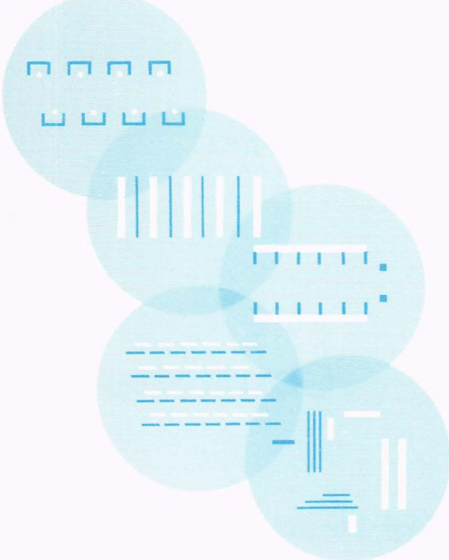


microelectronics

The term *microelectronics* is, strictly speaking, a misnomer since the most important characteristic of a microelectronic method of fabricating an electronic system is not necessarily smallness of size but the fabrication method itself. Both of the basic processes in use today make the electronic circuit from pure materials, and the devices are based upon solid-state theory as developed in modern physics. In this paper I shall use microelectronics to mean the fabrication of complete circuits by processing pure materials. I do not include any of the packaging procedures based on the use of small but essentially conventional components assembled in packages of disciplined geometry.

Microelectronics is intended to solve a number of problems in the design and production of electronic systems—problems of size, weight, cost, producibility (the ability to make large numbers of identical circuits quickly), and last, but far from least, reliability. For different equipments, these characteristics must be rated as having different orders of importance.

Electronics came into its own during World War II. The usefulness and versatility of electronic systems were demonstrated by such equipments as radar systems and the proximity fuze. After the war electronics assumed an increased military and industrial importance, with weapon systems incorporating increasingly larger amounts of electronics as they became more versatile and sophisticated. As an example of this trend, consider the curve of Fig. 1, where the growth in number of electronic components used in bombers is charted. The wartime B-29 used relatively few electronic components, while the 1960 B-58 used approximately 90,000.

It became apparent quickly that conventional methods of assembling systems from individual components would not allow necessary and important improvements to be made in reliability, size, and weight of electronic systems, hold down the spiraling costs of system production, or permit sufficiently high production rates in an emergency. The invention of the transistor in 1948 produced

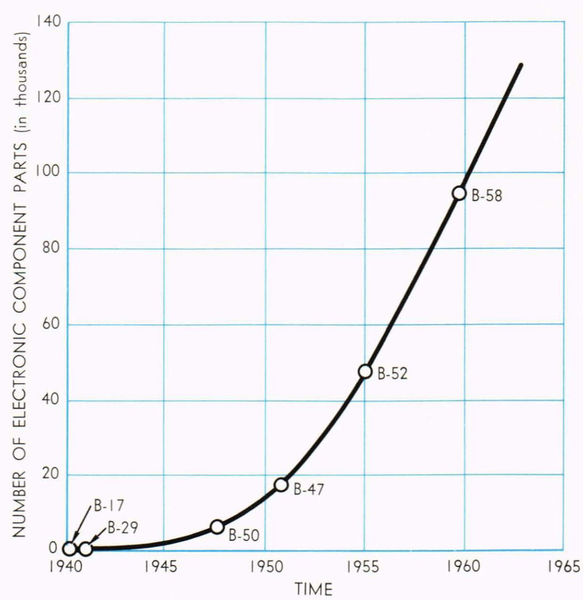


Fig. 1.—Trend of complexity of electronics in Air Force weapon systems (from *Science*, Vol. 132, Oct. 21, 1960: "Integration of Circuit Functions into Solids" by S. W. Herwald, Figure 1).

Advances in the sophistication and complexity of electronic systems have required development of new methods for producing the necessary circuitry. Two such methods that solve the problems in conventional circuits are those of thin-film and semiconductor electronics. These and the APL microelectronics laboratory facilities are described.

W. Liben

the APPLIED PHYSICS LABORATORY

some improvements, as early as 1953, in size, weight, operating temperature, and reliability. But this was not enough. Work was still going on to produce smaller and more reliable components capable of functioning at higher temperatures. Machines were being built to insert components automatically into supporting structures and to weld or solder them into circuits.

A potential breakthrough appeared when it was realized that it might be possible to fabricate, as an entity, an entire operating circuit, equivalent to an assemblage of many components, from basic pure materials. This concept appeared in the early 1950's.

The first fabrication technique proposed was the so-called "thin-film" method, in which the circuit, or portion of a system, was built up on an inert substrate using thin films of resistive, conductive, insulating, and dielectric materials.* As an illustration, a thin-film capacitor is made by depositing a conductive film on the substrate, which is usually glass; on this film is applied a layer of dielectric of known dielectric constant and thickness; finally, a second conductive film is applied.

With development in the late 1950's of the thermal-diffusion process for controlled doping of semiconductors, a second process was proposed. In this case, a complete circuit element could be fabricated in silicon by a sequence of controlled dopings of appropriate volumes. Transistors, diodes, resistors, and capacitors (a back-biased diode) could be fabricated and many useful circuits produced within these limitations.

A third process, often called "molecular electronics" and based upon semiconductor technology, envisaged construction of a complete circuit in a block of silicon in monolithic form; that is, individual components were not to be identifiable. This process has made slow progress because of the difficulty in designing such circuits.

The semiconductor diffusion process now widely used will be called the "semiconductor microelectronics" or "bulk microelectronics" process.

In the spring of 1960, an APL ad hoc committee was requested to survey the state of the art, examine its potential implications for the Laboratory, and recommend a course of action. In its report to the Director in July 1960, the committee stated that microelectronics was of great potential importance to the Laboratory in its development of electronic systems. The following recommendations were made:

> "It is recommended that the Laboratory establish a program in the field of microelectronics. This program should include:
> 1. Microelectronics laboratory capable of fabricating functional circuit blocks and systems.
> 2. Research and development in materials, circuits, mechanical design, interconnections, and solid-state applications.
> 3. Systems design involving the application of microelectronics considering such related areas as thermal problems, radiation damage, power supplies, and transducers.
> 4. Liaison and subcontracting." [1]

* A film is said to be "thin" if any one of its dimensions is less than the mean free path of a free electron in the film material.

