

MICROELECTRONIC THICK-FILM TECHNOLOGY AND APPLICATIONS

Screen-printing techniques are used with commercial materials to build ceramic-based circuit boards for small or densely packaged electronic circuits. Described here are the reasons for using the technology, the basics of materials and processing, APL's thick-film facility, and past and future applications.

INTRODUCTION

The integrated-circuit revolution has had a major impact on all forms of electronic systems, ranging from one-of-a-kind units built at APL to mass-production commercial devices. The systems are the result of new generations of large, complex integrated circuits, including memory devices, microprocessor and central processor unit chips, and gate arrays, that pack millions of transistors and related circuit elements on a single semiconductor die. This results in a high density of signals internal and external to the circuit die as is evidenced by the number of signal, power, and ground connection pads seen on the periphery of typical integrated circuits (Fig. 1). In very large scale integrated circuits, there can be more than 200 input/output (I/O) connections, with future projections of 500 I/Os. This high signal density naturally imposes increased density requirements on the next level of interconnection, the substrate or circuit board. Not only must the signals be moved on and off an individual chip, but several high-performance chips must be connected to exchange information at the rated speed. APL's systems usually have the added constraints that they must perform over wide environmental ranges and with a high degree of reliability.

Traditionally, integrated circuits have been connected by means of a dual in-line package wherein the chip is wired to a lead frame; the lead frame is then soldered to a circuit board. However, as the I/O number increases, that packaging technique consumes too much circuit board area and limits the speed of the device. APL's Microelectronics Group can address the needs of present-day circuitry in two ways. The first is by building hybrid (chip and wire) circuits on miniature circuit boards.¹ The second, referred to as surface-mount technology, uses single devices packaged in leadless ceramic chip carriers (see Fig. 1) that are soldered to multilayer thick-film ceramic circuit boards. The article by Clatterbaugh et al. elsewhere in this issue describes a portion of the work done at APL to ensure the reliability of the interconnection method; this article covers the technology and advantages of the ceramic board itself.

Ceramic circuit boards or substrates can be fabricated in two ways. The first method uses thin-film tech-

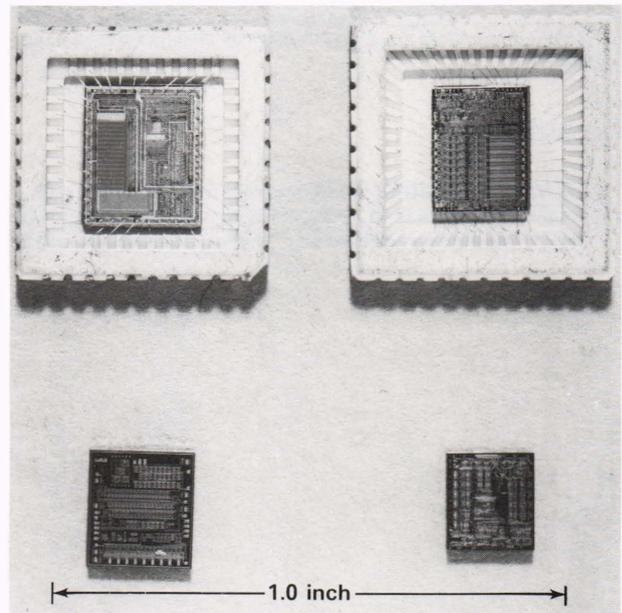


Figure 1—Typical integrated circuit dies used at APL. These medium- and large-scale dies, seen here both bare and in ceramic chip carriers, have fewer I/O pads on the periphery than are common today.

niques in which the ceramic blanks are coated with a thin layer of metal by vapor deposition (either evaporation or sputtering) and are then patterned photographically, one at a time. The process is limited to easily evaporable or sputterable materials such as gold, aluminum, and copper. For practical reasons, thin-film substrates are limited to one conductor layer.

