Device Photolithography:

An Overview of the New Mask-Making System

By F. L. HOWLAND and K. M. POOLE

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This paper reviews how photolithographic masks for silicon and thin-film integrated circuits are made. Increasing production and complexity of masks makes heavy demands on the operating time, reproducibility, and accuracy of the new mask-making system. The pattern generation step, in which the design is converted to a photographic image, is critical to the system. Advantages and disadvantages of other pattern-producing methods are discussed. The technique of producing patterns by optically scanning lines with a rotating mirror while mechanically stepping the photographic plate is described. This article develops the basic design parameters of address structure and operational speed for the primary pattern generator, and it defines the requirements for reduction cameras and the step-and-repeat camera for a system capable of meeting the needs for both thin-film and silicon integrated circuits. The article notes the system limitations imposed by optical generation of patterns and lens tolerances.

I. INTRODUCTION

The Electronic Materials and Components Development Area of Bell Telephone Laboratories has made the development of hybrid-integrated electronics, combining semiconductor and thin-film technologies, its major general field of activity for several years. Silicon integrated circuits provide the active elements for both digital and analog systems, and passive components can be incorporated if tolerances are not too tight. Thin-film circuits based on tantalum can provide stable resistors and capacitors which can be trimmed to precise values, while other thin-metal films can be used advantageously for conductors. Thus silicon and thin-film technologies together provide a sufficient set of elementary components for most systems functions. Equally important, the choice of silicon circuits made in the beamleaded, sealed-junction form and thin-film elements on ceramic or similar substrates give us complementary technologies which are physically compatible.

Both parts of this hybrid-device technology have come to depend primarily on photolithographic methods for delineating the areas in which material will be added, removed, or modified as the original substrate is successively transformed into the final circuit. Both parts of this technology have grown in volume of activity and in sophistication of technique. In doing so they have put increasing demands on mask-making laboratories for more masks per year and for more complex mask patterns.

The system described in this issue of *The Bell System Technical Journal* provides for both semiconductor and thin-film integrated circuits using facilities that are coupled by an information system. The mask-making system is designed to have the capability of meeting the demands for larger numbers of increasingly complex masks with a known time interval between the receipt of design information and the delivery of a complete set of masks.

II. HISTORICAL BACKGROUND

All mask-making systems can be described schematically as shown in Fig. 1. Two streams of information, one topographic and the second descriptive, must be provided.

The topographic stream starts with the designer who generates the input information on the topography for each mask level and stores the information using a program such as XYMASK. The information thus generated is not suitable for direct use in making artwork, so a post-processor is used to modify data and make it compatible with a specific artwork-generating system. After the processing and, if necessary, recycling to eliminate errors, the output data can be used to drive the artwork-generating equipment.

After the artwork is generated, a series of photo-reductions are performed and, if required, an array of images is produced using a step-and-repeat camera to produce the master photo mask. From this master, working copies are generated, the specific process depending on the ultimate need. Working copies can be emulsion or chrome on glass for semiconductor circuits, or emulsion on glass or transparent plastic for thin-film applications.

In parallel with the topographic information, descriptive information is also required. The descriptive information includes the tone of

