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U.S. ARMY MISSILE RESEARCH AND DEVELOPMENT COMMAND

TECHNICAL REPORT E-78-1

THICK-FILM FINE LINE PRINTING FINAL REPORT

Victor W. Ruwe, Kenneth Dean, and Robert E. Sulouff
Advanced Systems Directorate
Engineering Laboratory

September 1977

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Redstone Arsenal, Alabama 35809

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This report discusses the significant parameters in fine line printing (less than 0.005 lines and spaces) of thick-film microelectronic circuits. This considerations of the materials, substrate, paste rheology and the interaction of the elements in the manufacturing process are reported. The documented results of the experimental work are presented demonstrating 3-mil lines and spaces. The yield is presented as a function of line spacing, width, and length. The conclusions include process parameters to duplicate the results.

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CONTENTS

I. SUMMARY

This report details the investigation of significant parameters in fine line printing (less than 5-mil lines and spaces) of thick-film technology circuits. The topic is developed by consideration of the individual elements of the manufacturing process and by the interaction of the elements to achieve reasonable yields of actual printing patterns. This study has centered around the feasibility of producible line widths, spacings, and lengths that can be achieved with present state-of-the-art materials and equipment. The minimum values obtained were 0.003-in. lines and 0.003-in. spacings on alumina substrates.

The material considerations with regard to substrates, conductor, and dielectric pastes were first investigated. The composition of the substrate, the topological considerations, and the defect density are all important substrate parameters. The elements of the conductor and dielectric pastes and the characterization of each was a topic of investigation. The rheology of pastes and their corresponding response to processing is developed along with the drying and firing considerations. The mechanical aspects of screen preparation and alignment coupled with substrate properties has received significant attention.

The documented results of experimental work which achieved the desired goal of 3-mil lines and spaces provides application of earlier considerations. The use of test patterns was reported to provide many variables in a single test, each being mutually exclusive. The failures and successes of conductor dielectric and multilayer printing are also included.

The final conclusions state the feasibility and probability of fine line printing in thick film technology and recommend the important variables which require further study to improve yield and overall performance.

II. INTRODUCTION

The world of electronics has been advancing with unprecedented speed toward minimum size and increasing complexity along with ease of fabrication. The final goal, as always, is a better product at an economical price. The area of thick-film hybrid microelectronics is centered in the rush and has seen the strong influence of the quickly maturing microelectronic field. This influence is nowhere more strongly apparent than in the efforts to increase conductor density by reducing standard widths. The need for high density thick-film circuits thus demands conductor lines and spaces less than the standard of 10 mils.

The fabrication of fine lines and spaces using the thick-film technology is not a simple extension of present processes. The ease and simplicity associated with larger geometries does not willingly extrapolate to fine lines by making the openings in the stencil (screen) smaller. Careful considerations of individual materials and processes and the interactions involved must be studies to achieve reasonable results.

This report is to document the feasibility of achieving fine lines (0.003 in.) and spaces using thick-film technology. It is expected that additional investigation will be necessary to improve the manufacturing methods introduced in this initial feasibility study.

III. DISCUSSION

A. Material Considerations

The substrate and the thick-film pastes are the materials of primary interest in this investigation. The alumina substrate (Al_2O_3) is the basic building block of the circuit. The equipment used to apply the paste and the properties of the materials used all depend upon this basic substrate unit. The thick-film conductor and dielectric pastes are a complex mixture, processed to meet specific parameters. The transition from standard geometries to fine lines requires careful consideration of basic materials used in the process.

1. Substrate

The composition and finish of the substrate has a significant effect upon performance of a thick-film paste system [1]. In addition to the lot or process variant parameters of a substrate, the significance of thickness, camber, and waviness on the screen-substrate interactions are vital to the proper results (Figure 1). When the additional constraints of fine line printing are considered, the occurrence of burrs, blemishes, and blisters [2] can significantly reduce yield. The sorting of substrates as to physical dimensions and the imposition of more stringent requirements for camber and waviness become important considerations for a producible product in the realm of fine line thick-film.

2. Conductor Pastes

The thick-film conductor paste is composed of four parts (Figure 2) [1]:

1) The Vehicle — The vehicle is made up of an organic resin and a solvent. The screen printing properties of a paste are largely dictated by these two components. Following disposition by the screening process the solvent is driven off by a drying process. The organic resin is removed at the onset of the firing operation.

