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THICK-FILM NETWORKS

PDO 6984440, Final Report

G. A. Swartz, Project Leader

Project Team:

J. D. Blocher
H. B. Bonham
J. N. Blakely
B. J. Driscoll
A. L. Tindall

MASTER

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**Kansas City
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Final Report

This report was

Prepared by:

G. A. Swartz
D/842

Approved by:

A. O. Bendure
D/842

THE BENDIX CORPORATION
KANSAS CITY DIVISION
KANSAS CITY, MISSOURI

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ABSTRACT

The effort covered by Process Development Order 6984440 included investigation of screen printing parameters, screens and stencils, cermet paste, resistors, conductors, dielectrics, and microwave applications.

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SUMMARY

This endeavor was prompted by the need for packaging techniques which simultaneously achieve miniaturization, cost reduction, reliability, and reworkability.

The thick-film, or cermet, process consists of screen printing and firing conductor, resistor, and dielectric materials onto ceramic substrates. The process may yield discrete components such as resistors, capacitors, and conductors, or combinations of elements in the form of hybrid circuits. The screens are fabricated by exposing and developing a photolithographic image in an emulsion supported on an open-mesh screen.

Conductor and resistor materials are usually based on noble metal systems and consist of powdered metals mixed with glass frit. This mixture is suspended in resins with controlled flow characteristics to provide a paste with screen printing properties. Dielectric materials are similar, but the metallic elements are replaced by ceramic dielectrics.

A pattern is defined on a ceramic substrate by squeegee printing the desired paste through a screen stencil. The printed pattern is then dried and fired in an oxidizing atmosphere to remove the organic carriers and to fuse the glass frit. The fused glass provides cohesion of the film and adhesion to the substrate.

Multiple printings may be made by printing and firing the highest temperature material first, and successively printing and firing the lower-temperature materials. In some instances, successive materials may be fired at the same time. Firing temperatures may range from 450 to 1000°C.

Thick-film circuitry may be combined with discrete semiconductors, either nonencapsulated chips or miniature packages, to provide complete circuit functions.

The thick-film capability was established and tested by fabrication and evaluation of process development samples. This work has provided Bendix personnel with the expertise required, not only to fabricate thick-film elements, but also to evaluate the materials, processes, and workmanship required.

Prior work was performed on PDO 6984256. Early work consisted of familiarizing personnel with processes and techniques. Initial comparisons of screen mesh sizes were conducted during that period, as was the initial work on ESL7000 resistor paste, ESL5800 platinum/gold conductor paste, and single-layer dielectric crossovers.

Effort during the last reporting period included investigation of screen printing parameters, screens and stencils, cermet paste, resistors, conductors, dielectrics, and microwave applications.

The evaluation of printer parameters indicated increased film thickness with increases in breakaway and screen tension. The effects of squeegee pressure and speed were weak and inconclusive. The data varied considerably since the settings on the printer were inherently nonrepeatable. Printer modifications were made to correct these deficiencies, and test parts were rerun. Work stopped at this point; however, re-evaluation is expected to be completed under PDO 6984694.

A film-type screen emulsion which was sensitized and adhered to the screen, exposed, and developed-in-place offered advantages over the usual direct and indirect emulsions. A unique method of fabricating and adhering metal mask stencils to stainless steel screens was developed by use of reflow soldering techniques. Preliminary work was done on the development of bimetal masks; however, work was stopped before a satisfactory method of fabrication was developed.

A method was developed for the qualitative verification of thick-film materials. The fluorescent X-ray spectroscopy test method used is reasonably simple, nondestructive, and requires approximately two man-hours per sample. The test consists of a continuous qualitative scan of all elements in detectable quantities (usually 0.1 percent or greater) having an atomic number of 22 or higher. Quantitative analyses of homogeneous samples may be obtained by comparison to analyzed samples. The resistor films meet the requirement of homogeneity, but the conductor films do not. Materials verification may, however, be performed on conductor films by comparing them to a control standard.

Viscosity measurements of thick-film pastes were considered of little value as a process control since the viscosity of thixotropic materials depends greatly on both temperature and shear rate.

The resistor materials examined were the ESL3800 series and the ESL7000 series. The 7000 series is a palladium/palladium-oxide/silver system. The 3800 series is a noble metal system based on the platinum group metals.

Firing profiles of time and temperature versus resistance were plotted for the ESL3800 series material. These data were in reasonable agreement with the manufacturer's statements. Noise measurements for this material also were in agreement with advertised values. Life test comparisons of the ESL3800 and ESL7000 series showed the ESL3800 to be the more stable of the two.

The apparent sheet resistivity of thick-films is dependent on the geometry of the resistor pattern. A computer program was developed to determine the required active areas for given resistor values. Temperature coefficient of resistance (TCR) measurements indicated that resistors may be fabricated with TCR's of less than ± 100 ppm/ $^{\circ}\text{C}$ over a temperature range of -50 to $+125^{\circ}\text{C}$ by use of the ESL3800 series resistor material.

A procedure to determine optimum firing parameters for conductors with respect to substrate adhesion was established. It was shown that maximum adhesion was obtained when ESL5800B was fired at a peak temperature of 950°C and a belt speed of 2-1/2 inches per minute in the BTU Engineering Corporation, Explorer II Furnace. Maximum adhesion of the conductor film to the substrate was approximately 2 pounds for a parallel-gap-welded ribbon lead.

Dielectric insulating materials were examined for use as crossovers, capacitor dielectrics, and multilayer circuit insulation. Electro Science Laboratories 4747, with a dielectric constant of 10, and ESL4310, with a dielectric constant of 250, were used for fabricating capacitors. While both materials produced satisfactory capacitors, the ESL4310 was not satisfactory under high humidity conditions. ESL4747 and ESL4771 were used as encapsulants. An improvement in moisture resistance was observed, but an adequate solution was not found.

A multilayer pattern consisting of three conductor layers and two dielectric layers was obtained by use of ESL5800B, ESL8800R, and ESL5801 conductors. ESL4310 and ESL4640 dielectric materials were used for insulation.

A preliminary study was initiated to investigate the characteristics of thick films for use in microwave strip-line applications. Characteristics of substrates and conductors were examined. Conductor and device configurations were selected for evaluation and comparisons of materials. Initial pattern verification studies were made with etched printed circuit board layouts. The project was terminated before evaluation of thick-film characteristics was completed.

A typical thick-film hybrid microcircuit was fabricated to demonstrate the application of thick-film techniques, a laboratory-scale, thick-film capability was established, and the expertise required for thick-film technology was developed. Applications of thick-film technology were included on EP numbers 45996, 46220, 46215, and 46241 and on a new program. A proposal for a trimmable-chip resistor was made on PDO 6984668. Further development of precision printing techniques and the development of additional conductor materials is yet to be performed on PDO 6984694.

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DISCUSSION

SCOPE AND PURPOSE

This endeavor was prompted by the need for packaging techniques which simultaneously achieve miniaturization, cost reduction, reliability, and reworkability. Thick-film microelectronic networks provide these characteristics and permit versatility in hybrid design. As these requirements are applied to AEC electronic systems, a Bendix capability to perform manufacturing, failure, and post-mortem analyses and to make repairs will be mandatory. To meet this need, a fully-functioning laboratory was established and tested by fabrication and evaluation of process development samples.

The work reported has provided Bendix personnel with the expertise required to fabricate thick-film circuits and to evaluate the materials, processes, and workmanship required to fabricate hybrid circuits. Specific areas of investigation included screens and stencils; printing techniques and parameters; firing temperature versus time profiles; and resistor, conductor, and dielectric materials.

