SIMPLIFIED METHOD of HYBRID MICROCIRCUIT FABRICATION

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This process of hybrid construction is based on the use of active and passive components so that no externally bonded connections are required. Basically, standard etched circuit board material is used as the substrate to which all elements are attached by means of solder cream, with the soldering accomplished in seconds on a hot plate. The active elements are leadless inverted devices (LID's), which are the smallest packaged semiconductors available. Resistors and capacitors are in the form of chips and are available in a wide range of sizes. Assemblies have been completed that contain more than 100 elements with a 10:1 size reduction over previous assemblies.

In the field of microelectronics, or the realization of electronic circuits from extremely small electronic parts or elements, there has existed a wide variance between the approaches of the circuit designer and the microcircuit packaging specialist. The responsibility of the design engineer is to develop a working circuit that performs a specific function without too much regard for the intricacies involved in reducing the circuit to microminiature format. Frequently the prototype of the circuit is built using conventional circuit components. It is this device that the packaging specialist has to translate into an appropriate microcircuit.

Several options are available, such as thin-film, thick-film, or monolithic structures. The choice depends largely on the number of units desired, time,and cost. Thin-film circuits are made by vacuum deposition of conductive, resistive, or insulating materials on a substrate—or circuit base—to a thickness of several millionths of an inch. Thick-film circuits are made by deposition of various material in thicknesses up to 0.005 in., usually by silk screening followed by a high temperature firing. A monolithic circuit is one that is fabricated of circuit elements within a single block of semiconductor material. All of these methods require costly manufacturing facilities and considerable time from conception to the final product.

In the early phases of a circuit design, when only several experimental units are desired, monolithic techniques are not practical. In this case a hybrid circuit, i.e., one that embodies a combination of various circuit elements deposited on a substrate, with or without added discrete circuit components, represents a practical and useful expedient, either as the final product for a small number of units, or as an interim step toward a final design.

The decision to use any of these methods lies in the domain of the packaging engineer and depends on a number of factors, chiefly the extent of the production run and the application of the circuit. In the experimental laboratory it isn't feasible to use thin-film, thick-film, or monolithic circuits for sample microminiature breadboards because of the cost, long lead times involved, and the difficulty of making changes after the breadboard has been assembled.

The new technique of preparing microminiature hybrid circuits developed at APL permits the design engineer to build his breadboard with microminiature components, exposing him to the limitations and advantages inherent in such devices. It is no longer necessary for the packaging specialist to completely redesign a conventional circuit into its microminiature counterpart. The breadboard may need refining by a packaging specialist but, at least, the basic design will have been considered and prepared in a microminiature format. The interface problems between the design engineer and the packaging specialist have been effectively minimized, and the time lag between the design of the original circuit and its microminiaturized version has been significantly reduced. Using traditional film methods, once an experimental microminiature circuit has been built, modifications, changes, and repairs are difficult to make. The microminiature version still has to be tailored for the operational environment of the parent equipment and the available space.

The technique for microminiaturization in hybrid circuit form permits the design engineer, with a minimum of equipment and specialized knowledge, to design and construct his breadboard circuits directly in a microminiature format. No translation of circuit values or redesign is necessary. Once the design is established, the packaging specialist may suggest more suitable components by type, may make more efficient use of the available space, and may suggest the appropriate technique for long production runs. Since the circuit is not in its production form at this stage, the packaging expert applies his skills in arranging the optimum circuit format, selecting production components and methods of processing, and relating the circuit to the spatial requirements and environmental stresses to be encountered. The significant point is that he is working with a circuit that is already in microminiature format and that requires attention to detail rather than a massive translation from conventional electronic technology to the world of microminiaturization.

The methods, components, and laboratory equipment required for the hybrid method are simple enough so that a brief indoctrination is sufficient to provide the design engineer with the requisite background.