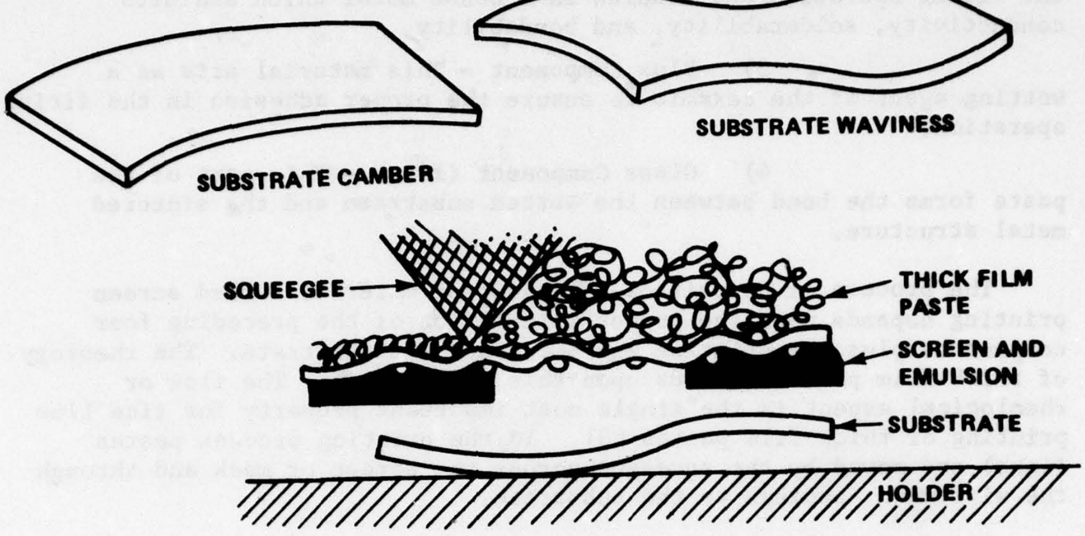

Figure 1. Substrate parameter influence on screen printing.

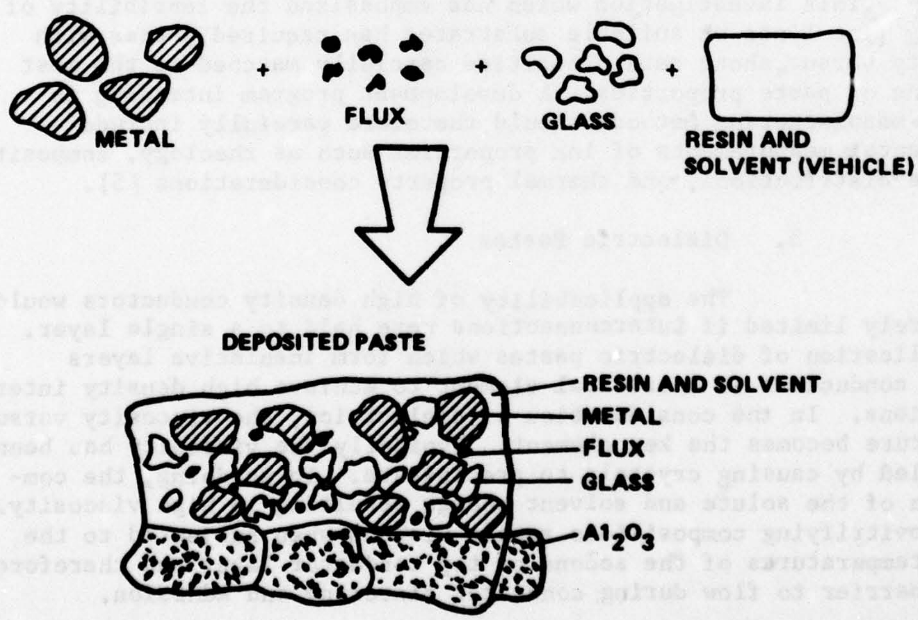

Figure 2. Paste components.

2) Metallic Component — This part of the paste is made up of one or more finely divided metallic powders sintered during the firing operation and results in a dense metal which exhibits conductivity, solderability, and bondability.

3) Flux Component — This material acts as a wetting agent of the ceramic to ensure the proper adhesion in the firing operation.

4) Glass Component (frit) — This part of the paste forms the bond between the wetted substrate and the sintered metal structure.

