An Introduction to the Navy Manufacturing Technology Program for Computerized Thick-Film Printing

DAVID F. ZARNOW, MEMBER, IEEE

Abstract—The objective of the Navy Manufacturing Technology Program for Computerized Thick-Film Printing is to establish advanced thick-film hybrid manufacturing capabilities that are cost effective and efficient when applied to the comparatively small quantities of thick-film hybrid microcircuits typically associated with defense avionics development and production programs. This program will establish a thick-film hybrid microcircuit manufacturing technology based on high-speed orifice writing processes, controlled by computer-aided hardware and software, for low-cost and fine-line deposition of thick-film materials onto ceramic substrates. As a result of this program, Navy microelectronic hardware acquisition costs will be reduced. Contractor production cycles will be shortened through the reduction or elimination of those costs presently associated with key labor-intensive thick-film manufacturing processes. Specifically, savings should be realized by elimination of 1) critical artwork generation procedures, 2) photolithographic preparation of stencil screens necessary for microcircuit fabrication, 3) intermediate production tooling as represented by the stencil screens, and 4) lengthy prototype-and-redesign cycles. The proposed manufacturing technology is directed toward, but not limited to, the hybrid microelectronics manufacturer who typically has modest thick-film and assembly capabilities, but has virtually no efficient in-house means to generate complex artwork. Currently, this manufacturer is constrained to the labor-intensive stencil screen preparation required for screen printing. Realization of this manufacturing technology will enhance even the smallest fabrication facility. It will provide not only a tooling-free microcircuit printing capability for prototype and limited production quantities, but a complementary microcircuit pattern design capability as well.

INTRODUCTION

THICK-FILM HYBRID microcircuit systems fabricated for defense development and production programs generally consist of a variety of microcircuits produced in relatively small quantities. A typical defense program effort calls for a system, usually consisting of eight to ten distinct hybrid microcircuits, to be built in prototype quantities of ten to 30 and produced annually in quantities of 100 to 300.

Most commercial thick-film applications, by comparison, are typically for few microcircuit types, but in large quantities. Automotive applications such as radios and voltage regulators for ignition systems are good examples. Comprised of one to three hybrids, these systems are built in vast quantities approaching, and many times exceeding, the millions of units.

In either case, however, whether for a commercial or a defense-related effort, the same basic thick-film technology is used. In fact, the hybrid microelectronics industry tacitly has

endorsed the premise that conventional thick-film technology is applicable to both because, in practice, it is applied to both!

It is the contention of this paper that this premise is false. As the diversity of microcircuit requirements continues to broaden, it becomes apparent that all thick-film applications can no longer universally conform to the dictates of the one "conventional" technology. Rather, for some very important economic and technical reasons, there is great motivation to significantly change, or at the very least to supplement, conventional thick-film technology. Obviously, process modification can occur either through natural evolution or by the impetus of a manufacturing technology program.

CONVENTIONAL THICK-FILM TECHNOLOGY

In order to better understand the motivations for changing the nature of the current technology, it is first necessary to gain an appreciation for the basic objectives of conventional thick film. This technology provides a custom interconnection scheme for microminiature solid-state "chip" components—such as integrated circuits, transistors, and diodes—as well as for passive chip capacitors and resistors. Thick film is truly a "hybrid" technology in that it draws upon the best there is to offer from the many worlds of microelectronics. Active solid-state and passive film devices, assembled together on the interconnecting thick-film substrate, define a hybrid microcircuit.

Fig. 1 readily establishes the attractiveness of conventional thick-film technology to provide an interconnection substrate as a component of the hybrid microcircuit. The process steps followed in a fabrication run for thick-film substrates are simple and straightforward. The thick-film fabrication run is simply an iterative process in which layer upon layer of various materials (ceramic-metallic glazes) are screen printed to different patterns. These are dried and fired successively onto ceramic substrates.

Simply stated, thick-film fabrication is a straightforward way to produce a lot of reasonably good substrates in a short period. Usually even with a modest thick-film facility, enough substrates can be produced in a day to keep a not-so-modest assembly facility occupied for weeks or even months. The performance of thick-film resistors, for example, is typically more than adequate for most linear circuit applications. Currently, multilayer thick-film fabrication is the only means to achieve the vast number of interconnections and the component densities required by many digital circuit applications.

Economic Characteristics

While the conventional thick-film technology is a good way to quickly produce quantities of one type of substrate, it is a

Manuscript received April 27, 1980; revised May 20, 1980.

The author is with the Advanced Microelectronics Engineering Staff, Naval Avionics Center, 6000 E. 21st Street, Indianapolis, IN 46218.