The second method, for historical reasons called thick-film technology, involves the use of patterns that are applied to ceramic substrates by screen-printing methods similar to those used to print labels on tee shirts. The inks or pastes are forced by a squeegee through openings in a photographically patterned emulsion that is supported by a fine mesh screen (Fig. 2). Subsequent processing includes drying and firing to convert the ink into a usable form, e.g., a conductor, resistor, or dielectric pattern. Thick-film systems have several distinct ad-

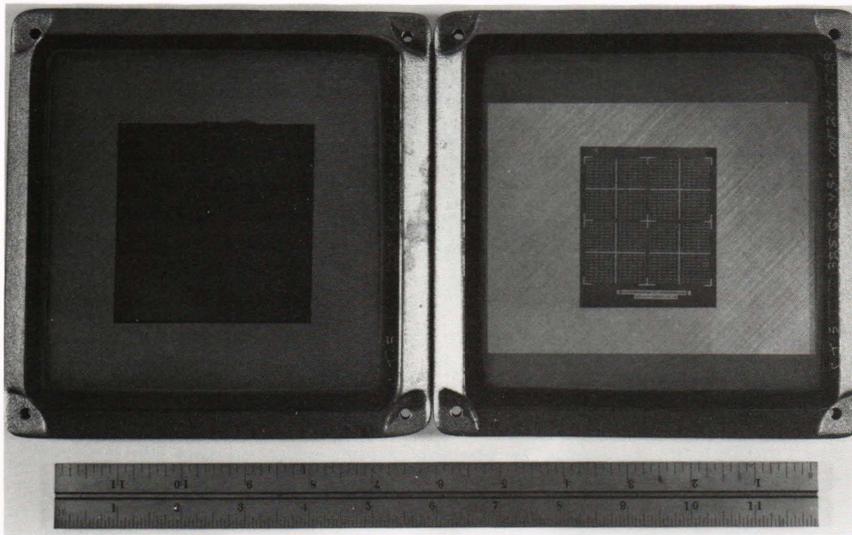


Figure 2—Typical high-precision screens used in the thick-film printing process. The screen on the right contains a patterned emulsion coating.

vantages over those made with thin films. The ink is a slurry that leaves only a sintered powder after the firing operation. Many more materials are compatible with thick-film processing than with thin-film techniques. Several types of conductors can be used, depending on whether the circuit is to be soldered or wire bonded. Insulating materials or dielectrics can be deposited; a wide range of dielectric constants is available, depending on the intended use. Resistors ranging from fractions of an ohm to several megohms can be built onto the substrates. Because of the wide choice of materials compatible with the processing, thick-film technology often enables the designer to engineer the circuit board more specifically to the needs of the circuit. Moreover, since thick-film processing is a sequence of print, dry, and fire operations, multiple power, ground, and signal layers can be deposited by alternating conductor and insulator layers (Fig. 3).

Very dense interconnection patterns can be built with signals distributed among several planes using separate power, ground, and signal planes. The composition of the layers can be varied according to service requirements. The inherent adaptability of thick-film processing complements APL's widely varying hardware requirements; it is a direct result of the variants that are available from the three basic ingredients of thick-film inks and, to a lesser degree, the adjustment of processing conditions.

BASICS OF THE THICK-FILM PROCESS

The thick-film process is a relatively simple concept. A substrate is silk-screened with a pattern using the required ink, and the ink is dried and fired to produce a hardened version of the desired pattern. However, the thick-film processes that are required to produce multilayer thick-film ceramic substrates are exacting. The base substrate is 96 percent alumina (Al_2O_3) with a surface roughness selected for good adhesion of the thick-film inks. The patterned screen, shown in Fig. 2, must be tightly controlled in both dimensions and in tension. The inks or pastes are composed of solvents, binders,

