Electron-beam pattern generator

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Introduction

The conventional process for making the masks which are used in the manufacture of integrated circuits is photolithography. A replica of the required pattern is first made and reduced photographically to the required size, using a very accurate optical system: often a very large demagnification is needed and the reduction may have to be made in two stages. The final replica is then used as a mask through which to expose a light-sensitive 'resist' which covers the material in which the pattern is to be made. After the resist is exposed and developed it forms a protective layer which shields the underlying material at the places where the pattern is to appear, while the rest can be etched away to leave the desired pattern. There are many possible variations, but all high-resolution processes share the need for a precise and usually high-definition mask.

Throughout the history of integrated-circuit manufacture there has always been a steady demand for smaller and smaller structures, and the resolution now required in the pattern and the mask approaches the fundamental limit set by the wavelength of light. If progress towards finer resolution is to continue, alternatives to optical techniques must be developed. The most promising of these is electron lithography, in which a beam of electrons is used to define the pattern in an electron-sensitive resist[1]. The pattern can be drawn directly on to the resist on the final substrate or used to make a mask which can be copied, for example using an electron-image projector such as that described in the article by J. P. Scott[2]. Electron lithography has two major advantages. First, the effective wavelength of an electron is typically very small; for an energy of 20 KeV, as used in the machine described here, the effective wavelength is about 0.05 nm — i.e. 10^4 times smaller than the wavelength of visible light. Such a machine is not limited by the wavelength and could in principle achieve a resolution many times higher than could be obtained optically, provided of course that the aberrations in the electron-optical system could be made sufficiently small. The second advantage is that since electrons are charged particles, the electron-optical system can be controlled and varied electrically while the pattern is being drawn. This feature can be used, for example, to adjust the alignment of the pattern on the substrate or to correct for any aberrations or distortions which may arise as the beam moves. This eases the requirements on the mechanical alignment and on the focusing and deflection systems.

The subject of this article is an electron-beam pattern generator which has been developed at Philips Research Laboratories, Redhill (PRL)[3]. This machine is normally used at a spot size of 0.25 μm, but this can be reduced to a value of 0.1 μm if required. The positional accuracy is close to ±1 μm, and the machine can cover a mask measuring 42x42 mm with high-resolution patterns in from 1 to 3 hours, depending on the area taken up by the pattern.

The machine has been providing a pattern-generation service for PRL, for the Philips Research Laboratories in Eindhoven and for other establishments within the Philips company for the last two years. Patterns have been successfully made on several hundred substrates, some as masks for ordinary photolithography, some as masks for use in the electron-image projector and some drawn directly on to the required substrate (this process is called 'direct slice writing'). Most of the patterns have been used in the fabrication of experimental transistors and integrated circuits; other applications have been in magnetic-bubble circuits and surface-acoustic-wave devices. The high resolution of the machine gives an improved packing density in both applications, and in semiconductor devices the small dimensions attained also allow high operating frequencies.

In this article we shall first give a general outline of the machine and its operation and then more detailed descriptions of the most important features. In the final section the performance achieved will be described and some examples of work done on the machine will be shown.

[1] See for example E. D. Roberts, Philips tech. Rev. 35, 41, 1975. We use some of the special resists developed at PRL as well as the standard types based on polymethyl methacrylate.
Fig. 1. The electron-optical column of the electron-beam pattern generator. The column is similar to that of a scanning electron microscope, and produces a beam of electrons focused to a spot of diameter 0.25 μm. This spot is scanned over the target under the control of a minicomputer so as to draw the required pattern directly on an electron-sensitive resist. Apart from the electron-optical column and the minicomputer the pattern generator consists of amplifiers and control circuits used for deflecting the beam, for adjusting the focus during scanning and for positioning the patterns.
General description of the pattern generator

The pattern generator is an adaptation of the scanning electron microscope (SEM) [4]. In the SEM a finely focused beam of electrons is scanned in a raster over the item of interest. Depending on the application the transmitted electrons, the reflected electrons, or the secondary-emission electrons are detected, and the signal produced is displayed visually by a synchronized raster on a screen. The pattern generator, which is shown in fig. 1, uses a similar electron-optical system, but a minicomputer is added, which drives the beam around in a complex path so as to draw a pattern directly on to a target covered in electron-sensitive resist. The resist is then developed and etched to produce a useful pattern directly or to make a mask which can be copied by other means. The pattern specification consists of a list of coordinates which are stored in the computer memory and so can be very easily altered or adjusted. Thus the process of pattern or mask making is both straightforward and flexible.