Fig. 1. Simplified block diagram of conventional thick-film process.

poor way to achieve either substrate variety or the turn-around responsiveness required in defense applications. Very often, for whatever reason, many iterations through the entire sequence of steps shown in Fig. 1 are required. Particularly when the hybrid microcircuit itself is the breadboard and not just the prototype, do thick-film cost effectiveness and turn-around efficiency really suffer. Only when the substrate delivery quantities exceed 500-1000 parts does amortization of thick-film preparation costs become possible. And only after the microcircuit pattern has been cast in stencil screen emulsion for the final time can conventional thick film be truly responsive to defense applications in a comprehensive way. The actual fabrication run for nearly every microcircuit, however complicated the microcircuit may seem, is anticlimactic compared to all of the human efforts required to prepare for the run.

Moving the thick-film substrate parts from the conveyor belt on a drying oven to one on a firing furnace, and then placing the parts on trays after the firing step, requires very little effort or skill. In contrast to this is the labor-intensive craftsmanship inherent to screen printing the microcircuit patterns onto a substrate. The art of screen printing is very much dependent on key prefabrication-run thick-film procedures. Fig. 2 is an expanded representation of the process flow taken in preparing for a fabrication run. Table I summarizes the potentially avoidable procedures and their associated labor and material costs—"up-front" costs that must be incurred even before the first pattern of any microcircuit can be screen printed. Table II also clearly demonstrates, by use of some conservative examples, that these up-front costs can compound significantly. This is true even if all of the substrates perform properly after only the first fabrication attempt.

Technical Characteristics

Proper design of thick-film components using current technology is no easy chore. Plodding through many layout and fabrication iterations until the target values for the thick-film components are achieved is often the only design approach taken. This uninspiring approach is typical for thick-film resistor fabrication, even when the circuit design is fixed. Lack of resistor design knowledge is at least partially indicative of a lack of understanding of the screen printing process—not a process which is, of course, easy to understand!

Traditional screen printing deposition methods contribute to discrepancies in a less-than-perfect ideal model for a resistive thick film. Most notably, film thickness is some function of the print geometry: the length and width of the resistor. The effective sheet resistance, in turn, is some inverse function of this thickness function and, to complicate matters, resistor value distributions are known to be dependently related to the printed film thickness vis-a-vis the print geometry!

For a small resistor, the print thickness of the deposit is roughly equal to the conductor film thickness plus the emulsion thickness of the stencil screen. Since the screen mesh is well supported by the conductor termination and the screen emulsion, and the screen opening for the resistor is small, a major deflection of the mesh toward the substrate by the squeegee is very unlikely. For a large resistor, the effective

print thickness is approximately equal to two wire diameters, so the squeegee can significantly deflect unsupported screen mesh into contact with the substrate.

Thus with screen printing a whole range of "three-dimensional" film geometries can be expected. Small resistor geometries will print thicker than ideally expected with convex surfaces, while large resistor geometries will be effectively thinner than ideally expected with concave surfaces. Also, there is less variance in the thickness of deposit for the larger resistor geometries. This is because the screen mesh is consistently brought into contact with the substrate in a very repeatable manner. Conversely, greater variance is a real barrier for small precision resistors. It can be expected then, for a given resistor size, that any differences in the myriad numbers of screen printing variables from one "established" printing process to another will result in effective differences in the physical, and thus the electrical, film characteristics and their repeatability.

A MANUFACTURING TECHNOLOGY PROGRAM

Objectives

The objective of the Navy Manufacturing Technology (MT) Program for Computerized Thick-Film Printing is to establish advanced thick-film hybrid manufacturing capabilities that are cost effective and efficient. This capability is intended to be applicable to comparatively small quantities of thick-film hybrid microcircuits associated with defense development and production programs.

This program will establish a thick-film hybrid microcircuit manufacturing technology based on high-speed orifice writing processes. These processes will be controlled directly by computer-aided hardware and software. This approach will fulfill both an economic and a technical goal. It will permit low-cost deposition of thick-film materials onto ceramic substrates and provide well-controlled high-resolution fine-line printing so necessary in defense applications.

Scope

The scope of the manufacturing technology program is purposefully broad in order to address all essential elements of computerized thick-film printing. As a manufacturing technology program, this program will build on the demonstrated feasibility of first generation computerized thick-film printers [1], [2]. The work effort is designed not only to establish the technological maturity of next-generation computerized thick-film printing, but also to demonstrate its attractiveness and superior salient features. At the same time the work effort should alleviate doubts and skepticism about the applicability of computerized thick-film printing to defense-related microelectronics programs.

