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THICK FILM FABRICATION OF ALUMINUM NITRIDE MICROCIRCUITS

L. H. Perdieu

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Final Report

L. H. Perdieu, Project Leader

Project Team:

S. W. Bandler

C. W. Boehning

M. A. Cunningham

L. W. McWilliams

P. M. Mizik

H. A. Morgenstern

J. E. Smoot

D. R. Swift

L. E. Warner

MASTER

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Technical Communications
Kansas City Division

AlliedSignal
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Abstract

A new substrate material, aluminum nitride (AlN), and 11 new thick film inks were analyzed to determine their chemical compatibility, their electrical properties, their mechanical properties, and their overall suitability for use in the manufacturing of high-power microcircuits with efficient thermal properties. Because high-power chips emit a great deal of heat in a small surface area, a new substrate material was needed to dissipate that heat faster than the substrate material currently in use. Overall, the new materials were found to be acceptable for accomplishing this purpose.

Summary

Aluminum nitride was evaluated as a thick film substrate material for the following reasons: (1) its thermal conductivity is seven times greater than that of the standard substrate material (aluminum oxide); (2) it is nontoxic and can be used in high-power applications with little risk to safety,¹ (3) its thermal coefficient of expansion (TCE) closely matches the TCE of silicon and gallium arsenide, making it useful for direct mounting of large VLSI dies; and (4) it uses similar processing and the same capital equipment as standard thick film printing.

Through a joint development effort by The Carborundum Company, The Ferro Corporation, and AlliedSignal Inc., Kansas City Division (KCD), a processing capability to manufacture AlN microcircuits with efficient thermal properties for high-power applications was developed. Through the use of infrared thermal scanning, it was determined that the circuit operating temperature was reduced by 24°C (80% reduction) when AlN ceramic was substituted for the standard substrate material (aluminum oxide) in a complex thick film multilayer circuit.

The test vehicle used for this technology transfer partnership was the Logic

Assembly for the T/R Module in support of KCD's Advanced Radar Group. The Logic Assembly has a high level of integration. This results in severe thermal management problems that limit the module's operation to room temperature when conventional substrate materials (such as aluminum oxide) are used. With the use of a high thermal conductivity substrate (AlN), thermal problems were resolved.

New thick film inks were evaluated because standard inks reacted chemically with aluminum nitride substrates, resulting in poor metallization bonding to the substrate and unpredictable resistor values.

Preliminary data indicated satisfactory results with most of the new materials. However, the capability to print resistors was abandoned because of the wide variation experienced in resistor values. A study was performed on standard resistor test patterns to determine the percent coefficient of variation (CV) of the new resistor inks. The average CV was found to be 11%. The variation was worse than this on actual parts, which was attributed to the complexity of the design of the test vehicle application. When printed on test pattern samples, the new resistors could

not be laser trimmed to nominal within a tolerance any tighter than 4 to 18 percent. Resistor stabilities averaged 3.8% (standard resistor stabilities average 0.2%).

The capability to print resistors on AlN should be pursued in a future study. The ink manufacturer is continually making improvements to these resistors. Overall,

the results of this evaluation were positive. The thermal conductivity of AlN substrates, the ability to metallize AlN, the ability to solder and wire bond to the metallization, the ability to laser contour/drill AlN, and the use of chip resistors will accommodate 90% of the Kansas City Division's current needs for better thermal management.

Discussion

Scope and Purpose

The purpose of this project was to define a processing capability to manufacture high-density, high-power microcircuits with efficient thermal properties. As the capabilities of radars have increased both in frequency/speed and complexity of signal processing, the power dissipation per unit area has increased rapidly. The power density for the Terminal Fix System (TFS) radar is already exceeding the capabilities of aluminum oxide, and future radars will have even more stringent requirements for efficient heat transfer.

Prior Work

Efforts to fabricate the high-density, high-speed T/R Logic Assembly using standard thick film materials resulted in an assembly that overheated when operating only slightly above room temperature. Until recently, aluminum oxide has been the main material choice for advanced electronic applications. However, with the trend toward higher circuit densities and faster operating speeds, thermal management has become a major concern.

Activity

Through a joint development effort by The Carborundum Company (manufacturer of AlN ceramics), The Ferro Corporation (manufacturer of thick film inks), and by AlliedSignal Inc., Kansas City Division (KCD), a processing capability to manufacture aluminum nitride (AlN) microcircuits with efficient thermal

properties for high-power applications was developed.

The test vehicle used for this technology transfer partnership was the Logic Assembly for the Transmit/Receive (T/R) Module in support of KCD's Advanced Radar Group (see Figure 1). The Logic Assembly has a high level of integration. This results in severe thermal management problems that limit the module's operation to room temperature when conventional substrate materials (such as aluminum oxide) are used. The power transmitted from the final assembly has a peak power density of $2.17 \times 10^6 \text{ W/m}^2$ (1400 W/in.²) and an average power density of $7.13 \times 10^3 \text{ W/m}^2$ (460 W/in.²). With the use of a high thermal conductivity substrate (AlN), thermal problems were resolved.