A mask for an integrated circuit contains a great deal of information — especially if the patterns are very finely detailed — although much of it is repetitive. For example a mask 42 × 42 mm contains 1.8 × 10^9 squares each 1 × 1 μm, so that even if the pattern occupies only 25% of the surface area, something like 4 × 10^8 squares may have to be drawn if a resolution of 1 μm is required throughout the mask. If the drawing is to take say 2 hours (a typical time for this machine), approximately 75 000 squares must be drawn each second. One of the main problems in electron-beam pattern generation is to obtain the required drawing speed without loss of resolution and accuracy. Particularly high demands are made of the deflection and focusing system, and in the PRL machine a two-stage deflection system together

![Diagram of the electron-optical column.](image)

Fig. 3. Schematic sectional view of the electron-optical column. Starting from the bottom of the diagram, we have the electron gun G, a coil BA for beam alignment, a beam breaker BB, an electromagnetic lens L1, a vacuum valve V and the objective lens L2. The main deflection coils (MD and Tr) and the coils of the trapezium generator (MD and Tr), separated from L2 by a Mumetal cylinder (hatched), are located between L1 and L2. The entire column can be rotated about its axis by the mechanism Rot (a micrometer screw driven by a stepping motor). Foc and St are the coils for focusing and astigmatism correction (see also fig. 6). P1 and P2 connect with two diffusion pumps.

The slice to be processed is located in a target holder TH on the table T(x,y), which can be displaced in two directions at right angles under the control of a computer. The electron beam (light grey) can scan a maximum of 2 × 2 mm and the mechanical stage allows an array of 22 × 22 such scanning areas to be drawn on a single target. Each area of 2 × 2 mm is marked out by an array of markers whose positions can be determined by making use of the back-scattered electrons. These electrons strike an annular phosphor-coated glass plate (dark grey), generating photons which are detected by four photomultipliers symmetrically arranged around the axis of the column. Photon collection by the photomultipliers is improved by the provision of aluminium mirrors. The video signal Vid thus produced is used for locating the markers and also for forming an image of the substrate as in an ordinary scanning electron microscope. This image is particularly useful for examining markers for defects.
with a mechanical stage are used to ease some of the problems.

The pattern which the machine has to draw — maximum dimensions 42 x 42 mm — is divided into sub-units of about 2 x 2 mm, whose corners are determined by markers on the target surface. These markers are used for alignment purposes and also to help in focusing the beam, as we describe in more detail later. In the present machine a separate pattern, such as an integrated circuit, is drawn in each subunit, although patterns covering more than one subunit could be drawn. The target can be moved on a mechanical stage controlled by the computer so that a 22 x 22 array of separate patterns can be drawn on a single target. These may be different designs or repeats of a single type, as required.

The pattern which is to be drawn in the 2 x 2 mm scanning area is divided into small trapezium-shaped blocks, up to 32 x 32 μm in size. The main deflection system moves the beam to the correct point in the field and then hands over control to an autonomous trapezium-generator unit with its own deflection coils and control circuits, which rapidly fills in a block of the required shape and size. The pattern is thus built up from a large number of small blocks drawn side by side (fig. 2). The fact that these may be trapezoidal in form means that patterns with sloping sides can be drawn neatly without the rough edges which would occur if the basic elements were simply squares or rectangles. The trapezium generator can operate very quickly because it deflects the beam over only very short distances and so does not need great stability. On the other hand the main deflection circuit has to be able to deflect the beam very much further, and is correspondingly slow. By dividing control of the scanning process between the two units we obtain much greater speed than would be possible using the main deflection system alone.