First-generation computerized thick-film printers are available [3]. Their productive capacities and efficiencies have been oriented toward iterative prototype applications. Their use has been tied to the capabilities of screen print technology (e.g., printed line and space dimensions no less than 250 μm) for the subsequent volume production of the finalized microcircuit.

Fig. 2. Expanded representation of preparation for a fabrication run (dashed area eliminated by computerized thick-film printing).

TABLE I
AVOIDABLE SCREEN PRINTING PROCEDURES AND
ASSOCIATED COSTS

ARTWORK GENERATION & INSPECTION ELIMINATED	1/2 HR/PRINTING x \$25/HR	- \$12.50/PRINTING
PHOTOLITHOGRAPHIC PREPARATION & INSPECTION OF STENCIL SCREENS ELIMINATED	1 HR/PRINTING x \$25/HR	- \$25.00/PRINTING
PRODUCTION TOOLING ELIMINATED (RUBYLITH MASTERS, ARTWORK FILING, SCREENS)	\$30/PRINTING	- \$30.00/PRINTING
EQUIPMENT PREPARATION--PRINTER SET-UP AND ALIGNMENT TIME REDUCED	1/2 HR/PRINTING x \$25/HR	- \$12.50/PRINTING
MATERIAL WASTE (10 GM/PRINT SAVINGS)	10 GM x \$17.00/GM	- \$170.00/PRINTING
PER SCREEN PRINTING SAVINGS		\$250.00/PRINTING

TABLE II
EXAMPLE OF UP-FRONT COSTS PER FIRM FOR TYPICAL
MILITARY APPLICATIONS

LINEAR MICROELECTRONIC SYSTEM--RESISTORS		
5 MICROCIRCUITS (1 CONDUCTOR, 3 RESISTOR PRINTINGS/MICROCIRCUIT)	5 x 4 x \$250	- \$5,000
DIGITAL MICROELECTRONIC SYSTEM--MULTILAYERS		
2 MICROCIRCUITS (3 CONDUCTOR, 5 DIELECTRIC PRINTINGS/MICROCIRCUIT)	2 x 8 x \$250	- \$4,000
UP-FRONT COSTS PER FIRM		
3 LINEAR SYSTEMS & 2 DIGITAL SYSTEMS -	(3 x \$5,000) + (2 x \$4,000)	- \$23,000.00

Necessary marketing ingredients are incorporated into the MT work effort so that sources for next-generation high-speed computerized printing technology will be readily available from the private sector. Just as markets and sources arose naturally for automated laser trimming and wire bonding systems, so too will they come about for the next generation of computerized thick-film printing systems, but with the aid of this program.

The program effort will benefit primarily the producers of defense-grade hybrid microcircuits. Specifically, it is directed toward the defense and aerospace companies and corporations that support currently over 100 prototyping and production facilities for electronic hardware.

Economic Considerations

In a general sense, this manufacturing technology is directed toward, but not limited to, the hybrid microelectronics manufacturer who typically has a modest thick-film and assembly capability. Because he typically has no efficient in-house means to generate complex artwork, he is constrained to the labor-intensive stencil screen preparation required for screen printing. Realization of this manufacturing technology will enhance even the smallest fabrication facility. It will provide not only a tooling-free microcircuit printing capability for prototype and limited production quantities, but a complementary microcircuit pattern design capability as well.

Combination and integration of the microcircuit design and fabrication procedures are the keys to establishing a cost effective thick-film manufacturing technology for defense development programs. Significantly, this will eliminate all of the prefabrication-run procedures shown enclosed in the dashed area in Fig. 2 and all of the associated costs listed in Tables I and II.

Currently, microcircuit layout procedures and artwork generation equipment, as has been shown, are distinct with re-

spect to the screen printing process and equipment. Microcircuit redesign currently cannot be accomplished at the screen printer. No redesigned microcircuits can be printed without first making a major commitment in labor and materials to generate new artwork and stencil screens. While the design of a microcircuit can be accomplished at the interactive graphics system, the printing of its patterns cannot. Similarly, printing of the patterns can be accomplished at the screen printer, but the designing of the microcircuit cannot.

Furthermore, personnel highly trained and efficient in the mechanics of interactive graphics design usually have very little working knowledge of the capabilities of the screen printing process. Conversely, personnel adroit at screen printing typically have very little appreciation for microcircuit design considerations. The potential for a misunderstanding to occur between the design and printing phases will be eliminated by their merger. With this integrated capability there no longer need be the periodic breakdowns in communication between design and fabrication centers, regardless of whether they are located on opposite coasts of the country or down the same hallway.