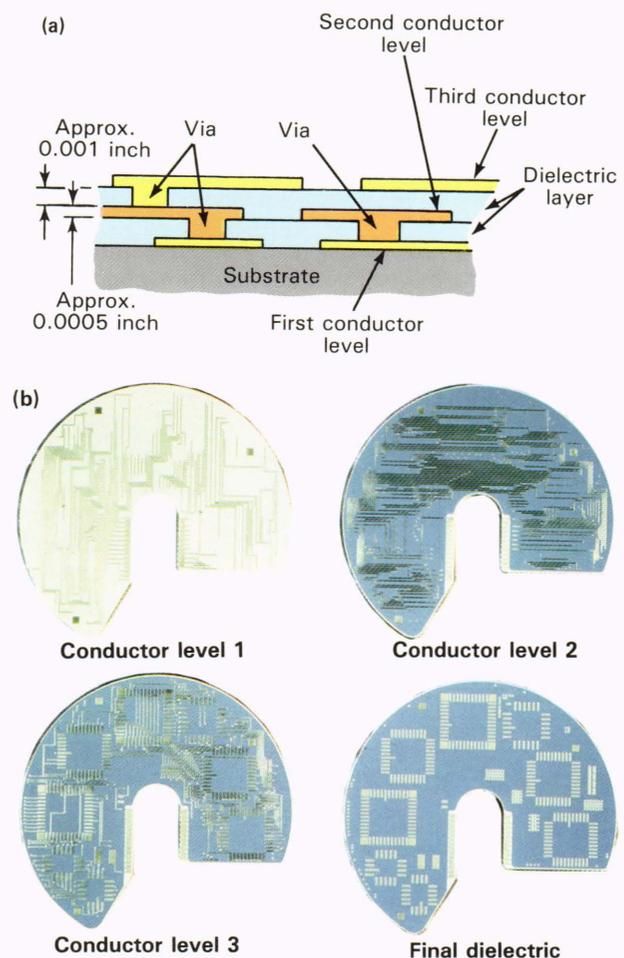


Figure 3—(a) A cross-sectional view of a multilayer thick-film substrate illustrating the various conductor layers and the intervening dielectric and via fill layers. (b) The actual conducting layers for a medical implant substrate.

and functional powders mixed into a slurry with a consistency akin to that of paint. The powders are metals,

metal oxides, and low-melting-point glasses in very specific ratios to produce conductors, resistors, or dielectrics. The first step in processing is deposition, which is done by forcing ink through openings in the patterned emulsion of the screen with a wiping arm or squeegee. To keep the desired printed pattern, the ink must be thixotropic; that is, it must flow under an applied shear stress but not under its own weight, similar to the behavior of butter. The substrates with the wet inks are carried through a 150°C dryer to remove the solvents and harden the deposit.

After drying, temporary binders hold the powder in place before the final sintering or firing operation. The binders are cellulose-based materials that burn away cleanly in the cleansed ambient air of the firing furnace, leaving the powder to fuse in the furnace's hottest region. The powders sinter together to form a dense cohesive body, such as a circuit track, that must also adhere to the underlying dielectric or ceramic layer. Adhesion agents, often transition metal oxides, are put into the powder system for that purpose. The materials react chemically with the powders and the underlying layer during firing. Because the cohesion is a result of interdiffusion within a layer and because adhesion results from chemical reactions between layers, the temperature sequence or profile seen by the parts is highly important. APL's thick-film facility uses a conveyor-type furnace with five independent microprocessor-controlled heater sections surrounding a high-temperature alloy muffle, which protects the furnace air from contamination and aids in airflow control.

Ultimately, the process is tailored to deposit the various types of inks in sequence and convert them to their functional form, i.e., to conductors, resistors, or insulating dielectrics. The true latitude of thick-film processing comes from the very wide range of functions available. For instance, the conductor composition can be varied from layer to layer in multilevel structures that would need high conductivity in the power, ground, and signal tracks but must have solderable surface-layer metallization. The choice of insulating dielectric depends on whether an in-situ capacitor or a low-capacitance insulating layer is desired. Similarly, resistor materials can be chosen according to the desired value and stability with changes in temperature, applied voltage, or mechanical stress. Resistors are usually selected for stable resistance but can at times be used as temperature or strain sensors.