PRIOR WORK

Prior work was performed under PDO 6984256. Early work consisted of familiarizing personnel with processes and techniques.

Direct emulsions were compared to indirect emulsions, and 165-mesh and 230-mesh stainless steel screens were compared. Work was begun on the ESL7000 series resistor pastes, and ESL5800 series platinum-gold conductor adhesion tests were conducted. Comparisons of single-layer crossovers indicated a need for a two-layer crossover configuration.

ACTIVITY

Screen Printer

Variables

A lack of run-to-run repeatability, especially in resistor parameters, prompted an investigation of screen printing variables. The variables investigated are defined below.

Breakaway (X_1)	The distance between the bottom of the screen stencil and the substrate;
Screen Tension (X_2)	The degree of stretch or tightness of the screen mesh on the frame;
Squeegee Pressure (X_3)	The amount of force exerted by the squeegee on the screen as it passes over the work piece; and
Squeegee Speed (X_4)	The speed of the squeegee during the printing stroke.

Printed film thickness was expected to be proportional to breakaway, screen tension, and squeegee pressure and inversely proportional to squeegee speed.

Satterthwaite¹ has described a method of randomly arranging variables and levels of variables to provide statistically significant results. This method greatly reduces the number of test runs required to analyze a system. The method by which the experiments are arranged is called "random balance."

Procedure

Breakaway was established by the use of standard feeler gages and was examined at 0.020, 0.030, and 0.040 inch.

Screen tension was established by the amount of torque used to stretch the screen in the stretching frame. The stretching frame consisted of a solid fixture with inside dimensions of approximately 16 by 18 inches, and a floating bar with three tensioning bolts on each side. The tensioning bolts were lubricated with a fluorocarbon compound to reduce variations caused by friction. The torque levels applied to the tensioning bolts were 7.5, 10.0, and 12.5 inch-pounds. After the desired screen tension was achieved, the printing frames were attached to the mesh with an epoxy adhesive. After the adhesive had cured, the mesh was trimmed from around the printing frame. To monitor screen tension in the printing frame, a method was devised so that the screen was depressed with a calibrated spring gage while the deflection was measured with a dial indicator. The correlation of torque on the stretching frame to screen tension on the printing frame is shown in Table 1.

Squeegee pressure was regulated by a calibrated spring in the squeegee head. The scale numbers used were 2, 4, and 6. These numbers are reference numbers only and have no dimensions. Force in pounds per inch of squeegee length with respect to the scale numbers may be determined from Figure 1. The squeegee was pneumatically operated and speed was regulated by an air-flow control valve. The speeds were 3.5, 7.0, and 10.5 inches per second. The order of the experimental runs and the arrangement of

Table 1. Screen Tension Test

Deflection (mils)	Force (g)	Deflection (mils)	Force (g)	Deflection (mils)	Force (g)
Screen One 7.5 Inch-Pounds*		Screen Two 7.5 Inch-Pounds*		Screen Three 10.0 Inch-Pounds*	
20	150	20	125	20	200
34	250	31	160	30	300
40	300	40	220	40	400
50	400	50	300	50	500
40	250	40	160	40	350
34	200	30	140	30	250
20	120	20	90	20	150
Screen Four 10.0 Inch-Pounds*		Screen Five 12.5 Inch-Pounds*		Screen Six 12.5 Inch-Pounds*	
20	160	20	200	20	200
30	275	33	300	30	300
40	375	40	400	40	410
50	490	50	525	50	550
40	300	40	350	40	375
30	210	30	250	30	250
20	140	20	150	20	150

*Torque applied on stretching frame.

Figure 1. Squeegee Pressure Versus Reference Number

variables are shown in Table 2. Constant screen emulsion thickness and furnace firing profiles were maintained throughout each run. Film thickness measurements were made by use of a Zeiss light-section microscope. Upon completion of the test runs in Table 2, additional runs were made to determine shrinkage of the resistor film thickness because of firing. This shrinkage factor is useful in predicting the necessary wet-film thickness from the desired fired-film thickness.

Results

The printer parameters were compared to resistivity and fired-film thickness. Each resistance value shown in the plots is the average of 10 resistors per substrate on five substrates, for a total of 50 resistors per plot point. The active area of the measured resistors was from 0.5 to 8.0 unit squares, and line widths were from 0.010 to 0.100 inch. The effects of geometry were not considered.

Resistor film thickness was measured with a Zeiss light-section microscope. The thickness values shown represent the average of five resistors per substrate on five substrates per run, for a total of 25 resistors per plot point. Line widths of the resistors measured were from 0.010 to 0.100 inch. Again the effects of geometry were not considered.

Trend lines (o) were drawn through the average of each level. Optimum printing conditions should occur where the spread in resistance or thickness is least and where the slope of the trend line is lowest. Figures 2 and 3 show the relationship of resistance and film thickness to breakaway. The increase in slope between 30 and 40 in Figure 3 indicates that 0.030-inch breakaway should provide optimum film thickness and repeatability. Figures 4 and 5 show the relationship of resistance and film thickness to screen tension. Here optimum conditions should occur between 10.0 and 12.5 inch-pounds. Figures 6 and 7 show the relationship of resistance and film thickness to squeegee pressure. The absence of a strong trend may be due to the high degree of variability of data. Figures 8 and 9 show the relationship of resistance and film thickness to squeegee speed. Figure 8 indicates maximum resistance for a speed of 7 inches per second. This trend is opposite to that expected. Figure 9 shows no strong trend. Effects of squeegee speed are probably minor, and the true effect is lost in the high degree of variability of data.

As shown in Table 2, Run Number 8 was repeated five times to provide data on process repeatability. The same high degree of variance as that which occurred throughout the test was shown here. The high degree of variability encountered was believed to have been caused by the lack of repeatability in setting the printer parameters. It was concluded that breakaway, screen tension, and squeegee pressure were the major contributors to variations in screen printed patterns, while squeegee speed was considered a minor contributor.

Table 2, Screen Printer Evaluation Parameters

Run Number	X ₁	X ₂	X ₃	X ₄
1	40	12.5	4	3.5
2	30	12.5	2	7.0
8-1	40	12.5	6	7.0
3	40	7.5	4	10.5
4	30	7.5	2	10.5
5	20	7.5	4	7.0
6	40	10.0	2	10.5
7	20	7.5	2	3.5
8-2	40	12.5	6	7.0
9	20	10.0	4	3.5
10	30	12.5	6	3.5
11	20	12.5	6	10.5
8-3	40	12.5	6	7.0
12	40	10.0	2	7.0
8-4	40	12.5	6	7.0
13	20	7.5	6	10.5
14	30	10.0	6	3.5
15	40	12.5	4	7.0
16	30	10.0	6	3.5
17	30	10.0	6	3.5
8-5	40	12.5	6	7.0
18	20	7.5	2	7.0

X₁ Breakaway height in mils (screen to substrate)

X₂ Screen tension in inch-pounds

X₃ Squeegee pressure in non-dimensional units (Ref. No.)

X₄ Squeegee speed in inches-per-second

Note: Runs were made in the order listed. Run No. 8 was repeated where shown to provide data on process repeatability.