The envisaged computerized thick-film printing technology will make it natural for one set of personnel to be responsible for both layout design and fabrication, and possibly even documentation. In the layout phase of a hybrid development effort the interactive graphics systems is used to produce check plots of the substrate pattern. Similarly, in the deposition phase, the screen printer is used initially to produce trial prints of the thick-film substrate prototype. The check plotting and trial printing of traditional thick-film technology will be combined to form "check printing" in computerized printing technology. The substrate "check print" then not only serves as a prototype, but it can actually be used as the basis for "hybrid breadboarding" of the circuit. If the hybrid breadboard performance is unsatisfactory, then a new modified check print substrate can be written, processed, and tested. In this way, computerized thick-film printing will make hybrid microcircuitry easier and faster to build, thereby making it cheaper.

Technical Considerations

One of the most perplexing problems in conventional thick-film technology is the inability to achieve well-controlled high-resolution fine-line printing. Fine-line printing, it must be understood, does not refer only to the classical definition. It is more than the ability to deposit materials in lines whose lateral dimensions are small, or so that the distance between adjacent lines is small. Fine-line printing means this and much more for defense-related thick-film applications. It means the ability to maintain constant print thickness and film thickness uniformity over the entire substrate area while making small narrow lines and spaces.

In a microwave application, for example, a conductor line whose width is a "fine" 250 μm may exhibit significantly different impedance characteristics depending on whether it has a flat surface or a rounded one, or if it has variations in its film thickness. Although conventional thick-film technology is

capable of producing relatively fine lines in the classical sense, the surface and edge topography variations also produced severely limit thick film's usefulness for high-frequency applications.

The reliability of wire bonds in hybrid microcircuits that are assembled with standard chip-and-wire processes is very much a function of the topography of the bonding sites. The wire bond sites on an integrated circuit chip are consistently flat and smooth as a result of their fabrication process. This affords the operator of the wire bonder a good chance to make a reliable initial bond. Completing the electrical connection to the thick-film conductor line, making the final bond, is exactly the opposite.

The thick-film screen printing process creates the projections and pinnacles in the surface of the thick film. It is left to the operator of the bonder to choose a reasonably flat plain on the film to act as a good site for the bonding tool. Again, if the film can be made flatter and smoother, the wire bonding operation will become easier to accomplish. And if wire bonding becomes easier, it not only becomes faster, but it will become more reliable as well.

THE WORK EFFORT

The Navy Manufacturing Technology Program for Computerized Thick-Film Printing, sponsored by the Naval Air Systems Command, is a development of the Naval Avionics Center (NAC). A two-year two-phase effort has been contracted by NAC to establish a mature and desirable computerized thick-film printing technology [1]. Fig. 3 gives a comprehensive overview of the entire program, showing the division of program responsibility and the emphasis of both NAC and contractor proposed efforts.

The proposed NAC effort emphasizes economic and technical comparisons between state-of-the-art screen printing and computerized printing technologies. It also encompasses the enhancement of the emerging computerized printing technology. Layout, design, and analysis software for microelectronics applications are proposed to be adapted directly to the technology of computerized thick-film printing. Finally, findings will be disseminated in an effort to promote computerized thick-film printing to the microelectronics industry.

This paper details the thrust of the contractor's efforts and program responsibilities for developing the hardware for computerized thick-film printing technology. As of this writing, the contracted effort is underway. It is in the second task of the first phase which deals with the hardware implementation for a computerized thick-film printer.

The first phase of the contracted effort consists of establishing the manufacturing technology for orifice deposition of conventional thick-film materials. This is defined as the actual ability to deposit thick-film materials without adversely affecting the basic inherent reliability of the fired films (as documented and published by the material vendor based on screen printing deposition). The first phase encompasses implementing the writing system equipment vis-a-vis compositional and morphological properties, fluid mechanics and dynamics, and economic factors associated with thick-film materials.

In this phase a high-speed orifice writing system will be configured, proofed and refined, and fully documented. System optimization, production capability and capacity, efficiency, and effectiveness will be established to specified levels.

The second phase consists of demonstrating both the prototyping and limited production efficiencies for the manufacturing technology. Microcircuit layout constraints that are process-related will be determined. Limited volume production methods will be established.

PHASE ONE

Phase 1 consists of three principal tasks:

- 1) selection of candidate thick-film materials for orifice deposition,
- 2) fabrication, documentation, optimization, and characterization of an automated high-speed orifice writing system,
- 3) film characterization.

Phase 1, Task 1

Two thick-film systems (a system is composed of a conductor, a dielectric, and resistor materials) are selected by the contractor from different thick-film paste manufacturers. The systems must have wide defense industry acceptance. They must also be viable candidates for orifice deposition on the basis of 1) morphological considerations (functional phase particle size and shape, paste rheology, vehicle modification or substitution, etc.) and 2) orifice flow characteristics necessary for target production rates, target line resolution control, and target thicknesses.