APL'S THICK-FILM LABORATORY

The Microelectronics Group has established a modern, efficient, 900-square-foot, thick-film fabrication laboratory. All the critical manufacturing equipment required for multilayer substrate production is contained either within this laboratory or in the main microelectronic facility. The process starts with patterning the screens and ends with the final firing (see Fig. 4).

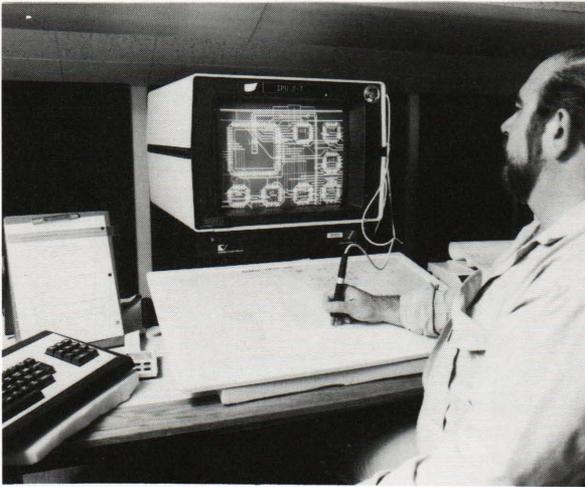
The screens with photosensitive emulsion coatings are exposed to a controlled ultraviolet light source using a photomask generated by computer-aided design; they are

then developed with an aerated spray of pure water. After being inspected, the imaged screen is mounted into the screen printer and aligned to print on a previous pattern or a blank ceramic. The procedure followed by the operator ensures that the various machine parameters are within the tolerances required by the properties of the ink that is to be used. The substrate, the screen, and the squeegee must be parallel so that the thickness of the applied ink is uniform across the entire substrate. Test parts are produced and inspected before production parts are printed. A light section microscope is often used at this point as a noncontact way of measuring the thickness of the wet ink for quality control. Control of the thickness of the wet print ultimately controls the thickness of the fired print—a necessary step in the control of conductor resistance, solderable film thickness, voltage breakdown of dielectrics, and especially the as-fired values of resistors before they are adjusted to final values.

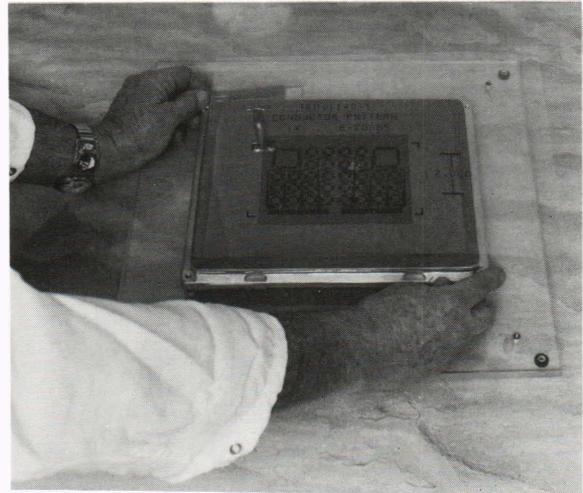
Drying is done with a continuous belt dryer that can reach temperatures up to 250°C. The drying step hardens the ink image on the substrate. The pattern, although not yet permanent, is hard to the touch and allows close inspection and handling. At this stage, the ink can still be removed with a solvent if defects are found. The firing furnace is a five-zone continuous-belt model. Before the substrates are fired, the furnace must be certified by a process called profiling, in which a thermocouple is attached to the belt and towed through the furnace to check that the furnace has the correct temperature versus time sequence needed for the ink being fired. Each type of ink used has a recommended time/temperature profile supplied by the manufacturer. Most important in the profile is the ramp rate—the rate of temperature change—and the total time at peak temperature. The furnace, through its microprocessor controller, can be closely adjusted for temperature in each zone and belt speed, allowing for a wide variety of profiles to be developed to meet any currently produced ink. The heaters surround the center section of the muffle, a long Inconel tube through which the belt carries the parts. The atmosphere inside the muffle must be monitored to ensure high enough flow rates and purity. A specially equipped, dedicated air compressor and filtering system supplies clean, dry air to the furnace.

