 5-cm by 5-cm field. The line should be 4 μm (two address units) wide and have an optical density greater than two. Stability and reproducibility should be within ± 1 μm, or ± 20 ppm (parts per million). As the machine has fast random access rather than a raster scan, the writing time is proportional to the area covered, and the machine should be able to cover 20 percent of the field within five minutes.

Although the above requirements are sufficient for all of the expected reticles for the next few years, they are also sufficient for about 90 percent of the expected masks. The specifications allow a 4-μm feature of one mask level to be registered within an 8-μm feature of another level. Because of the method of programming the computer, there is very little extra computation time involved in drawing a mask as compared with a reticle.

The electron optical column was built from commercially available parts, and does not represent the ultimate in performance. However, it has been demonstrated that the electron beam is potentially a very valuable tool in the manufacture of reticles and integrated-circuit masks.

## II. DESCRIPTION OF THE SYSTEM

Figure 1 shows a block diagram of the equipment. A Digital Equipment Corporation PDP-9 computer is used to generate data for an interface to control the electron beam. Input information to the computer is obtained from design programs such as XYMASK.[2] The division of work between the computer and the interface is best explained by describing the technique used to draw patterns.

As shown in Fig. 2, patterns are drawn using line segments rather than picture points. The line segments may be up to 256 addresses long and the patterns are filled in at a rate of 1 μs per address. This is an important aspect of the system as it allows 20 percent of a 25,000 by 25,000 address structure to be covered in less than three minutes.

To draw the unfinished feature shown in the blowup of Fig. 2, the

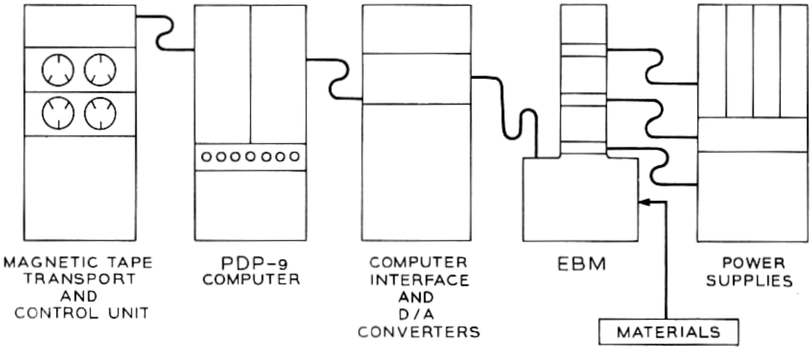

Fig. 1—Block diagram of the equipment.

coordinates of the four indicated points are read into the computer. The start point and length of a single line segment are fed to the interface. While the interface is controlling the beam to draw that particular line segment, the computer is calculating the position and length of the adjacent line segment. This division of work between the computer and interface minimizes the amount of information to be supplied to the system and gives the system a programming flexibility as will be discussed later.

Both familiar forms of graphics, a television like raster and point-by-point plotting, were rejected for this system. A raster-type genera-

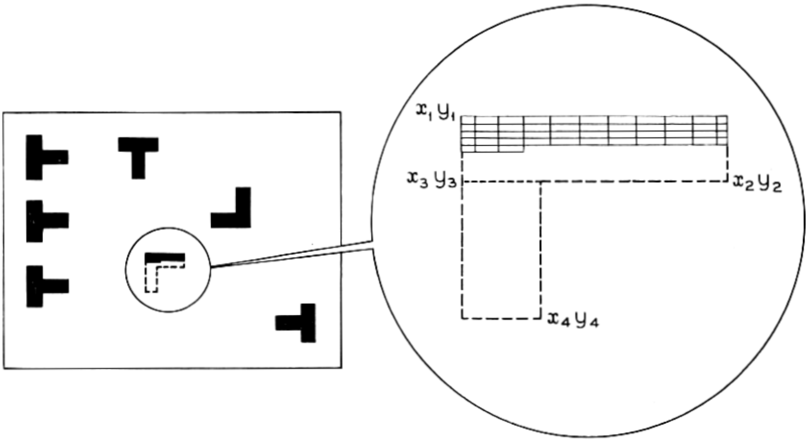

Fig. 2—Method of filling blocks using line segments.

tion is very inflexible in comparison to a random-access system and requires the transmittal of large quantities of information which is generally obtained on a large computer, thus incurring additional costs. Point-by-point plotting under the control of the computer would make generation times impractically long. Although the pattern generator uses line segments, it is a true random-access machine since a line segment may be one address long.