[1] J. G. Chubbuck, S. N. Foner, W. A. Good, and W. Liben, "Recent Developments in Microelectronics and Their Impact on APL Programs," Report to the Director, APL, July 1960.

These recommendations were accepted, and a Microelectronics Group was established on November 1, 1960.

For the first year after its establishment, the Group's activity was confined to thin-film work. During this time it was impressed on us that dust is a serious problem, particularly in the defects it produces on photographic masks that are used to expose the resist and on the capacitors where it causes shorts and arcing. With this awareness of the dust problem in thin-film technology, and knowing that semiconductor processing is also sensitive to the presence of dust, the design and construction of the present semiconductor laboratory was initiated in January 1962. The new semiconductor laboratory and the older thin-film facility were enclosed in a single "clean" laboratory. Other facilities were provided as well, including a machine shop, vapor degreasing, potting, and mask fabrication.

This paper describes both the thin-film and semiconductor processes used in the APL microelectronics laboratory and the facilities available. It should be understood that many variations of these processes are in use today in other laboratories and plants in this country and Europe.

Semiconductor Microelectronics Fabrication Facility

Semiconductor microelectronic circuits are made by selective doping of a silicon wafer by diffusion of the dopant at high temperatures. At present, the process can produce transistors, diodes, and resistors. If a diode is operated in the back-biased condition, it behaves as a nonlinear capacitor whose capacitance depends upon the value of the bias voltage used. The construction of these components is shown in Fig. 2. Silicon, rather than germanium, is always used as the semiconductor material since it is readily available and is more useful at higher temperatures. If a filamentary volume in the silicon wafer is properly doped so that it has a resistivity ρ,† the resistance of the filament is given by the usual relation,

$$resistance = \frac{resistivity \times length}{cross\text{-}section\ area}.$$

However, this semiconductor resistor deviates in two ways from our usual concept of a resistor. First, the doping in the device is not uniform with depth, and the functional relationship between the doping concentration and the depth depends on the details of the diffusion process. Second, the substrate is not an insulator and, therefore, may be called an active substrate. If the resistor is doped oppositely to the substrate, the interface is a *p-n* junction and is therefore a diode. If this junction is back-biased, it acts as a capacitor so that the resistor-substrate combination is in reality a distributed resistance-capacitance. If it is forward-biased, the active substrate shunts the resistor. Typical dimensions of a semiconductor resistor are: length, 250 microns; width, 25 microns; and depth, 5 microns. We can now see how the presence of an active substrate seriously affects the operation of the semiconductor microelectronic circuit.

From this description of resistor fabrication we see how a diode can be made. It is only necessary to diffuse into the substrate a button of dopant that is opposite in polarity to that of the substrate, and of controlled area, depth, and concentration. The process of making a transistor is now also self-evident; the substrate acts as the collector, and the *n* diffusion region serves as the base and might be about 50 microns in diameter. The *p* diffusion region serves as the emitter and might be 25 microns in diameter. An additional procedure very useful to the circuit designer is the use of an isolation barrier of dopant opposite in sign from that of the substrate and extending completely through the wafer. This barrier interposes two junctions between the silicon on one side of the barrier and that on the other, and therefore isolates from each other the components on either side of the barrier.

The technique used to control the area on the silicon slice where diffusion is to occur is to employ a fused quartz (SiO_2) masking film with openings for the diffusion. Quartz has excellent high-temperature properties and is a good barrier to the diffusion of most dopants. The successive steps in

† The resistivity of a semiconductor is $(mqn)^{-1}$, where m is carrier mobility, q is its charge, and n is the concentration of charge carriers due to doping.

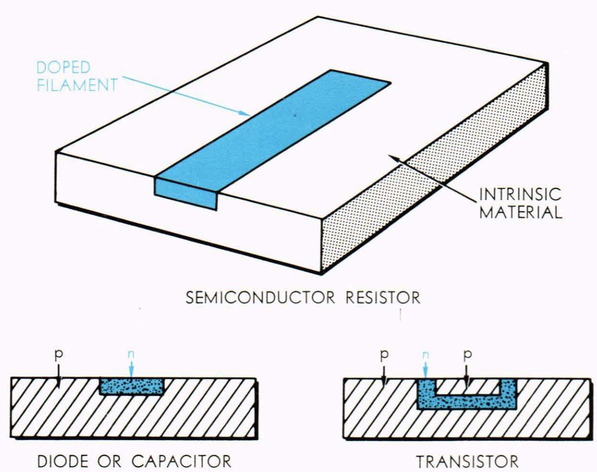


Fig. 2.—Basic structure of components in a semiconductor wafer.

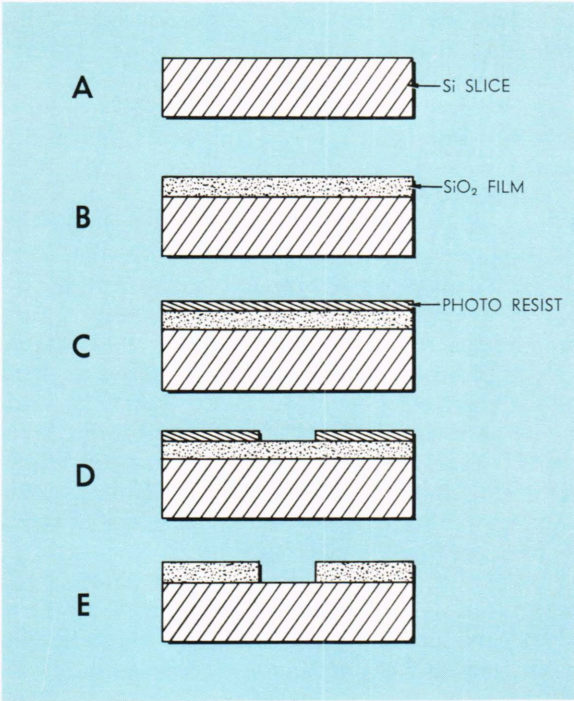


Fig. 3.—Steps used in fabricating a quartz mask on a silicon wafer.

the process will be described with the help of Fig. 3. A slice of silicon, appropriately doped, is ground down to the usable thickness, usually about 0.005 in. The surface is polished, using small-grit-size aluminum oxide on a soft lap, until it is reasonably flat and has a high polish. A chemical etch is then used to remove the final surface layer of broken crystallites, and the wafer is now ready for the masking operation, Fig. 3A.