This sequence of print, dry, and fire operations is repeated for each subsequent layer of dielectric, conductor, and resistor inks until a complete multilevel substrate (Fig. 5) is ready for testing, quality assurance activities, and higher level assembly.

Quality assurance for the thick-film substrates consists of inspection, functional testing, and electrical testing. Functional testing verifies that the surface can be soldered or wire bonded as the application dictates. Electrical testing consists of checks for continuity along a given conductor path and isolation between separate conductor paths. Previously, testing for continuity and isolation was done manually. The recent acquisition of an automated test system enables us to test large and dense circuit boards that cannot practically be fully tested manually.



(a) Design



(b) Pattern screens



(c) Print inks on boards

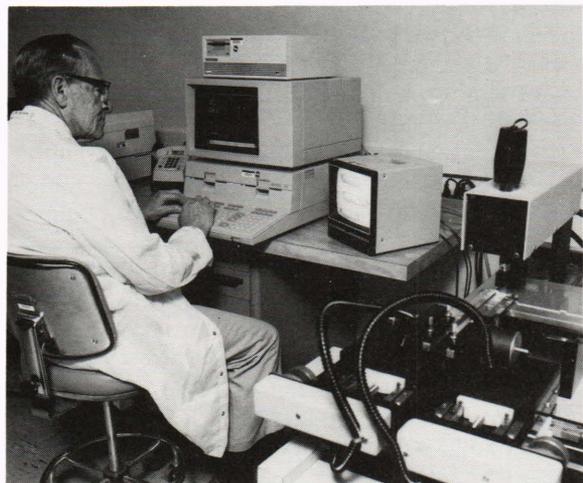


(d) Dry ink



(e) Fire

Repeat
for
multi-
layer
boards



(f) Shorts/opens test

↓
Deliver for assembly

Figure 4—The process of creating hardware from ideas.

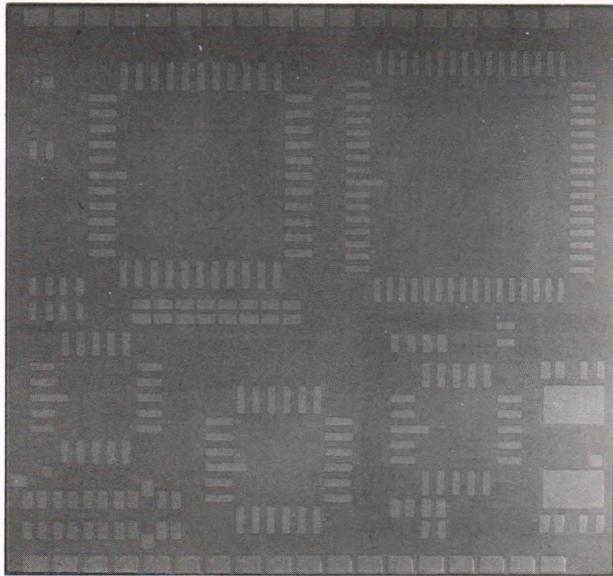


Figure 5—A programmable encoder substrate for the Bird-Borne Transmitter Program. The unit is 5.08 by 4.70 centimeters and contains three buried levels of conductors.

THICK-FILM DEVELOPMENT AND APPLICATIONS

The Group has been actively involved in the design, fabrication, testing, and qualification of thick-film circuitry for several years. The first major system was the Human Tissue Stimulator developed around 1978. The heart of that system consisted of three multilevel hybrids,¹ each containing seven buried conductor layers. One of the hybrids (Fig. 6) contained 32 medium-scale integrated circuits with over 600 wire bonds (i.e., connections between integrated circuits and substrate wires). As chip technology progressed, the use of large integrated circuit dies allowed a reduction in the number of die and wire-bond interconnections, but the requirement for multilevel high-density substrate interconnections increased.