A further element in the control system is concerned with retaining the focus of the beam so that high resolution can be obtained throughout the pattern. In general it is not possible to make an electron-optical system which is entirely free from aberrations and so an element of compromise in the design is inevitable. In our pattern generator the deflection system has been designed to minimize deflection distortion, but at the expense of appreciable aberrations, such as astigmatism and field curvature, which affect the size and shape of the spot. A precisely square scanning area is obtained which is accurate to within a small fraction of 1 μm throughout. The aberrations affecting the spot are predictable and are continuously corrected as the beam moves about by special circuits within the deflection amplifiers. A spot size smaller than ½ μm is thus obtained. The fact that such correction is possible is one of the advantages of electron-beam systems compared with their optical counterparts.

The data input to the minicomputer (DEC PDP8) which controls the machine is in the form of lists of the coordinates, shapes and sizes of the trapezia which go to make up the patterns required. These are derived from the patterns themselves by a computer (ICL 1904S) using the CIRCUITMASK [4] language; a special processing program then generates the parameters of the trapezia and arranges them in the order in which they are to be drawn. The result is transferred to the PDP8 on magnetic tape and stored in the disc-memory unit to be called up when required. No further processing is needed. The patterns can be checked visually on a storage oscilloscope connected to the deflection system. Data relating to several circuits may be stored at one time and the computer operator feeds in separate information on how the different patterns are to be arranged together on the mask. This is particularly useful, as it allows the designer to include test patterns and circuit variations on a single mask.

Column and control system

In fig. 3 a schematic sectional view of the machine is shown. Contrary to the usual practice the column has the electron gun at the bottom, which brings the work chamber to a convenient height for loading. The pumping system is fully automatic; there is a vacuum valve halfway along the column, which closes automatically when the work chamber is opened to load a substrate, so that the lower half of the column remains evacuated. The mechanical stage is propelled by rods which pass through vacuum seals to two ball screws. The screws are driven by stepping motors, each motor step moving the target area 25 μm for a total movement of 44 mm.

The electron gun is of our own design and is aligned mechanically with a little assistance from the beam aligner. The current to the target can be switched off when required by the 'beam blanker' halfway along the column. This works by deflecting the beam sideways so that it cannot reach the target. The deflection is electrostatic, with two sets of plates.

Fig. 4 shows a block diagram of the complete control system of the pattern generator. Some of its important parts and functions will be discussed in more detail in the following sections.

[4] The deflection coils directly beneath the electron detectors were designed by Ir R. Vonk and Ing. N. G. Vink of the Philips Video Division, Eindhoven.


The main deflection system

The main deflection system is used to move the electron beam across the $2 \times 2$ mm scanning area and place it accurately in the position required for each trapezium; control is then assumed by the autonomous trapezium generator. It is controlled directly by the computer via two 15-bit digital-to-analog converters which in turn drive the $x$ and $y$ amplifiers feeding the main deflection coils. The least-significant bit of the converters corresponds to $1/16 \mu m$ of deflection.

The size of the electron-beam scanning area is determined by the pattern resolution required and the reproducibility of the beam-scanning system. In this machine the beam diameter is normally about $0.25 \mu m$ and the deflection must be accurate to better than this if the resolution is to be fully used; $0.1 \mu m$ is usually required. Among the factors which affect the reproducibility of the beam position are drift in the power supplies and deflection amplifiers, eddy currents and buildup of contamination in the column. These limit the total number of separate points in the $2 \times 2$ mm scanning area which can be addressed to the required accuracy to $10^8$. Higher accuracy would entail reducing the scanning area accordingly and the present $2 \times 2$ mm size was chosen as a suitable compromise.

Special care is taken to ensure that the scanning area is free from distortions, and in particular that its outline is precisely square. This is checked every few weeks using a calibrated substrate with a group of accurately spaced markers, and small electrical adjustments are made to ensure that the element is square to within $\frac{1}{2} \mu m$.