The Electron Beam Machine (EBM), with its associated power supplies and the photographic materials which go into the work chamber, will be discussed in detail in following sections.

### 2.1 *The Electron Beam Machine*

In the EBM, a beam of electrons writes directly on photographic plates thereby utilizing the good resolution inherent in electron beams. As in the case of CRTs, where the overall resolution is dependent on the phosphors, the resolution of the EBM is limited by the recording medium. For reticle and mask generation, where Kodak High Resolution Plate (HRP) emulsion is used to achieve the desired plotting speed, the resolution or edge definition of a line is limited to about 0.5 $\mu$m.

The electron optical column consists of a triode gun with a reentrant Wehnelt cylinder, two demagnifying lenses and one projection magnetic lens. The two demagnifying lenses are used to produce a 4-$\mu$m-diameter image just below the second lens, and the projection lens reproduces this image at a 35-cm working distance. The long working distance makes it possible to scan a 5-cm field with deflection angles of less than 5°. An electrostatic deflection system is used in preference to a magnetic system, in which eddy current and hystersis in the chamber walls would reduce the speed and accuracy to below acceptable limits. Because of the small deflection angles and apertures used, deflection defocusing with the electrostatic system presents no problem.

The current of the 15-kV beam is in the range of 0.1 nA to 1 nA. The large *f* number of the final lens (8000) enables a 4-$\mu$m beam to be achieved using commerically available lenses,* and keeps aberrations to negligible proportions. The operating pressure of $10^{-5}$ Torr is produced by a liquid nitrogen trapped 4″ oil diffusion pump.

### 2.2 *Control of the Beam*

As was indicated before, patterns are composed from line segments, which may be up to 256 addresses long. Figure 3 shows a block diagram

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* Made by Canal Industrial Corp. (Canalco), Rockville, Maryland.

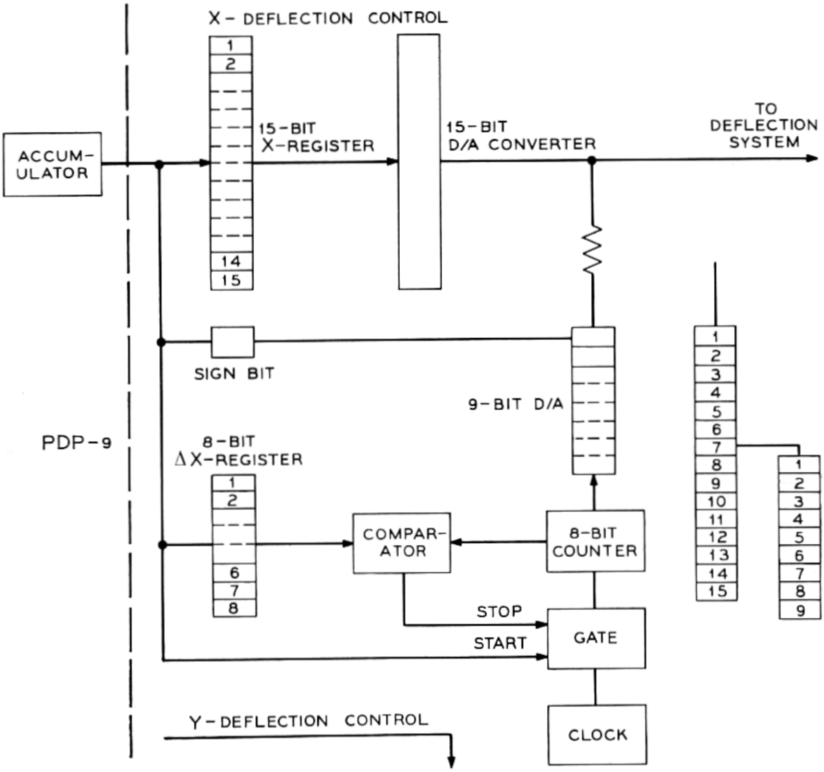

Fig. 3—Block diagram of computer interface.

of the computer interface which controls the beam during the generation of the line segment. Only the $x$-axis control is shown; the $y$-axis control is identical.