A large gate-array hybrid is used in the Self-Injurious Behavior Inhibiting System (1984), again with a multilevel thick-film substrate.¹ As the hybrid technology matured, the need for testability of the large scale and very large scale integrated circuit chips called for the adoption of special geometries on the thick-film substrate to facilitate on-board chip testing.

The need for testability and ease of assembly and repair has brought about the adoption of another form of assembly technique that uses thick-film multilayer substrates called surface mounting. It uses a large multilevel ceramic substrate as a circuit board and mounts both active dies in individual packages and passive components by simple solder reflow techniques.² Such assemblies have been used successfully on both the Programmable Implantable Medication System and the Bird-Borne Transmitter Program (Fig. 5). Similar assemblies are being built for the radar altimeters of the TOPEX and NROSS satellites.

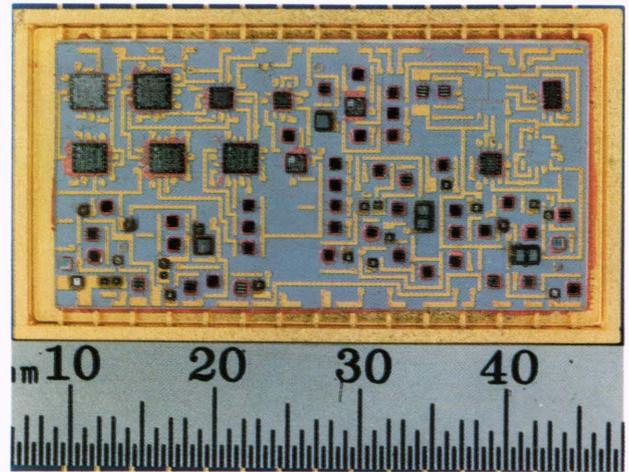


Figure 6—The multilayer thick-film hybrid for the Human Tissue Stimulator. The substrate contains seven buried noble metal layers and is assembled with 32 medium-scale integrated circuits (using epoxy) and over 600 wire bonds.

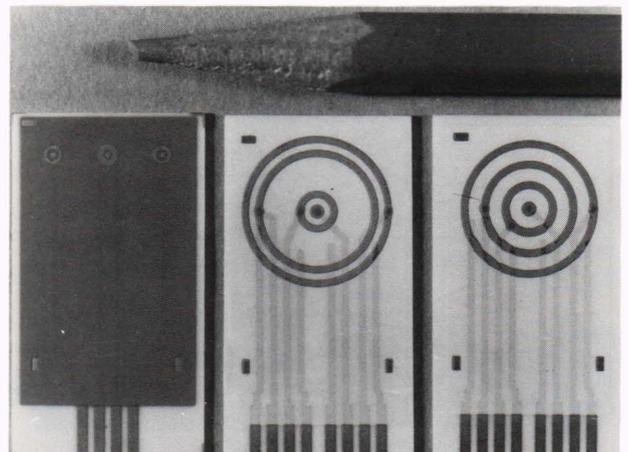


Figure 7—Three designs of Standard Virgo sensors that measure seawater's electrical conductivity.

Thick-film circuits also have a role in the creation of low-cost, high-performance sensors. Thick-film conductivity sensors have been designed, developed, and tested successfully within the Microelectronics Group and subsequently deployed at sea in the Standard Virgo Program. Various designs are shown in Fig. 7. The as-fired impedance of the sensors is usually too high to achieve the desired sensitivity. To lower the impedance, a surface-conversion process was developed to increase the effective surface area of the thick-film metal.