This program is limited to depositing one specific form of commercially available thick-film material. Only thick-film powder morphology systems—commonly referred to as thick-film pastes, inks, or electronic compositions for screen printing—will be considered. Specifically, only gold and gold-platinum conductor pastes, low- K dielectric pastes (the dielectric constant K must be no greater than 15), and ruthenium-based resistor pastes presently used in defense-related thick-film microcircuits will be used.

Computerized printing, from a materials standpoint, will yield thick-films of established reliability, performance, and wide defense industry acceptance. Part of this effort is to establish the proper organic vehicle for orifice deposition of the functional phase constituents of a given powder morphology system, and to insure that the fired films deposited by orifice printing exhibit physical, mechanical, and electrical properties comparable to those deposited by traditional screen printing processes. Furthermore, any intentional modification of any physical characteristic of the functional phase metal, metal oxide, and glass frit powders that constitute an existing powder morphology system (including any metallo-organic additives) is not within the scope of this program.

The organic vehicles used for screen printing purposes may be altered or replaced in order to accommodate the functional phase powders to an orifice deposition approach. However, they must be employed solely to suspend the functional phase constituents of the commercially available materials.

Fig. 3. Overview of Navy Computerized Thick-Film Printing Manufacturing Technology and proposed program responsibilities.

Phase 1, Task 2

This task is concerned with the construction and documentation of the automated high-speed orifice writing system. The envisaged orifice writing system, shown in Fig. 4, must be based on the following concepts:

- 1) off-the-shelf commercially available components, when possible;
- 2) integration of microcircuit design and printing capabilities;
- 3) *in situ* variability of microcircuit pattern print information via software instructions;
- 4) directly additive material deposition;
- 5) constant print thickness control independent of the print geometry;
- 6) efficient material management.

As has been discussed, many of these concepts are simply non-existent with respect to traditional thick-film technology in general and screen printing in particular.

The hardware implementation for the orifice writing system is comprised of four basic subsystems. They are

- 1) a commercially available microcomputer-based interactive desk-top computer equipped with video interactive graphics and a flatbed plotter in order to provide the programming (in a high-level user's language such as Basic) and editing capability needed to design and encode a microcircuit pattern and also equipped as necessary to exercise control over the subsystems and other essential peripherals;
- 2) a digitally controlled translation subsystem (e.g., X-Y table);
- 3) a digitally controlled orifice deposition subsystem based on a suitable methodology for dispensing thick-film pastes and which is able to employ one more interchangeable styluses;
- 4) a surface tracking assembly or subsystem to track substrate camber and provide print thickness and thickness uniformity control when dispensing.

All microcircuit patterns for the writing system will be predefined solely on the basis of software instructions stored on a mass storage medium such as magnetic tape or disk. A stored instruction file then can be loaded into the memory and the necessary instructions to direct the system to write the microcircuit pattern can be executed sequentially by the desk-top computer. The instruction file then can be iteratively executed or edited *in situ* in an efficient fashion to produce printed thick-film substrates.

Equipment utilized in association with this manufacturing technology will not rely on any intermediate tooling (such as stencil screens, image transfer tapes, masks, artwork films, photoresists, resists, etc.) in order to selectively deposit thick-film materials. Furthermore, the system will be capable of accepting each thick-film conductor, dielectric, and resistor material in fluid form as it comes from the paste manufacturer. It then will be able to directly deposit each in independent writing cycles.

COMPUTER/CONTROLLER SUBSYSTEM

Fig. 4. Block diagram of high-speed orifice writing system.

As a consequence of this phase, the management of precious thick-film materials will be greatly enhanced. No more than 10 g of material to charge the system for printing will be allowed. Currently, it typically requires a minimum of 20 g with screen printing just to wet the screen, not to mention the resulting material waste! With the writing system, only the amount of material that is required is used because, ideally, that is all that needs to be dispensed from the stylus. The system can accept cartridges or syringes as reservoir material sources, providing that the functional phase powders remain in suspension and do not settle out. Also, the interchangeability of styluses of differing orifice diameters will improve writing efficiencies for specific applications.

The proofing and refining of automated printing concepts will be based on material systems chosen in the first task of this phase. Automated printing concepts will be considered proofed and refined when the hardware implementation for the writing system achieves operational status within target limits. These target limits are defined in terms of the universal deposition variables: fired film thickness, fired film line/space resolution, and printing (writing) cycle time. The writing system will operate efficiently, with a constant orifice diameter, over the matrix of deposition variable ranges depicted in Fig. 5 and parametrically presented in Table III.