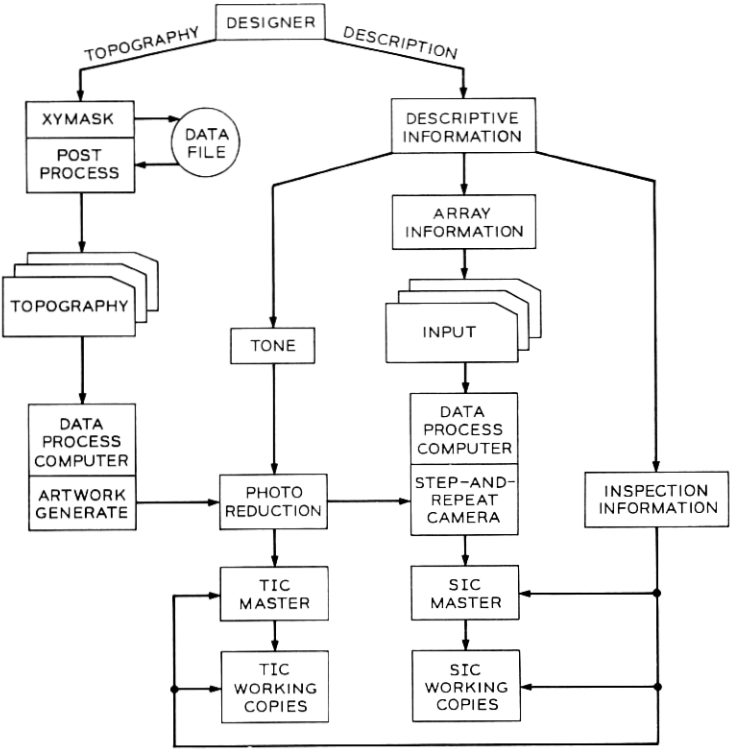

Fig. 1—Schematic of the mask-making process.

the mask; that is, are there clear features on an opaque background or are there opaque features on a clear background? The tone is established by the specific process to be used for delineating the pattern in the final product. For masks requiring the step-and-repeat operation to generate the array, information concerning the specific pattern of images must be defined and the necessary data generated for producing the array. Finally, the descriptive information must include drawing numbers, tolerances, and critical features to be used as inspection points; this information relates to the final inspection of the master and working copies. The descriptive information is as critical in mask making as the topographic information. Because of the combined topographic and descriptive information paths and the complex of processes, management of a mask-making laboratory is a very important part of the system.

As device complexity has increased, with a consequent increase in the amount of data required to describe the topography of an image, computer-controlled artwork generators have been developed. Two distinct types of artwork-generating equipment have evolved. The first are mechanical systems, such as a coordinatograph, the Gerber,* or a mechanical reticle generator which operates by moving a generating head on a mechanical XY stage or moving the recording medium past a fixed optical head. The second type uses an electron beam and camera to generate the artwork.

The mechanical systems which generate the artwork feature-by-feature have a potential address structure that is not fully utilizable because of errors in the mechanical systems. In general, however, they can be operated reproducibly with 6000 addresses in the X and Y directions. Because of the nature of the mechanical motion, the time required to produce a given piece of artwork is sensitive to both the complexity and the size of the feature.

An example of the use of an electron beam and camera system is the SC 4020.† This system is capable of generating a pattern at electronic speeds by moving an electron beam over a cathode ray tube and photographing the image. It produces a mask rapidly but the address structure is limited and, as a consequence, it can only be used for low-precision artwork generation.

After the artwork is generated it is, in general, reduced in size. Typical reduction cameras for both silicon and thin-film circuitry produce images that are reduced by a factor of from 10 to 30 from the original artwork. These cameras are all physically large and require high-quality lenses to minimize distortion. At this step the master mask for thin-film applications is produced. Working copies for device processing are generated by contact printing.

For silicon integrated circuits the image produced by the reduction camera is typically ten times the final size. The final reduction and the fabrication of the circuit array is done on a step-and-repeat camera. Because of the complexity of the array, in terms of the variety of images to be produced, the cameras are computer controlled. For a typical mask the primary interest is, of course, the formation of an array of precisely placed images of the primary pattern that is required for the fabrication of the working device. In addition, however, special patterns such as test patterns for checking processing and alignment features are also

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* Gerber Scientific Instruments Company, South Windsor, Connecticut.

† Stromberg Data Graphics, San Diego; California.

required. Since a typical semiconductor integrated circuit requires from nine to twelve mask levels to complete the device fabrication, the step-and-repeat camera must provide not only for the final optical reduction but also for the precisely controlled and reproducible positioning of the images so that registration from one mask to another in the set is achieved. In the past step-and-repeat cameras could place an image with a reproducibility of ±1.5 μm. However, the errors in the mechanical drive and position-sensing systems made absolute positioning considerably less accurate.