The wafer is placed in a furnace, supported in a quartz boat. A carrier gas such as nitrogen is bubbled through a flask of deionized water at 91°C so that it becomes saturated and then passes through the furnace. The water vapor is converted to high-temperature steam, which in turn reacts with the silicon to convert the surface to silicon dioxide, Fig. 3B. A typical film thickness of 0.4 micron is produced in 30 min. at 1050°C.

A layer of light-sensitive photo-resist about 3 microns thick is next applied to the masking layer and is set by baking, Fig. 3C. A photo-resist may be described as a photosensitive monomer. If a selected area is exposed to light and subsequently developed, the exposed part polymerizes and becomes firmly bonded in place. The unexposed part washes away in the developer, exposing the quartz mask. To prepare the photographic mask used in the exposure we start by making a drawing, magnified in size 100 times, of the area where the diffusion is to occur. This drawing is made on a laminate of clear and opaque plastic sheets by cutting away the opaque film, leaving an opening through which light passes; this is called the artwork. The artwork is next photographed, using a reduction of 100, on a high-resolution photographic plate. This produces on the plate full-size opaque areas located where the diffusion is desired. The plate is now registered on the resist-coated silicon wafer, the combination is exposed to light, and the wafer is then removed and developed, producing openings in the resist where diffusion is to occur (Fig. 3D).

The wafer is now placed in a fluoride etching solution to remove the exposed silicon dioxide, and the protective resist is then removed in a stripping solution. We now have a silicon wafer with a quartz mask containing openings where the diffusion is to occur, and which is now ready for diffusion.

The dopants commonly used to produce n-type silicon are phosphorous, antimony, and arsenic; to produce p-type silicon, they are boron, gallium, and occasionally aluminum. The basic process is to maintain the silicon and its dopant at a high temperature (in the range of 700° to 1300°C). The doping atom diffuses into the silicon crystal and replaces an atom of silicon in the lattice, thus forming a substitutional alloy. The distribution of doping atoms in the silicon is a function of the temperature, diffusion time, and the concentration of doping atoms at the crystal surface.

A number of methods are used to obtain the correct concentration of dopant at the silicon surface; the silicon slice and doping compound may be sealed into a quartz box; a known amount of doping compound may be deposited on the wafer surface and allowed to diffuse into the silicon; or an inert carrier gas such as nitrogen may be mixed with the desired concentration of dopant molecules and allowed to flow over the surface of the wafer. We are now using the carrier-gas technique, though our diffusion equipment is sufficiently versatile to permit the use of other techniques.

Figure 4 is a section through a transistor and a resistor diffused into a silicon wafer. It is apparent that a number of diffusions are required to build up a complete circuit on the wafer. After the first diffusion is completed, the quartz mask is removed by fluoride etching, and the entire process is repeated to introduce the second doping agent into its specified location on the wafer. Each diffusion may affect the previously performed diffusions, so the details of each diffusion must be selected to affect the previous diffusions in a known way.

Two methods are used to interconnect the diffused devices and to form external connections.

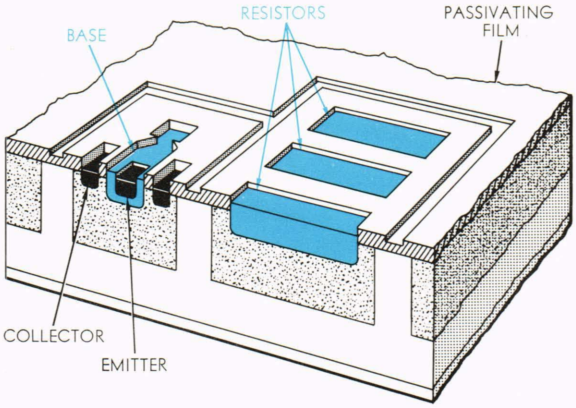


Fig. 4.—Cross section of a diffused transistor and resistor.

The preferred method, used wherever the topology permits, is to deposit a conductive stripe of aluminum by vacuum evaporation. This aluminum conductor rests on the protective film of quartz and connects to the desired points on the device through holes etched in the mask. Where topology does not permit the use of an evaporated aluminum conductor, a gold wire is thermocompression-bonded between the two points to be interconnected (which process is described below). In particular, when a point on a semiconductor circuit is to be connected to a terminal on the header, the thermocompression bonder must be used.

The complete semiconductor microelectronic circuit is always small, typical dimensions being 0.06 × 0.08 in. Since the silicon wafers are approximately an inch in diameter, it is obvious that many identical circuits can be made on a single wafer with one series of operations; typically, one hundred circuits are produced on a wafer. Basically, it is just as easy to produce a hundred circuits as it is to make one. The procedure is to reverse the full-size photoreduction of the artwork by contact printing and then rephotograph it one hundred times onto a second high-resolution plate to form a square matrix of photographs. This is the step-and-repeat process. This new photograph is the mask used to expose the photo-resist on the mask aligner.

After the diffusions are completed and the aluminum interconnections have been made by evaporation, the wafer is separated into individual circuit dice. This operation is performed on a diamond scriber: the wafer is mounted on a sliding table and passed under a diamond tool that scribes a set of parallel lines in the silicon between the individual circuits; the wafer is then rotated 90° and the process is repeated; the wafer is then broken along the scribed lines, and each circuit die is mounted on a multi-terminal header. The thermocompression interconnections and connections to the terminals are now made, and a cap is sealed to the header. As might be expected, very precise equipment and careful processing techniques are required to obtain an acceptable yield of satisfactory individual circuits.

Equipment and Procedures—A description of the equipment and procedures used in the APL microelectronics laboratory follows. Rough grinding of commercial silicon wafers is done on the lapping machine shown in Fig. 5. A thin plastic carrier punched with eight holes is placed in each of the three steel cylinders on the metal lap, and a silicon wafer is placed in each of the holes; a metal weight is then placed on each carrier. When the metal lap rotates, the steel cylinders rotate also, causing the carriers and wafers to rotate in turn. A grinding compound consisting of a suspension of aluminum oxide in oil is dripped on the steel lap for the actual grinding operation.