Figure 2. Average Resistance Versus Screen Breakaway Height, ESL3814

Figure 3. Resistor Thickness Versus Screen Breakaway Height, ESL3814

Figure 4. Average Resistance Versus Screen Tension, ESL3814

Figure 5. Resistor Thickness Versus Screen Tension, ESL3814

Figure 6. Average Resistance Versus Squeegee Pressure, ESL3814

Figure 7. Thickness Versus Squeegee Pressure, ESL3814

Figure 8. Resistance Versus Squeegee Speed, ESL3814

Figure 9. Resistor Thickness Versus Squeegee Speed, ESL3814

Printer Modifications

Design changes and modifications were incorporated in the screen printer at this time to provide easy setup and to improve registration and repeatability. These modifications included X, Y, Z, and θ adjustments and improvements in the screen-mounting features. The Z adjustment now provides the capability for contact printing. Squeegee pressure and speed controls were not altered. Initial setup time was reduced by approximately half. A given screen may be removed and replaced within 0.002 inch of its original position. Screen-to-screen breakaway height is constant, thus eliminating this adjustment when changing screens. The modified printer is shown in Figure 10.

Modifications were considered successful. However, it was deemed necessary to re-evaluate the effects of printer parameters on the properties of thick-films. The experimental arrangement of those test runs is shown in Table 3.

A new set of resistor substrates was fabricated as before. Screen tension was held constant, and 22 runs each were made with ESL3813 and 3814 resistor paste. Evaluation of the data had not been completed when the project was terminated. Data evaluation is expected to be completed under PDO 6984694.

Screens and Line Definition

Emulsions

Three types of screen emulsion systems were investigated. Indirect emulsion, in which a material is exposed, developed, and pressed into a screen, was employed first. This system produces screens with consistent emulsion thickness and a flat printing surface, but the service life is short. Direct emulsion, in which a screen is impregnated with a liquid emulsion and dried, was the second method. The direct emulsion is exposed and developed in place. This direct emulsion system provides good reproduction of line width and length and provides long service life; however, pattern edges tend to stair-step with the screen mesh, and thickness variation is a problem. Finally, Ulano direct emulsion was tried. This emulsion is similar to the usual indirect emulsions in that it is supported on Mylar film during sensitizing and adhering, but it is exposed and developed in place on the screen mesh in a manner similar to that of the direct emulsions. Ulano direct emulsion is sensitized and adhered with an aqueous solution of ammonium bichromate in alcohol. The ratio of sensitizer to alcohol controls the proportion of the emulsion thickness absorbed by the screen mesh, and thus controls the emulsion thickness which remains below the screen surface. The life of this stencil method is between usual direct stencil life and indirect emulsion life. The data shown in Tables 4 and 5 were taken from test pieces fabricated in the configuration shown in Figure 11. Ulano direct emulsion was sensitized with one part of 9 percent

Figure 10. Modified Screen Printer

Table 3. Re-Evaluation of Printer Parameters

Run Number	X ₁	X ₂	X ₃	X ₄
1	0.040	10.0	4	3.5
2	0.030	10.0	2	7.0
A	0.030	10.0	4	10.5
3	0.040	10.0	4	10.5
4	0.030	10.0	2	10.5
5	0.020	10.0	4	7.0
6	0.040	10.0	2	10.5
7	0.020	10.0	2	3.5
B	0.030	10.0	4	10.5
8	0.040	10.0	6	7.0
9	0.020	10.0	4	3.5
10	0.030	10.0	6	3.5
11	0.020	10.0	6	10.5
C	0.030	10.0	4	10.5
12	0.040	10.0	2	7.0
D	0.030	10.0	4	10.5
13	0.040	10.0	4	7.0
14	0.030	10.0	4	10.5
15	0.020	10.0	2	7.0
16	0.030	10.0	6	3.5
17	0.020	10.0	6	10.5
18	0.030	10.0	6	3.5

X₁ Breakaway (screen to substrate)--
0.020, 0.030, 0.040 inches

X₂ Screen tension--10.0 (in. lbs)

X₃ Squeegee pressure--(Reference
Numbers 2, 4, and 6)

X₄ Squeegee speed--3.5, 7.0 10.5 (ips)
.93, .64, .31 (on timer)

A, B, C, D = Verification runs using
parameters of No. 14.

Table 4. Resistor Thickness, ESL3813

Substrate	Resistor	Wet Thickness (mils)	Dry Thickness (mils)	Fired Thickness (mils)	Resistance (Kilohms)
3813-A	1	2.000	1.720	0.800	3.989
	2	2.160	1.840	0.900	2.039
	3	2.480	1.800	0.920	0.043
	4	2.200	1.480	0.860	0.553
	5	2.200	2.160	0.920	0.416
3813-B	1	2.200	1.800	0.920	4.160
	2	2.280	1.880	0.820	2.030
	3	2.200	1.980	0.860	1.029
	4	2.280	1.720	0.840	0.543
	5	2.040	1.880	0.880	0.398
3813-C	1	2.240	1.760	0.920	4.349
	2	2.520	1.840	1.000	2.043
	3	2.400	1.920	0.960	1.122
	4	2.420	1.720	0.800	0.665
	5	2.640	1.720	0.840	0.393
3813-D	1	2.000	1.560	0.920	4.167
	2	2.040	1.720	1.020	2.151
	3	2.200	1.720	0.800	1.070
	4	2.280	1.760	0.080	0.606
	5	2.240	1.840	0.960	0.414
3813-E	1	2.240	1.720	0.880	4.076
	2	2.500	1.860	0.860	1.900
	3	2.240	1.920	0.880	1.047
	4	2.280	1.800	0.960	0.548
	5	2.120	2.040	0.920	0.405
Average		2.256	1.806	0.901	1.606

Table 5. Resistor Thickness, ESL3814

Substrate	Resistor	Wet Thickness (mils)	Dry Thickness (mils)	Fired Thickness (mils)	Resistance (Kilohms)
3814-A	1	2.040	1.360	0.096	105.4
	2	2.080	1.460	0.920	52.09
	3	2.160	1.560	0.880	26.24
	4	2.360	1.680	0.720	13.87
	5	2.040	1.300	0.860	8.186
3814-B	1	2.160	1.420	0.820	105.0
	2	2.120	1.500	0.880	53.02
	3	2.160	1.480	0.800	26.15
	4	2.040	1.480	0.880	14.04
	5	2.040	1.220	0.840	8.508
3814-C	1	2.040	1.640	0.760	116.3
	2	2.100	1.940	0.800	53.96
	3	2.120	1.400	0.920	26.79
	4	2.040	1.560	0.880	14.37
	5	2.140	1.440	0.840	8.263
3814-D	1	1.840	1.480	0.800	103.2
	2	2.280	1.440	1.080	51.18
	3	2.160	1.480	0.940	26.41
	4	2.120	1.580	0.920	13.69
	5	2.120	1.460	0.800	8.237
3814-E	1	1.840	1.720	0.880	110.5
	2	2.120	1.360	0.800	53.56
	3	2.040	1.600	0.900	26.45
	4	2.360	1.400	0.840	14.18
	5	2.040	1.340	0.900	8.321
Average		2.102	1.492	0.865	

- R_1 40 MILS BY 320 MILS = 8 SQUARES
 R_2 40 MILS BY 160 MILS = 4 SQUARES
 R_3 40 MILS BY 80 MILS = 2 SQUARES
 R_4 40 MILS BY 40 MILS = 1 SQUARE
 R_5 40 MILS BY 20 MILS = 0.5 SQUARES

Figure 11. Resistor Evaluation Circuit

aqueous solution of ammonium bichromate in two parts of ethyl alcohol. The total emulsion thickness was 0.0011 inch, and the thickness of emulsion below the 200-mesh stainless steel screen surface was 0.0006 to 0.0007 inch. These parameters provide the desired 0.0008- to 0.0010-inch thickness for fired films of ESL3813 and 3814 resistive cermets.

