Microelectronics: Lithographic Technologies Progress

For reasons of economics and performance, it is desirable to miniaturize the microelectronic devices known as integrated circuits to the maximum extent possible. But diffraction of the ultraviolet light used in the photolithographic process that delineates the circuits limits the minimum size of their features. Researchers have speculated for several years that one day the use of beams of electrons to delineate circuit patterns would overcome the diffraction limitation in that the wavelength of the electrons would be only a fraction of an angstrom. While formidable problems have slowed the development of electron beam lithography, some recent advances indicate progress.

Groups led by Hwa Yu, Robert Dennard, and Philip Chang at IBM's Thomas J. Watson Research Center, Yorktown Heights, New York, working together, used a scanning electron beam apparatus controlled by a computer to fabricate an 8192-bit random access memory with an area of 1.8 square millimeters, by far the most complex and densely packed device yet made by this technique. At Bell Laboratories, Murray Hill, New Jersey, researchers under the direction of Donald Herriott have developed a quite different type of scanning electron beam system. This system now routinely produces high-quality masks that are then used in conventional photolithography to determine what locations on an integrated circuit chip are exposed to the ultraviolet light. Finally, research under way in several laboratories on a photolithographic process in which x-rays are used in place of ultraviolet light suggests that the high resolution inherent in the scanning electron beam technique may be combined with the economical aspects of photolithography by using electron beams to produce masks for short wavelength and hence largely undiffracted x-rays.

There is good reason for increasing the degree of miniaturization. Speed of operation is enhanced because electrons have smaller distances to travel. Circuits are more reliable when more components are on a common substrate because wiring between devices is reduced. And the cost per electric function (such as storing a binary bit of information or making a logic decision) decreases because the cost of producing a complex integrated circuit does not differ greatly from that of a simple one. Miniaturization of electronic circuits has already permitted the development of products including accurate long-range missiles and high-speed super computers as well as small inexpensive pocket calculators and digital wristwatches.

At present the transistors, diodes, capacitors, resistors, and interconnections that together comprise an integrated circuit are delineated in a series of steps, one of which is the contact printing process called photolithography. Ultraviolet light shining through a mask carrying a circuit pattern exposes the pattern in a layer of photosensitive organic polymer, or photoresist, on a silicon wafer. When the exposed photoresist is developed, either the exposed (positive resist) or the unexposed (negative resist) regions dissolve. The undissolved resist outlines those areas of the silicon to be subsequently either impregnated with impurity dopants that control its electrical properties or coated with a metallic conductor that interconnects the components of the circuit. Several masks and sequences of such processing operations are needed to make a complete circuit.

The mask itself consists of a glass substrate covered with a photographic emulsion or a harder material, such as chromium, in which the circuit pattern is produced photographically. Depending on the distance between the mask and the silicon wafer during the exposure step, diffraction of the 4000-angstrom ultraviolet light, variations in the wafer flatness, errors incurred in transferring the original pattern to the final mask, accumulations of dirt in the mask, and distortions produced when the mask is pressed against the wafer variously conspire to limit the minimum size of features (usually the width of the metal interconnections) to from 2 to 7 micrometers.

While the minimum size of features that can be exposed photolithographically approaches the resolution of optical microscopes, the same cannot be said for the relation between electron beam pattern generation and electron microscopes. High resolution transmission electron microscopes can resolve features as small as 2 or 3 angstroms and special scanning electron microscopes can resolve a few tens of angstroms, but electron beams cannot be used to delineate such small dimensions. The fundamental limit is given neither by the electron wavelength nor even by the diameter of the electron beam. Instead, electron scattering effects that cause the energetic (10,000 to 25,000 electron volts) electrons effectively to expose a wider area of the electron sensitive resist than that delineated by the incident beam constitute a practical limit to obtaining small dimensions. This scattering phenomenon can be especially troublesome when several features with small dimensions are so closely spaced that the scattering regions overlap, although features as small as 500 angstroms have been produced in the laboratory.

Researchers at IBM did not attempt to utilize the maximum achievable resolution of an electron beam system in fabricating their 8192-bit random access memory (Fig. 1). Instead, the investigators settled for demonstrating that the best available silicon processing technology was compatible with a tenfold increase in the density of components on a chip. They redesigned a circuit that scientists at IBM's Essex Junction, Vermont, facility had earlier fabricated using conventional technology, and scaled down the entire circuit so that the area was reduced by a factor of about 10 with a chip size of 1.1 by 1.6 millimeters and with minimum dimensions of about 1.25 micrometers.