Polishing of the surfaces is done on torsional-oscillating laps covered with a felt-like cloth and bathed with a suspension of aluminum oxide powder in water. The wafers are waxed to a steel cylinder and placed on the soft lap. Oscillation causes the cylinders to move slowly around on the lap. By using successively smaller grit sizes (down to 0.03 micron), an acceptable polish is obtained. The surface layer of broken crystallites is finally removed by etching.

A standard chemical laboratory is available for resist processing, mask etching, and stripping.

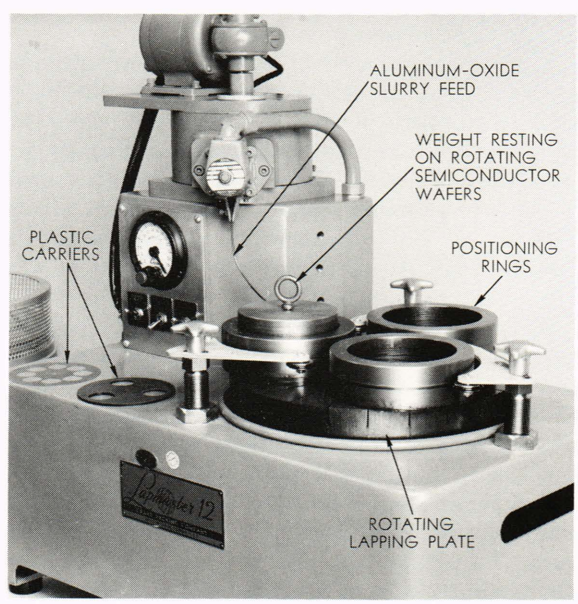


Fig. 5.—Machine used for the first lapping operation on rough-cut silicon wafers.

The artwork is cut on a precision X-Y coordinatograph that is capable of ruling lines the full width of a 45-in. square table with a maximum error of 0.0015 in.

Photographic processing of the exposed plates is also critical. The processing solutions are maintained at 68° ±0.5°F. The wash water is continuously filtered and cooled so as not to exceed 68°F. The photographic plates used are capable of resolving 1500 lines/mm. The photographic lens must be of high quality, with the principal requirement being that it be capable of projecting sharp-line edges with virtually no aberration. We have found that a lens that is capable of producing the full, theoretical, classical resolving power does not necessarily produce sharp-line edges. To simplify matters, our lenses are selected empirically for use with green light and at one reduction and one aperture ratio.

The photographic mask is aligned on the silicon wafer so that registration marks on both coincide. This is done on the mask aligner shown in Fig. 6. The alignment is monitored by means of the telescope. The wafer is rotated by a micrometer screw and is shifted in the X-Y directions by the pantograph. The ultraviolet source is used to expose the resist when alignment is completed.

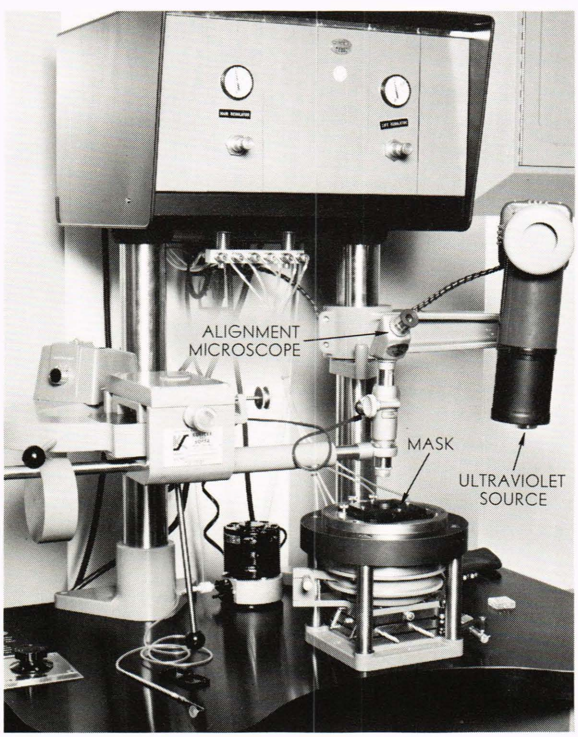


Fig. 6.—Mask aligner used to register the photographic mask on the silicon wafer and to expose the resist.

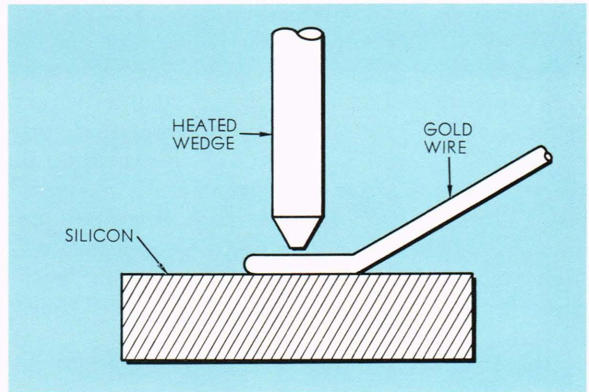


Fig. 7.—Essential elements and their arrangement required to thermocompression-bond a wire to a silicon wafer.

The diffusion operation is carried out in a group of six diffusion furnaces. A separate furnace is used for each dopant for maximum control of cleanliness. These furnaces are electrically heated, and each has three zones. The center zone, about 10 in. long, can be set to any temperature between 600° and 1300°C, with a tolerance of ±0.5°C. Temperatures are continuously recorded on a strip-chart recorder capable of showing changes in furnace temperature of 0.25°C. The outer zones are guard zones used to minimize heat losses from the center zone.

The thermocompression bonding of fine wires to a surface is illustrated in Fig. 7. The surface to which the wire is to be bonded is heated to about 300°C, and the wire is brought to the correct point. A sapphire wedge (preferably also heated), with a radius of tip curvature of about 0.001 in., presses the wire into the substrate, forming a good mechanical bond between the two. The equipment used is shown in Fig. 8.

The microelectronics laboratory is equipped to carry out all operations (starting with commercial rough-cut silicon wafers) necessary to fabricate semiconductor, microelectronic circuits, to develop new processing and control procedures, and to refine old ones.