The process of deposition of conductor material termed screen printing depends upon the proper interaction of the preceding four components plus the printing equipment and the substrate. The rheology of thick-film pastes depends upon this interaction. The flow or rheological aspect is the single most important property for fine line printing of thick-film pastes [3]. In the printing process pastes (inks) are moved by the squeegee across the screen or mask and through the wire mesh openings to the substrate.

The aspects of rheology have been investigated extensively in the context of thick-film technology. The uniquely developed paper by R. M. Stanton [4] on rheology during the printing process has included certain theoretical aspects which have helped to bridge the gap to actual printing problems. This mention of work on rheology has been included to provide a balanced introduction to the topic of fine line printing. This investigation which has emphasized the feasibility of printing fine lines on suitable substrates has required pastes with viscosity versus shear rate properties carefully matched to the most demanding of paste properties. A development program intending to improve manufacturing methods should therefore carefully include instrumental measurements of ink properties such as rheology, composition, particle distributions, and thermal property considerations [5].

3. Dielectric Pastes

The applicability of high density conductors would be severely limited if interconnections were held to a single layer. The application of dielectric pastes which form insulative layers between conductors is a critical element to achieve high density interconnections. In the consideration of dielectrics, the viscosity versus temperature becomes the key element. Typically the viscosity has been controlled by causing crystals to precipitate. In so doing, the composition of the solute and solvent change resulting in high viscosity. These devitrifying compositions remain viscous when subjected to the firing temperatures of the second or top conductor layer and therefore form a barrier to flow during conductor sintering and adhesion.

The via formation where interconnection between successive layers of conductors is made is a specific area of consideration for dielectrics. The edge profile becomes a significant parameter in conductor formation. The surface roughness and probability of pinhole formation become critical when fine line printing is considered. The analysis of dielectric properties and typical problems will be demonstrated in the experimental results, Sections III.C.3 and III.C.4.

B. Process Considerations

The effective use of the previously mentioned materials of substrate, conductor paste, and dielectric paste is the primary aim of this section. Materials that are compatible and processible must be able to be screened, dried, and fired to close tolerances in fine line printing. The influence of photographic, screen preparation, and process interactions will be developed.

1. Photographic

The original definition of conductor lines and spaces and dielectric patterns is well within the present photographic technology. The generation of accurate size and shape edges with maximum contrast becomes more critical the smaller the geometry. Care must be used to insure homogeneous reduction of original artwork and proper handling procedures for increased yield. The particle contamination problems associated with improperly controlled or clear photographic areas can drastically reduce yield and hence producibility.

2. Screen Preparation

The printing screen and emulsion thickness are considered two of the most important elements of the thick-film process. Screen frames are used for supporting the woven mesh and are generally made of aluminum. The cast aluminum frames are used because of their ease of manufacture, strength, and reusability. The cast frames are often warped, stressed, and have numerous burrs and projections. Therefore, the frames must be machined to eliminate these defects. The top and bottom surfaces of the frame should be parallel to within 0.005 in.

The screen material commonly used is stainless steel. Although many weaves are possible, a plain square weave has been shown to be a durable pattern for thick-film technology [6]. The investigations detailed in this report were limited to a mesh count of 325/in. The wire diameter of the screen material was 0.0011 in. The screen material was mounted at 45° on the aluminum frame to provide maximum opening in the stencil pattern. These process considerations have been determined to be critical to the printing performance and were maintained throughout the evaluation.

The screen stencil performs as a mask or mold to define the geometry and to some extent the thickness of a print. The stencil is typically a plastic or gelatin coating referred to as an emulsion. The hybrid or direct-indirect stencil was used as the preferred technique to ensure maximum process flexibility along with excellent resolution and good screen lifetime. Evaluation of preferred emulsion thicknesses are detailed in the results, Section III.C.1.

3. Process Interactions

The paste on the proper screen to be printed onto the proper substrate still requires processing. The squeegee speed, pressure, material, hardness, angle, and stroke direction are carefully controlled printing considerations. The breakaway distance and the leveling and drying also introduce additional parameters which must be considered. The firing profiles of the materials and the actual profiles of the furnaces along with the atmosphere further influence the results. This section of the report could in no way develop the possible interactions or the significance of each processing parameter upon yield; however, the special considerations which relate to fine line deposition of wet pastes do restrict the considerations significantly.

