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Two Interconnection Techniques for Large-Scale Circuit Integration

Abstract: Studies of the feasibility of custom-interconnected, large-scale integrated circuits required the development of means for converting computer-generated wiring instructions into metallic conductors on a semiconductor wafer. The resulting equipment took two forms. In one, ultraviolet light serves to expose phctoresists on a mechanically translated wafer; the other employs an electron beam. Both systems were adequate to produce two-mil-wide conductors, but differ in their potential for achieving high production rates or very thin lines.

Introduction

An investigation of the feasibility of using computer-generated instructions to interconnect semiconductor structures into large-scale integrated circuits recently occasioned the development of systems capable of giving those instructions a physical embodiment.[1,2] Although production speed was not critical in that study, it was decided to confine attention to techniques having some reasonable potential for use in production.

• *Performance requirements*

The interconnection equipment was required to accept instructions on magnetic tapes and to generate from them two-mil-wide conductors placed in street-and-avenue fashion over the surface of a 1¼-inch silicon wafer. An absolute accuracy of better than ±0.5 mil was required, and it was expected that future work would call for line widths of 0.5 mil and a positional accuracy of 0.1 mil. Initial speeds up to 0.2 inch/sec were needed and potential speeds up to 2 inch/sec were to be anticipated. Further, since a wafer made ready for interconnection represents considerable processing effort and computer time, it was essential that the yield from the interconnection process be extremely high.

• *Possible approaches*

The interconnection operations we considered center about a material process whose stages are (**a**) evaporating 1 micron of aluminum over a wafer already containing tested circuit elements, (**b**) coating that wafer with photoresist, (**c**) exposing the photoresist under programmed control, and (**d**) conventional development of the resist image and, subsequently, etching away the unwanted metal.

It was assumed from the first that it would be impractical to employ nonmechanical exposure systems using either cathode-ray-tube or direct-electron-beam exposure of a stationary wafer, the reason being that to achieve the absolute deflection accuracy that is necessary (1 part in 3000, initially) would demand a marked advance in the technology of beam deflection. Although an interesting CRT system has been developed by Lathrop,[3] one using a fiber-optics faceplate to improve the optical efficiency, to use a CRT system would yet require inclusion of an intermediate photographic mask to reduce the exposure time to a reasonable level. Hence, such a scheme could increase the cost significantly, and cause the yield to be reduced by flaws in the phosphor, the optical system, and the photographic plate. As another alternative, mechanically scanned optical systems using rotating mirrors were rejected because of their complexity, programming difficulties, and depth of focus limitations.

In the two systems built, wafers are translated under the energy-source while attached to a table driven by stepping motors so as to carry out programmed X–Y movement. During translation the photoresist is exposed either by ultraviolet light or an electron beam. Both systems proved well able to meet initial specifications, but differ considerably with respect to their complexity and their potential for further development.

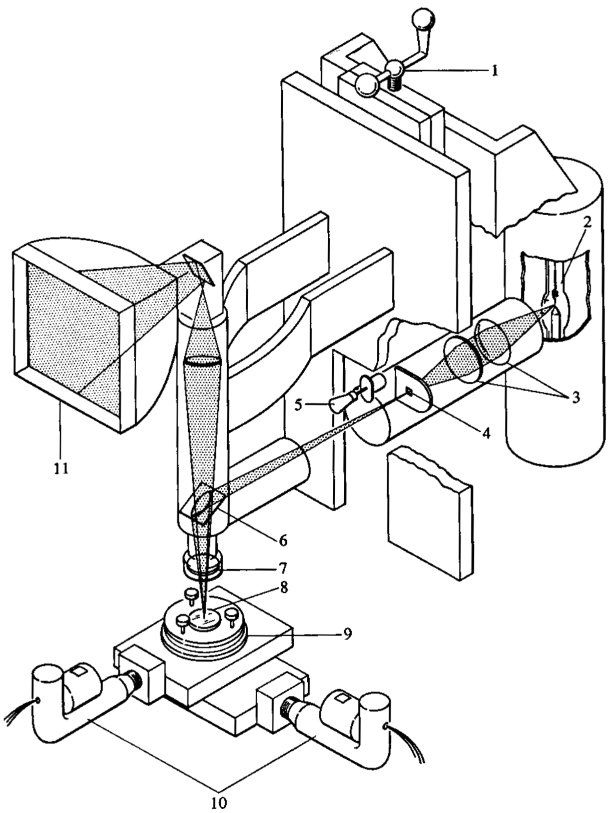


Figure 1 The optical exposure system with elements identified: **1**—focusing adjustment; **2**—ultraviolet lamp; **3**—condensing lens system; **4**—square aperture; **5**—tape-controlled shutter; **6**—beam splitter; **7**—lens; **8**—wafer; **9**—adjustable support assembly (with vacuum chuck); **10**—tape-controlled X–Y stepping actuators; **11**—viewing screen.