Once the experimental stage has been completed, the packaging engineer can (a) plan modular sectioning to produce a complete testable function for each module, (b) establish the power dissipation and operating temperature range for the microminiature components, and (c) establish interrelationships between passive devices combined to perform a circuit function in lieu of establishing individual values for the components, selecting components that are readily available, and choosing lead and contact assignments for ease of manufacture and compatibility with other circuits.

Limitations of Film Processes

A major limitation of film circuits is the inability to obtain large values in resistors and capacitors through deposition techniques. As a result, film circuits are built to conform to the available limited values. Addition of high value resistors and capacitors as discrete components, or "chips," to the basic circuit to form a hybrid greatly increases the versatility and flexibility of film microcircuits.

The two types of film circuit, thin-film and thick-film, are made by the deposition of passive components, such as resistors, capacitors, inductors, and conductors onto a substrate to which active devices are attached by ultrasonic bonding, thermocompression bonding, welding, soldering, or conductive cements. The difference between the two types lies in the process and not in the thickness of the film. In either case, a glass, beryllia, or alumina substrate acts as a support for the vacuum evaporated or screened materials. The materials of which the thin films are formed may be gold, nichrome, copper, tantalum, tin oxide, or aluminum, with silicon monoxide as an insulator. Thick-film hybrids are usually manufactured by masking and silk-screen printing of conductive, resistive, or insulating inks onto the same substrates, followed by firing at high temperatures. Active and additional passive devices are then added. The chief advantage of thin-film over thick-film is the ability to provide precise resistors and conductors through control of line width, line spacing, thickness of deposition, and trimming. The equipment used to fabricate thick-film and thin-film circuits varies considerably in cost, with thin-film being the more expensive.

In the film methods, careful handling during manufacture is mandatory and special equipment such as vacuum chambers and component trimming machines are required. Conductors, resistors, and capacitors are formed in film circuits by means of multiple masks (at least three), one for each process or layer. Neither thin-film nor thick-film processing can produce wide ranges of resistance with one mask. Even for minimum results, close tolerances must be maintained in the shape and thickness of the layers. Each mask is a separate piece of artwork requiring considerable skill to create and special equipment to refine to the close tolerances needed. Reduction in the number of masks, or in the need for close tolerances, would reduce both time and cost.

In both types of film process, capital equipment is a major factor. This is more so in the case of thin-film hybrids, which require clean-room facilities, vacuum chambers, and close tolerance masks. Thick-film hybrids require a large furnace designed so that the screened substrate is belt-driven through a number of heat zones, followed by a resistor trimming machine. The close tolerances and the specialized equipment call for the use of highly skilled manufacturing personnel.

Development of the APL Hybrid Microcircuit Technique

The new process had its beginning over two years ago with an attempt at soldering semiconductor chips at low temperature in order to preserve the circuit integrity of the semiconductors throughout the mounting process. Capacitors are also affected by the mounting heat but tend to stabilize after a short period of time. In previous soldering methods, the header or flat pack was heated to 410°C. The semiconductor chip was then placed on the gold-plated pad (a mounting surface integral or attached to the printed circuit) and agitated while the gold interface melted. Under some conditions a gold preform, or small quantity of shaped eutectic gold solder, was used between the pad and the chip to provide a good bond. Each additional chip was then bonded in the same manner so that chips were exposed to the maximum temperature until the last chip had been bonded. The number of chips was limited (about 5 or 6) by time and temperature because some of the chips inevitably became electrically degraded in the process.

Our first attempts to substitute various low temperature solders for the eutectic gold solders produced rosin joints with no metallic contact between the solder and the gold surface of the chip. When some pressure was applied, soldering action took place but the results were not completely satisfactory. The chips tended to float off the solder pads as soon as the solder melted unless externally constrained. Activated rosin in the solder accelerated the soldering process, but the chips still would not solder properly without external pressure. Some chips did adhere on one edge of the solder meniscus. Increasing the temperature did not improve results.