To draw a line segment $\Delta X(\Delta X \leqq 256)$ addresses long in the $x$ direction starting at $(x_1, y_1)$, $x_1$, $\Delta X$ and $y_1$ are loaded into the $X$-register, $\Delta X$ register, and $Y$-register, respectively. The beam is blanked at this time but the voltages corresponding to $x_1$ and $y_1$ are generated by the $X$ and $Y$ Digital-to-Analog Converters (DACs) and are applied to the deflection system. Therefore, when the beam is unblanked, it is at $(x_1, y_1)$. A start signal from the computer unblanks the beam and opens the gate to allow a continuously running clock to increment the 8-bit counter, which is initially set in the zero state. The output from the 8-bit counter is converted to an analog signal by the eight less-significant bits of the 9-bit DAC. The output of the 9-bit DAC is attenuated by a factor of 64 and is added to the output of the 15-bit

DAC. In this way, a voltage ramp is generated to move the beam from $x_1$ to $x_1 + \Delta X$. The comparator compares the $\Delta X$-register with the 8-bit counter and turns off the gate and blanks the beam when they are equal. The most significant bit on the 9-bit DAC allows lines to be drawn in both positive and negative $x$ and $y$ directions.

This method of generating line segments offers a number of advantages. It has already been mentioned that locating each address with the computer makes the generating time impractically long. With the interface described, the line segment is generated at 1 μs per point. If the $X$-register were incremented directly from the clock pulse (thereby eliminating the 9-bit DAC and the 8-bit counter), then, depending on the initial state of the $X$-register, some of the more significant bits will change states. When this happens, large transients of the output voltage will occur. The use of the $\Delta X$ converter system insures that only the less significant bits are switched while the beam is on. The sketch inserted to the right of Fig. 3 is meant to convey this idea. Experimentally it has been found that switching transients in the 9-bit DAC appearing at the deflection system are within tolerable limits.

The output of the DAC drives the deflection plates directly. At the beginning of a line segment, before the beam is unblanked, 10 μs are allowed for the output to settle. While the output is settling, the interface is loaded, which takes 11 μs. At the end of a line segment it is necessary to wait only 1 μs after the counter stops before blanking the beam.

### 2.3 *High-Precision Digital-to-Analog Conversion*

The best commercially available DACs have 13-bit resolution with 0.01-percent accuracy. There are DACs with 15-bit resolution and 0.01-percent accuracy, but these are not consistent with DAC because the lesser significant bits are not reproducible.

Normal practice in DAC is to switch accurately controlled voltages through precision resistors using transistor switches for their speed. The resistors form a binary series and the currents from the resistors are summed through a load. A simplified sketch of a 3-bit DAC of this type is shown in the left side of Fig. 4. It is because of the instabilities across the transistor switches that only 0.01-percent stability can be achieved.

DACs have been developed for this system whereby the voltage is regulated after switching as shown in the right side of Fig. 4. Notice that parallel current-source regulation is used instead of series-

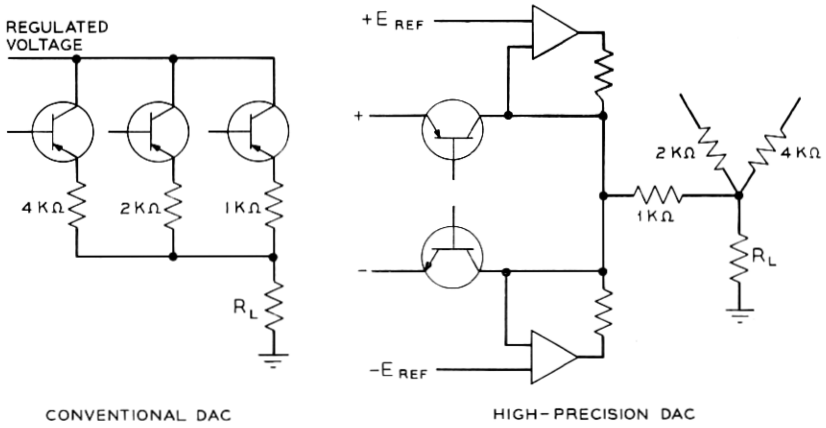

Fig. 4—Simplified diagram of conventional and high-precision DACs.

voltage regulation. Operational amplifiers which act as current sources compare the switched voltages with a reference and compensate for any variation by either supplying more or less current to the load. Details of this circuit have been described elsewhere.[3]

Using such a circuit, it has been shown experimentally that after the switch the voltage can be regulated to ±0.0001 percent or ±1 ppm. Only the more significant bits need be built in this fashion. An 18-bit system was built, in which 13 bits are conventional and only the five more significant bits are regulated in this way.