The principal advantage of the electron beam system is that of exposure speed. Using current electron-optical technology to expose one-mil-wide lines on KTFR photoresist allows speeds of 500 inch/sec to be obtained. An additional advantage follows from the fact that the convergence angle for an electron beam forming a 1-mil-diameter spot is typically 10^{-2} radians and the resulting depth of focus for a $\pm 10\%$ change in spot size is ± 10 mils, which is large enough to preclude any problems from wafer distortion or variations in wafer thickness. It is expected that in future work, the diameter of the electron beam can easily be reduced to less than 1 micron while retaining a depth of focus of several mils. In a corresponding optical system, the combined effect of the diffraction limit and the very limited depth of focus would make it extremely difficult to maintain adequate line-width control over the expanse of a wafer. Some incidental advantages of electron-beam techniques are the ability to program the beam diameter and current, to deflect the beam over small distances with great accuracy, and to operate within a clean environment.

Although lacking the speed potential of the electron beam system, the optical system admits quite reasonable absolute speeds (say, 5 inch/sec) and can be given a greater effective speed by employing a relatively simple parallel exposure system. Further, the fact that the optical system is free from vacuum-access delays may also mitigate the speed differential between the two systems. In first cost and complexity, the optical equipment has a marked advantage over the electron beam system. That irradiation effects are absent from the optical system may also prove a point in its favor; nonetheless, work to date with the electron system has been completely free of trouble from that source.

The data channel

Both the optical and the electron-optical exposure systems receive their inputs from identical data channels. The computer output tape (a standard 200-bpi tape) is read by an IBM 7702 incremental tape unit* at speeds up to 300 6-bit characters/sec. Three 6-bit characters are read for each instruction. Of these, four bits of the first character provide beam control (on or off), motor selection (X or Y), motor direction, and a stop code specifying the end of a run. The last two bits of the first character are available for such accessory functions as control of line-width or generation of a diagonal line. The second and third characters of an instruction carry the required line length (in mils) against which the stepping motor count is matched.

The optical exposure system†

The optical exposure system is shown schematically in Fig. 1 and in the photograph of Fig. 2. The light source is a compact, high-pressure 100-watt mercury lamp whose arc is imaged by a quartz condensing lens system onto a square-hole metal aperture. (The position of the condensing lens is adjusted so that the aperture opening is uniformly illuminated.) An electromechanical shutter is located in front of the aperture to interrupt the light beam. Upon command, the shutter opens or closes with a response time in the order of 4 to 5 msec. The shuttered beam is then reflected from a 90-percent reflective mirror down through a $10\times$ microscope objective and focussed onto the photoresist-coated specimen. Simultaneously, some reflected light from the wafer returns upward through the objective lens, through the mirror, and through an eye-piece onto a viewing screen. The image of aperture is thus reduced to $\frac{1}{10}$ of its actual size. The light spot and wafer detail (that is, the circuit elements) could be seen on the view screen at $200\times$, a magnification allowing accurate registration between the structure of the specimen and the support and its coordinate system, as will be discussed below.

* The incremental feature means that, when required, each character is called, independently and without tape-acceleration delays, from a small (48-bits) auxiliary memory in the unit.
† This work reported by A. E. Brennemann.

Figure 2 Optical exposure system.

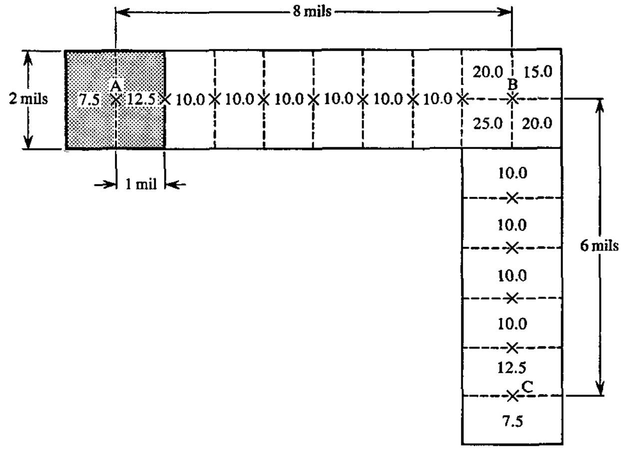


Figure 3 Schedule for line scan exposure.