Chemical bonding, i.e., the use of conductive epoxies, was considered as an alternative. While this method has its uses in designing and assembling breadboards for dimensioning purposes, or for circuits that do not have to operate under severe environmental constraints, it is not suitable for aerospace applications because of the phenomenon known as outgassing—the expulsion of residual gases in the bonding material after assembly.

Normally there exists a thermal barrier between the heat source and the surface being heated. The temperature difference is about 33°C and must be overcome before the component can be successfully soldered. The absence of direct thermal contact at the interface results in the solder melting before the component reaches the soldering temperature. This results in poor soldering or a rosin joint since the flux rises to the surface before the solder liquifies.

At this point experiments with solder cream began. Solder cream is a paste, with a consistency similar to that of cake frosting, made up of micro balls of solder alloys suspended in a liquid flux. Ordinarily the flux acts as an electrical and thermal insulator. However, when heated for about 30 minutes at a temperature of 120°C or more, the flux shrinks, creating a mechanical, thermal, and electrical path through the solder balls. The chip is thus placed in intimate contact with the mounting pad, eliminating the thermal barrier between the solder and chip that would have caused them to reach soldering temperatures at different times. This is the heart of the process—the heat reaches the chip directly through the metallic contact with the solder cream. Since both chip and solder now reach solder temperature simultaneously, the wetting action of the liquid solder holds the chip flat on the solder pad while the solder cools. This final process takes about 30 seconds for a substrate 0.030-in. thick.

This feature allows an unlimited number of chips (active and passive) to be mounted in one operation in less than one minute and at low temperatures (230°C). One assembly already completed has 52 components which were soldered in one operation including the substrate and the case. (See Fig. 1.)

The ability to properly solder chip components does not constitute the end result; it is only one step in the overall problem of providing a reliable,

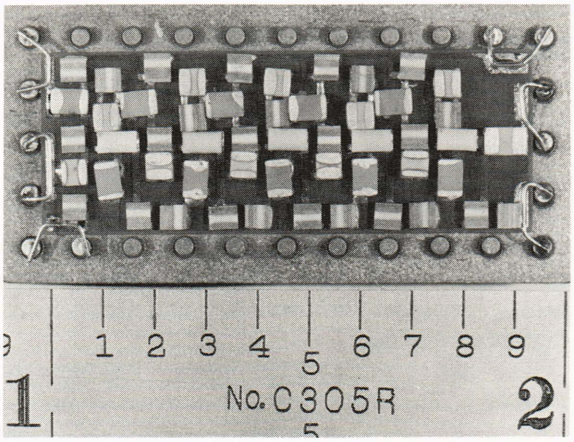

Fig. 1—Assembly containing 52 components that were soldered in one operation.

low-cost hybrid package. Other problem areas that demand attention can be categorized as follows:

1. All components, active and passive, must be testable prior to assembly.
2. All components should be easily replaceable without damage to the circuit.
3. No flying leads or wires that can be damaged by normal handling should protrude from the substrate.
4. Minimum skill should be required for assembly.
5. Number of required operations should be minimized.
6. All critical assembly controls should be automated.
7. Cost and quantity of necessary capital equipment should be minimized.
8. High production should be possible with little or no change in the assembly system.
9. It should be possible to handle large numbers of components and/or large size assemblies.
10. It should be possible to eliminate interconnections by combining multiple functions on a single substrate.

It would be advantageous to have a single system that would solve all of our problems. This is, of course, impossible, but we can achieve most of our goals by using a packaging scheme based on a printed circuit board of fiber glass and epoxy plus leadless inverted active devices (LID semiconductors), chip capacitors, resistors, and inductors. A typical LID device is shown in Fig. 2.

LID's satisfy three of our basic aims, viz., completely testable prior to assembly, small in size (0.040 × 0.075 × 0.035 in.), and no flying leads. They also have the advantage of being easily soldered to the substrate, and they furthermore allow passage of conductors between the contact pads. A monolithic microelectronic chip with its associated flying leads is comparable in size to a LID. The area required for a flip chip is 0.001 in.^{2}, whereas the LID requires 0.003 in.^{2}, but with the added feature of permitting pass-through conductors. This feature effectively reduces the area required for the LID to make it comparable to that of monolithic chips. Figure 3 illustrates this feature of the LID device.