The main deflection system does not need the very rapid response time of the trapezium generator but since the deflection distances are much greater some precautions still have to be taken to ensure an adequate...
speed of operation. The deflection coils are therefore surrounded by annealed Mumetal rings 0.2 mm thick stacked axially and separated by spacers of the same thickness. The purpose of this is to prevent the magnetic flux from the coils from entering the objective lens where they would generate eddy currents during rapid changes in the deflection fields. These eddy currents would take a long time to decay and so would increase the time taken to stabilize the beam in a new position. As a further precaution the input data is arranged so that the beam does not take large jumps from one part of the scanning area to another. Pattern elements are drawn systematically from top to bottom and left to right, and even when there are no pattern elements to be drawn, the deflection system does not skip the region but moves through it with the beam current switched off. Thus rapid changes of magnetic fields are avoided and the effects of eddy currents and hysteresis in the coils are minimized. The system settles to within 0.03 μm within 100 μs.

The sensitivities of the x- and y-deflection systems are also in the control of the computer and can be varied by a few per cent to change the dimensions of the scanning area.

The trapezium generator

The trapezium generator has a special set of deflection coils which are similar to those of the main deflection system but have fewer turns and so are of lower inductance. The currents through them are determined by a logic unit driving very high speed digital-to-analog converters which feed a pair of fast amplifiers. The positions of the coils and the gain of the amplifiers are carefully adjusted in relation to the main system so that the trapezia are not drawn the wrong size, or tilted with respect to the x- and y-axes. It is also important that the deflection characteristics of the coils should match those of the main system. This is because when blocks are drawn side by side, the width of the blocks (which is determined by the trapezium generator) and their spacing (determined by the main deflection system) must be precisely the same if they are to fit together properly.

The logic unit is the heart of the trapezium generator. It receives from the computer numbers denoting the height, width and edge angles (see fig. 5) of the required trapezium and calculates, in digital form, the voltages needed to deflect the beam. These digital signals are applied to digital-to-analog converters which drive the beam to and fro in ½-μm steps over the region in which the trapezium is required. This region can be up to 32 × 32 μm (256 steps), but the beam scans only within the required area, as shown in fig. 5. In this way trapezium shapes (including squares, rectangles and triangles as simple cases) can be filled in very rapidly; at the maximum stepping rate (corresponding to 10 MHz), each one takes at most 6.55 ms. The edges of the figures are reasonably smooth since the step size is somewhat less than the spot size.

Focusing the beam

The size of the spot which the electron-optical system can focus on the substrate determines the fineness of the detail which can be reproduced in the pattern. A number of measures have to be taken to ensure that the spot size is preserved throughout the pattern. The variations arise in three ways: first because the focus of the beam tends to vary during deflection; secondly because even with an undeflected beam the focus may drift slowly with time owing to variations in the EHT supply, build-up of contamination in the column and so forth; and thirdly because the target is unlikely to be exactly flat, nor will the movement of the mechanical stage be perfect, so that the height of the substrate will vary slightly as the stage moves.

The current density of the beam has an approximately Gaussian variation with distance from the centre-line. Near the focus the beam is circular in section, or elliptical if there is astigmatism. As the astigmatism does not vary greatly with time or with the position of the cross-section above or below the focus, it is sufficient to correct for it manually at the start of each mask. The variation in the position of the focus is greater: a correction for this is made automatically at the beginning of each 1.9 × 1.9 mm pattern. Both corrections are determined by scanning the beam across two perpendicular edges of one of the markers at a steady speed in an L-shaped pattern. The rise times of the signal as the edges are passed give a good estimate of the size and shape of the spot: two equal and short rise
times denote a narrow well focused beam; long and unequal rise times indicate that the beam is diffuse and elliptical. The information obtained from this measurement is used to adjust the current in a focus coil and in two astigmatism-correction coils (stigmators) which can be used to adjust the size and shape of the beam. The focus coil is a simple air-cored solenoid. The astigmatism is corrected by a pair of magnetic quadrupole deflection amplifiers. The currents in the \( x \)- and \( y \)-deflection coils are monitored and a current proportional to \((x^2 + y^2)\) is applied to the focus coil to compensate for the known curvature of the focal surface. This is a well established technique used in some cathode-ray-tube displays. In addition, signals proportional to \(xy\) and \(x^2 - y^2\) are used to derive the currents to the stigmator coils to correct for the known