The minimum line-width of interconnections is changed manually by substituting another aperture of a different size. An aperture size of 20 × 20 mils is used to produce a light spot of 2 × 2 mils on the wafer surface and thus to produce a 2-mil-wide interconnecting line within the photoresist. The X–Y positioning table that supports and moves the specimen under the beam is diagrammed in Fig. 1 and the microscope projecting system and the X–Y table are shown photographically in Fig. 2. The X–Y table is supported and guided by two cross-mounted ball-rod type slides. The driving mechanism employs a precision lead screw whose nut is attached to the movable slide; the screw itself is driven from a precision gear reducer connected to a pulsed stepping motor. A summary of performance data is offered in Table 1.

• *Forming the interconnection pattern*

After the wafer has been metallized, the entire surface is coated with photoresist,* and the final pattern is formed in two steps. First the circuit areas are exposed to ultraviolet light through a glass photographic-mask pattern. This step is performed on standard equipment commonly used in integrated circuit technology. Second, the patterns for interconnections and input-output terminals are formed through the use of the programmed light beam system.

To begin this second step, the wafer is mounted on the vacuum chuck of the light beam system. The wafer surface is viewed in the microscope view-screen with a yellow filter (5500Å) inserted in front of the source, permitting the wafer to be visually aligned for orthogonality and correct focus without exposing the resist. At the same time, the 2 × 2 mil light spot is accurately indexed to the starting point of the interconnection program with a tolerance of better than ±0.5 mils. When all adjustments have been made, the shutter is closed and the yellow filter is removed. Control of the shutter and the table is transferred to the tape unit, and the program is started.

The X–Y table moves the wafer under the light beam, exposing only those areas where interconnection lines and terminal pads are required. At the completion of the program the resist image is developed in the conventional way. A typical resist pattern is shown in Figures 4 and 5 before the aluminum has been etched. The periodic array of patterns in the circuit areas of Figure 4 are those formed with use of the photographic mask, while the interconnecting lines and terminal areas are those formed with the programmed light beam system. Figure 5 is an enlarged photograph of a circuit area of Figure 4 showing the light-beam generated interconnection lines.

Table 1 Mechanical characteristics of the optical exposure system.

X–Y table travel	2 inches × 2 inches
Linear table speed	0.200 inch/sec (both axes)
Positioning accuracy (measured)	±0.25 mil on a 1-mil grid over area of 1 × 1 inches
Backlash	~0.1 mil
Pitch of lead screw	20 turns/inch
Lead screw accuracy	Lead error is 0.08 mil/inch with a no-back-lash fit.
Rotation of motor	90 degrees per step
Gear reduction	12.5 to 1

* The photoresist used in this experiment was Kodak Thin Film Resist (KTFR).[4] A 3000 Å thick layer of resist was applied and sensitized on the aluminized wafer by standard techniques in preparation for exposure to the light beam. The spectral range of absorption for polymerizing the resist is about 3500 Å to 4400 Å, with a maximum at 4100 Å. A strong line existing at about 4050 Å in the mercury arc spectrum is particularly useful for exposing this resist.

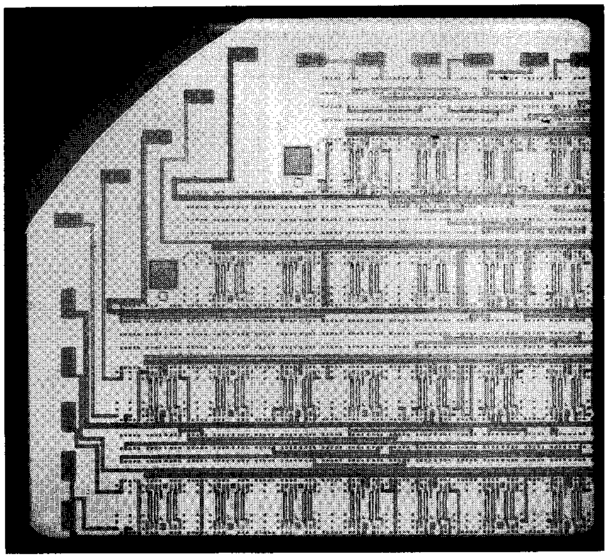


Figure 4 Part of an optically interconnected wafer.