Chip capacitors and chip resistors offer direct advantages over monolithic devices when considering extreme values with small sizes. Chip resistors are available in the 0.050 × 0.050 in. size

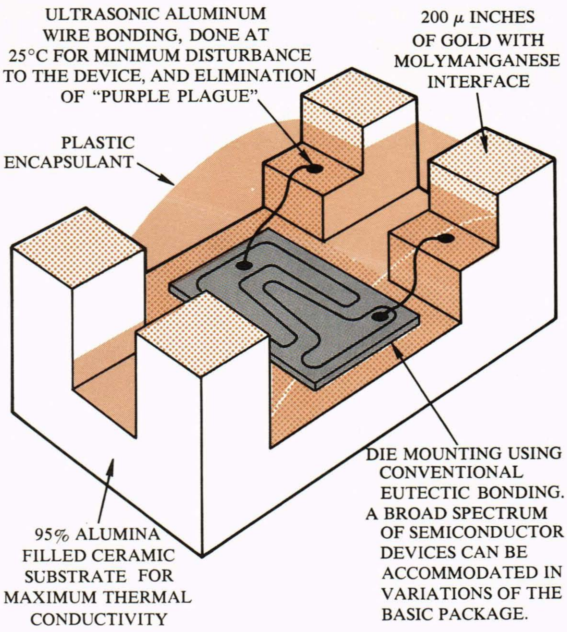

Fig. 2—Typical LID device.

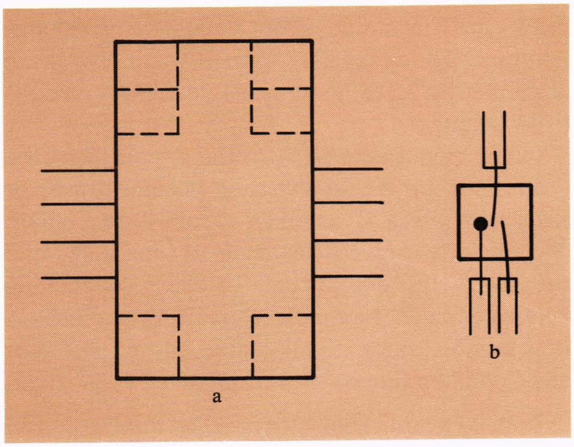

Fig. 3—(a) A LID device showing pass-through conductors.
(b) A comparable monolithic chip.

in values from 10 ohms to 10 megohms with tolerances to 0.10%. Thin-film resistors in this range would be difficult to fabricate because of size or because of differing film thickness requirements for large and small valued resistors on the same substrate. Monolithic and thin-film capacitors can be readily fabricated in small values but would be impossible in values larger than 300 pF in an area as small as 0.050 in.^{2} The chip capacitors have the added advantage of being replaceable directly on the printed substrate, using a small soldering iron, without fear of damaging the printed circuit board. A single size chip of 0.050 × 0.050-in. accommodates values from 1 pf to 10,000 pF.

Nature of the Technique

The building of a circuit begins with a circuit schematic and the conditions for its ultimate use. A paper layout of the schematic is used as the basis for a photo negative from which a printed circuit board is made. The substrate (copper laminate) is etched with ferric chloride to form the pattern of the printed conductors. The discrete components in chip form are then imbedded in the solder paste. The components used are the smallest available. Resistors and capacitors are about 0.050-in.[2] and the semiconductors are 0.040 × 0.075-in.

All components are tested for electrical values and mechanical integrity. They are then tagged and stored in containers according to type and value. (Kits in a wide range of values and tolerances are available from component manufacturers.) The epoxyglass printed circuit boards are handled with care to ensure cleanliness and to avoid damage.