Thick Film Processing

Printing aluminum nitride networks is no different from printing aluminum oxide networks, except specially formulated pastes are used. These pastes contain glass systems that are compatible with aluminum nitride substrates. Standard resistor pastes reacted violently with aluminum nitride substrates. Outgassing caused large holes in the films. Resistor values were always high, sometimes as much as 800% over nominal value. This made predicting fired resistor values an impossible task. See Table 1 for a comparison of aluminum oxide and aluminum nitride properties.

The new glass systems were developed by The Ferro Corporation's Electronic Materials Division and they are proprietary. Screen selection remains the same for the

Figure 1. Aluminum Nitride Power Hybrid on Sheet of AlN

new pastes, and drying aluminum nitride networks is no different from drying aluminum oxide networks.²

Firing aluminum nitride networks requires a special furnace profile. The aluminum nitride profile is 42 minutes in duration with a 9 to 10 minute peak at 850°C. See Figure 2 for the furnace profile.

Analysis of AlN Thick Film Inks

Thick film materials have been developed that are compatible with aluminum nitride (AlN) substrates. A family of glass compositions chemically compatible with AlN has been the key to the successful development of these pastes. The glass compositions also provide excellent wetting and bonding on AlN substrates. Using the

Table 1. Properties of Aluminum Oxide Versus Aluminum Nitride

Properties	Aluminum Oxide	Aluminum Nitride
Thermal Conductivity	25 W/m•K	170 W/m•K
Dielectric Constant	9.9	8.8
TCE	6.5 (10 e-6/K)	4.1 (10 e-6/K)
Resistivity	10 e14 ohm/cm	10 e14 ohm/cm

Figure 2. Furnace Profile for Aluminum Nitride Materials

developed glass compositions and reactive bonding compounds, the following pastes have been developed:

- A series of gold conductors including a gold paste (30-010) for wire bonding with gold wires, a mixed-bonded gold alloy paste (30-011) for wire bonding
- with aluminum wires, a platinum gold (Pt/Au) paste (31-012) for use with tin lead (Sn/Pb) solder, and a low shrinkage gold paste (30-012) for via fills;
- A crossover and multilayer hermetic dielectric (10-054); and

- Resistors including 1 ohm/square (89-001), 50 ohms/square (89-005), 100 ohms/square (89-007), 1,000 ohms/square (89-008), and 10,000 ohms/square (89-009).³

A study was performed on standard resistor test patterns (see Figure 3) to determine the percent coefficient of variation (CV) of the new resistor inks. The average CV was found to be 11%. The variation was worse than this on actual parts, which was attributed to the complexity of the design of the test vehicle application. When printed on test pattern samples, the new resistors could not be laser trimmed to nominal within a tolerance any tighter than 4 to 18 percent. Resistor stabilities averaged 3.8% (standard resistor stabilities average 0.2%).

Line Resolution

A conductor trace having an artwork width of 15 mils was printed using platinum/gold paste 31-012 and an aluminum oxide platinum/gold paste. The width of the 31-012 trace measured 7 percent less than the width of the aluminum oxide paste with the same printer setup (that is, 31-012 had slightly better resolution). Five mil lines and spaces were achieved with 31-012 paste using the conductor test pattern shown in Figure 4.

Conductor Resistance

Conductor resistance was measured using the 200-square electrical inspection pattern shown on the conductor test pattern in Figure 4. The conductor test pattern was printed 20 times for each conductor paste using a 325-mesh screen. The average resistivity for 31-012 was 22 milliohms/square. The average resistivity for 30-010 was 3.5 milliohms/square.

Solderability

The conductor test pattern shown in Figure 4 was printed 40 times with 31-012 and then dipped into 63/37 Sn/Pb solder. Wettability was 100%.

Bonding Strength of Gold Film

The bonding strength of the platinum/gold film to the aluminum nitride substrate was tested by a soldered wire pull test performed on pads that were 80 mils by 80 mils. Wires were attached to 20 pads by dipping in 63/37 Sn/Pb solder. The wires were then pulled at a 90° angle. The average pull strength was 6.8 lb, with 0 out of 20 pulls being below 2 lb, the minimum acceptable pull strength. After humidity aging (85°C/85% RH/1000 hours), the average pull strength was 3.8 lb, with 3 out of 20 pulls being below 2 lb (see Table 2).

A test was run to determine the effect of multiple conductor firings on pull strengths comparing AIN parts (31-012) to alumina parts. After 20 conductor firings, the AIN parts had an average pull strength of 4.3 lb and the alumina parts had an average pull strength of 4.2 lb (see Table 3).

Reactivity

During the fabrication of the Logic Networks, a reaction between the gold conductor (30-010 for gold wire bonds) and the dielectric (10-054) was observed. As with any multilayer application, the networks experienced multiple high-temperature firings. Single printed dielectric (solder stops) were printed over the 30-010 gold conductor which was printed directly over AIN. After five or six high-temperature firings, the single printed dielectric began to blister (see Figure 5).