To print fine lines the squeegee speed and pressure should insure a smooth flow of material through the screen openings and result in a corresponding even deposition of material which will remain on the substrate (Figure 3). Printing parameters can sometimes be altered to achieve the desirable end. The properties of the thick-film paste should be controlled to insure production speeds and results consistent from lot to lot. Additional studies of methods to examine and predict behavior of materials in a prescribed process would therefore be a natural extension of the feasibility study indicated here.

C. Experimental Results

This section of the report details the efforts performed to demonstrate the feasibility of fine line printing of thick-film conductors. The investigation of printing results designed to produce fine lines and spaces was developed through three different studies. The first study was related to printing of the test pattern of fine lines on substrates ground and unground. The second study involved the printing and firing of the fine line test pattern over a single printed dielectric pattern. The final experiment included the printing of the fine line pattern over a double layer of dielectric. The results are summarized as to failures per size and spacing of each of the studies.

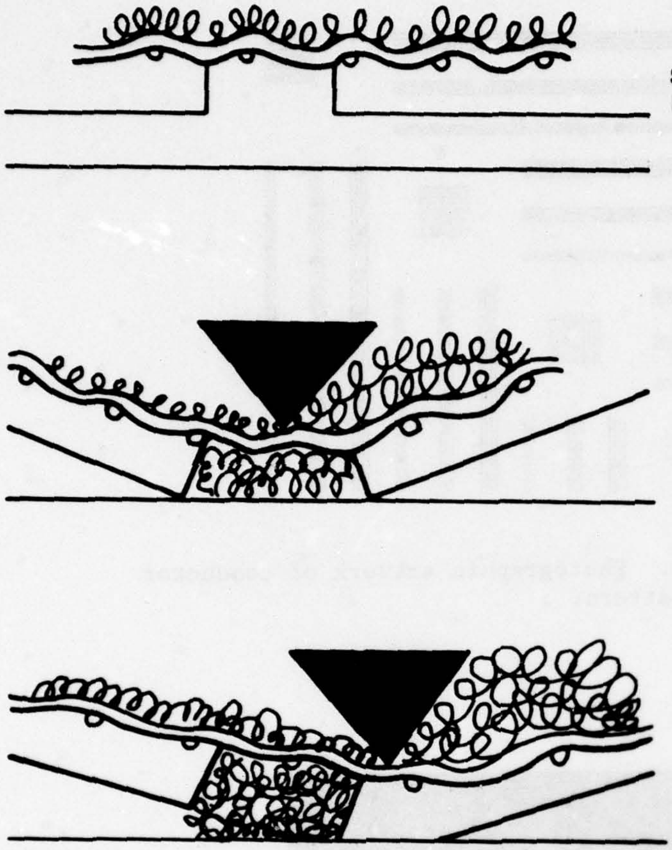

Figure 3. Disposition of material.

1. Test Patterns

In an effort to evaluate different printing results under similar testing situations, a standard pattern of lines and spaces was designed. The pattern as shown in Figure 4 includes lines both parallel and perpendicular to the left-to-right stroke of the squeegee head. The dielectric pattern is shown in Figure 5. The L-shaped design produces several step-up and step-down edges along with a dielectric top layer pattern to evaluate the influence of dielectric upon the conductor printing process. Backlighted photographs of the actual stencil screens are shown in Figures 6 and 7 for the conductor and dielectric test patterns.

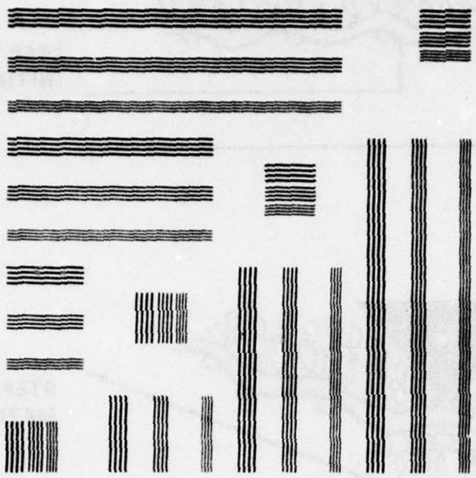

Figure 4. Photographic artwork of conductor test pattern.