Solder cream is applied to the circuit board by means of a probe, hypodermic needle, brush, or silk screen press. The solder cream must contain 3% silver to prevent leaching of the silver end caps from chip components or the gold backing from semiconductors. Solder cream is available in most combinations of solderable alloys. Our preferred combination is 96½% tin and 3½% silver.

Solder Cream Application—The application of solder cream to a single etched circuit board is accomplished by using a hypodermic syringe loaded with the appropriate alloy (Sn-Ag). Each pad is coated with a metered amount of solder cream according to the chip size and pad area. The system is quite tolerant to the amount applied. Generally the volume of solder cream will be reduced to one-third after it has melted. Large numbers of circuits would dictate the use of a mask and a silk screen press. The mask thickness would determine the amount of solder applied to each pad (0.003-0.005 in.). The simplest solder cream applicator is the common toothpick sharpened to a small point. The pot life of the applied solder cream is at least two hours, which would be sufficient time to process many hundreds of chip components.

Chip Loading—Each chip is placed on the appropriate solder coated pads and gently pressed into the solder cream. While the cream is still soft, the components can be centered accurately on the pads. This process is continued until all of the chip components are properly mounted. Any excess solder cream around the pads will not affect the circuit integrity. As soon as the proper solder temperature is reached, the surface tension of the liquid solder will draw the excess material around the joint and provide a solder filet. Solder cream when applied directly across adjacent pads so as to present the worst case condition (short circuit) resulted in excellent solder joints without a single short (1,000 joints tested).

Chip Soldering—The volatile materials in the solder cream must be evaporated to provide the proper thermal path for good soldering. Any oven usable in the 90° to 120°C range can be used to bake out the unwanted thinners. The amount of time required for normal chips is 10 minutes. Thirty minutes is needed for monolithic chips.

The heating device used for component soldering is a Corning PC-35 hot plate in which the heating element is completely contained within a pyroceram top. This unit has an adjustable temperature range from 120° to 510°C. The factory calibration of these units is only nominal; each unit is individually calibrated in the laboratory before being used for component soldering. The temperature range of the hot plate is suitable for most solder types, but requires about thirty minutes to stabilize at a given temperature. After this stabilization period, the heating unit will hold the preset temperature within ±4°C.

After all chips have been embedded, the loaded printed circuit board is baked in an oven for 10 minutes at about 110°C. At this temperature the solder paste solidifies and binds the devices to the board. Although there is no electrical continuity through the solder in the cold state, once it has been subjected to the bake-out there is excellent continuity for the embedded components. This continuity indicates that the board and component are in metallic contact; this accounts for the subsequent reduction in soldering time and the wetting action which prevents the chip from moving beyond the limits of the solder pads.

Another advantage of the technique is the possibility of using conductive plated-through holes in the base structure for making connections through the substrate to the back side without using wires. The procedure currently in use for making plated-through holes is simple enough. The epoxy board is etched as usual and then coated with two or three coats of thick clear lacquer. The holes are then drilled through at appropriate points with standard high-speed drills. The previous method using ceramic substrates would require the use of diamond drills to achieve the same results. The preferred method uses a combination of electroless (chemical) copper plating sufficient for electrical conduction followed by electroplating to the required thickness. Electroless copper alone is not recommended since electroless plating requires hours for a 0.001 in. thickness. This process will plate the entire substrate in addition to the holes; however, the plating over the lacquered area will be removed when lacquer thinner is applied. The protruding edges of the plated holes can be removed with an abrasive if desired. Figure 4 illustrates the successive steps in this process.