![Fig. 6. The focus coil (centre), the coils for correcting astigmatism (the stigmators, left) and a coil for scanning the substrate (when the column is used as an SEM). Each stigmator consists of four vertically wound coils forming a magnetic quadrupole. One unit is aligned with the \(x\)- and \(y\)-axes, the other is at 45° to them. The focus coil is a simple solenoid, with compensating coils placed around it to improve the symmetry of the field. In reality it is mounted inside the stigmators.](image)

lenses: one of these has its major axes parallel to the \(x\)- and \(y\)-directions of deflection, while the major axes of the other are rotated through 45°; see fig. 6. To find the value which gives the best focus a series of measurements are made as the focus-coil current is altered in small steps. When the stigmators have been adjusted, the currents in the stigmators and the focus coil are varied until the shortest possible rise times have been obtained. It is not sufficient to make the rise times equal; an elliptic spot inclined at 45° to the marker edges will also give equal rise times but they will be longer. Only small rise times provide a guarantee that the beam is free from astigmatism.

As the deflected beam moves away from the marker new aberrations arise which depend on the position of the spot. The chief ones are curvature of the surface of best focus, which means that the beam reaches a focus which may be slightly above or below the target surface, and astigmatism. The aberrations do not change appreciably with time or with small variations in the height of the target. They can therefore be measured once and for all when the machine is made and the necessary corrections can be built into the design of the astigmatism. These corrections maintain the size of the spot substantially constant throughout the 2 x 2 mm scanning area.

A large number of the electrons in the beam pass through the layer of electron resist and into the substrate, where some are scattered and reflected back into the resist again a small distance from the point of entry. These 'back-scattered' electrons broaden the skirts of the intensity distribution in the spot. The effect of this is that the size of the pattern elements after development is altered by the presence of surrounding pattern material. This 'proximity effect' becomes important only for details of less than about 1 \(\mu\)m. In our machine we overcome the problem by increasing the dimensions of fine details in the pattern specification to compensate for the expected reduction during processing. This is readily done during processing of the pattern data before it is fed into the minicomputer.

The marker system

The manufacture of integrated circuits usually requires the use of several masks which are exposed successively on to the same silicon slice (fig. 7). Very often the final circuit contains patterns defined inside
each other by the successive masks and the relative positions of the masks are then at least as critical as the resolution of the fine details. The PRL electron-beam pattern generator can define pattern elements 1 \( \mu \text{m} \) wide to an accuracy of 1/16 \( \mu \text{m} \) and it must therefore be possible to align different masks to much the same accuracy. This could be achieved with a laser interferometer to control the mechanical stage, but an alter-

native, used here, is to rely on an accurate array of markers on the substrate; this can be located by the electron beam and used as a reference. The markers are deposited on the substrate before the processing in the machine begins.

If, as is usually the case, each subunit is used for a separate circuit it is not necessary that all the markers should be equally spaced; it is necessary only that their positions should be identical for all the masks of a set. This is relatively easy to arrange if all the marker arrays for a particular set of masks are derived from the same master, using an electron-image projector or are defined using a very accurate optical repeater.

The markers are 20 \( \times \) 20 \( \mu \text{m} \) squares and are arranged in a square with spacing of 1.9 mm so that each 2 \( \times \) 2 mm area encompasses 4 markers at a time. The mechanical stage is used to position the substrate to \( \pm \) 100 \( \mu \text{m} \) and the electron beam then searches a

![Fig. 7. A set of optical masks (a-e) used in making a simple integrated circuit (f). Magnification 40 x. In conventional mask-making a simple pattern such as one of these (usually called a 'reticle') is repeated on a special 'step-and-repeat' camera to make a mask containing a large number of identical units in a two-dimensional array. The electron-beam pattern generator makes the complete mask directly from data stored in the controlling minicomputer; several different types of pattern can easily be included on the same mask if required. (This figure is taken from F. T. Klostermann [9].)
atomic number of the marker material must be very different from that of the substrate. Gold (atomic number $Z = 79$) and tantalum ($Z = 73$) are suitable for markers of chromium ($Z = 24$) on glass; tantalum is preferred for use on silicon ($Z = 14$) because it is compatible with the further processing of the device. It is usual to protect tantalum markers with a thin layer of silicon nitride, which does not unduly affect their back-scattering properties.