Bimetal Masks

While 0.010-inch lines and spaces are generally considered the practical limit for both direct and indirect screen emulsions, 0.005-inch lines and spaces have been printed with the Ulano direct process described above. However, edge definition and line uniformity are not satisfactory; therefore, other methods must be sought. One method is to print an entire area with cermet conductor material and to etch the desired circuit pattern. A second method is to screen-print the circuit pattern directly with metal mask stencils.

Metal masks may be fabricated by selectively etching a circuit pattern into one side of a bimetallic foil and etching a supporting mesh pattern into the opposite side. This method requires perfect alignment of the exposure pattern on opposite sides of the foil, since it is desirable to etch the mesh pattern only in the area of the stencil pattern. To avoid this problem, the mesh pattern was etched into a supported metal foil. The stencil pattern was then registered over the mesh pattern. Using photoresist masking, the foil was then electroplated around the stencil pattern to the desired thickness. This approach proved to be impractical because of problems encountered in registering the stencil pattern over the etched mesh pattern. It was therefore abandoned.

A second bimetal mask was fabricated by stretching a 0.001-inch-thick brass foil and adhering it to a standard printing frame. Using a positive photoresist, the stencil pattern was exposed and developed on the printed, down side, of the foil. The foil was then electroplated with nickel in all areas except the desired stencil pattern. The remaining positive resist was re-exposed with the mesh pattern and developed. The mesh pattern was then etched in the brass foil through the stencil pattern openings. Resolution of the 0.005-inch lines and 0.003-inch spaces appeared adequate, but 0.003-inch lines and 0.001-inch spaces were less than adequate. The 0.001-inch lines were not resolved. Better control of resist exposure, electroplating, and etching must be attained to provide the required resolution. The mask-making process must, apparently, have a minimum capability of resolving 0.002-inch lines and spaces if consistent reproduction of 0.003-inch lines and spaces is expected.

The brass foil was glued to the printing frames with Armstrong A-2 adhesive and with a 2-to-1 ratio of Epon 828 and Versamid 140. The Armstrong A-2 proved unsatisfactory. The Epon/Versamid system provided a marked improvement; however, additional adhesives must be examined to provide maximum durability and long life for the masks. This work is to be continued under PDO 6984694.

Suspended Metal Mask

The suspended metal mask consists of a thin metal stencil adhered to a standard wire-cloth printing screen. The metal foil stencil replaces the photographic emulsion stencil used on general-purpose screens. The metal foil stencil provides sharper line definition and better resolution (0.004- to 0.005-inch lines and spaces) than emulsion-type screen stencils.

A method of attaching an etched metal foil stencil pattern to stainless steel fabric attached to a printing frame was developed. The completed assembly provides an indirect, suspended, or floating, metal-mask screen stencil for use in the screen printing of precision patterns. Fabrication of the foil stencil consists of electroplating tin-lead onto the foil and etching the desired pattern into the foil with a suitable etchant. The pattern is defined with photoresist.

The etched and plated foil is positioned (plated side up) on a preheated assembly block such as aluminum. The assembled screen is then lowered to contact the foil (Figure 12). The tin-lead plating acts as solder to adhere the foil stencil to the stainless steel fabric. The assembly block which supports the soldered foil and screen assembly is then removed from the heat source and allowed to cool until the solder has solidified. Electroplating the stainless steel fabric with a nickel strike, followed by a gold strike (approximately 50 microinches), greatly improves the solderability of the stainless steel screen fabric and alleviates the necessity of using corrosive soldering fluxes.

The above method of stencil attachment provides intimate contact between the stencil and the screen fabric over the entire stencil area. Thus, buckling of the screen or stencil, slippage between screen and stencil, and distortion of the stencil image are virtually eliminated, thereby providing a more nearly exact reproduction of the stencil image when printed on a substrate.

Etched Films

Three methods of etching ESL8831 gold conductor patterns were examined: etching in a saturated solution of iodine in potassium iodide at 50°C, etching in a hydrofluoric solution, and a 15-second alternate etching in each of the before-mentioned etchants. The first and third methods worked well, but both seemed to leave a very slight discoloration on the substrate. Further examination indicated the presence of bismuth and lead, probably in the oxide form, since a difference in resistivity could not be detected between the discolored area and the blank substrate. Bismuth oxide and lead glass were present in the cermet paste. Measurements of a pattern with 0.005-inch lines and 0.005-inch spaces indicated that the etched lines were 0.0046-inch wide with 0.0054-inch spaces on a 0.0005-inch-thick film.

Figure 12. Suspended Metal Mask-Method of Attachment

Four attempts were made to etch thick-film platinum-gold. Method 1 was immersion in an iodine-potassium iodide solution. Method 2 was immersion in a hydrofluoric solution. Method 3 was an alternate etching in each of the above. Method 4 was immersion in aqua regia.

Only Method 4 (aqua regia) would etch the platinum-gold. This etch took about 7 minutes. It is doubtful that any resist will hold up in aqua regia for that long.

Cermet Paste Evaluation

The purpose of this portion of the investigation was to provide a reliable and repeatable test method for the characterization and verification of thick-film materials.

Thick-film materials are composed of metallic or metallic-oxide conducting particles, metal-oxide glass-forming compounds, and metal oxides which act as modifiers to the glass formers. Organic resins and solvents are added to the above materials to provide screen printing characteristics. The organic portions of the paste are removed by evaporation and oxidation during the drying and firing cycles. Only the inorganic portions which remain after firing were examined at this time. The glass formers provide cohesion of the film and adhesion to the substrate. An alkali-free glass forms the binder. Lead oxide (PbO) is added to lower the melting point. Bismuth oxide (Bi_2O_3) is added to improve solderability. Bismuth oxide is also an excellent flux which lowers the viscosity of the melt.

Resistor Paste Analysis

Two samples of cermet resistor paste were submitted to the Materials Test Laboratory with a request for a method to quantitatively analyze thick-film resistor materials. These samples were supplied as films of varying thickness on ceramic plates and as oven-baked chunks which could be easily ground into powder. The powder was used for analysis of elemental composition; the films were used to determine the thickness necessary for fluorescent X-ray procedures. The test method consisted of (1) a continuous qualitative scan of all elements in detectable quantities (usually 0.1 percent or greater) having an atomic number of 22 or higher, and (2) quantitative analysis by comparison with analyzed samples to determine the quantity of distinguishing elements such as gold, iridium, or lead which were present.

Qualitative elemental scans showed the first sample, ESL3813 cermet paste, to be an iridium/gold alloy in a leaded-glass matrix; the second sample, ESL3814 cermet paste, was iridium only in leaded glass.

A Norelco air path fluorescent X-ray spectrograph using a tungsten-target tube for primary X-ray generation and a lithium fluoride analyzing crystal

was used for both the qualitative elemental scans and the quantitative comparison analysis. The spectograph will automatically record the presence of all elements with an atomic number of 22 or greater in a continuous scan. These are recorded by a chart scan where the peak heights are directly related to the existing amount of the particular element being recorded. Elemental scans of both ESL3813 and ESL3814, as films, together with a scan of a blank ceramic substrate, are shown in Figure 13. These scans were made by placing the thickest sample of each type of film (ESL3813, 2.00 mil; ESL3814, 1.92 mil) over the same masking aperture under identical conditions of primary beam excitation. Thus, as outlined in the first part of the proposed test method, the overall composition of any similar sample may be rapidly determined. In the scan of the blank ceramic substrate, the peaks recorded are those produced by the primary tungsten radiation.