III. MASK-MAKING PRECISION, STANDARDS, AND CAPACITY

With this background of the mask-making process and the then-available equipment to produce the mask, the changing complexity, as measured by the number of coordinates required to describe the image of the masks for both silicon and thin-film circuits, has had a major impact on the capability of mask-making systems to meet the demands. Projection of our future needs for integrated-circuit masks suggested that we will have to provide for: (*i*) a minimum feature size five thousand times smaller in linear dimension than the over-all size of the circuit pattern; (*ii*) incremental sizes of about one-fifth of this minimum feature size; (*iii*) reproducibility of about one part in 25,000; and (*iv*) absolute accuracy of about one part in 10,000 (both reproducibility and accuracy being referred to the over-all size of the pattern). Examination of the state of the art of lens design suggested that cameras could be built to be consistent with these needs, provided that we adopted a set of standard mask formats and that we designed lenses and cameras for each standard field size and reduction ratio.[1]

Such a set of standards has been chosen (Table I). They provide for large thin-film circuits with a nominal field size of 12.5 cm and a smaller format, 5 cm, which both provides for medium-sized thin-

TABLE I—STANDARD MASK SIZES

Principal Function	Field Size	Minimum Line Width	Address Size
Thin-film circuits	12.5 cm 5.0 cm 2.5 cm	25 μm 10 μm 5 μm	5 μm 2 μm 1 μm
Semiconductor circuits	5.0 mm	1 μm	0.2 μm

film circuits and serves as an intermediate step in semiconductor-mask fabrication. A third standard may become necessary for small, fine-lined, thin-film masks and appropriate values are listed in Table I. Semiconductor integrated circuits seem likely to remain under 5 mm square, and a single standard field for a step-and-repeat camera is sufficient. This set of standards embodies (*i*) a decision to "go metric" in device design, (*ii*) a compromise between design flexibility and the capital cost of equipment, and (*iii*) a preference that the address units, which quantize internal device dimensions, be such that large integral multiples be immediately identifiable.

In the same period of time in which the growth in the complexity of mask patterns has occurred there has been a parallel increase in the demand for numbers of masks. This growth has been the direct result of a need for larger numbers of masks to fabricate a given device coupled with an increase in the number of designs. To illustrate this growth of demand, information has been collected from a variety of Bell Laboratories groups covering the period from 1966 to the present and estimating the needs for the early 1970s. The results are shown in Fig. 2.

The growth in demand for silicon integrated circuits, SIC, from 1966 through 1969 has been nearly exponential and has been in part inhibited by our inability to produce sufficient quantities of masks. Because of the increased numbers of people designing integrated circuits, the growth will continue to be slightly greater than linear during the early 1970s. Thus, somewhere between 7,500 and 8,000 pieces of artwork per year will be required by 1972 or 1973.

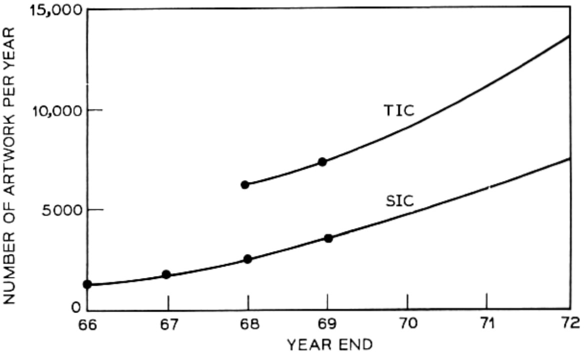

Fig. 2—Growth in demand for artwork for silicon and thin-film integrated circuits.

Because the silicon integrated circuit and thin-film circuits are intimately connected in design, it can be expected that the need for thin-film masks, TIC, will also rise during the early 1970s as shown in Fig. 2. In part, this growth represents the need for increasing numbers of masks for crossovers and tantalum circuits that are combinations of resistors, capacitors, and crossovers.

If we take the composite of these two trends, we find that development activities will require that approximately 14,000 pieces of artwork be generated per year by 1972. To meet this demand, it was decided to build two mask-making laboratories, one at the Murray Hill, New Jersey, location and one at the Allentown, Pennsylvania, location. Each laboratory was to have a master mask capacity of 10,000 per year.