The markers are used to adjust the deflection system every time the mechanical stage is moved to present a new $2 \times 2$ mm scanning area to the beam. The procedure consists of 6 steps as follows; see fig. 8.

1. The substrate is moved to bring four markers into one deflection area ($K$, $L$, $M$ and $N$ in fig. 8).
2. Marker $K$ is located by moving the beam rapidly over the surface in a raster covering a $128 \times 128$ μm square (the ‘coarse search’). The centre of the marker is then defined accurately in terms of the beam-deflection coordinates by a ‘fine-positioning’ routine. The beam is stepped eight times across each edge of the marker in turn taking very small steps ($1/16$ μm), and the effective $x$- and $y$-coordinates of the centre are calculated from the signals received. Fine positioning takes about 80 ms and is repeatable within $\pm 1/16$ μm for markers of $20 \times 20$ μm. The beam focus is checked and adjusted at this stage.
3. A second marker $L$ is found in the same way. The computer checks that the $x$-coordinates of $K$ and $L$ are identical; if they are not, owing to residual rotational errors in the mechanical stage or to the slight rotation of the deflection field in focusing, then the error is corrected by rotating the deflection coils about the column axis. This, too, is done under computer control.
4. A third marker $M$ is located and the sensitivities of the $x$- and $y$-deflection amplifiers are adjusted by the computer until the distances $KL$ and $LM$ as measured by the deflection system are identical. The $x$-coordinates of $L$ and $K$ are checked and, if they are not identical, the deflection-coil assembly is rotated round the column to compensate.
5. The pattern is now drawn in this area. The setting-up procedure has ensured that distances and angles specified in the data will be accurately reproduced on the substrate. However, the coordinates of the details in the pattern as specified in the data are taken relative to the marker system. A simple translational adjustment has to be made to the coordinates during scanning to take account of the fact that owing to the inevitable inaccuracies in the mechanical stage the measured positions of the markers will always be slightly different from those expected.
6. Finally, the substrate is moved until the next four markers, $M NOP$, appear in the scanning area and the process is continued.

For experimental purposes it is sufficient to draw a separate circuit in each subunit, but for production it may often be necessary to join patterns in several neighbouring subunits to form larger circuits. The deflection field has been tailored to have a precisely square outline to within a fraction of $1 \mu$m, so the scanning system is capable of retaining its accuracy over a larger pattern provided that the array of markers can be made sufficiently regular. This is not a simple matter as a set of marker masks are needed, each of high accuracy. The best available step-and-repeat cameras[6] are capable of maintaining the marker spacings constant to about $0.1 \mu$m, which is adequate for the present state of integrated-circuit development, and
Fig. 10. Part of a mask for making metal interconnections for integrated circuits. The photograph shows how much detailed information can be present in a pattern.
one possible approach is to generate all the masks of the set separately on such a machine. An alternative is to make one master mask on a step-and-repeat camera and then copy it accurately to produce the other members of the set. It is found in practice that small but significant inaccuracies are introduced by conventional copying processes; the best method appears to be to use a high-accuracy electron-image projector such as that described in the article by J. P. Scott [2].

Performance of the machine

The main criteria by which a mask-making machine should be judged are its speed, the positional accuracy of the patterns and the quality of the masks produced.

Speed

For patterns with low coverage, the dominant factor that determines the speed of operation is the time taken to move the mechanical stage; for complex patterns with high coverage the trapezium generator takes the most time.