Thickness measurements of films on ceramic plates were made by placing the samples over a 0.25-inch aperture and using a fixed-time-counting mode of operation. The resulting data are shown in Tables 6 and 7. These two tables show that samples of these compositions in thicknesses equal to or greater than 1.5 mil (0.0015 inch) would be infinitely thick for X-ray spectrographic analysis.

Results of quantitative analyses on the powdered chunk samples are shown in Table 8. These analyses were made by using synthetic standard curves obtained by mixing pure elements into spectrographic-grade carbon. Varying amounts of the pure elements were weighed into standard sample weights of the carbon. Taking fixed time counts of these standards as plot points on a graph, calibration curves were generated for each element analyzed (iridium, gold, and lead). To obtain a linear response from the X-ray counting circuitry, it was necessary to dilute each of the powdered samples 20 to 1 with spectrographic grade carbon. While this could affect accuracy, especially in a nonhomogeneous sample, it eliminated (or reduced by a factor of 20) any matrix or interelement effect. Correlating analyses were performed by emission spectroscopy. For part 2 of the test method to be performed, it was necessary to supply the material as a uniformly-thick film, (0.0015-inch minimum) on a ceramic plate. A fixed time mode of operation was used on the X-ray spectrograph. Quantitative results were obtained by comparison to an analyzed sample.

Both qualitative and quantitative information can be obtained from films that provide homogeneity and uniform density. The two resistor films examined meet these requirements.

Conductor Paste Analysis

Work done on analysis of resistor materials was continued to include conductor materials. Table 9 lists several conductors and compares their

Figure 13. Fluorescent X-Ray Spectrograph Scans of Films

Table 6. Element Thickness Measurements,
ESL3813

Film Thickness (mils)	Total Counts in 10 Seconds		
	Gold	Iridium	Lead
0.56	838	2337	1127
0.68	819	2339	1119
0.76	824	2375	1122
1.30	961	2724	1313
1.46	950	2724	1324
2.00	962	2714	1326
Blank	120	83	120

Table 7. Element Thickness Measurements,
ESL3814

Film Thickness (mils)	Total Counts in 10 Seconds	
	Iridium	Lead
0.84	3193	1288
0.88	3177	1257
0.92	3171	1315
1.44	3693	1709
1.54	3663	1723
1.92	3709	1664
Blank	83	120

Table 8. Quantitative Analysis, Powdered Chunk

Sample	Iridium (Percent)	Gold (Percent)	Lead (Percent)
ESL3813	20	11.5	24
ESL3814	30	- - -	26

recommended firing temperatures, resistivities, and recommended applications. Samples of these materials were prepared by screen printing two coats of the conductor paste on 96 percent alumina substrates. The samples were dried between printings and both coats were fired simultaneously. Those samples were submitted to the Materials Test Laboratory for analysis. The test method used was again fluorescent X-ray spectrographic analysis. Qualitative elemental scans of the heavy elements which comprised the samples are shown in Figure 14. Peak heights are relative measurements and are not absolute quantitative measurements of concentration. Quantitative measurements require that a uniform sample surface area, limited by an aperture, be presented to the X-ray beam. Count rates must be determined over a fixed time period, and results are compared to an analyzed sample. The method of sample preparation provides a minimum of 0.0015-inch thickness, which is opaque to the X-ray spectrograph. Samples prepared in this manner may be retained for extended periods of time without fear of deterioration.

The conductor films which were examined did not provide homogeneity and uniform density and, therefore, did not provide quantitative data. Dark field pictures of several conductor films are shown in Figure 15. Photographs 1, 3, and 8 show samples fired by the manufacturer; the remainder were fired by Bendix processes. While quantitative results cannot be obtained from the conductor films because of nonuniformities, useful qualitative information can be obtained by comparison to a control sample. Examination of eight samples of thick-film conductor materials on aluminum oxide substrates and fired chunks of these same materials showed that the overall chemical composition of each sample could be readily determined by X-ray methods. Elemental scans on the X-ray spectrograph showed the composition of the eight samples, listed in the order of concentration, to be as follows.

ESL5800	Gold, platinum, bismuth, palladium, lead
ESL5800B	Gold, platinum, bismuth, palladium, lead
ESL5801	Gold, platinum, bismuth, palladium, lead
C-6010	Gold, platinum, bismuth, lead
EP8236	Gold, platinum, bismuth, lead
ESL8800B	Gold, bismuth, lead
ESL8800D	Gold, bismuth, lead
ESL8831	Gold, bismuth, lead

Quantitative values could not be obtained with any degree of accuracy because of the porosity of the thick films and the poor grinding characteristics of the fired chunks.

Viscosity Measurements

Viscosity measurements were made on ESL3800 series resistor materials using a Model RVT Brookfield Viscometer with an SCR-14 spindle in a small

Table 9. Thick-Film Conductors, Summary

Material Identification	Primary Conductor	Firing Temperature (°C)	Resistivity (Ohms/Square)	Primary Use
ESL8800B	Au	850 to 1000	0.003 to 0.001	General Purpose
ESL8800D	Au	850 to 1000	0.003 to 0.001	Resists solder leach Fine line, TC bonds
ESL8831	Au	850 to 950	0.002 to 0.004	Fine line, high conductivity Au/Si Eutectic Bonds
ESL5800	Pt/Au	900 to 975	0.05 to 0.10	High adhesion to substrate
ESL5800B	Pt/Au	850 to 1000	0.05 to 0.12	High adhesion to substrate
ESL5801	Pt/Au	750 to 900	0.05 to 0.12	See ESL5800 Lower firing temperature
AU-C-6010	Pt/Au	950	0.07	Resists solder leaching
DUP EP-8236	Pt/Au	760 to 1000	0.05	High adhesion, excellent solderability

Figure 14. Fluorescent X-Ray Spectrograph Elemental Scans,
Conductor Materials

Figure 14 Continued. Fluorescent X-Ray Spectrograph Elemental Scans, Conductor Materials

Figure 14 Continued. Fluorescent X-Ray Spectrograph Elemental Scans, Conductor Materials

Figure 14 Continued. Fluorescent X-Ray Spectrograph Elemental Scans, Conductor Materials

ESL 5800B
MFG SAMPLE 140X

ESL 5800B
BENDIX SAMPLE 140X

ESL 8831
MFG SAMPLE 140X

ESL 8831
BENDIX SAMPLE 140X

Figure 15. Photomicrographs of Conductor Materials

ESL 5800
BENDIX SAMPLE 140X

ESL 5801
BENDIX SAMPLE 140X

AU-C6010
BENDIX SAMPLE 140X

ESL 6800B
MFG SAMPLE 140X

Figure 15 Continued. Photomicrographs of Conductor Materials

ESL 8800B
BENDIX SAMPLE 140X

ESL 8800D
BENDIX SAMPLE 140X

DP-EP8236
BENDIX SAMPLE 140X

Figure 15 Continued. Photomicrographs of Conductor Materials

sample cup. Measurements were taken at various spindle speeds from 0.5 to 20.0 rpm. Table 10 summarizes this data. Variations of approximately 20 percent are shown.