The secondary reference source used for comparison includes a primary standard and was also made using the principle of parallel-current source regulation. The resistors in the most significant bits and in the secondary voltage standard are stable to ±1 ppm/°C.*

An 18-bit DAC was built and tested successfully, but only the 15 most significant bits are used in the present application. One of the measurements made to test the DACs is illustrated in Fig. 5. The input to one DAC was held constant while the input to a second one was incremented and the output voltages were summed and recorded. The arrow indicates the step which resulted when the most significant, or first, bit was turned on and all other bits were turned off. Each step corresponds to a change of the least significant bit and equals a 4-ppm change in the total deflection voltage. It was found that the combination of the 13-bit DAC and the high-precision 5-bit DAC was cali-

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* Resistors manufactured by Julie Research Laboratories, Inc., New York, New York.

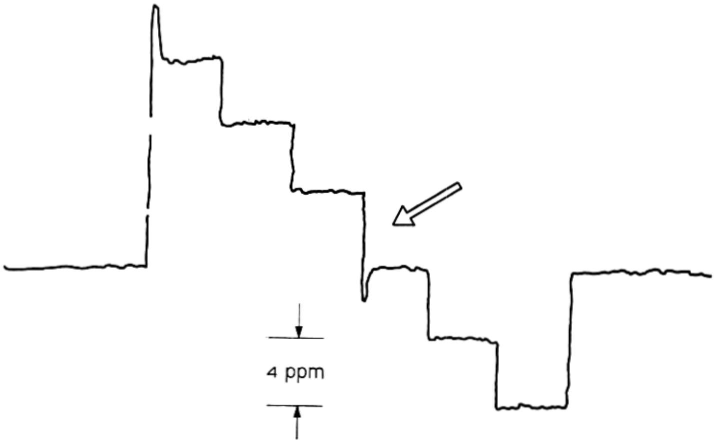

Fig. 5—Output voltage of the 18-bit DAC showing the matching of the most significant bit switch within a structure of the least-significant bits.

brated to better than $\frac{1}{2}$ ppm and that the least significant bit was clearly resolvable. Other similar measurements have shown that the 24-hour stability of the 18-bit DAC is ±1 ppm.

### 2.4 *Programming*

Because the system has random access and because of the particular division of work between the computer and its interface, programming of the electron beam pattern generator is simplified and results in elegant solutions. However, the biggest speed factor is the small amount of input information required by the system in comparison with other graphics systems.

XYMASK is a rather general program and the output of this design program must be "postprocessed" for the particular pattern generator. Since the computer of the electron beam pattern generator is available for large portions of the drawing time, a considerable amount of the computation normally done in postprocessing is done in real time in the PDP-9.

It has been shown how the electron beam pattern generator fills in rectangles at the rate of one address per microsecond. Circles, as well as complex geometries bounded by quadratic functions and lines of any given slope, may also be filled in at the same rate. This was made possible by "integer arithmetic," which avoids the use of multiplication and division in determining the boundaries of those geometries.[4] Algorithms based on integer arithmetic, which are run during the free time on the PDP-9, allow the programming of complex geometries in real time. The programming is described in detail elsewhere in this issue.[2]

### 2.5 *Electron-Sensitive Materials*

The photographic plates used in the EBM consist of 6 μm of Kodak HRP emulsion on a flat glass plate coated with a thin layer of chromium. The glass flatness is better than ±0.27 μm per linear cm and the optical density of the chromium layer is 0.04. The chromium layer has a resistivity less than 1000 Ω per square and is used to dissipate the charge of the electrons.

An interesting feature of electron beam exposure of these plates is that the image formed occurs in about the upper micrometer and a half of the emulsion. For projection exposure of the patterns produced by the electron beam system, this reduces the depth-of-field requirement on the projection system. Experiments on electron sensitization of photoresists have been performed at the Western Electric Engineering Research Center, Princeton, New Jersey, and are described in the following paper.[5]

## III. STABILITY AND CALIBRATION OF THE SYSTEM

When drawing a mask, it is essential to maintain stability for at least the time required to complete the pattern, typically five minutes. In order to insure registration of mask levels made at different times, it is essential to be able to maintain calibration over a long period of time. The EBM has been designed to have a short-term stability and long-term recalibration capability of better than ±1 μm or ±20 ppm over the entire field. This section contains a discussion of systematic and random errors and a description of the calibration method.