Based on NAC experience, values for the limits of the ranges have been chosen. Computerized thick-film printing will be highly competitive with the type of screen printing found in typical defense facilities when it meets the following target ranges for thickness, resolution, and write cycle.

- 1) **Thickness:** $t_0/2 \leq t \leq 3t_0/2$, where t is the fired film thickness based on the orifice deposition approach and t_0 is the vendor-recommended fired film thickness based on screen printing. The fired film thickness uniformity tolerance is ten percent over the entire range as shown in Fig. 6(a).

Fig. 5. Matrix of deposition variables for proofing and refining automated orifice printing concepts.

TABLE III
DEPOSITION PARAMETER VALUES FOR FIRED FILM
CHARACTERISTICS

Permutation Number	Fired Film Thickness at 90% Thickness Uniformity Control* t (micrometers)	Fired Film Line/Space Resolution** w (micrometers)	Write Cycle Time*** T (seconds)
1	$t_0/2$	100	30
2	$t_0/2$	100	60
3	$t_0/2$	100	90
4	$t_0/2$	150	30
5	$t_0/2$	150	60
6	$t_0/2$	150	90
7	$t_0/2$	200	30
8	$t_0/2$	200	60
9	$t_0/2$	200	90
10	t_0	100	30
11	t_0	100	60
12	t_0	100	90
13	t_0	150	30
14	t_0	150	60
15	t_0	150	90
16	t_0	200	30
17	t_0	200	60
18	t_0	200	90
19	$3t_0/2$	100	30
20	$3t_0/2$	100	60
21	$3t_0/2$	100	90
22	$3t_0/2$	150	30
23	$3t_0/2$	150	60
24	$3t_0/2$	150	90
25	$3t_0/2$	200	30
26	$3t_0/2$	200	60
27	$3t_0/2$	200	90

* t_0 is the vendor recommended fired film thickness based on screen printing.

**Tolerances shown in Figure 6.

***Based on 25% printed area density for a 25 mm x 25 mm substrate.

* Sufficiently flat so as to be compatible with thermocompression and ultrasonic wire bonding processes.

Fig. 6. Print thickness, thickness uniformity, and line resolution control tolerances (cross sections shown). (a) Thickness control. (b) Flatness of print.

- 2) **Resolution:** $100 \mu\text{m} \leq w \leq 200 \mu\text{m}$, where w is the fired line width or space between adjacent fired films. The fired film width tolerance characteristics over the entire range are those depicted in Fig. 6(b).
- 3) **Write cycle:** $30 \leq T \leq 90$ s, where T is the write cycle time per substrate print and is based on a 25 mm $\times$ 25 mm substrate printed to a 25-percent area density.

- 3) orifice diameter,
- 4) orifice shape,
- 5) pneumatic pressure,
- 6) ink viscosity.

Phase 1, Task 3

The writing system will be capable of producing prints that when fired will be free of voids, pinholes, and ragged edges under visual inspection by microscope at 30X with transmitted and incident light. Fired lines will be sufficiently flat (as defined in Fig. 6(b)) to be compatible with manual and automated thermocompression and ultrasonic wire bonding processes.

The contractor will perform a parametric characterization of the writing system. The sensitivities of the subsystem parameters and their relationship to the thick-film material characteristics will be established. Their interactive tendencies to effect change in the fired film integrity will be identified.

From a user standpoint, this information will be extremely valuable because it will relate the deposition variables (previously defined) to the actual writing system operating parameters. Film thickness and line/space resolution of fired films and the print cycle time of the writing process will be documented and presented graphically. They will be related in nomograph form as functions of system parameters including, but not limited to

- 1) writing speed,
- 2) stylus height above the substrate,

The contractor will undertake a complete characterization of all fired films (conductor, dielectric, and resistor films) for each material system selected based on applicable and industry-accepted military testing procedures (e.g., MIL-STD 883). Testing will cover conductivity, solderability, and adhesion for conductors; dielectric constant, dissipation factor, insulation resistance, and breakdown voltage for dielectrics; and sheet resistance and temperature coefficients for resistors. The purpose of this task is to quantify the degree of distinguishability between the two deposition processes—screen printing and orifice writing—based on the characteristics of the fired films. All film characteristics at variance with the data published by the material vendor for screen printed films will be identified.

PHASE TWO

Phase 2 consists of three principal tasks:

- 1) demonstration of volume substrate production,
- 2) demonstration of prototyping efficiency,
- 3) establishment of microcircuit layout constraints.