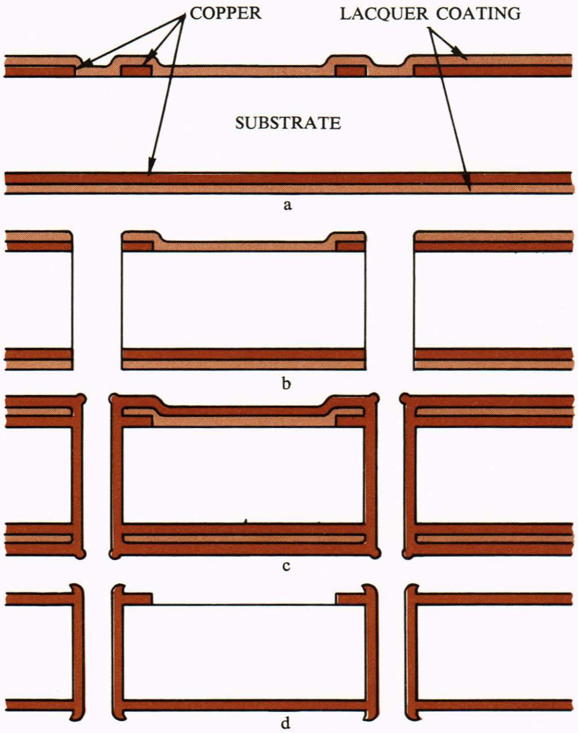

Fig. 4—Electroless plating process.
(a) Etched circuit board, lacquer coated.
(b) Etched circuit board with drilled holes.
(c) Lacquered circuit board completely plated.
(d) Plated-through holes with lacquer and excess copper removed.

Applications

Cost reduction has been achieved through the use of low-cost equipment and existing in-house facilities. The total equipment required for fabricating hybrid microcircuits consists of a standard photo-etch printed circuit facility, small oven, hot plate, low-power (10) microscope, tweezers, and other small tools.

Time reduction has been made possible by reducing or eliminating many of the previously required operations. The delay line shown in Fig. 5 required less than 4 man-hours from concept to finished product. The actual assembly time was less than 10 minutes.

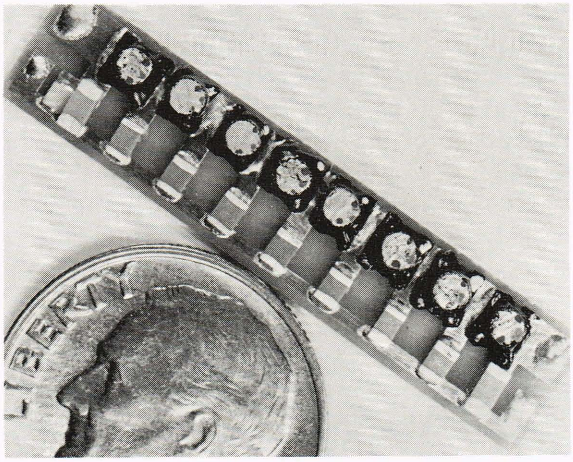

Fig. 5—Delay line.

The RF amplifier, mixer, and IF amplifier with a gain in excess of 90 dB, Fig. 6, attest to the ability to cope with complex circuits. This is truly a hybrid microcircuit that embodies standard size components with 57 chip devices to achieve a 5 to 1 size reduction over a previous miniature assembly. Performance was also improved along with ease of assembly.

Reliability tests are now being conducted with many units with good results. Thermal shock tests of the solder joints have been made without a single failure. The test samples were subjected to $-45°C$ followed by immersion in boiling water and back to $-45°C$ without degradation of any of the soldered joints.

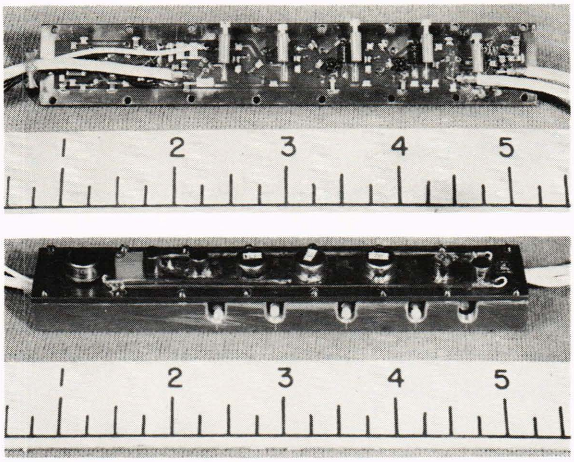

Fig. 6—Two views of RF amplifier, mixer, IF amplifier, and AGC system.