Unlike photolithography, in which the entire pattern is exposed at once, scanning electron beam lithography is a serial process in which the electron beam writes the circuit pattern point by point. The scanning may be a raster scan akin to the sweeping of the electron beam in a television picture tube, except that the beam is turned on only when a position being scanned is to be exposed. In the so-called vector scan method, the beam goes directly to points that need exposing and does not waste time passing over points that will not be exposed.

In either case, a mask is not required because the beam is controlled electronically. For example, in vector scanning, a computer containing the circuit pattern in its memory can direct the beam to the starting coordinates of certain basic shapes, such as rectangles, into which the pattern has been broken up. These elements are then filled in by a rasterlike scan. The requirements on the system that deflects the beam of electrons on its way from the electron source to the target are quite stringent for this type of scanning, in part because the magnetic fields that deflect the electron beam produce eddy currents in metal parts of the system which, in turn, generate small magnetic fields. These fields can distort the image traced out by slightly deflecting the beam. Corrections are required for the interaction of the focusing fields and the fields produced by the deflection system.

The scanning system developed at IBM by Chang and his co-workers has a beam size that can be varied from 500 angstroms to 0.5 micrometer and a scanning field of 8000 beam positions in each direction. The minimum size of circuit features is usually 4 or 5 beam diameters. Thus fields with dimensions of 2000 line widths on a side can be exposed. The IBM researchers used a beam diameter of 0.25 micrometer with a concomitant field size of 2 millimeters. The electron optical system also has a longer focal length than scanning electron microscopes in order to permit the large deflections of the electron beam needed to write over a 2-millimeter distance while keeping the deflection angle small to avoid distortions.

Many observers think, however, that it will be very difficult to simultaneously increase the size of the field much further toward the 5-millimeter dimensions of the largest present-day integrated circuit chips and to maintain submicrometer resolution. Increasing the focal length also increases aberrations in the magnetic lenses that focus the electron beam, thus reducing the electron beam current and the speed with which patterns can be written. One partial solution developed at Texas Instruments in Dallas by Gilbert Varnell and his co-workers is called dynamic focusing. As the deflection increases, the focusing of the electron beam is changed to account for the distortion. The Texas Instruments researchers are using a scanning electron beam system with dynamic focusing under the control of a computer to make a 256-bit random access memory with lateral dimensions reduced by a factor of 4 as compared with its photolithographically fabricated counterpart.

Integrated circuits are actually three-dimensional entities and must be reduced in size proportionately in all three dimensions, according to IBM's Yu. In addition, even such aspects as the concentration of impurity dopants and operating voltages must be scaled accordingly when the size is decreased.

For example, the traditional method of incorporating doping impurities into semiconductors is to coat the semiconductor surface with the impurity or one of its compounds and cause it to diffuse a short distance into the surface by heating the semiconductor to a high temperature. However, it is difficult to control the depth to which the impurities penetrate when the depth becomes much less than 0.5 micrometer. A method now coming into commercial use and called ion implantation overcomes this problem. When ions of the desired impurity bombard the semiconductor surface, both the depth of penetration of the ions and the distribution within the semiconductor can be controlled to a certain extent by the energy of the incident ions and by the relative orientation of the ion beam and the crystal lattice of the semiconductor. The IBM scientists used this method of doping exclusively during the fabrication of the memory circuit to make doped regions as shallow as 0.2 micrometer.

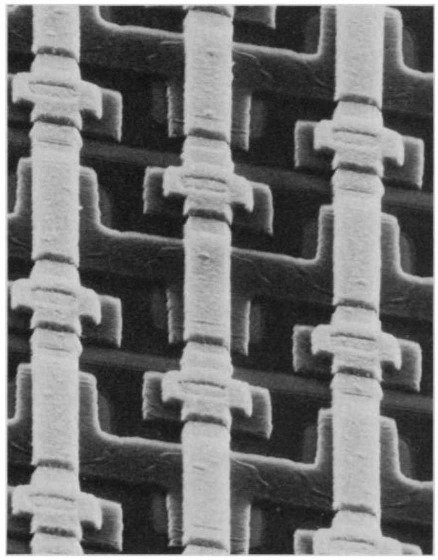

Fig. 1. Scanning electron micrograph of a small portion of the 8192-bit memory array fabricated at IBM. The vertical, light-colored lines are aluminum interconnections about 2.3 micrometers wide. Each short cross line on the aluminum contacts one memory cell. The narrow horizontal lines also contact each memory cell and have widths from 1 to 1.5 micrometers. [Source: R. T. Miller, IBM]