IV. CHOICE OF PATTERN GENERATOR

Pattern generation is a key element in the total process of maskmaking in the sense that the difficulty of meeting the many demands placed on this step is so great that the adjacent steps of the process must largely be tailored to the choice of pattern generator. The overall process resulting from each plausible choice of pattern generator design must then be evaluated before a final system choice is made.

The nature of the problem logically requires relative motion in two dimensions between a writing element and a recording medium. The functional requirements which have been discussed in the previous section suggest a digitally controlled plotter having resolution corresponding to 25,000 by 25,000 address points in the pattern field and a plotting time for the more complex patterns of about 10 minutes.

Reviewing the pattern generators which have previously been used, we first have machines such as automatic coordinatographs and automatic drafting machines with optical exposure heads. A machine of this type could be designed to give the desired resolution. The plotting time for complex patterns on such machines has already exceeded ten hours. Another approach is the reticle generator which makes a set of elementary figures available from which every mask will be assembled. We have not found any set of figures which offer sufficient speed and flexibility.

The following three approaches to pattern generation appear to have sufficient resolution, accuracy and speed to meet our requirements: drum recording, electron-beam recording and light deflection. Each is discussed in turn.

4.1 *Drum Recording*

In the drum recorder the recording medium is wrapped around a cylinder as shown in Fig. 3. The two dimensions of motion are now achieved by synchronizing the rotation of the drum and translation of either the drum or writing head parallel to the axis of rotation. If we insist on a system capable of writing on various areas of the recording medium in an arbitrary sequence (random access), this system offers no advantage over a flat-bed plotter; however, it does make it possible to create any pattern by continuous rotation of the drum and a synchronized translation. After unwrapping the recording medium, the image would appear as though it had been created by a TV-like raster. It is this concept of a uniformly swept raster which makes a mechanically scanned system feasible.

This pattern generator could be engineered within a relatively wide range of sizes, tolerances on the precision of the translational mechanism, on the concentricity of the drum, and on the thickness of the recording medium becoming increasingly tight in smaller machine sizes. A 12.5-cm pattern size would be possible, while a 25-cm size unit would be relatively simple to develop. The primary problem in

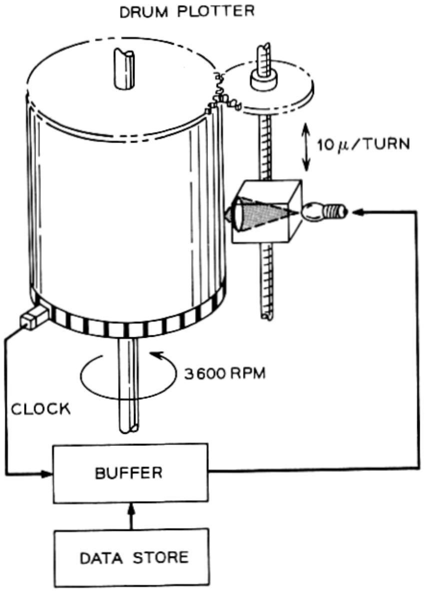

Fig. 3—Schematic of a drum plotter.

this approach is that the recording medium must be flexible. The combination of a silver halide emulsion on a film base does not have sufficient dimensional stability for our purposes. An alternative which was considered was laser machining some appropriate coating from a metal based multi-layer medium. Brief experiments suggested that such a medium would not be easy to handle and, being opaque, would have to be used in front-lighted reduction cameras. Such cameras are inefficient and the drum approach was dropped from further consideration.

4.2 *Electron Beam Recording*

An electron beam machine in which a finely focussed beam writes directly on a recording medium of appropriate resolution and sensitivity is a probable approach to pattern generation. An electron beam recorder can be designed for a beam size of a few microns and a field of several centimeters.[2] Choice of a 5-cm field allows direct generation of one standard format and allows the other standard sizes to be produced in cameras using glass condenser illumination. Pattern description for this system is a simple extension of previous work for cathode ray tube systems. This technique seems to offer system compatibility; the major uncertainties which existed at the time at which a selection had to be made (November 1967) were whether the desired accuracy could be obtained, and whether the sensitivity of electron beam systems to unwanted electric and magnetic fields would limit its reproducibility. These uncertainties were sufficiently great that this approach was not chosen for our initial system, but development work was continued to provide a compatible system which might be advantageous for future large-area devices such as color and document-mode *Picturephone®* camera tubes and magnetic domain devices. This machine is described in a companion paper.[2]