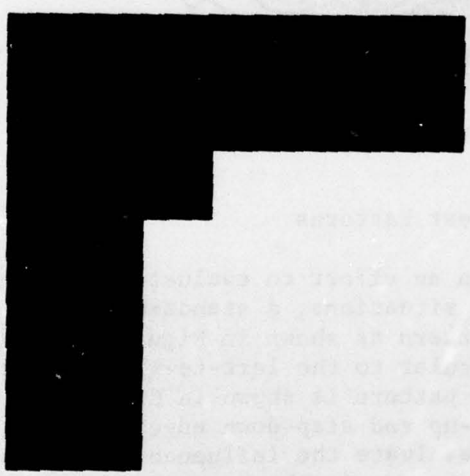

Figure 5. Photographic artwork of dielectric test pattern.

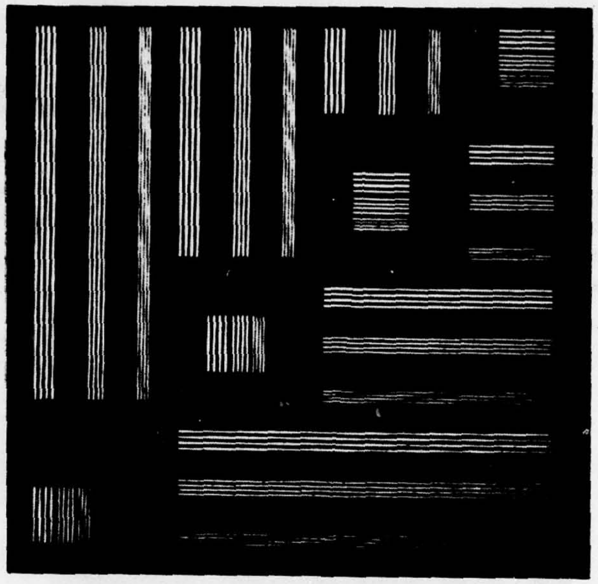

Figure 6. Stencil screen of conductor test pattern.

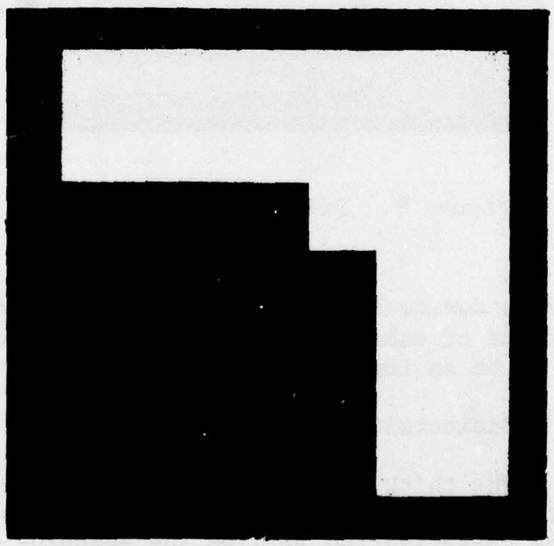

Figure 7. Stencil screen of dielectric test pattern.

2. Conductor Printing

The printing of the conductor test pattern on the substrate is shown in Figure 8. The substrate is shown backlighted to improve examination of the lines and spaces. The pattern is resolved in all cases with the 3-mil lines and spaces less than 1% failure (open or shorted) in short line length and approaching 20% failures in longer line length perpendicular to squeegee travel. The Appendix summarizes the results of this study of conductor printing on substrates. A failure is categorized as open or short (catastrophic).

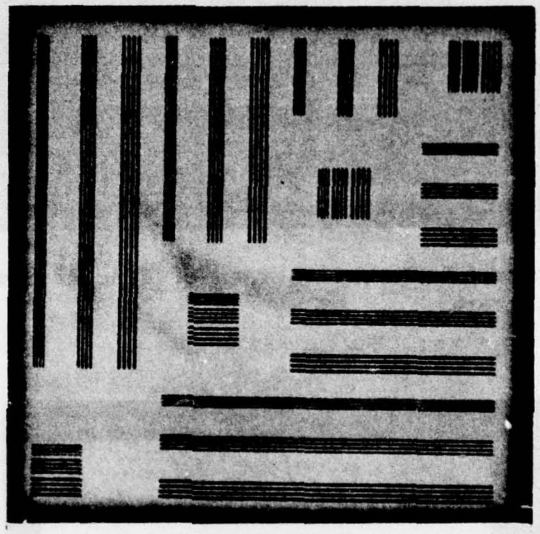

Figure 8. Printed substrate.

Typical failures due to substrate defects are shown in Figures 9 and 10. The effect of substrate thickness variations on the print quality are shown to be an important printing parameter.