Apart from the still-limited size of the scanning field, a principal difficulty with the serial scanning of electron beams is the relative slowness of the process. Chang has estimated that his system could expose a 2-millimeter square field having features 1 micrometer in width in less than 10 seconds. But a typical semiconductor wafer today has a diameter of 5 to 7.5 centimeters and thus hundreds of integrated circuit chips are made from one wafer. With photolithography, it takes about 10 seconds to expose an entire wafer through one mask. The exposure speed of the scanning electron system could be increased by increasing the electron beam current, although this solution has problems of distortion associated with it. Another solution is to find more sensitive electron resists. But even with these improvements, high speed scanning systems would remain to be developed.

Mindful of these difficulties, researchers at Bell Laboratories have built a conservatively designed scanning electron beam system which they have named the electron beam exposure system (EBES). This system is used about half the time for fabrication of experimental devices, such as a 1024-bit random access memory whose lateral dimensions were halved as compared to its conventional counterpart. The remainder of the time EBES produces masks for other laboratories at Bell to use in photolithographic production of integrated circuits or other devices. According to Herriott and Fabian Pease of Bell Laboratories, production of masks in one step by scanning electron beams is both faster and more economical than the older methods involving several pattern generation, reduction, inspection, and duplicate mask-making steps.

Equally important is the improved quality of the mask made by EBES as compared to ordinary masks, so that even when the EBES masks do not have smaller features than conventional ones, they have many fewer defects and consequently the yield (ratio of finished circuits that work to the total number manufactured) is increased.

Overall, EBES differs substantially from Chang's system at IBM. Rather than a scanning field whose width is based on a beam having 8000 positions, the Bell system has a scanning field only 128 micrometers wide based on a 0.5-micrometer beam having 256 positions. The immediate consequence is that the distortions due to aberrations and other sources are for the most part absent, so that complex compensating mechanisms do not need to be devised. Also EBES uses a raster scan, which minimizes data processing and hence can be quite fast.

For writing over areas larger than this small field size, a continuously moving mechanical table under the control of a laser interferometer was developed. The interferometer monitors the position of the table (and the wafer or mask sitting on it) and feeds back the position information to an error control system that repositions the electron beam if the table is not where it is supposed to be. (The use of a laser interferometer in conjunction with a scanning electron beam system was pioneered by O. Cahen, R. Sigelle, and J. Trotel of Thomson-CSF, a French company. But the French workers did not have a continuously moving table.) With this combined moving table and scanning electron beam system, areas up to 100 millimeters on a side can be exposed.

For example, a circuit pattern to be repeated on each chip of a wafer containing several integrated circuit chips is decomposed into strips 128 micrometers wide. The core memory of the controlling computer is loaded with the first 128-micrometer-wide segment. This portion of the pattern is successively exposed on each of the chips on the wafer as the table moves the wafer under the electron beam. Then the table is repositioned at the starting point, the second 128-micrometer strip is written in the same way as the first. This cycle is repeated until each segment has been written on every chip on the wafer. With this method and with electron resists (developed by L. F. Thompson, M. J. Bowden, and their co-workers) that are about 100 times as sensitive as the polymethyl methacrylate that is commonly used in electron beam lithography, the Bell scientists can achieve an exposure speed of 1 square centimeter per minute.

In order to accurately position the table before each strip is exposed (and also to obtain an occasional check on the position of the electron beam during the exposure), registration or fiducial markers are used. These are raised areas on the wafer whose position can be monitored by the observation of electrons that are scattered when the electron beam strikes the markers. A similar scheme is used at both IBM and Texas Instruments and is essential in order to ensure that successive exposures (corresponding to the several masks needed to make a complete circuit) of a circuit pattern are properly aligned. A set of three such markers can be used to adjust the size and orthogonality of the x and y axes as well as the position and orientation of the pattern. Alignments to within 0.1 micrometer are possible with this method. The IBM researchers have also used such registration markers to "stitch together" adjoining fields—like tiles on a floor—thus effectively enlarging the field size.