Another basic sensor that is achievable using thick films is the thermistor. The Group is actively engaged in developing a combined thick-film thermistor-conductivity sensor. Stability and temperature response data have been acquired for several thick-film thermistor inks. Techniques for resistance control, seawater passivation, and lead interconnections are under development to make the devices compatible with the requirements of the underwater sensing module.

SUMMARY

The Microelectronics Group has been active in thick-film design, development, and testing for several years. Many reliable thick-film circuits have been delivered to important programs and various oceanography experiments at APL. They were developed through an interactive process that includes both the end user and Group engineers. Such a design and development flow for thick-film substrate or sensor development is shown in Fig. 4. The end user is an integral part of the development process, specifying important information such as function, environmental constraints, and testing requirements, as well as participating in design reviews, engineering decisions, and actual testing operations. Quality assurance and inspection are also integral parts of the development process, and APL has well-qualified personnel and modern equipment to perform those operations.

A new, modern, thick-film applications laboratory has been created with state-of-the-art processing and testing equipment. It is fully operational and is available to supply substrates and sensors to APL. Engineering support is available from the Group's circuit design, development, and fabrication staff.

Although thick-film devices have been useful in the past, new applications and techniques will make the technology increasingly useful in the future. Printing technology is enabling larger boards to be fabricated. Ad-

vancements in ink technology allow the resolution of smaller features that, along with increased numbers of layers, afford the signal line densities needed for today's signal-intensive devices. Either planned or under consideration are techniques that allow greater versatility and reduce costs or fabrication time. A device for adjusting resistor values by means of a laser beam can also be programmed to adjust circuits to specific functions such as output frequency or offset voltage. A new commercial materials system uses thick-film techniques to make multilayer cofired substrates, thus bringing in house the capacitance advantage of cofired ceramic technology, with a great decrease in manufacturing time. A pen or a direct writing system will eliminate the need for artwork and screens by writing directly on a ceramic substrate from a tape generated by a computer-aided design system. This technique allows the very rapid building of a few or prototype circuits for performance checks. Beyond the specifics of the thick-film substrates, such devices and techniques are part of a continuing effort to ensure the benefits of today's technologies to APL.

REFERENCES

- ¹H. K. Charles, Jr., and G. D. Wagner, "Microelectronics at APL: The First Quarter Century," *Johns Hopkins APL Tech. Dig.* **6**, 130 (1985).
- ²H. K. Charles, Jr., and B. M. Romenesko, "Ceramic Chip Carrier Soldering, Cleaning and Reliability," in *Proc. 1982 IEEE Electronic Components Conf.*, pp. 369-375 (1982).

THE AUTHORS

BRUCE M. ROMENESKO (right) is a senior staff physicist in the Microelectronics Group. He holds a B.S. from the University of Wisconsin and a Ph.D. in solid-state physics from the University of Maryland. After working at Teledyne Energy Systems for three years in heat transfer and semiconductor materials development, he joined APL in 1979. Mr. Romenesko's assignments have included supervising the Process Development and the Substrate Fabrication Sections of the Technical Services Department, where he was responsible for establishing the Thick Film Laboratory. He now supervises the Microcircuit Assembly Section and coordinates the design and fabrication of the electronic hardware for the NROSS signal processor.

PAUL R. FALK (left) was born in Baltimore in 1948. He joined APL's Microelectronics Group in 1977 as a photographer specializing in hybrid photolithography. He received an A.A. from Catonsville Community College in 1983 and is pursuing a B.S. in information systems management at the University of Maryland. Mr. Falk is currently working as an engineering assistant in the Process Development Section of the Microelectronics Group.

KENNETH G. HOGGARTH (center) was born in England in 1925 and attended Cornell University and the University of Maryland with course work in chemical engineering and solid-state physics. He joined APL in 1967 as a member of the Milton S. Eisenhower



Research Center's Solid State Technology Branch, where his work principally concerned vapor deposition processes for thin films. In 1985, Mr. Hoggarth joined the Microelectronics Group, where he is working in thick-film fabrication and development.