### 3.1 *Systematic Errors*

The reproducibility with which the beam can be deflected a distance $y$ is related to the stability of the accelerating voltage $V_b$, the deflection voltage $V_d$, and the distance $L$ from the deflection plates to the sample by the equation

$$\frac{\Delta y}{y} = \frac{\Delta V_b}{2V_b} + \frac{\Delta V_d}{2V_d} + \frac{\Delta L}{2L}. \tag{1}$$

These errors are all zero at the center of the field and increase out to the edge of the field. The expression $\Delta y/y$ in equation (1) is the fractional change in $y$ which occurs for a given set of instabilities, measured from one corner of the field. Since *every* point on the reticle must be within the specified tolerance, it is not sufficient to require, for example, that the root mean square of the three terms on the right side of equation (1) be less than ±20 ppm; rather, the sum of their absolute values must be less than 20 ppm.

The steps taken to insure good stability and low transients in the deflection voltage have already been described. High-voltage stability was obtained by using a commercially available* 0- to 20-kV supply with estimated stability under constant load of better than ±10 ppm per hour. Variations in the distance $L$ can arise either from surface non-uniformities on the electron-sensitive material or from a lack of reproducibility in referencing successive samples to the top of the sample holder. Surface variations are held to less than ±0.5 ppm and ±5 ppm is allowed for referencing successive samples.

### 3.2 *Random Errors*

In addition to the sources of errors just described, there are two sources of random error which must be considered. First, any insulating material in or near the path of the beam will tend to charge to the cathode potential, and the resultant electric field will cause the beam to deflect away from the computed position on the electron-sensitive material. Experiments conducted with this system indicate that charging of the electron-optical components is not a problem when proper cold-trap techniques are used. A small charging effect was observed under worst-case conditions when photographic emulsion on glass substrates was used without any metallic underlay; however, no detectable effect was observed on hundreds of samples with metallic underlay.

Second, time-varying magnetic fields at any frequency from essentially d.c. to several kHz (in particular 60 Hz) limit reproducibility by deflecting the beam from the programmed position by an amount which is proportional to the magnitude of the field and to the square of the interaction distance. Therefore, in a system with a long working distance, it is especially important to shield against magnetic disturbances. This problem is made difficult by the fact that the shielding must extend over a wide bandwidth down to very low frequencies. However, successful shielding has been obtained in the past by using an enclosure made up of successive layers of highly conductive material and of high-permeability magnetic material. A simple multi-layer

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* Power Design Model HV 1584-R, produced by Power Design, Inc., Westbury, New York.

shield which was constructed has reduced deflections due to 60-Hz magnetic fields and to slow changes in the field of the earth to less than ±1 $\mu$m. A larger shield is being designed[6,7] to enable the electron beam apparatus to operate in magnetic environments somewhat noisier than those found in most research laboratories.

### 3.3 *Calibration*

The calibration technique, which uses electron-beam-induced sample current, is shown schematically in Fig. 6. The alignment target consists of a gold grid on a chromium substrate. When the electron beam is swept over the target, the current through the picoammeter varies due to the different back-scattering coefficients of gold and chromium. Figure 7 shows a chart recording of the changes in the sample current when the beam passes over a gold stripe. The stripe can be detected with a S/N of better than 100 and its position can be determined to within ±0.5 $\mu$m. The calibration will be accomplished by adjusting the accelerating voltage or the deflection voltage to maintain a constant number of address units between the fiducial marks.

## IV. RESULTS

### 4.1 *Electron Beam Writing Characteristics*

Figure 8 shows a photograph of two intersecting lines written with the electron beam on the HRP emulsion with the chromium underlay. These lines are 4 $\mu$m wide and were written by single passes of the beam. The edge fuzziness of the lines is less than 0.5 $\mu$m, and no rounding off can be observed at the corners of the intersection. The optical density of the lines is about three.

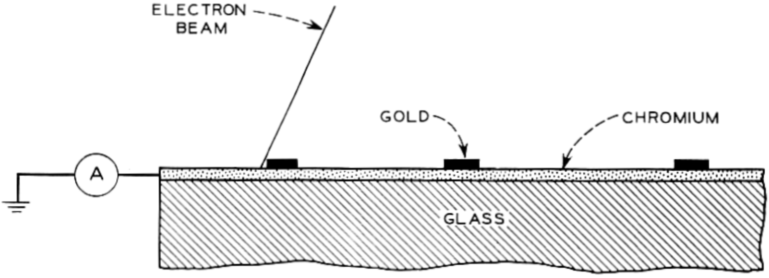

Fig. 6—Diagram of the calibration target.