3. Dielectric Printing

The thick-film printing of dielectric pastes does not require a test pattern for resolution of fine lines and spaces. This section of the investigation applied the scanning electron microscope to chart the surface finish of three different dielectric pastes. Shown in Figures 11, 12 and 13 are cross-sectional views of three different dielectric pastes.

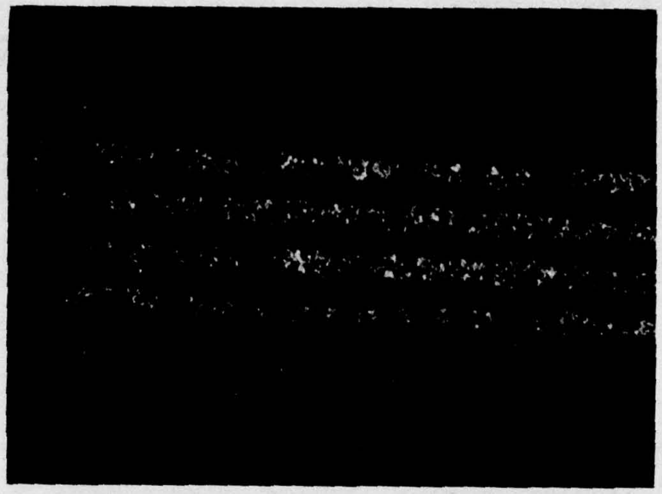

Figure 9. Printing failure due to thin substrate.

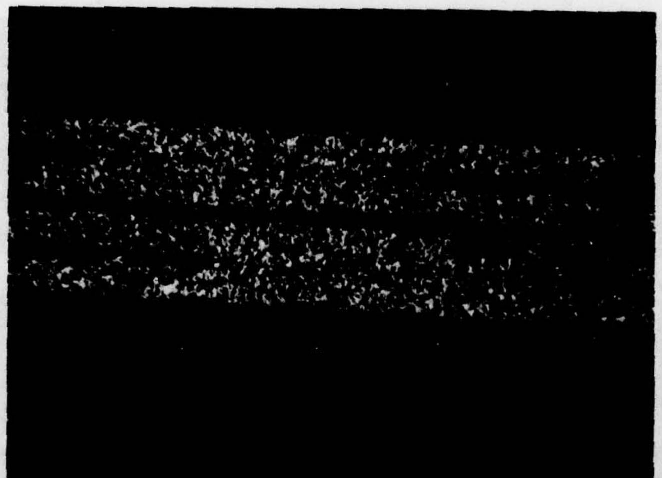

Figure 10. Printing failure due to thick substrate.

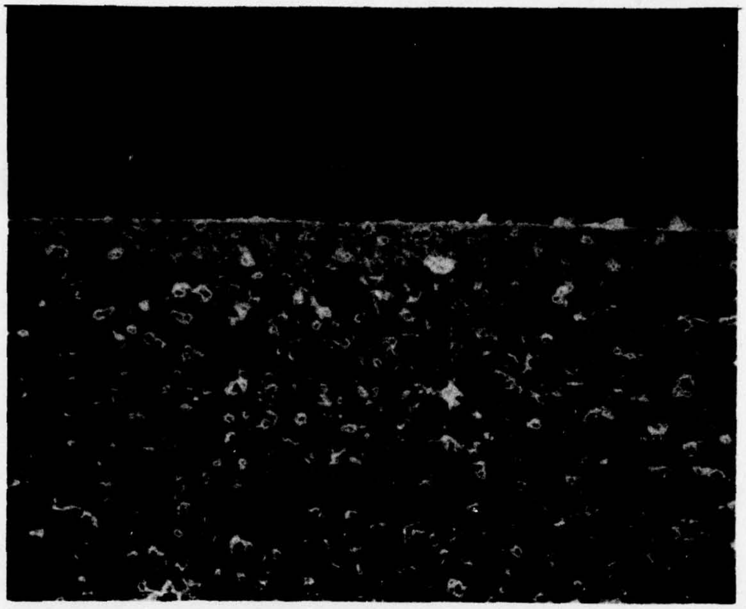

Figure 11. Cross-sectional view of dielectric Paste A, indicating surface roughness (200X).