Thin-Film Microelectronics Facility

Thin films of metals and non-metals can be deposited by many processes. Examples are evaporation at high temperature in a high-vacuum chamber, pyrolytic decomposition of gaseous compounds, sputtering, reactive sputtering, silk-screening, anodization, chemical reduction, electroplating, and electron-beam decomposition. The process having the greatest potential usefulness for our purposes is that of vacuum evaporation. By this method we can deposit the greatest range of materials, including all metals, nearly all inorganic compounds, and glasses. We can control precisely the film dimensions and purity. Multiple layers of different materials can be deposited in one pass through a vacuum evaporator. Furthermore, we foresee that this process will permit us eventually to fabricate all the passive and active components on a glass substrate during a single pass through the evaporator. In view of these considerations, we selected the high-vacuum evaporation process as our basic procedure for fabricating thin-film microelectronic systems.

The basic evaporation process is illustrated in Fig. 9. If the crucible containing the evaporant, in a perfect vacuum, is raised in temperature, the evaporant vaporizes to generate a vapor pressure that is exponentially related to the temperature (we assume crucible vapor pressures to be negligible). The evaporant molecules move in straight lines and are deposited on the first cool surface they encounter, which in our case is the circuit substrate. The glass substrate area to be coated is defined by an opening in a thin metal mask in contact with the substrate. The film thickness is controlled by the evaporation time, vapor source geometry and temperature, and the separation of the substrate from the vapor source. If a substantial amount of gas were present in the evaporation chamber, the molecules would collide with these gas molecules, to be deflected or even to form new compounds.‡ The result might be no film at all, or very poor films at best.

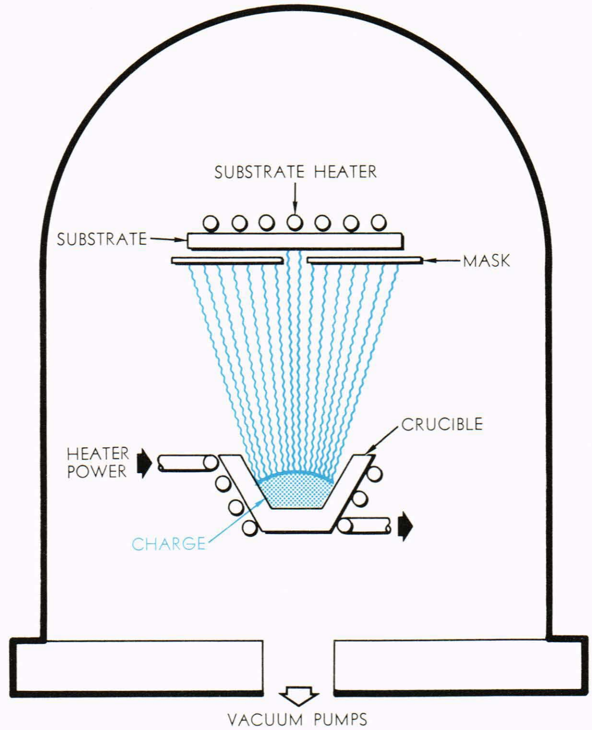


Fig. 9.—Basic arrangements required to form thin films by thermal vaporization in a vacuum.

We presently have the capability of producing resistors, capacitors, and inductors by thin-film technology. Resistors can be made from a few ohms up to one megohm, capacitors from a few picofarads up to 0.02 microfarad, and inductors up to about 10 microhenries. All other components must be conventional, small-size components attached to the substrate. We often refer to these as "add-ons." In recent years, a number of thin-film active devices have been proposed. The one appearing to have the best chance of producing a useful device soonest is the field-effect transistor. Its construction is illustrated in Fig. 10. All of its elements are thin films so that it can be produced by vacuum evaporation. A voltage applied to the gate electrode controls the flow of majority car-

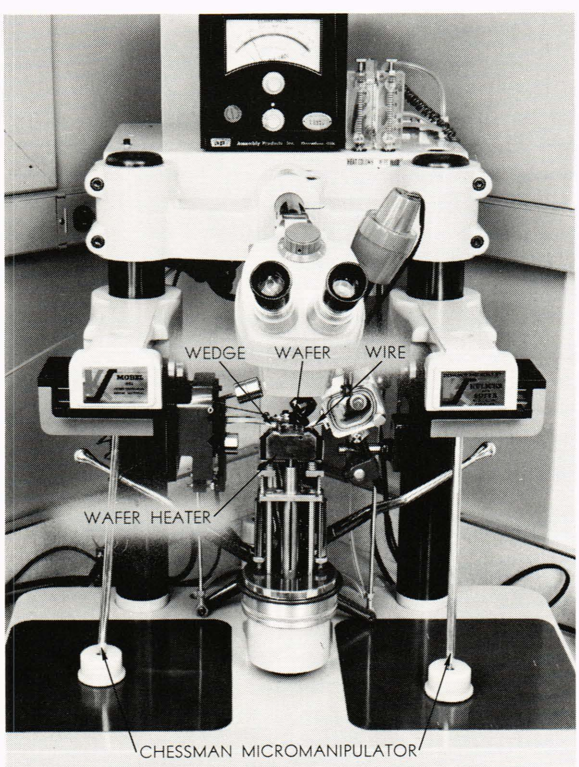
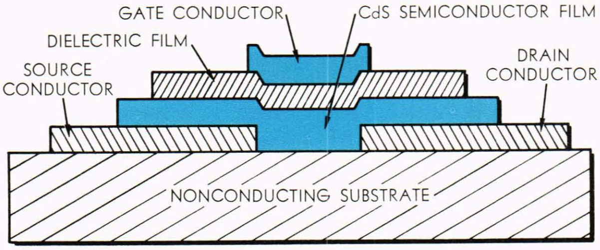


Fig. 8.—Thermocompression bonding machine used to bond fine wires to silicon wafers.

‡ The concept of mean free path (L) is important in this connection. It is well known that if N_o molecules leave the source located a distance x from the substrate, $N_o \exp(-x/L)$ molecules will arrive at the substrate. Since L is inversely related to the pressure and is roughly one meter at 10^{-4} Torr, and the substrate-to-source spacing is about 6 to 10 in., we see that working pressures should be less than 10^{-5} Torr. Actually, even smaller pressures are desirable because of other effects of the residual gases on the films. The entire subject of the interactions between the residual gases and the vapor stream and the film is one that is not yet fully understood but is certainly of great importance. A great deal of research needs to be done on this problem before we have a good understanding of the effect of the residual gases on the film properties.