While viscosity is an important factor in determining printing parameters and printed line characteristics, its strong dependence on both shear rate and temperature make the usefulness of viscosity measurements questionable as either a process control or as a material verification parameter. This implies that temperature control in the screen printing facility is an important factor in determining process repeatability. Also, contrary to results reported in the section on the screen printer, shear rate (determined by squeegee speed) is expected to affect printed film thickness.

Resistors

Two basic cermet-resistor systems were examined. The ESL7000 series is a palladium, palladium-oxide, silver system. The resistivity and TCR of this system are controlled by the ratio of pure metals to metal oxides. This ratio is established by the firing process. During firing, two chemical reactions occur: the oxidation of palladium, and the reduction of palladium oxide by silver. These reactions do not reach an equilibrium condition. Since the reactions do not stabilize, the resulting resistors may drift in value as their environment forces either oxidation or reduction. The ESL3800 series is based on the platinum group of metals. The conductive components are stable prior to firing and are not changed by oxidation or reduction during firing. Therefore, the ESL3800 and similar systems provide much more predictable and stable resistors than the palladium-palladium oxide-silver systems. Because of the inherent stability of the noble metal systems with respect to the metal/metal oxide systems, most of the following work was performed on the ESL3800 series of resistor materials.

Resistor Firing

To optimize firing conditions for the ESL3800 series of resistor materials, it was necessary to examine resistor furnace profiles. These profiles determined the effect on final resistance of time at constant temperature and the effect of temperature at constant time. The optimum conditions (indicated by a minimum resistivity) were a temperature set point of 915°C and a total firing cycle of 71.5 minutes as shown in Figure 16.

Resistor Refire Sensitivity

Figure 17 illustrates the effect of refiring ESL3800 series resistor material. It is a plot of the average resistance obtained after each of five refires at the original profile temperatures. ESL3814 (10,000 ohms-per-square paste) is much more sensitive than ESL3813 (1000 ohms-per-square paste). This trend is expected to increase as resistivity increases.

Table 10. Resistor Paste Viscosity

RPM	Average Viscosity (cps)	Span (cps)	Span (Percent)
ESL3814			
0.5	1,169,375	227,500	19.45
1.0	618,437	110,000	17.79
2.5	285,625	61,000	21.36
5.0	163,625	32,500	19.86
10.0	98,224	15,750	18.03
ESL3813			
0.5	1,951,875	102,500	5.25
1.0	1,054,500	148,750	15.05

Figure 16. Time, Temperature Profile for ESL3800 Resistor Paste

Figure 17. Resistance Versus Number of Refires, ESL3813, ESL3814

Resistor Noise Measurements

Resistors fabricated in the configuration previously shown in Figure 11 were measured for noise index. The measurements were taken with a Quan-Tech Laboratories Resistor Noise Test Set, Model 2136. Two groups of 25 each were fabricated with ESL3813 and ESL3814. Test results from those groups (Table 11) show that for a given resistivity noise increases with resistance or the number of unit squares in series, and that noise increases with resistivity. Electro Science Laboratories claims a noise index of 0 to -5 db for 3814 paste when measured on a 0.130-inch-square resistor, and states that decreasing resistor size will increase noise, thus accounting for the higher noise index exhibited by these test units.

Resistor Life Testing

To evaluate and compare the life characteristics of ESL7000 and the 3800 series, large resistor samples fabricated from both series were produced and tested. These samples were placed in an oven at 125°C and measured at discrete intervals of time. After 1000 hours of testing, the results summarized in Table 12 were obtained.

Effects of Geometry

The apparent sheet resistivity of a given resistance material changes as the ratio of resistor length to width changes. The sheet resistivity in ohms per unit area is a function of area. This becomes a serious problem when several resistors of different values and geometry are made on a single substrate, and it becomes most pronounced when resistor areas are less than 5 to 10 unit squares.

It has been necessary in the past to estimate resistor areas for the various values required and make artwork, screens, and test samples. Errors are then determined by resistance measurement and corresponding changes are made in the artwork before retesting. Several such test runs may be required for a complex network or circuit. To alleviate this costly and time consuming procedure, a computer program (RESIS) was developed so that active areas for required resistance values may be determined directly. Initial calibration data for a given lot of resistor material is obtained from a test pattern such as that shown in Figure 11. Measured resistance in ohms per square versus active area in unit squares is fed into the program, along with desired circuit resistance values. The computer uses the method of least squares to solve a third degree polynomial which describes sheet resistivity versus active area, prints out the coefficients, plots the curve, if desired, and prints out the required active areas for the desired circuit resistance values. It is necessary to establish the calibration data only once for a given lot of material. This data is then reused when new resistor areas must be determined.

Table 11. Resistor Noise Index

Substrate							
Resistor Number	6 (db)	7 (db)	8 (db)	9 (db)	10 (db)	Avg (db)	Resistance (Kilohms)
ESL3813 Resistor Paste (1 Kilohm per Square)							
5	-12.5	-15.5	-13.0	-13.5	-12.5	-13.4	0.5
4	-10.0	-11.0	- 7.5	-10.8	-11.0	-10.0	1.0
3	- 8.0	- 8.0	- 9.0	- 8.5	9.0	0.8	2.0
2	- 5.0	2.0	0.5	- 2.5	9.0	0.8	4.0
1	5.8	7.3	3.6	8.8	4.0	5.9	8.0
Substrate							
Resistor Number	1 (db)	2 (db)	3 (db)	4 (db)	5 (db)	Avg (db)	Resistance (Kilohms)
ESL3814 Resistor Paste (10 Kilohms per Square)							
5	4.0	3.0	3.0	4.5	3.5	3.6	5.0
4	5.0	6.0	8.0	8.0	6.0	5.8	10.0
3	7.5	10.5	8.0	9.5	8.5	8.8	20.0
2	12.5	13.0	16.5	13.5	17.0	14.5	40.0
1	18.0	15.0	19.2	17.2	21.8	18.2	80.0

Table 12. Resistor Life Testing
(1000 Hours at 125°C)

Resistor Paste Type	Resistivity (Ohms per Square)	Average Deviation (Percent)
ESL7013	1,000	3.7
ESL7014	10,000	0.88
ESL3813	1,000	0.41
ESL3814	10,000	0.025

Temperature Coefficient of Resistivity

The remaining electrical parameter investigated was the variation of resistivity with temperature, that is, the 3800 series temperature coefficient of resistivity. The results are shown in Figures 18 and 19. Cold TCR is the variation in resistance as temperature varies from +25 to -50°C; hot TCR is the variation in resistance as temperature varies from +25 to +125°C.

Conductors

To establish a furnace profile for firing ESL5800 series platinum-gold conductors, 72 substrates were printed and fired. The substrates were divided into 24 groups, each group differing from the others by its profile. To evaluate the conductors, a weld schedule for parallel-gap welding ribbon leads to conductors was established, and the mean of ten pulls was recorded for each group. This pull strength is indicative of film strength and the film-to-substrate adherence. The results are shown in Figures 20 and 21. These figures show that a sintering temperature of 950°C will maximize pull strength, while minimizing the effects of belt speed. Since the fabrication of thick-film networks requires refiring conductors during resistor processing, a fast belt speed (2.5 inches per minute) is desirable.

Dielectric Materials

The most frequent problem associated with crossovers was short circuiting between the upper and lower conductors. The major source of this problem was traced to contamination, the primary component being airborne dust which was trapped in the wet dielectric film while drying. Although protection from the atmosphere during drying did much to reduce the problem, it was found necessary to double print dielectric insulation and to provide intermediate drying.