A new hybrid design recently constructed has more than 100 chip components including 17 semiconductors and five integrated circuits within a 2½-inch-diameter board (Fig. 7). This assembly eliminates many connectors by combining a number of functions on one board. The size reduction over previous assembly is at least ten to one.

A Colpitts oscillator and power splitter in the 215 MHz range was designed and built in an area of less than ¼ in.², using the microcircuit techniques. Chip components were used throughout, except for the tuning coil. Four isolated ports were provided, each delivering −10 dBm into 50 ohms impedance, through an isolation pad. The unit operates in a temperature environment that ranges from 4°C to 60°C with a frequency change of less than 300 KHz and an output level change of 0.2 dB. Figure 8 compares the microunit with a conventional circuit package possessing the same capabilities. Note the 10 to 1 reduction in volume for the hybrid circuit.

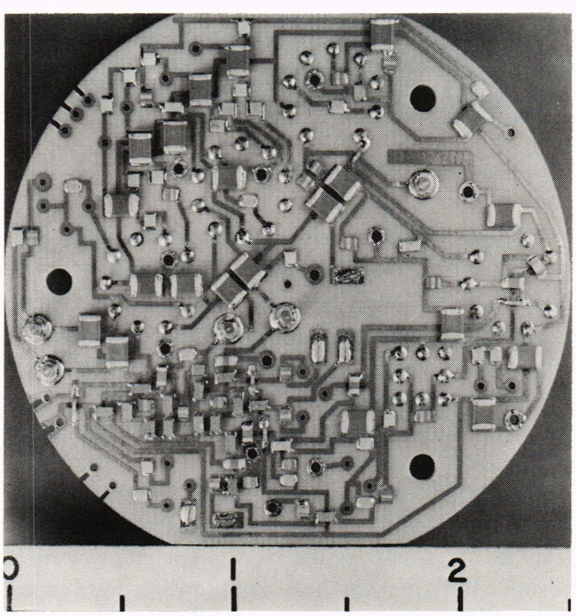

Fig. 7—New hybrid design that contains more than 100 chip components.

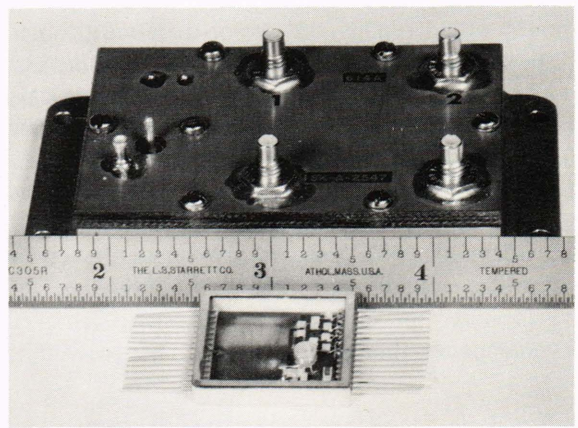

Fig. 8—Comparison of a microunit containing a 215 MHz oscillator and power splitter with a conventional circuit package having the same capabilities.

Summary

The fabrication of microminiaturized hybrid circuits with simple tools using existing facilities has been accomplished. The manufacturing process involved mounting semiconductors safely at low temperatures, elimination of all bonded wires, elimination of the costly thin- and thick-film equipment used to fabricate passive elements, and exclusive use of chip components which are available in wide value ranges in small sizes.

At this time we have completed assemblies that have in excess of 100 active and passive elements. Some of the assemblies fabricated by this technique are small (⅓ x ¾ inch) and others are large (3 x 5 inches) attesting to its flexibility. One of the items could not have been completed using existing techniques on the time scale required.

Probably the major advantage gained is in time reduction over any previous scheme. The time required using this technique is measured in days rather than months from initial design to operating equipment.