NOTE: ALL FILMS ARE APPROXIMATELY 0.1 MICRON THICK

Fig. 10.—Evaporated thin-film field-effect triode.

riers through the semiconductor from source to drain. Devices have been made with trans-conductances up to 10,000 μmohs. This Laboratory is among many that are attempting to develop a fabrication procedure that will give a good yield of useful elements.[2]

A thin-film resistor is made in the form of a narrow rectangle, with its resistance value given by

$$R = \left(\frac{\rho}{t}\right)\left(\frac{L}{W}\right),$$

where ρ is the resistivity of the material used, and L, W, and t are its length, width, and thickness, respectively. If the film is a square, $L = W$, and the resistance equals (ρ/t). This ratio is designated as the ohms/square or sheet resistance; the ratio (L/W) is known as the aspect ratio. Since the film thickness used is comparable to the electronic mean-free-path, the resistivity is substantially larger than the bulk value and is a function of the thickness. Nichrome is the resistance material most commonly used. We use pure chromium and have also done some experimental work with tungsten and rhenium. Commonly used values of ρ/t are 100 to 500 ohms/square. The width usually lies between 0.001 and 0.01 in. Very narrow lines are more difficult to control and can only be used where wide tolerances are specified or where the finished component can be trimmed to value.

Thin-film capacitors are made by first depositing a conductive film, then forming upon this a dielectric film of controlled thickness, and finally a second conductive film to complete the capacitor. The conductive film is usually of aluminum, while the dielectric is commonly silicon monoxide, of dielectric constant equal to 6, and about 4000 Å thick. Capacitance values of about 0.01 microfarad/cm^2 are usual. A typical capacitor construction is shown in Fig. 11.

Inductors are made by forming a narrow filamentary spiral or rectangular grid. Flat spirals can give only limited values of inductance with low Q values.

[2] D. Abraham, *Thin Film Electronic Amplifiers*, CF-3029, The Johns Hopkins University, Applied Physics Laboratory, May 13, 1963.

The components on a substrate are interconnected by depositing low-resistance films of aluminum. Where necessary the interconnections can cross each other if separated by an insulating film. This type of interconnection is one of the reasons microelectronic circuits are proving to be so reliable.

When it is necessary to bond wire leads to a thin film substrate we bond 0.005-in.-diameter aluminum wire ultrasonically. The welding tip is driven horizontally at 40 kc/sec by a magnetostrictive transducer. Interconnection wires can also be attached by soldering, by spot-welding with a special welder where both electrodes are applied to the same side of a thin film, and by percussion-arc welding.

Most subsystems require a number of substrates, which must be interconnected into an assembly in some manner. Two techniques have been employed for this; in one, the substrates are placed side by side on a flat surface and interconnected; their leads are then brought out, after which they are potted; in the second, the substrates are stacked on each other, interconnected, and finally potted.

Thin-Film Equipment and Procedures—Thin-film work in the APL microelectronics laboratory requires the processes and equipment that we will now describe. The first step in converting a schematic to a piece of hardware is to allocate the components to a minimum number of wafers. We generally use 1 × 1 × 0.048 in. substrates of fire-polished, high-temperature glass. The components on each wafer are then sized and arranged, subject to certain controlling factors: space required for add-ons; resistors (taking into consideration temperature coefficient of resistance, aspect ratio, tolerances, useable ohms/square, and power dissipation); capacitor areas; and arrangement to permit maximum use of evaporated interconnections. Further, each wafer must be producible by a feasible sequence of evaporations.

For each material deposited on a substrate an

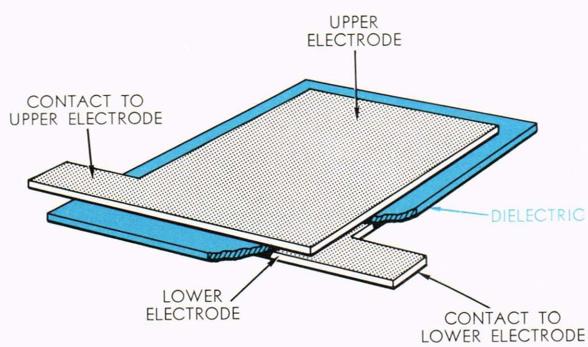


Fig. 11.—Construction of a thin-film capacitor.

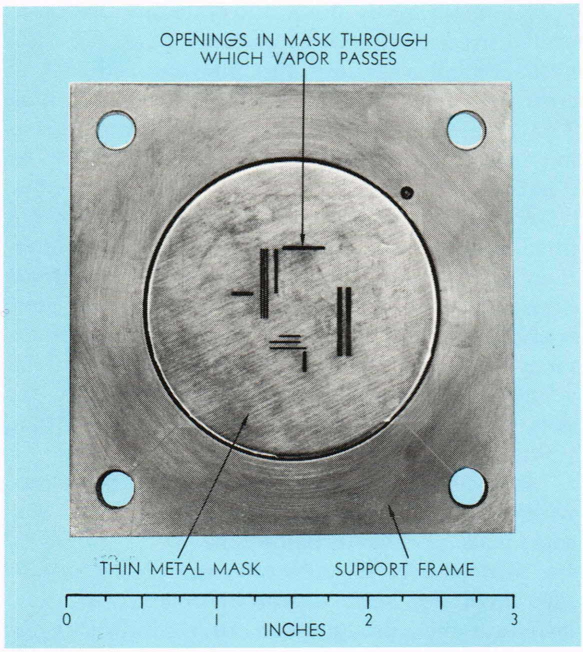


Fig. 12.—Evaporation mask in its support and registration frame.

evaporation mask must be prepared. To do so, a scale drawing is made for each material, and this is then reproduced, enlarged 10 times, on the laminate by means of the precision coordinatograph. This step is identical to that used to cut the artwork for the semiconductor circuits. The artwork is now photographed on a high-resolution plate using a 10:1 reduction. The resulting picture is a full-scale replica of the openings in the evaporation mask.