The time taken to move the substrate so that all sub-units have been covered and to adjust the focus of the beam and the gain and rotation of the deflection system is about 20 minutes for a $22 \times 22$ array of patterns making a $42 \times 42$ mm mask. Much of this is settling time to allow the mechanical table and the coil rotator to come to rest. A considerable reduction of this time is possible.

The trapezium generator takes 6.4 seconds to cover a 1-mm square, so to cover one third (a typical fraction for a high-coverage pattern) of a $42 \times 42$ mm mask takes about 60 minutes. To this must be added the settling time needed between trapezia to allow the digital-to-analog converters, the deflection amplifiers and the eddy currents induced in the metal parts to settle down. This takes about 100 $\mu s$, so for, say, 600 circuits each with $10^4$ trapezia a further 10 minutes must be added for the settling time. Loading and unloading the substrate, pumping down and starting the program takes only 2 to 3 minutes. Adding up all these times, the total time for a $42 \times 42$ mm mask is in the range 1 to 3 hours, depending on the proportion of the area taken up by the pattern.

Positional accuracy

The machine was designed to make mask patterns with a positional accuracy of $\frac{1}{4} \mu m$ and this target has been reached. Reproducibility of pattern position can be measured by writing two images on the same substrate, which is removed from the holder and replaced between the two writings, with the same markers being used for registration on both occasions. Fig. 9 shows
two such images etched in chromium. The alignment is very satisfactory. This level of precision is obtained except where there are very obvious defects in the markers.

**Pattern quality**

The quality of the patterns obtained with the electron-beam pattern generator can be seen from figs. 10 to 14; these are photographs made during the last two years. *Fig. 10* is a part of a mask for making the metal interconnections for experimental integrated circuits and shows how much information such a pattern can contain. *Fig. 11* is a pattern with 0.5-μm details, demonstrating the resolution that can be obtained. The very high resolution can also be seen from *figs. 12 and 13*: *fig. 12* shows an integrated circuit written directly on the slice; *fig. 13* shows a number of patterns for magnetic-bubble circuits, with a smallest line width of 1 μm. Finally, *fig. 14* shows 1-μm aluminium tracks on silicon; this pattern was again written directly on the slice.

*Fig. 13.* Part of a magnetic-bubble circuit of permalloy, made by the electron-image projector, starting from a mask drawn by the electron-beam pattern generator. Since this machine assembles figures from trapezia whose shape and dimensions can be freely chosen, it can give very complicated shapes with smooth contours. The width of the narrowest tracks is 1 μm.

*Fig. 14.* Aluminium tracks on silicon made from a pattern written directly on the slice. The tracks are 1 μm wide. (The scale is in units of 1 μm.)
New developments

A new research machine is now being commissioned which will handle 100-mm slices and will incorporate a number of improvements suggested by the experience of two years' operation. Among these will be a new mechanical table using a laser-based measurement system which improves the positioning accuracy and so overcomes the need for closely spaced markers. In some cases the presence of these markers is very undesirable, for example in VLSI circuits and in surface-acoustic-wave devices, both of which require an uninterrupted pattern over a large area.

Measures are also being taken to improve the settling time, and as a result the new machine will be several times faster; indeed an increase of at least ten times the speed of writing can be expected in the more distant future. This may make direct slice writing a reasonable commercial proposition.

Summary. An electron-beam machine for making complex and precise patterns such as those required for integrated circuits is described. A 0.25-μm diameter beam of electrons controlled by a computer draws patterns on a metallized substrate covered in electron-sensitive resist. After development and etching a pattern is produced (maximum dimensions 42 × 42 mm) which can be used directly or as a mask to be copied by other means. A two-stage deflection system is used. The first stage (relatively slow) deflects the beam to within a 2 × 2 mm square, the second stage (relatively fast) draws the appropriate part of the pattern inside the square. The pattern is made up from trapezia of maximum size 32 × 32 μm. The patterns can be positioned to an accuracy of ± ± μm with the aid of a set of markers predeposited on the substrate. A complete mask containing details as small as 0.5 μm takes 1 to 3 hours to draw.