Phase 2, Task 1

The viability of the manufacturing technology for limited volume production applications will be demonstrated. Three

Fig. 7. Passive microcircuit layout for volume microcircuit production.

groups of 200 passive microcircuits (conductors and resistors only) for each material system will be fabricated and delivered to NAC. Fig. 7 shows the passive microcircuit and Table IV lists the resistor dimensions. Even and odd number resistors are of different sheet resistances. Each set of 200 substrates for each material system will be fabricated with increasing sheet resistances: the first set with a low-range pair of resistivities, the second with a mid-range pair, and the third with a high-range pair.

At NAC these microcircuits will be compared to microcircuits that have been prepared using a state-of-the-art screen printing system. The two groups will be analyzed and characterized by the "lumped" parameter method developed at NAC [4]. This statistical method will be used to distinguish between the two contributors to thick-film resistor termination effects—the material diffusion phenomena and the deposition process phenomena. Predictor equations will result which mathematically will describe resistance as a function of resistor geometry.

The families of predictor equations established for both groups will be compared to directly distinguish between deposition processes. As previously discussed, the effective sheet resistance is very much a function of the resistor geometry since controlling all aspects of print thickness is elusive in screen printing. In computerized thick-film printing, as developed by this effort, print thickness control by feedback methods will be self-sustaining. Film thickness will be constant

TABLE IV
RESISTOR GEOMETRIES FOR LIMITED VOLUME
MICROCIRCUIT PRODUCTION (EVEN NUMBER
AND ODD NUMBER RESISTORS OF DIFFERENT
SHEET RESISTANCE)

No.	L x W (Millimeters)	L x W (Mils)*	No.	L x W (Millimeters)	L x W (Mils)*
1	2.286 x 0.762	90 x 30	20	3.810 x 1.524	150 x 60
2	2.286 x 3.048	90 x 120	21	0.381 x 0.762	15 x 30
3	0.381 x 1.524	15 x 60	22	3.048 x 3.048	120 x 120
4	3.048 x 1.524	120 x 60	23	1.270 x 0.508	50 x 20
5	1.143 x 1.524	45 x 60	24	1.524 x 1.016	60 x 40
6	1.143 x 3.048	45 x 120	25	0.762 x 1.524	30 x 60
7	0.762 x 0.508	30 x 20	26	1.524 x 2.286	60 x 90
8	3.048 x 1.016	120 x 40	27	1.524 x 1.524	60 x 60
9	0.762 x 0.762	30 x 30	28	0.381 x 0.508	15 x 20
10	1.143 x 2.286	45 x 90	29	2.032 x 1.016	80 x 40
11	1.524 x 3.048	60 x 120	30	1.143 x 0.762	45 x 30
12	0.508 x 1.016	20 x 40	31	2.286 x 1.524	90 x 60
13	3.048 x 0.762	120 x 30	32	0.762 x 3.048	30 x 120
14	1.016 x 1.016	40 x 40	33	0.508 x 0.508	20 x 20
15	2.286 x 2.286	90 x 90	34	0.762 x 1.016	30 x 40
16	0.762 x 2.286	30 x 90	35	1.905 x 0.762	75 x 30
17	1.524 x 0.508	60 x 20	36	1.524 x 0.762	60 x 30
18	0.254 x 0.508	10 x 20	37	1.016 x 0.508	40 x 20
19	4.572 x 1.524	180 x 60	38	2.540 x 1.016	100 x 40

*1 mil = 0.001 inches

Fig. 8. Circuit schematic for passive resistor microcircuit used to demonstrate transition efficiency of combined layout-and-print approach.

and independent of resistor geometry for the group printed by the writing system. Therefore, the equations for this group should be influenced only by the material diffusion phenomena.

The actual difference between corresponding equations in the two groups will be a direct quantification of the lack of uniformity in the screen printing process. Consequently, having this information will demonstrate that concern need remain only for the material diffusion phenomena and not for the deposition process. It then will be fair to conclude that the resistor design process will be simplified significantly by changing to a superior deposition process.

Phase 2, Task 2

This task will demonstrate the transition efficiency of the combined microcircuit layout and print approach from the circuit schematic, to the pattern layout, through the the prototype iterations of printing and editing (i.e., "check printing"), and to limited production. The actual turnaround efficiency from the circuit schematic to a working prototype will be documented for a unique passive resistor circuit. The circuit, shown in Fig. 8, is unique in that it will be fabricated under the following very special conditions:

- 1) all resistor geometries must be simple rectangles (no serpentes or top-hats allowed),
- 2) all resistors must be of one sheet resistance resistor material,
- 3) all resistors must be fabricated to value without trimming to within ten percent,
- 4) the paste's solids-to-solvents ratio must be constant for all resistors,
- 5) the microcircuit size must not exceed a size for a typical package (i.e., 12.7 mm X 22.225 mm).