We have used two mask-making processes. In the oldest—the chemical-etching method—a sheet of 0.003-in.-thick beryllium copper is shaped to the correct size and mounted in a frame having registration marks. Photo-resist is applied and baked. The photographic plate is now registered in intimate contact with the resist. The resist is exposed to ultraviolet light and developed. During development the unexposed resist washes away, exposing the metal. The mask is now placed in a pressure-spray etcher. Ferric chloride solution at 100°F is sprayed onto the mask, and in about three minutes the exposed metal is dissolved away. The protective resist is now stripped to complete the mask. Such a mask is shown in Fig. 12.

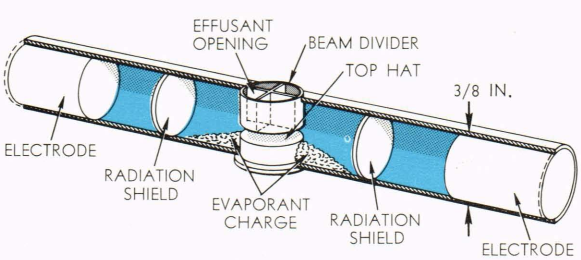


Fig. 13.—Pencil crucible used as a vapor source in vacuum evaporation.

In the second process, the mask is electroformed. The photographic negative made in the chemical etching method is reversed by contact printing.§ The resist is applied to a thick plate of polished stainless steel, exposed through the reversed negative, and developed. In this case, the resist remains in place where the mask openings will finally be located. The plate is now suspended in an electroplating tank, and nickel is built up in those areas where the resist has been removed. When the nickel film has built up to about 0.003 in. thick it is removed from the plating tank and the electroformed mask is separated from the stainless steel plate. Electroformed masks are preferred to etched masks since they can be made to closer tolerances. The etching process produces ragged edges due to material inhomogeneities caused by the grain structure. There may be as few as four masks or as many as fifteen in a complete set for one substrate.

The vapor sources used depend upon the material to be vaporized. We use silicon monoxide for dielectric, insulating, and protective films. For SiO we have developed the crucible shown in Fig. 13. It is 0.375 in. in diameter and is made by spot-welding 0.002-in. tantalum foil. The vapor flows through a 0.25-in. hole split into quarters by dividers at right angles. This construction ensures strong beaming action of the vapor stream. The "top-hat" ensures that the vapor will contain no particles since these are the principal cause of film defects. The radiation shields help to produce a center section of uniform temperature. Heating is supplied by passing currents through the tantalum foil. This pencil crucible has proved to be a very good silicon monoxide source.

The evaporation of metals is far more difficult than that of insulators since liquid metals are chemically very active. We can evaporate chromium from pencil crucibles and get a useful crucible life. Aluminum and gold are usually evaporated by hanging short lengths of the wire in the form of an inverted U on the turns of a tungsten spiral. Gold may also be evaporated from open boats of refractory metal.

At one time ceramic crucibles were commonly used. The present trend is away from these crucibles, however, for several reasons. They have a long thermal time constant, in some cases requiring thirty minutes to stabilize the temperature. Non-

§ In place of this reversal, the original photograph can be used with a positive resist, that is, a resist that is fixed in place where not exposed.

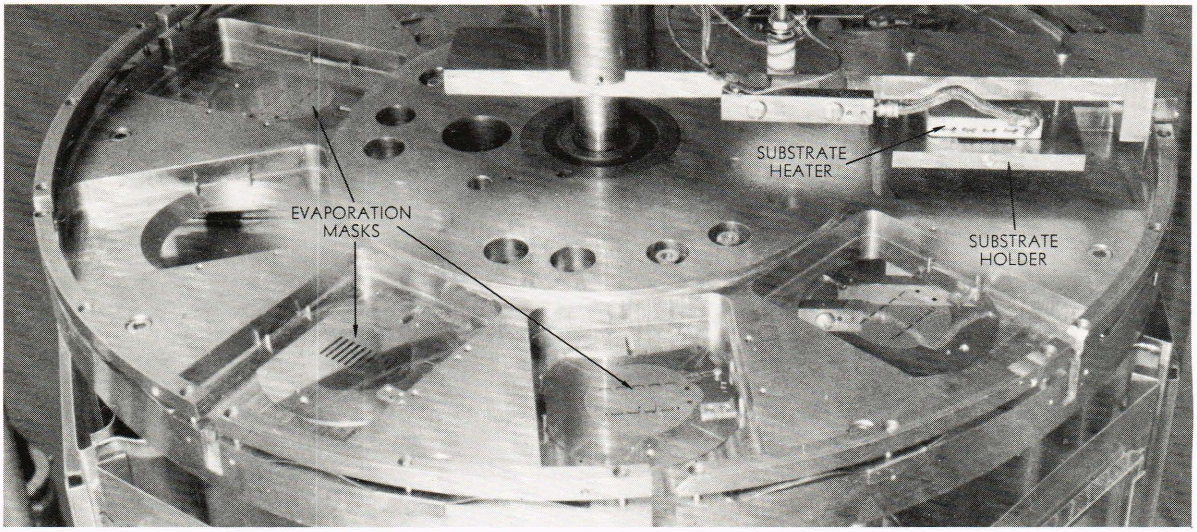


Fig. 14.—Fixed mask and movable substrate arm at the top of the multi-station vacuum evaporator.

reactive ceramic crucibles for use with liquid metals are rare; boron nitride and aluminum nitride are newly introduced and are claimed to be stable though they are expensive. Large amounts of heating power are required since heat transfer to the charge is inefficient.

We use Corning 7059 glass for our substrates. It is cut to size, and all necessary holes and notches are cut for add-ons and substrate assembly. The substrate is then thoroughly cleaned, using conventional ultrasonic cleaning, solvent-vapor degreasing, and distilled-water washes.

The film depositions are performed in a "carousel" that consists of nine vertical deposition channels, each with the elements shown in Fig. 9; i.e., a fixed vapor source, a fixed evaporation mask, and a movable substrate holder. The vertical channels are arranged in a circle, and the entire device is housed in an 18-in.-diameter glass bell-jar high-vacuum chamber. The substrate holder shown at the end of the radial arm in Fig. 14 has a heating element and thermocouple; only one is used. It can be rotated by motor drive from one mask to another, and will register with great precision on each mask. The fixed evaporation masks may also be seen in place in this figure.