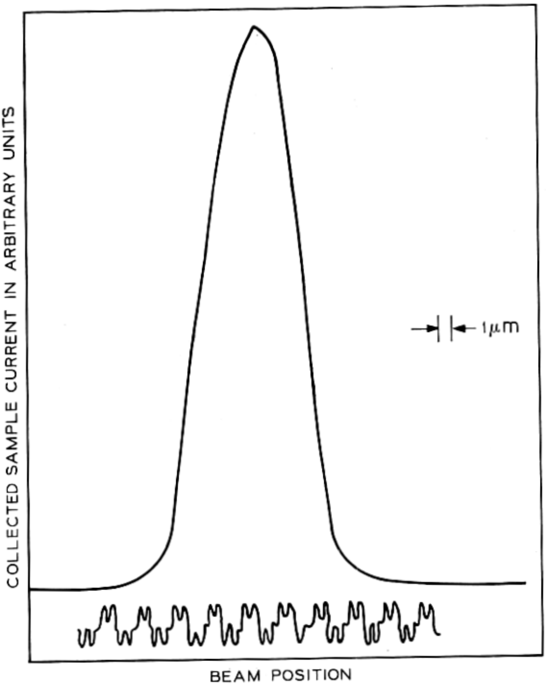

Fig. 7—Recording of calibration output. One complete cycle of the alternating signal gives four equally spaced reference marks, each of one address unit. To calibrate, number of address units between fiducial marks is held constant.

### 4.2 *Reticle and Mask Patterns*

Figure 9 shows a reticle produced by the electron beam pattern generator over a 5-cm by 5-cm field. This pattern is a lower-level metallization beam cross-over test reticle. The information for this pattern was obtained as an input deck to XYMASK. It was run on XYMASK on an IBM 360/50 and postprocessed on the same machine with a postprocessor written for the electron beam pattern generator. The outer edge of a corner of a path is purposely programmed with a circle. The generation time for this pattern is about three minutes. Figure 10 shows a test pattern for XYMASK, illustrating the sloped-line capability of the electron beam pattern generator. This pattern was also generated in less than three minutes.

Figure 11 shows a mask consisting of a 27 by 27 array of the patterns shown in Fig. 9. It should be emphasized that the pattern was drawn

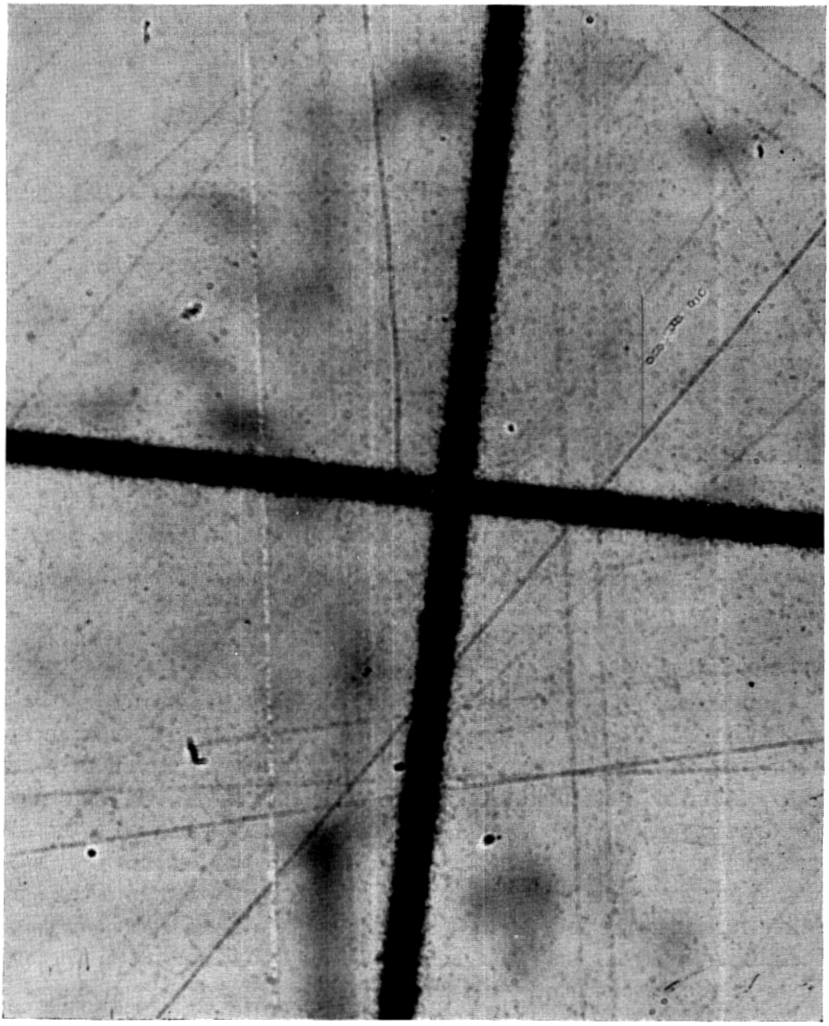

Fig. 8—Photograph of two intersecting 4-$\mu$m lines formed from single passes of the beam.