While this is a rigorous test for orifice writing concepts, it is not necessarily unlikely for a manufacturer of hybrid microelectronics to encounter these types of fabrication constraints

in actual development programs. At the same time, the constraints placed on the fabrication of this circuit make it next to impossible to employ screen printing. Screen printing would require alternative measures. With computerized thick-film printing the task can be handled directly. For computerized thick-film printing it is a matter of expeditious trial and error to find and maintain the desirable print thickness for each resistor. Establishing the appropriate effective sheet resistance by finding and holding the proper print thickness is truly a test of the maturity of computerized thick-film printing.

Based on experience acquired during this phase, the contractor will complete a cost effectiveness and efficiency analysis of the orifice writing technology in microcircuit design and production. The contractor will identify cost factors associated with each stage of microcircuit development where computerized thick-film printing is involved.

Phase 2, Task 3

This task concerns the intrinsic features of the manufacturing technology with respect to microcircuit layout procedures. Characteristics unique to the technology will be documented both for conductor/resistor microcircuits for analog circuit applications and for multilayer conductor/dielectric microcircuits for digital applications. These then will serve as layout and fabrication guidelines so that taking full advantage of the new capabilities offered by computerized thick-film printing will become the rule rather than the exception.

CONCLUSION

There are great economic and technical inducements for changing the nature of thick-film technology, particularly with respect to a defense-related environment for hybrid microelectronics development. In this regard, computerized thick-film printing is a viable alternative to the traditional screen printing process. The economic and technical benefits and general desirability of computerized thick-film printing

demonstrated by this Navy manufacturing technology program should give rise to its rapid acceptance in the defense industry.

REFERENCES

- [1] Naval Avionics Center contract N00163-79-C-0175, Mar. 27, 1979, to RCA Corp., Government Systems Div., Missile and Surface Radar, Moorestown, NJ.
- [2] M. Shankin, "Write it, don't screen it!," in *Proc. 1978 Int. Microelectron. Symp. ISHM*, Minneapolis, MN.
- [3] Reverse Engineering Corporation, Van Nuys, CA, industry survey, Sept. 17, 1979.
- [4] D. F. Zarnow, "A new approach to thick film resistors," in *Proc. 1979 Int. Microelectron. Symp. ISHM*, Los Angeles, CA.

Computerized Thick-Film Printer

RONALD F. KOLC

Abstract—The computerized thick-film printer has been developed as a manufacturing tool for the efficient and economical production of small quantities of thick-film hybrid microcircuits. Its capability for fine-line definition onto ceramic substrates is based on the use of a high-speed orifice printing process. The printer reduces the time and cost of developing and producing thick-film hybrid microcircuits. Timesavings result because the printer can eliminate some of the steps involved in progressing from the design to screen printing of the circuits. Costsavings result because the printer can eliminate certain key labor-intensive thick-film manufacturing processes. Specifically, savings should be realized by the elimination of 1) critical artwork generation procedures, 2) photolithographic preparation of stencil screens for microcircuit fabrication, 3) intermediate production tooling as represented by the stencil screens, and 4) lengthy prototype-and-redesign cycles. The computerized thick-film printer provides the user with a pattern-design and printing capability suitable for producing prototypes and small-quantity production runs of hybrid.

INTRODUCTION

CONVENTIONAL thick-film technology is a good approach for the rapid production of quantities of a single type of substrate. On the other hand, it is not effective in achieving either the substrate variety of the turnaround responsiveness required in defense applications, which typically require small quantities of many different types. Very often, for a variety of reasons, the process requires many iterations throughout the entire sequence of steps shown in Fig. 1. Thick-film cost-effectiveness and turnaround efficiency can suffer, particularly when the hybrid microcircuit itself is the breadboard and not just the prototype. Only when the substrate delivery quantities

Fig. 1. Simplified block diagram of conventional thick-film process.

exceed 500-1000 parts does the amortization of thick-film preparation costs become possible. And only after the microcircuit pattern has been cast in stencil screen emulsion for the final time can conventional thick-film be truly responsive to defense applications in a comprehensive way.

The keys to establishing a cost-effective thick-film manufacturing technology for defense development programs lie in the combination and integration of the microcircuit design and fabrication procedures. Fig. 2 shows the stand-alone system with its integrated design and printing capabilities.

Manuscript received March 20, 1980; revised May 5, 1980.

The author is with RCA Government Systems Division, Missile and Surface Radar, Borton Landing Road, Moorestown, NJ 08057.