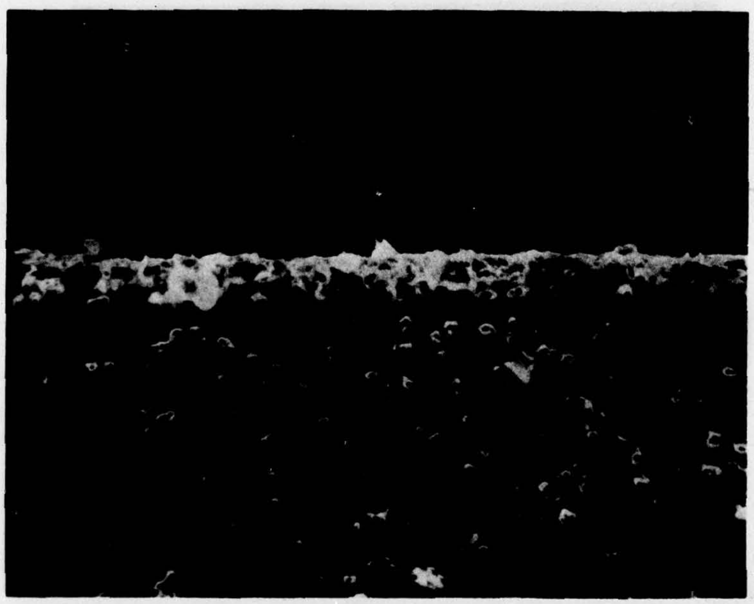

Figure 12. Cross-sectional view of dielectric Paste B, indicating surface roughness (200X).

Figure 13. Cross-sectional view of dielectric Paste C, indicating surface roughness (200X).

4. Multilayer Printing

The most significant area of investigation following demonstration of printing of fine lines on proper substrates is the study of fine line printing over dielectric material. Figure 14 is a backlighted substrate which has the conductor pattern printed over the dielectric pattern. The influence of the step at the substrate-dielectric can be seen in Figures 15 and 16.

IV. CONCLUSIONS AND RECOMMENDATIONS

The printing of 0.003-in. lines and spaces and larger has been evaluated and demonstrated. The high density conductors obtained were found to be strongly dependent upon the proper selection and application of the following:

a) Photographic — The art work must be precise. The photo emulsions should be dense to prevent undercutting.

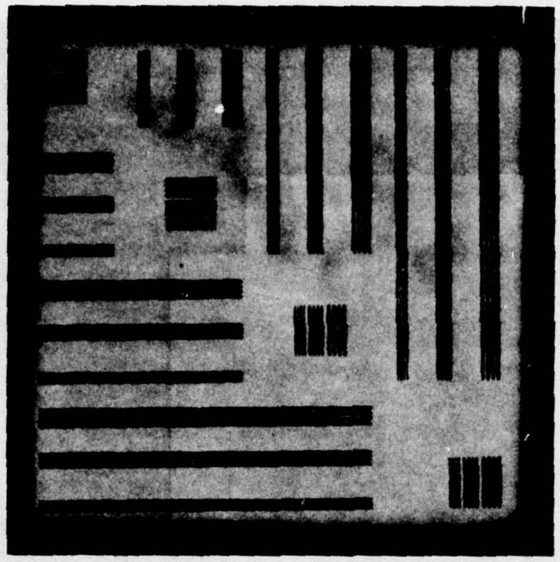

Figure 14. Conductor pattern printed over the dielectric pattern (2.8X).

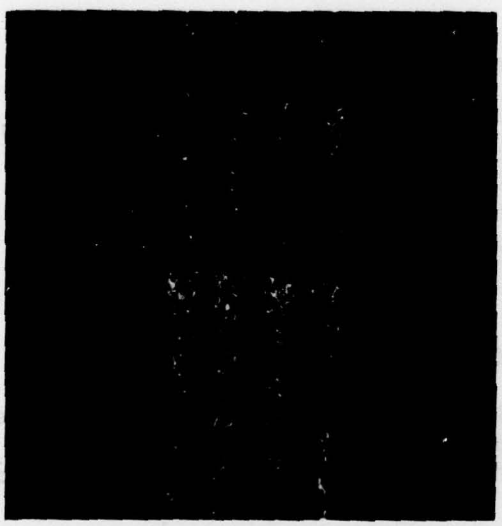

Figure 15. Conductor printing over single layer of dielectric.