4.3 *Light Deflection*

Of the three approaches, only deflection of a light beam seemed capable of meeting our anticipated requirements. Since the combination of plotting time and number of resolvable elementary areas in the pattern field requires exposure times of less than one microsecond per resolvable area, the use of a laser beam to achieve a small, very bright writing spot was indicated. Deflection of a laser beam can be accomplished by electro-optic or acousto-optic elements, but available deflector materials were not of sufficient quality to give plotting times less than one or two hours. Reflection from a spinning mirror, however, can give speeds up to and beyond those required as long as we accept a uniformly rotating mirror as the basis for our system. This led to a rotating-mirror pattern generator design where a modulated light beam would be swept across a photographic plate in one direction at a rate of about 50 scans per second, while the plate holder would move in the direction perpendicular to the scan lines. In less than ten minutes 25,000 overlapping scan lines could build up the complete pattern image. Again, in this system, we have employed continuous rotation of the higher-speed scanning member to achieve the desired plotting rate in a mechanical system. Implementing this approach requires that a lens be mounted adjacent to the rotating mirror, a diverging input beam being collimated by the lens and refocussed onto the recording medium after reflection. Because of the inverse relationship between the aperture of a lens and the diameter of the smallest spot which the lens can image and because the field angle for which a lens can be designed is sensitive to the relative aperture size, the lens and mirror sizes enlarge rapidly as the desired pattern size is diminished.[3] Specifically, the design appears impracticable at the largest standard pattern size of Table I and relatively easy at a 25-cm pattern size. Thus, the initial pattern size for this machine design is rather firmly bounded by optical-design considerations on the one hand and by considerations of plate size, governing the size of both processing equipment and reduction cameras, on the other. 8 by 10 inch photographic plates are commercially available and, in ¼ inch thickness, can be obtained with sufficient flatness. Translating to metric units gives a maximum usable area of about 13.8 cm by 23.4 cm. This puts an upper bound of 7.3 μm on the address unit size, and 7.0 μm seems a reasonable value. A review of the optical design based on this value led to reasonable sizes for the individual components and for the over-all machine.

Pattern description for the primary pattern generator (PPG) requires that the topographical data be sorted into a sequence controlled by the directions of scan, and presented to the generator at a predetermined rate. These are novel requirements relative to our experience in computer aids to mask-making.[4] While the sorting operation requires large files in the off-line data-processing system, the operation is not a costly one. A larger problem is created by the need to present data to the generator from its on-line controlled computer at a predetermined rate of about 2 million bits per second. The strategy used to meet this demand is such that most of the core memory is required for storage of coded data describing the current scan line and the changes required to go from the current line to those immediately following, and thus all characteristics of features, particularly where they include slant and curved edges, have to be computed off-line and coded for transfer by means of a magnetic tape. At this time this is a significant disadvantage in the choice of the PPG as opposed to a random-access generator such as the electron beam machine.

The characteristics of the PPG previously discussed determine the design requirements which it must meet. With reference to Table I, it is evident that for thin-film circuits optical reduction of the image plate from the PPG is required. A reduction camera that reduces the image 1.4 times is required for the bulk of the thin-film circuits that have a minimum line width of 25 μm. A second camera with a 3.5 reduction ratio is also required for 10 micrometer minimum lines on a smaller field. This camera is also used for silicon integrated circuits. A third reduction camera for 5-μm lines may be required in the future if 5-mm lines are required on small areas. Conventional glass condenser systems are not practical for these cameras, and large area diffuse sources with Fresnel lens condenser systems are used to meet our requirements.[5] The cameras have been designed with no operator adjustments for either reduction ratio or focus.

For silicon integrated circuits the image produced by the 3.5× reduction camera is used as the reticle in the step-and-repeat camera which provides an additional 10-times reduction.[6] The step-and-repeat camera, in addition, generates an array of images—each with a 5-mm maximum field size and a maximum array size of 10 cm by 10 cm.