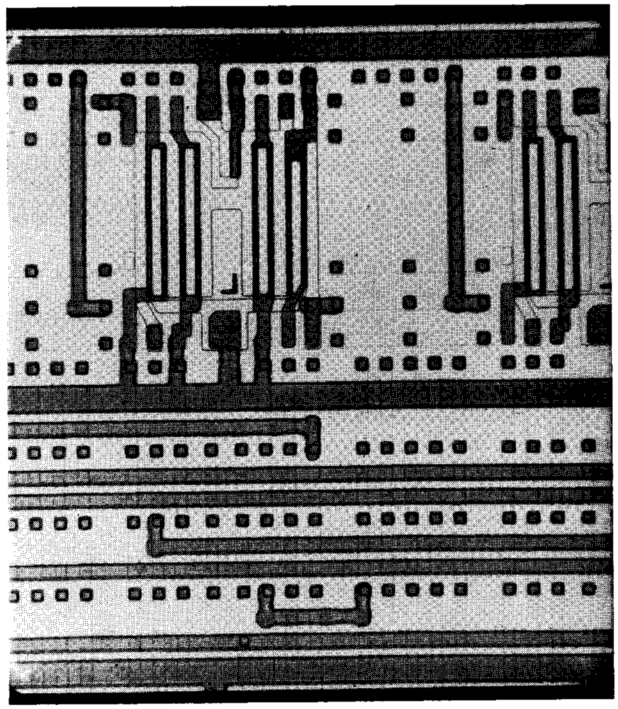


Figure 5 Detail of optically generated conductors.

The final circuit pattern is formed by removing the excess aluminum with a phosphoric acid etchant and removing the residual resist.

• *The exposure routine*

The optical system we have described allows interconnection lines to be exposed in several different ways. The method described in this work was used because of its simplicity. In its basic form it comprised the following steps:

First: Turn on the light beam and pause.
Next: Move the X–Y table under the beam at constant speed for the length of line required.
Next: Stop the table motion and pause.
Then: Turn off the light beam.

Figure 3 illustrates in detail how this routine would be used to expose two orthogonal 2-mil wide lines: one line measuring 8 mils from A to B and the other measuring 6 mils from B to C. In Fig. 3 the numbers shown within the incremental areas of the lines give the approximate exposure times that these areas receive for an X–Y table motion of 200 mils per second. Prior to the start of that exposure routine, the electronic system would have received commands from a program to expose an 8 mil long line from A to B.

The routine begins as the shutter in front of the light beam opens and exposes the 2-mil-square area centered around A for a period of about 7.5 msec. After this exposure the light beam remains stationary and the table begins to move to the left in 1-mil increments at 200 increments per second. Its velocity is essentially constant. Except at the extremities of the line, each area receives an average exposure of about 10 msec. After traversing 8 increments the table is stopped at B, after which the shutter remains open for an additional 7.5 milliseconds before it closes.

It can be seen that no exposure would occur at the line extremities if the shutter opened and closed exactly with the beginning and end of table motion. Hence, the delay periods are necessary to insure adequate exposure in areas at A and B. However, because of that necessity, non-uniform exposure occurs within the incremental squares at A and B. The exposure times are from 7.5 to 12.5 msec in these areas. It is this variation which accounts for the irregular interconnection line terminations seen in Figures 4 and 5.

The line from B to C is formed in the same manner through the execution of another set of commands from the program. The area around B receives additional exposure, as described above, before the table is moved to C. Thus the incremental area around B is doubly exposed with accumulated exposure times ranging from 15 to 25 msec. As before, this non-uniform exposure accounts for the irregularities at the junction of the two interconnecting lines seen in Figures 4 and 5.

In Figs. 4 and 5, the entire expanse of interconnecting line patterns as well as the input-output terminal patterns were formed by the described routine. The exposures were adequate to polymerize the photoresist and all the tolerances were within the ± 0.5 mil limit required.