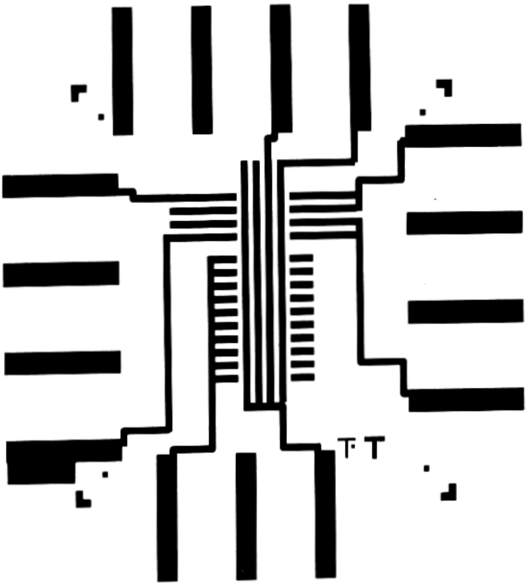

Fig. 9—Reticle produced by the electron beam.

over the 5-cm by 5-cm field without step-and-repeat in less than eight minutes.

### 4.3 *Stability*

From independent measurements of all the sources of error described in Section 3.2, it has been predicted that with the present equipment, the reproducibility of a pattern should be better than ±1.5 μm over the entire 5-cm by 5-cm field. Stability experiments have been performed by drawing grid patterns on the same plate at fixed-time intervals and measuring any displacements. Stability of ±1 μm has been observed for five-minute time periods. Experiments to measure the stability for longer periods of time are in progress. The largest source of instability is 60-Hz magnetic fields and the second largest is fluctuations in the accelerating voltage.

Experiments performed some time ago over a 4-mm by 4-mm field, which was the maximum field of the deflection system at that time, showed that stability better than ±1 μm could be obtained over a period of 24 hours. Measurements were made by two independent methods: by the use of a Preco comparator and by contacting two plates made 24 hours apart on a single plate using the image integration process developed by R. E. Kerwin and examining the results under a high-powered microscope.[8]

The following steps are being taken to improve long-term stability over the 5-cm by 5-cm field to ±1 $\mu$m in the near future. A large four-layer magnetically shielded enclosure is being constructed. The enclosure will have a clean-room interior and will have two sets of walls separated by a one-foot gap. Each wall will be made up of aluminum on the inside and molypermalloy* on the outside, separated by approximately two inches. This shield is designed to attenuate d.c. and 60-Hz magnetic fluctuations by factors of at least 200 and 5000, thereby reducing all beam position instabilities due to magnetic disturbances to less than ±0.1 $\mu$m. The customized high-voltage power supply is expected

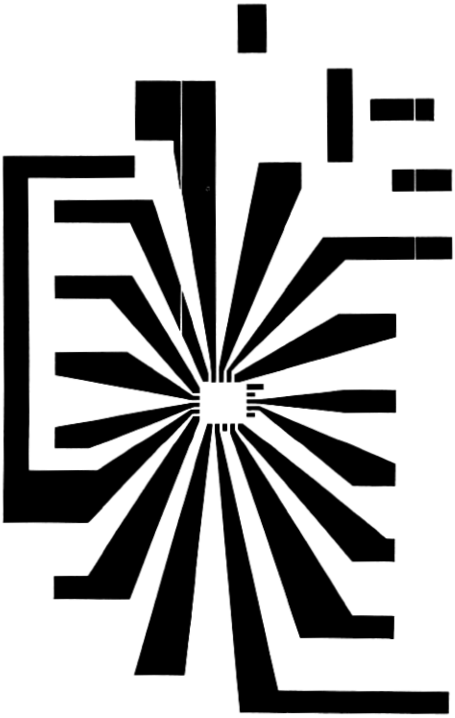

Fig. 10—Test pattern for XYMASK illustrating sloped line capability of the pattern generator.