The capital cost of scanning electron beam systems, researchers point out, may amount to several hundred thousand dollars as compared to the several tens of thousands of dollars of a photolithographic exposure system. It is obvious why manufacturers would hesitate to invest in the several scanning systems required to make production quantities of integrated circuits if there were any alternative. And there are at least two alternatives. For either of these, the expensive scanning electron beam machines would be restricted to producing masks (pattern generation) with the fine features needed. Production of actual circuits (pattern replication) would be analogous to the present photolithography with electrons or x-rays replacing ultraviolet light. The first alternative involves projecting electrons through a mask. Although various such devices have been tested, problems associated with both distortions and registration have yet to be satisfactorily solved. The second alternative is a system that involves projecting x-rays through a mask.

Henry Smith and his associates at the Massachusetts Institute of Technology's Lincoln Laboratories in Lexington described an x-ray lithographic technique in 1972 which scientists say is primarily responsible for the current interest in x-rays. The Lincoln Laboratory investigators made masks (by conventional techniques) of thin layers of gold on silicon substrates. For the 8.3-angstrom x-ray radiation used, gold is absorbing and silicon is transmitting. Some researchers are now using Mylar as a substrate, because it is more convenient to work with and is more transparent at some x-ray wavelengths than silicon.

For example, Daniel Maydan and his colleagues at Bell Laboratories use Mylar substrates in conjunction with short wavelength 4.6-angstrom x-rays. The shorter wavelength x-rays are also attenuated less than the longer wavelength x-rays by beryllium, so that this material can be used as a window to separate the evacuated x-ray source from the target chamber for rapid sample changes.

Advantages of X-rays

Because of the short wavelength of the x-rays, diffraction effects are not a problem, and unlike electrons, x-rays are not readily scattered, so that the resolution of patterns made with x-ray lithography is limited mainly by that of the mask, and by certain distortions that arise because the mask does not sit in contact with the wafer beneath it. Another advantage of x-rays was recently described by Ralph Feder, Eberhard Spiller, and John Topalian of IBM. These investigators found that features with high aspect ratios—that is, whose depth is much greater than their width—can be exposed in resists by x-rays. With electron beams, aspect ratios of at best 3 : 1 or 4 : 1 can be achieved, as compared with 15 : 1 or more with x-rays. This effect might enable, for example, very narrow metallic interconnections to carry high currents, because the cross-sectional area could remain high. Finally, scratches or dust on the mask are not a problem for x-rays because of their short wavelength and their penetrating power, whereas they are a considerable problem in photolithography.

A major difficulty with x-rays is that it takes a high x-ray flux to expose many of the existing resists. With available x-ray sources, exposure times until recently were more than 100 times those of conventional photolithography. Robert Brault of Hughes Research Laboratories, Malibu, California, has developed a metal acrylate resist that is some 50 times more sensitive than polymethyl methacrylate. The addition of metals, such as barium, which absorb x-rays efficiently means that the resist has a higher absorption coefficient for x-rays than do organic resists containing only light atomic weight elements.

A second approach is to raise the x-ray flux, but a fundamental limitation is the melting of the metal target from which x-rays are produced by bombarding it with electrons. One partial solution is the use of rotating metal targets in the x-ray tube which can increase its output by about 20 times as compared with tubes with stationary targets because the entire target is not heated at once.

Registration is s second major problem with the x-ray technique. At present a completely satisfactory method for aligning a mask with registration marks has not been developed, and hence use of x-rays is now restricted to those devices that can be made with only one mask. The optical techniques used with photolithography can also be used with x-rays, but may be of limited value when circuits having features with dimensions of 1 micrometer or less are needed. John McCoy and Paul Sullivan of Hughes are working on an automatic alignment system that electronically detects the position of x-rays passing through transparent regions of the mask. Piezoelectric transducers controlled by a feedback system connected to the detectors would physically position the mask to within 0.1 micrometer, comparable to the alignment accuracy of scanning electron beam systems. However, problems with the electronics have prevented achieving this level of performance.

At present, there is no alternative to conventional photolithography that does not have unsolved problems. Even when perfected, scanning electron beam lithography may turn out to be too expensive for direct fabrication of integrated circuits. Although emphasizing that it is still too early to make a sure prediction, investigators manage nonetheless to convey that the best hope for the future may lie in the combination of scanning electron beam systems to generate masks with circuit fabrication by a projection technique, such as x-ray lithography.—ARTHUR L. ROBINSON

Additional Reading

IEEE Transactions on Electron Devices, ED-22 (July 1975). The entire issue is devoted to lithographic techniques.