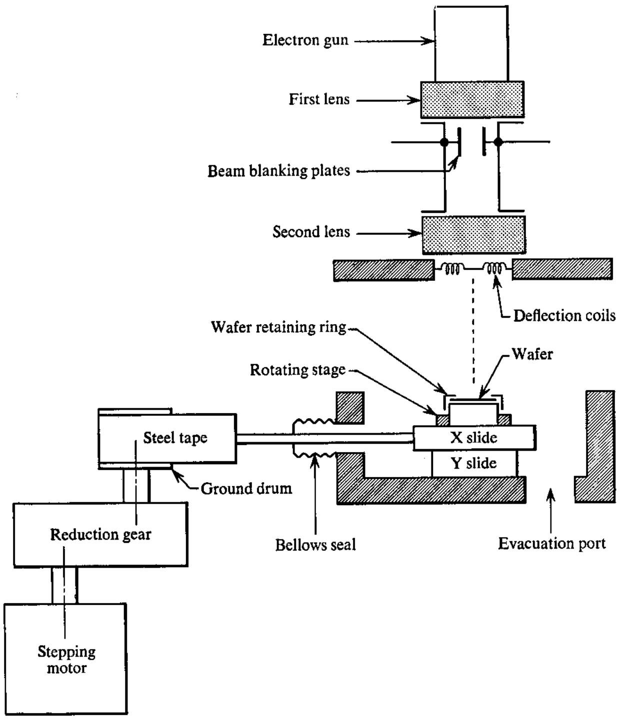


Figure 6 Schematic of the electron beam system.

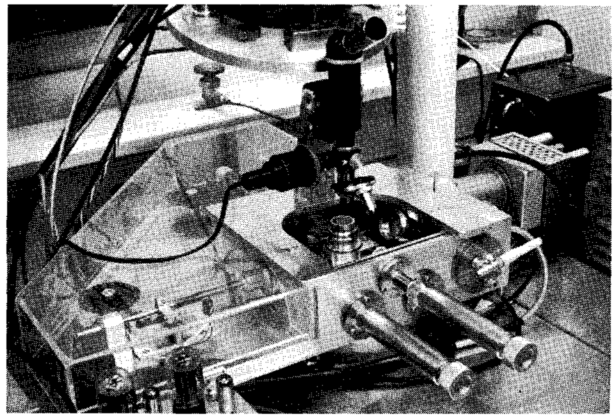


Figure 7 Electron beam stage with optical microscope.

The electron-beam system*

The electron-beam system is shown schematically in Fig. 6 and photographically in Fig. 7. The beam-forming portion of the system employs an electron microscope gun and two magnetic lenses to produce focussed spots down to 1 micron in diameter.[5] The large 2-mil spot used for the interconnection operation is obtained by defocussing the 1-micron spot after the registration operation has been completed. Although defocussing involves a sacrifice of over three orders of magnitude in electron intensity, the intensity remaining is more than adequate for the speed required (0.2 inch/sec).

The mechanical drive uses stepping motors, coupled through precision reduction gearing, to rotate a steel drum. A steel tape anchored to the drum surface converts the peripheral movement into a true linear motion which is transmitted to the stage via a bellows-type vacuum seal. To eliminate backlash effects, a unidirectional stress is maintained on the tape and all members of the gear train by springs attached to the stage. The total inertia of the system is dominated by the motors, which can therefore be operated at speeds close to their no-load ratings. Performance data for the mechanical system are given in Table 2. The system was evacuated by a conventional 4-inch oil diffusion pump to a pressure of 10^{-5} Torr. No cold traps were employed.

* This work reported by Brown, Hatzakis, Speth, and Thornley.

- *Preparation and registration*

As the first step in preparation, the aluminum coated wafers are immersed in a 10-percent solution of potassium dichromate at 65°C for 3 minutes, this being done to improve the adhesion of the resist.* After rinsing, the wafers are dried at 50°C and spin-coated at 7000 rpm with KTFR diluted 1:1 with KMER thinner, forming a film having a thickness of 3000 Å. The operations following the dichromate dip are performed in a positive-pressure dust hood. The resist-coated wafers are then placed, without prebaking, in the vacuum system where they are to be exposed.