V. SYSTEM DESIGN

In completing our account of the new mask-making system, we should recognize that not all devices are square. Many thin-film integrated circuits are rectangular. As long as a camera is to be used to image a rectangular pattern, the diagonal measure of the pattern is a dominant consideration. It is not necessary, however, to compound this penalty by fitting a square pattern field within the circular field of the cameras and then constraining a rectangular pattern to lie within the square. Thus the field of the pattern generator was enlarged from 25,000 address units square to 32,000 units (22.4 cm) and, at the same time we enlarged the width to 26,000 units (18.2 cm) since the space was available.

Fiducial marks which provide for registration of patterns in the step-and-repeat camera are plotted in the corners of the 32,000- by 26,000-unit rectangle. In addition, the pattern generator writes two strips of system data, one above and one below the rectangle. The first strip shows the identification number of the particular pattern generator used and the sequence number in octal form. The second strip contains the drawing number of the pattern in three forms. One is the normal form for the direct use of mask shop operators, but in addition the number is repeated in two binary-coded formats suitable for machine reading. One is designed to be read when the pattern generator plate is in the reduction camera and the other to be imaged by the 5-cm field-reduction camera and read when the resulting reticle is in the step-and-repeat camera.

These provisions for machine reading of the drawing number are part of a supervisory and scheduling system known as the Mask Shop Information System (MSIS).[7] Earlier experience with mask-making laboratories of more modest capacity than our 10,000 per year objective taught us that the scheduling system can be the factor determining the time to complete a job. The equipment design which has been outlined here and which will be detailed in the following papers can therefore shorten the time to complete a job only if we add a system for storage and rapid retrieval of all the data required to make and inspect the masks and keep the necessary records. Scheduling each phase of each job is included; as each step after pattern generation is due, the MSIS displays to the camera operator the drawing number of the pattern generator plate or reticle and the location of that plate in the physical storage trays provided. The system then reads the plate number and advises the operator if an error has been made. At the step-and-repeat stage, all data describing the step-and-repeat array is fed to the on-line control computer.[6]

VI. SYSTEM APPRAISAL

While we have not yet had sufficient experience with MSIS, nor with a level of demand for masks which would have fully exercised MSIS, we can make a preliminary appraisal of the remainder of the system.

The PPG has accomplished essentially everything we set out to do. For the first time in many years, artwork generation is no longer the pacing item in mask making; we have a machine which takes simple patterns or patterns of a complexity we would not previously have attempted, makes patterns in which 10 percent of the area is exposed or patterns in which 90 percent is exposed, semiconductor device patterns, thin-film patterns, test patterns—and even digitized photographs—and turns them out with inhuman regularity. While the optical-design pattern bound us into a very narrow size range, the resulting machine is the right size for the operator's convenience. This is not to say that there is no room for further improvement in the area of artwork generation. We see future device applications in which the higher resolution offered by an electron beam machine could be of major importance, sufficient to justify incorporating such a unit—compatible with the PPG system standards in format and plate size—into the mask-making laboratories.

Turning to the reduction cameras, we feel that the basic system decisions which were made—separate fixed cameras using Fresnel condenser illumination with monochromatic light—were sound. We do believe that further improvements in system performance might be obtained through achieving closer tolerances in lens fabrication; essentially the state of the art of lens design has run ahead of lens assembly techniques. This comment applies even more strongly to lenses, such as the one for the step-and-repeat camera, which are aimed at feature sizes of a few wavelengths of light. The step-and-repeat camera lens proved extremely difficult to build, and appears to have distortion of about one part in 5,000 arising from fabrication tolerances; we would argue that paper designs of lenses of higher performance—perhaps seeking comparable resolutions over a larger field—should be held suspect until actual models are built and tested.

The new step-and-repeat camera is a development of a different kind from most of the other parts of this program. No single characteristic of this unit shows an order of magnitude improvement over earlier equipment, nor does it contain conceptually new major elements. The improvements which have been made, factors of two or three in smallest feature width, in linear field dimensions, in linear array dimensions, and in speed, are cumulative in their impact and are essential to the satisfaction of our anticipated needs.

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