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* Supplied by Allegheny Ludlum Steel Corporation, Brackenridge, Pennsylvania.

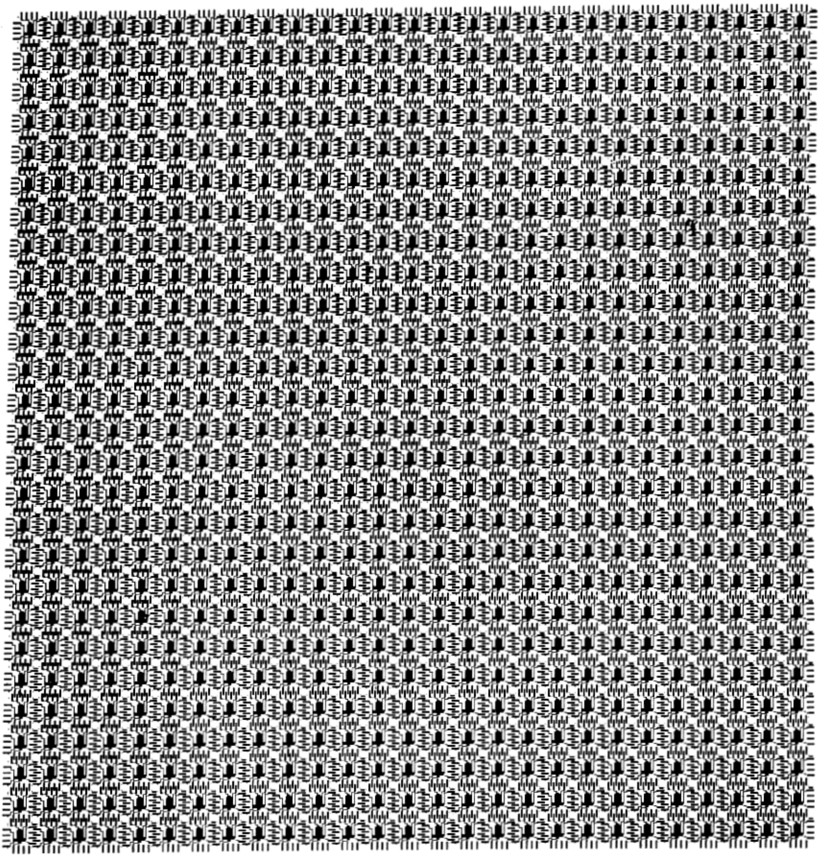

Fig. 11—Mask level containing an array of 27 × 27 of the patterns shown in Fig. 9.

to contribute less than ±0.1 $\mu$m to the beam position instability. The ±1-ppm stability of the DAC is more than adequate (±0.05 $\mu$m) and it is expected that the variations in the plate flatness and registration will contribute less than ±0.25 $\mu$m.

## V. CONCLUSION

An electron beam pattern generator has been developed which has a field size of 5 cm by 5 cm. The line width is 4 $\mu$m and the lines drawn were shown to have an edge fuzziness of less than 0.5 $\mu$m. The optical density of lines produced on HRP emulsion by a single pass of the beam is about three. Experiments on a 4-mm by 4-mm field size showed a stability better than ±1 μm over a period of 24 hours. In preliminary experiments on a 5-cm by 5-cm field an instability of ±1 μm for five minutes has been observed. Measurements indicate that the instability on the 5-cm by 5-cm field over a five-minute time period is caused mainly by 60-Hz magnetic fields; high voltage fluctuations become important for longer time periods. It is anticipated that improved shielding and a new high voltage supply can produce long-term stability of ±1 μm.

When completed, the electron beam pattern generator may be used to produce reticles, which will be compatible with the step-and-repeat camera described in a following paper.[9] Alternatively, the system may be used to make masks directly, with a minimum line width of 4 μm registering inside an 8-μm feature of another level. Although a 4 μm line width is not small by electron beam standards, its generation and control over a 5-cm by 5-cm field without step-and-repeat has not been reported before.

A linewidth of 4 μm over a 5-cm by 5-cm field was selected for reticle making. Smaller linewidths can be obtained with better lenses. There are many possible applications involving various combinations of linewidths and field sizes. The present system can possibly be extended to write with a 1 μm linewidth over a 5-cm by 5-cm field or with sub-micrometer linewidth over a 1-cm by 1-cm field. In addition, the long depth of focus and sub-micrometer resolution capability are important characteristics of electron beam systems for pattern generation directly on semiconductor slices.

## VI. ACKNOWLEDGMENTS

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