Subsequent to metallization and the application of photoresist, the wafer is placed on a rotating mount on the X–Y stage, Fig. 6. An optical microscope is mounted over the stage and one table-drive motor is excited to move the wafer over a (nominal) 1-inch range while the wafer detail is viewed, Fig. 7. Wafer rotation provides adjustment of the orthogonality of the circuit detail with respect to the X–Y axes; this adjustment is rapid and introduces negligible error. After adjustment, the stage is moved to bring the reference detail (Fig. 8) into the optical field. (This detail is very near the edge of the wafer; its format is designed to obviate rotational ambiguity and to provide good contrast for the subsequent electron-optical detection.) The distances (X and Y coordinates) between the preassigned wafer-program start point and the location of the microscope cross hairs on the reference detail are noted. The electron column is lowered, evacuated, and set up to scan the reference detail with a nominal 1-micron beam having the current (5×10^{-8}A) required for the actual line exposure. The secondary emission signal obtained from the reference detail is displayed as a brightness modulation on a cathode ray

* Evaluation of standard commercial negative photoresists [6] had indicated that KTFR was the most satisfactory, for our purpose, both with respect to exposure latitude and to the quality of the etched patterns.

Table 2 Mechanical characteristics of the electron beam exposure system.

X–Y table travel	2 inches × 2 inches
Linear table speed	0.200 inch/sec (normal) 0.35 inch/sec (max)
Positioning accuracy	±0.5 mil absolute over area 2 × 2 inches
Backlash	0.05 mil
Rotation of motor	1.8 degrees per step
Gear reduction	16 to 1

tube scanned in synchronism with the electron beam. The magnification of the reference detail is adjusted by controlling the ratio of the scan amplitudes on the detail and display tube. The electron beam is then statically positioned to the point of the reference detail at which the cross hairs intersected in the earlier optical measurement. To complete the process of registration, the table is then moved through the previously noted distance. The referencing operation is accurate to 0.1 mil.

• *Electron-beam exposure*

After registration is completed, the beam focus is changed to provide the required 2-mil resist image and the apparatus is now ready to begin tape controlled exposure. The operation employs a 2-mil diameter, 14-kV beam, carrying a current of 5×10^{-8}A. It proceeds linearly, in straightforward fashion, at a writing speed of 0.2 inch/sec. Afterward, the exposed image is developed in a mixture of toluene, xylene, and benzene (3:3:1 by volume) without agitation for 3 minutes, sprayed with xylene for ½ minute and rinsed in de-ionized water for 5 minutes. The excess water is spun off and the wafer is post-baked at 130°C for 30 minutes. Then the aluminum is etched in 20% sodium hydroxide at 44°C, rinsed and spun dry. The final operation of stripping the resist is accomplished by immersing the wafer in J-100 solvent* at 90°C for 4 minutes, after which it is rinsed and spun dry.

Results

Figures 4 and 5 have shown parts of an optically generated interconnection pattern containing lines having widths of 2 mils and 5 mils. The 5-mil lines, which provide power and ground connections for the circuits and the contact areas (*lands* or *pads*), are exposed by repeated passes of a 2-mil light spot on 1-mil centers. The small irregularities, most easily noticed in Fig. 5 at the ends of each straight conductor section, are attributed to starting delays, to overshoots from the stepping motor drive system and, as well, to uneven exposures.

* Indust-Ri-Chem Laboratory, Richardson, Texas.

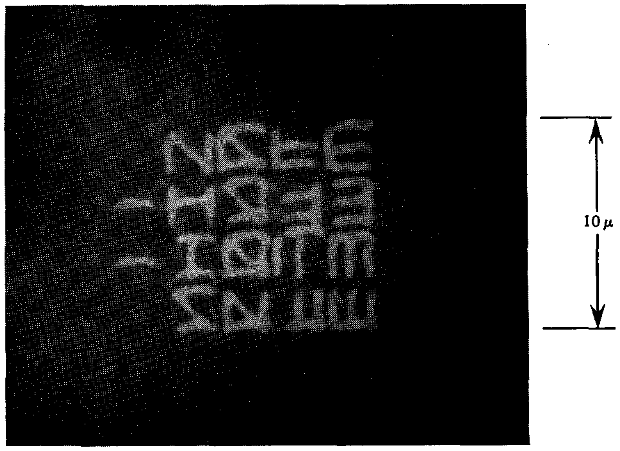
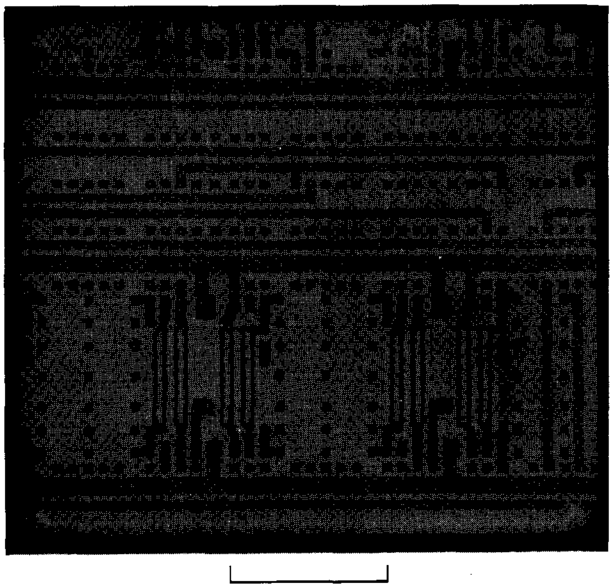