Figure 18. Temperature Coefficient of Resistance, ESL3813

Figure 19. Temperature Coefficient of Resistance, ESL3814

Figure 20. Conductor Adhesion Versus Sintering Temperature

Figure 21. Conductor Adhesion Versus Furnace Belt Speed

Capacitors and Crossovers

The configuration shown in Figure 22 was used to evaluate techniques and materials for fabrication of capacitors and crossovers. The active area is approximately 0.0049 square inch. Twenty-five substrates were fabricated with ESL5800B gold-platinum-base electrodes, ESL4747 crossover dielectric, and ESL5801 counter electrodes.

The advertised dielectric constant for ESL4747 is 10, and the capacitance yield is 1900 pF/in.²/mil. The measured thickness of the dielectric was 0.00155 inch, and the capacitance of the test pattern was expected to be 6.0 pF. Table 13 shows measured capacitances for 85 crossovers. The average value was 5.7 pF, which correlates well with the calculated theoretical value. Substrates 1 through 5 in Table 13 were destructively tested to establish dielectric breakdown voltage. Breakdown was evaluated as the point where leakage current exceeded 15 nanoamperes. In all cases, leakage was less than the limiting value until arcing occurred. Breakdown voltage had a range of 1100 to 2250 vdc, with an average value of 1460 vdc. These data are shown in Table 13. Substrates 6 through 11 were placed in a humidity chamber and operated for 10 days at 65°C and 95 percent relative humidity with 40 vdc applied. No appreciable change in capacitance could be detected; however, the dielectric breakdown voltage decreased to a range of 650 to 1200 vdc, with an average value of 935 vdc. Substrate 12 was mechanically damaged during handling and was eliminated from further testing. Substrates 13 through 17 were encapsulated with ESL4771 and tested, as were substrates 6 through 11 above. Again, no appreciable change in capacitance was noted, but the dielectric breakdown voltage decreased to a range of 950 to 2500 volts, with an average of 1380 volts. The dielectric breakdown voltage which occurred after the humidity test is shown in Table 14. The dissipation factor was less than 0.1 percent for these units, and could not be measured because the measuring instrument was not sufficiently sensitive.

The procedure used to evaluate ESL4747 was again used to evaluate ESL4310 ceramic dielectric coating. Initial capacitances and dielectric breakdown voltages are shown in Table 15. The rated dielectric constant for ESL4310 is 250, and the capacitance rated yield is 50,000 pF/in.²/mil. The measured thickness of the dielectric coating was 0.00135 inch, and the capacitance was expected to be 180 pF. Table 15 shows the measured capacitance for 85 crossovers. The average value was 210 pF, which is approximately 15 percent higher than anticipated. The dielectric breakdown voltage ranged from 350 to 750 vdc, with an average value of 550 vdc. Substrate number 10 had two shorted crossovers after fabrication, and was not used for further testing.

All crossovers of substrates 6 through 12 shorted after 6 to 24 hours in the humidity chamber. Substrates 13 through 18 were encapsulated with ESL4771 and placed in the humidity chamber. These units shorted in approximately 24 hours. Substrate numbers 20, 21, and 22 were encapsulated with ESL4747

Figure 22. Crossover Evaluation Circuit

Table 13. Dielectric Crossovers, ESL4747

Substrate Number	Crossover 1		Crossover 2		Crossover 3		Crossover 4		Crossover 5	
	pF	Volts	pF	Volts	pF	Volts	pF	Volts	pF	Volts
4747-1	1	1500	5	1200	5	1225	6	1700	5	1425
-2	5	1650	6	1600	5	1700	5	2250	6	
-3	5	1200	6	1450	6	1350	5	1450	6	1450
-4	5	1650	5	1550	5	1400	5	1650	5	1100
-5	5	1600	6	1550	5	1150	5	1600	6	1100
-6	5		6		6		5		6	
-7	5		6		6		5		6	
-8	5		6		5		5		7	
-9	5		5		6		7		6	
-10	5		6		6		6		6	
-11	6		6		6		6		6	
-12	--		--		--		--		--	
-13	5		6		7		6		7	
-14	6		6		6		6		6	
-15	6		6		6		7		6	
-16	6		6		7		6		6	
-17	6		6		6		6		6	
Average capacitance = 5.7 pF										

Table 14. Dielectric Breakdown Voltage After Humidity, ESL4747

Sample Number	Breakdown Voltage Between Pins* (Volts)				
	1-6	1-5	1-4	1-3	1-2
Unencapsulated					
6	750	800	800	1100	750
7	700	850	850	1200	1100
8	900	1150	1050	1000	1200
9	900	900	950	750	950
10	1100	950	900	1150	1150
11	750	650	800	1100	1000
Encapsulated					
13	1700	2000	1250	1500	1100
14	2500	1300	1400	1000	1100
15	1300	1600	1900	1350	1250
16	2000	1050	1100	1150	950
17	1100	1300	1300	1250	1050
*See illustration on page 66.					

Table 15. Dielectric Crossovers, ESL4310

Substrate Number	Crossover 1		Crossover 2		Crossover 3		Crossover 4		Crossover 5	
	pF	Volts	pF	Volts	pF	Volts	pF	Volts	pF	Volts
4310-1	210	600	220	500	219	550	220	475	219	550
-2	210	475	219	550	219	525	217	700	216	525
-3	215	575	206	625	218	525	216	425	216	550
-4	209	500	217	350	223	750	223	500	219	475
-5	205	475	219	550	216	750	219	550	220	650
Unencapsulated										
-6	204		215		217		223		217	
-7	212		220		216		214		208	
-8	199		213		210		213		204	
-9	203		216		211		215		206	
-10					short		short			
-11	201		213		209		212		207	
-12	207		221		216		219		187	
Encapsulated with ESL4771										
-13	203		205		208		208		206	
-14	206		209		204		208		205	
-15	190		207		208		207		202	
-16	198		203		204		203		201	
-17	189		202		203		204		200	
-18	196		209		206		205		202	

Average capacitance = 210 pF

and subjected to the full humidity cycle. Six of 15 crossovers survived. The six surviving units exhibited an average capacitance of 250 pF, and ranged from 192 to 301 pF. This represents an average increase in capacitance of approximately 20 percent. Substrates 23, 24, and 25 were operated at 40 vdc in ambient conditions (20 to 25°C and 30 to 60 percent relative humidity) for 10 days. These units exhibited no appreciable change in capacitance. The average dissipation factor was 2.3 percent, with one unit (not averaged) at 6.0 percent. The manufacturer's rated value is less than 1.5 percent.

Multilayers

Multilayer processes were investigated using the configurations shown in Figure 23. In the initial attempt, the first electrode was printed with ESL5800B and fired in accordance with the profile shown in Figure 24. The dielectric layer was printed with two layers of ESL4310, each layer being dried individually. The top electrode was printed with ESL5801. The dielectric layers and the top electrode were co-fired to the profile shown in Figure 25. Eight of ten units exhibited shortcircuit conditions after firing.