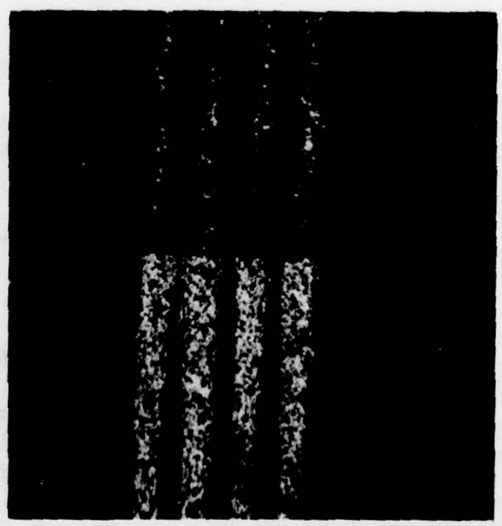

Figure 16. Conductor printing over double layer of dielectric.

b) Screen – The frames should be ground flat. A 325 mesh, 0.0011-in. wire diameter, plain square weave screen at 45° was found to produce accurate line widths and spaces.

c) Stencils – The hybrid or direct-indirect stencil provided excellent geometric transfer of art work to finish print.

d) Substrate – A flat substrate (0.001 in./in.) with thickness held to plus or minus 0.002 in. and parallelism to within 0.001 in./in. is an important initial criterion. (The surface finish is 8-10 μin.)

e) Pastes – The rheological properties of the thick-film pastes must be prepared for fine line printing. The partial size and vehicle may require custom fabrication to produce acceptable results,

f) Guidelines – The spacings should be increased to 1.5 times the line width (to eliminate shorting). Care should be taken to provide optimized line width and spacing configurations with regard to substrate yield.

Table 1 indicates the yield versus line width, spacing, and length. These results can be evaluated for the proposed substrate size and metallization pattern to determine capability of the technology.

The feasibility of fine line printing within a carefully controlled laboratory situation has been demonstrated. The process parameters necessary for continuous production levels and the specific guidelines to improve yield of high density thick-film microcircuits provide logical extensions of this initial study.

TABLE 1. FAILURE RATE SUMMARY (OPEN OR SHORTED)

	X Axis				Y Axis			
	Length (in.)				Length (in.)			
Line Width and Spacing	0.650	0.400	0.150	0.100	0.650	0.400	0.150	0.100
0.003	15%	5%	1%	1%	20%	1%	1%	5%
0.004	4%	1%	1%	1%	10%	3%	1%	1%
0.005	1%	1%	1%	1%	2%	1%	1%	1%

Appendix. SCREEN PRINTING AND FIRING DATA

TABLE A-1. CONDUCTOR

Screen Mesh	325
Screen Material	S. S. 0.0011-in. wire diameter
Screen Tension	0.250 lb/0.020-in. deflection
Screen Stretch	45°
Screen Manufacturer	Microcircuit Engineering Corporation
Emulsion Thickness	0.0005-in.
Emusion Type	Microcircuit Engineering Corporation
Printer Model No.	Presco 330
Squeegee Material	Polyurethane
Squeegee Hardware	60D
Squeegee Pressure	2 lb/in.
Squeegee Speed	6 in./sec
Breakaway Distance	0.040 in.
Direction of Stroke	Forward (L → R)
Paste Drying Time	15 min
Paste Drying Temperature	80 – 125°C
Furnace Model No.	BTU YQ 4-81-7-120
Zone Temperature (°C)	
1	575
2	860
3	955
4	995
5	990
6	990
7	950
Belt Speed	4.0 in./min
Substrates Type	96% Alumina

TABLE A-2. DIELECTRIC

Screen Mesh	325
Screen Material	S. S. 0.0011-in. wire diameter
Screen Tension	0.250 lb/0.020-in. deflection
Screen Stretch	90°
Screen Manufacturer	Martin Marietta
Emulsion Thickness	0.001-in.
Emulsion Type	Appli — K
Printer Model No.	Presco 330
Squeegee Material	Polyurethane
Squeegee Hardness	60D
Squeegee Pressure	2 lb/in.
Squeegee Speed	6 in./sec
Breakaway Distance	0.040-in.
Direction of Stroke	Forward (L → R)
Paste Drying Time	15 min
Paste Drying Temperature	80°C to 125°C
Furnace Model No.	BTU VQ 4-81-7-120
Zone Temperature (°C)	
1	575
2	860
3	955
4	995
5	990
6	990
7	950
Belt Speed	4.0 in./min
Substrates Type	96% Alumina

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