Figure 8 Optical micrograph of electron beam reference detail.

Figure 9 Electron-beam generated conductors.



Overexposure also causes line-width broadening, as can be seen at the beginning and end of certain lines in Fig. 5. The line width is also a function of the reflectivity of the aluminum surface. Thus, for a light-forming aperture of given size, a relatively grainy or milky surface produces a wider line than does a shiny one.

An electron-beam-generated pattern is shown in Fig. 9. This pattern was formed by a two-step process in which an optical mask is used to expose the circuit areas and the intra-circuit detail before the electron beam is used to expose the inter-circuit lines. The reduced amplitude of the line irregularities that are visible here is due to the fact that

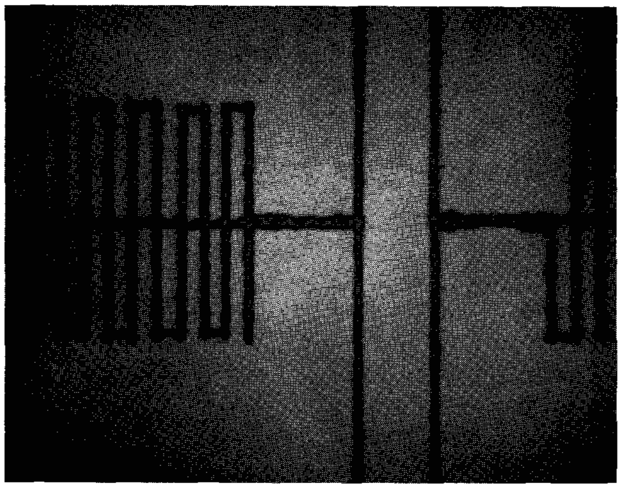


Figure 10 Lines exposed by electron beam. Width = 0.3 mil.

the drive motors employed are not the same as were used in the optical scheme, and due to the speed at which the electron beam can be switched. With lines of this scale, overexposure with electrons does not significantly change the line width (however, overexposure may make it impossible to strip the resist after etching).

Fig. 10 shows contact lands drawn with a 0.3-mil beam moving on 1-mil centers. Variations in line width caused by speed variations are now clearly visible but are not severe enough to threaten the continuity of the line.

For both systems, the running time to interconnect a group of circuits (typically, 48) on a 1¼-inch wafer was about 30 minutes. It is expected that the use of presently available high-speed stepping motors, operating at 2000 steps/sec, would allow the overall processing time per wafer, including registration, to be brought below 5 minutes.

Conclusions

Both the optical and electron beam methods can be used for programmed interconnection lines on integrated circuits. The optical beam method is more suited for producing line widths of about 2 mils and larger. Both methods are satisfactory for producing widths in the range of 2 mils down to 0.2 mils. The electron beam has the advantage for line widths of about 0.2 mils to the submicron region as the optical system becomes diffraction limited in this range.

Each method has its specific advantages over the other when both are considered from a usage standpoint. One advantage of the optical system is that no vacuum system is needed in its operation; another is the absence of possible radiation damage to the integrated circuits being processed. Finally, the equipment is comparatively low cost.

The electron beam has the advantage of being able to produce the smaller line widths that will be needed in future integrated circuits. The electron beam method is also capable of faster exposure speed, thus reducing the time for writing programmed interconnection patterns. The electron beam has a greater depth of focus; therefore the line width is unaffected by small changes in the circuit topology.

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