To produce high-quality films, the substrate must be maintained at approximately 250°C. This is accomplished with the heater, and the thermocouple is used for automatic control. Using this equipment, a sequence of nine depositions can be made without breaking the vacuum. Metal-film thicknesses are monitored by measuring the resistance of a monitor substrate placed adjacent to the circuit substrate. The capacitor dielectric thickness is monitored by a beam of monochromatic light reflected from the front and back surfaces of the dielectric. The resulting two beams are focused on a detector where they mutually interfere. The resulting intensity depends on the phase difference between the two beams, and this in turn depends on the film thickness. The detector output current is recorded and the evaporation is terminated when the desired film thickness has been reached, as determined from this record. A thin-film circuit made at APL is shown in Fig. 15. This is one of the three circuit wafers that make up a battery-

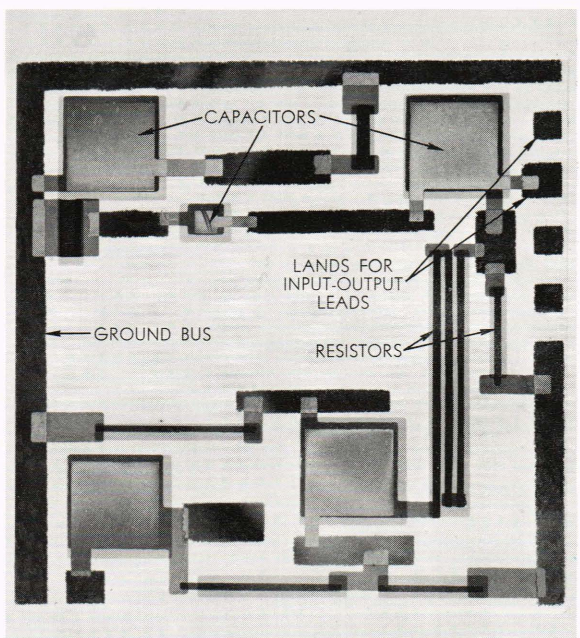


Fig. 15.—A typical evaporated thin-film microelectronic circuit before add-ons are attached.

operated 15-mc FM receiver.

Internal wire interconnections are now made using the ultrasonic welder. A complete set of circuit substrates can then be assembled to form a system.

A third circuit-fabrication technique combines the good features of both semiconductor and thin-film processes; it is the so-called "hybrid" circuit. In this case, transistors and diodes are fabricated in a silicon wafer, and a film of quartz is applied to the entire die. This quartz film acts as a protective film and as an inert substrate for thin-film components deposited by evaporation. Holes are etched in the quartz using photo-lithographic techniques, and the semiconductor and thin-film components are then interconnected by evaporated aluminum conductors.

Circuit Design

Up to this point we have carefully avoided mentioning the problems of circuit design. It should be apparent by now that the materials and processes used impose serious restrictions on the circuit designer. The Microelectronic System Design Project is studying these problems and developing good design procedures for microelectronic circuits. We now believe that with a minimum amount of reeducation, present-day circuit specialists can design thin-film circuits. This should be so since the circuits are made up of identifiable components on an insulating substrate. However, the design of semiconductor circuits is much more difficult because they are made in an active substrate and because coupling between components is a serious problem. Other factors that must be considered are high temperature coefficients, limited power-dissipation capability, wide fabrication tolerances, capacitances associated with junctions, and interaction of fabrication steps.

In the case of the thin-film circuit, we can make resistors, capacitors, and inductors; active elements and diodes cannot now be made. Transistors and diodes must be attached to a substrate in the form of add-ons. Resistors from a few ohms up to about 50,000 ohms can be made easily. Even 1-megohm resistors can be produced if enough substrate area is used. Capacitors ranging from a few picofarads up to 0.01 microfarad/cm^2 can be made. Inductors as big as 10 microhenries can be made, though a very large area must be used. If the circuit cannot be made within these limitations, add-ons must be used.

We expect that the design of semiconductor circuits will require not only a knowledge of circuit design, but of semiconductor theory and technology as well. Therefore, the art will be in the hands of a new group of specialists for at least the next few years.

The picture is not without its bright side for the circuit designer. The new methods of fabrication will make it possible to produce new components and devices not previously feasible. An example is a distributed resistor-capacitor made by replacing one electrode of a capacitor with a resistance film. This device is now easy to make in many modifications, and a wide variety of frequency characteristics is available. This same device can also be made easily in a semiconductor circuit.

At the present time, semiconductor microelectronic circuits are principally useful in the digital field where wide tolerances are acceptable. Digital data processors use large numbers of identical circuits, which are produced by the semiconductor process in large numbers as a matter of course. Also, research is in progress to develop semiconductor gates that dissipate a few microwatts instead of milliwatts—an important advantage if large numbers of circuits are to be packaged tightly. For the next few years we do not expect to see any revolutionary developments in this area; we do expect, howeyer, to see a gradual improvement in fabrication techniques, with substantial improvements in component tolerances and yields. This should result in a substantial decrease in price and an extensive exploitation of the semiconductor microelectronic circuits.

In the field of thin-film microelectronic circuits, we will probably have the introduction of new devices of major importance, such as new active elements, distributed parameter networks, cryogenic switches, opto-electronic devices, and finally, single elements performing a complete circuit function. In addition, we will have a substantial improvement in component tolerances and more extensive use of new materials.

The reliability picture looks very hopeful. While actual-life test data are still of a preliminary nature, predictions of failure rates of 0.001% per 1000 hr are common; this is a substantial improvement over present failure rates.

At a recent conference[3] it was predicted that by 1972 one-fourth of all electronic systems will be built of microelectronic circuits, and this will amount to one billion dollars in value. Of this, 80% will be for semiconductor and 20% for thin-film circuitry. While the thin-film circuits will have greater versatility, the big application will be for the semiconductor microelectronic circuits in electronic data processors.

[3] R. C. Sprague, "The Electronics Components Industry and Microelectronics," from *Proceedings of the Conference on the Impact of Microelectronics*, Illinois Institute of Technology, June 26–27, 1963; reprinted as Technical Paper 63-8 by Sprague Electric Co., North Adams, Mass. (undated).