The above process was repeated; however, the profile of Figure 24 was used to fire the dielectric and second conductor layers. Of eight units fabricated, none exhibited shortcircuits after firing. At this point, a second dielectric layer and a third conductor layer were added, as shown in Table 16. Each layer was individually dried and the combination was co-fired according to the profile of Figure 25. After final firing, one unit exhibited a shortcircuit condition between the first and second conductor layers. The measured thickness of ESL4310 dielectric between the first and second conductor layers was 0.0012 inch. The measured capacitance was 3270 pF, and the dissipation factor was 0.9 percent. Anticipated values were 1975 pF and less than 1.5 percent. The measured capacitance for the ESL4640 layer was 19,500 pF, and the dissipation factor was 2.1 percent. Anticipated values were 18,750 pF and less than 1.5 percent. Further investigation is necessary to determine the causes of the lack of agreement between measured and theoretical values of capacitance and dissipation factor for both crossovers and multilayer applications of the higher-K materials.

Microstrip Lines

A preliminary study was initiated to investigate the characteristics of thick-films for use in microwave stripline (microstrip) applications. The general method of construction is shown in Figure 26, along with critical dimensions and a set of typical parameters. Microstrip configurations may be divided into two general classes: transmission lines and lumped elements, both of which may be utilized in the same circuit.

The microstrip transmission line shown in Figure 27 was selected for evaluation of materials and processes. The characteristic impedance of the

FIRST CONDUCTOR LAYER

DIELECTRIC LAYER

SECOND & THIRD
CONDUCTOR LAYER

COMPOSITE

MULTILAYER CONFIGURATION

Figure 23. Multilayer Configuration

Figure 24. Conductor Time/Temperature Profile

Table 16. Multilayer Circuit Configuration

Layer	Material	Number of Prints
First Attempt		
First Conductor	ESL5800B	1
Dielectric	ESL4310	2
Second Conductor	ESL5801	1
Second Attempt		
First Conductor	ESL5800B	1
Dielectric	ESL4310	2
Second Conductor	ESL8800B	1
Dielectric	ESL4640	3
Third Conductor	ESL5801	1
Printing Parameters		
Breakaway Height	0.030 in.	
Squeegee Pressure	4 (Reference Number)	
Squeegee Speed	7.0 in. /sec

Figure 25. Dielectric Time/Temperature Profile

Figure 26. Microstrip Transmission Line, General Construction

Figure 27. Microstrip Transmission Line, Materials Evaluation

transmission line is determined by the ratio of conductor width to dielectric thickness for a given dielectric constant, as shown in Figure 28, and wavelength may be taken from Figure 29. This pattern was used by Tek-Wave, Incorporated, during the evaluation of substrate and conductor parameters.²

Four general properties required for substrates are low-losses at microwave frequencies, good adherence for conductors, smooth surfaces (better than 5 microinches RMS), and no deformation during circuit processing. The characteristics of several substrates and conductors are shown in Tables 17 and 18.

Applications

An experimental microstrip support assembly was completed, and several microstrip transmission lines were fabricated and tested on a support assembly. The measured characteristic impedance of the three wide lines on those assemblies is within 5 percent of that predicted by Wheeler³ when his results were modified for microstrip geometry.

An experimental microstrip hybrid junction was designed. This type of device has a variety of applications in general rf assemblies.

Four microstrip transmission lines were fabricated as shown in Figure 31. Fiberglass-epoxy board 1/16-inch thick (nominal) with a dielectric constant of 4.9 at 1 kHz was used. Board processing resulted in a shrinkage of 0.0035 inch on all line widths. Electrical connections to each finished board were made with OSM 248-2 or OSM 248-5 launchers.

Slotted-line techniques were used to determine the wavelength of a 1.0 to 2.4 GHz signal on all transmission lines. For board 2 (0.0570-inch design width), the measured attenuation constant was approximately 3.9 db/meter.

Time-domain reflectometer techniques were used to determine the characteristic impedance of all lines. The resulting data are shown in Table 19.

Hybrid Circuits

A thick-film hybrid circuit is shown in Figures 32 and 33. The circuit was fabricated on a 1-inch-square by 0.025-inch-thick 96-percent alumina substrate. ESL5800B platinum-gold first conductors, ESL7000 series resistor material, ESL4747 crossover insulation, and ESL5801 platinum-gold second conductors were used. The resistors were trimmed to a tolerance of ± 2 percent by airbrasive techniques, and the capacitors and semiconductors were attached by reflow soldering. This circuit was fabricated for display purposes. No tests other than normal operational checks were conducted.

Text continued on page 87.

Figure 28. Characteristic Impedance of Microstrip Line

Figure 29. Wavelength of Microstrip Line

Table 17. Microwave Substrate Characteristics

Material	Tan δ at 10 GHz	Er	k (W/cm-°C)	Application
Alumina	2×10^{-4}	9.6 to 9.9	0.2	Microstrip
Sapphire	10^{-4}	9.3 to 11.7	0.4	Microstrip (lumped- element)
Glass	4×10^{-4}	5	0.01	Lumped- element
BeO	10^{-4}	6	0.5	Compound substrate
Rutile	4×10^{-4}	100	0.02	Microstrip
Ferrite-granet	2×10^{-4}	13 to 16	0.03	Microstrip compound

Table 18. Microwave Conductor Characteristics

Material	DC ρ Relative to Cu	Skin Depth at 2GHz (μ)	Surface Resistivity (Ohms/sq x $10^{-7} \sqrt{f}$)	Adherence Conductor Film or Substrate	Method of Deposition*
Ag	0.95	1.4	2.5	Poor	E, Sc
Cu	1.00	1.5	2.6	Very Poor	E, P
Au	1.36	1.7	3.0	Very Poor	E, P
Al	1.60	1.9	3.3	Very Good	E, V
W	3.2	5.6	4.7	Good	EB, V
Mo	3.3	5.7	4.7	Good	EB, Sp
Cr	7.6	4.0	7.2	Good	E
Ta	9.1	4.4	7.9	Very Good	SP, EB
Mo/Mg	5xMo	- - -	- - -	Very Good	SC
*E--Evap, EB, Electron Beam Evap., Sc--Screening, P--Plating, V--Vapor Phase, Sp--Sputtering.					

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Figure 32. Schematic Diagram, Thick-Film LID Hybrid Circuit

Figure 33. Thick-Film LID Hybrid Circuit, Pictorial Breakdown

ACCOMPLISHMENTS

A laboratory-scale, thick-film facility was established and tested. Expertise was acquired to provide capability of fabricating thick-film components and circuits, as well as to evaluate materials, processes, and workmanship.

General trends that related screen printing parameters to printed film thickness were established. Modifications which were incorporated into the printer were successful in terms of improved repeatability of registration and quality of printed patterns. Full evaluation of the modifications was not completed.

Three basic screen emulsions were examined and classified according to application. A unique method of fabricating and adhering metal mask stencils to stainless steel screens was developed; however, the development of bi-metal mask stencils was not completed.

A method of using fluorescent X-ray spectrographic techniques was developed for qualitative verification of thick-film materials. Required resistor areas may be determined directly from given resistance values by the use of a computer program. Viscosity measurements were not considered useful because of the strong dependence of viscosity on temperature and shear rate. Techniques developed for use of resistor, conductor, and dielectric materials were considered successful, with the exception of the high-dielectric-constant insulation, which proved to be moisture sensitive. The suitability of thick-film conductors for microwave applications was not determined.

FUTURE WORK

Applications of thick-film technology are now employed on EP 46241 for Lawrence Livermore Laboratory development hardware. No further work is planned on PDO 6984440; however, additional related work on trimmable resistors planned for PDO 6984668 is to be completed on PDO 6984694.

It is recommended that additional work be performed on precision printing techniques (that is, bimetal masks and printer parameters) in support of projected future programs.

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