Three separately fired layers of dielectric were printed between each conductor level of the Logic Networks (40 to 45 µm total

Figure 3. Thick Film Resistor Test Pattern

thickness). Triple-printed dielectric over 30-010 gold conductor did not blister after multiple high-temperature firings. This suggests that multiple firings plus the presence of air at the immediate interface between 30-010 gold conductor and 10-054 dielectric may be necessary for the reaction between these materials to occur.

Single printed solder stops on networks fabricated at the same time with a different gold conductor (30-011 for aluminum wire bonds) and 10-054 dielectric did not blister after multiple high-temperature firings.

In applications involving multiple high-temperature firings, 30-011 gold has significantly better adhesion than 30-010 gold. The bonding strength of the gold film to the aluminum nitride substrate was tested on actual parts fabricated by Ferro. The pull test results showed a significant difference between the bonding strength of the gold for gold wire bonds (30-010) and the bonding strength of the gold for aluminum wire bonds (30-011).

Nickel-plated gold lead frames were attached to 28 pads on actual parts using 50/50 Pb/In solder. Then, the lead frames were pulled at a 90° angle. The average

Figure 4. Thick Film Conductor Test Pattern

pull strength for 30-010 was 200 grams. The chief cause of failure was solder pad metallization failure; that is, the metallization peeled away from the AlN. For 30-011, the average pull strength was 435 grams and the chief cause for failure was the lead frame peeled from the solder. These parts experienced over 20 high-temperature firings at 850°C before pull testing.

Analysis of AlN Ceramic Substrates

Thermal Conductivity

The thermal conductivity (TC) of a substrate metallized with thick-film conductor material is lower than a bare AlN substrate. The thermal conductivity of a bare substrate was measured to be 198 W/m·K, a typical value for AlN. Then a uniform coating of thick film metallization was squeegeed over the substrate and fired. The thermal conductivity of the metallized substrate was measured at 135 W/m·K

Table 2. Pull Strength Before and After Humidity Aging

Material	Type of Cleaning	Before Humidity Aging		After Humidity Aging	
		Average	Standard Deviation	Average	Standard Deviation
AlN	No Clean	5.8	1.51	3.1	0.89
	Standard Clean	6.8	1.96	3.8	1.66
	Alternate Clean	6.6	0.99	3.4	1.24
Al ₂ O ₃	No Clean	4.4	1.13	1.4	0.93
	Standard Clean	4.2	1.05	1.0	0.53
	Alternate Clean	4.4	0.85	1.2	0.77

Table 3. Pull Strength After Multiple Conductor Firings

Material	Firing Condition	Before Thermal Aging		After Thermal Aging	
		Average	Standard Deviation	Average	Standard Deviation
AlN	No Firings	4.0	0.52	2.5	0.84
	20 Firings	4.3	0.78	0.8	1.32
Al ₂ O ₃	No Firings	3.9	0.79	2.6	1.18
	20 Firings	4.2	0.96	2.1	1.06

using the short-pulse-length TEA CO₂ laser technique.

In multilayer thick films, heat-generating components must go down on the substrate level because the thermal conductivity of a substrate printed with a

coating of dielectric is extremely poor—43 W/m•K.

Oxide Growth

Oxide growth per high-temperature firing (850°C) is only 20 angstroms (acceptable).

Figure 5. Photomicrograph of Dielectric Blisters

However, AlN substrates fired above 1100°C will oxidize. Because KCD's standard refire process (to anneal cracks caused by laser drilling) goes above 1100°C, it is mandatory that AlN substrates bypass the refiring process.

Camber

Hole drilling has no effect on camber (see data, before and after hole drilling, in Table 4). Substrates should be 100% tested for camber prior to printing.

Table 4. Substrate Camber Before and After Drilling Holes

Part Identification	Before	After	Thickness
1	6.2	6.0	25.3
2	16.3	16.9	25.9
3	22.6	33.1	24.9
4	7.8	7.6	26.6
5	27.3	34.3	27.2
6	16.6	23.4	27.1
7	5.7	5.4	25.3
8	8.3	4.9	25.9
9	7.3	4.3	26.3
10	5.1	4.0	27.1
11	4.1	3.2	25.1
12	4.8	6.1	26.8

The following camber measurement technique is used at KCD. A height gage is drawn across the part to determine the high point. The distance from the high point to the top of the flat surface is measured (using a height gage). The average part thickness is subtracted from the high point distance to determine camber.

Bending Strength

Forty pieces of ceramic (20 were AlN and 20 were alumina) were put through a three-point bend test. All pieces were the same length, width, and thickness. The AlN ceramics broke with 19% less force than the alumina ceramics.

Cleaning

AlN is compatible with the present KCD cleaning processes. This was determined by running three experiments. First the

substrates were subjected to the individual portions of the present cleans to determine if there were any adverse interactions. Second, the substrates were cleaned using the production processes and wire pull strength measured for those cleans. These results were then compared to no clean at all. Third, the time interval between cleaning and printing was investigated to determine if a timing specification would be required.

There are two production processes used to clean substrates at KCD. There is a "standard clean" that uses individual pieces of automated equipment and an "alternate clean" that is used when the automated equipment is down. The standard clean starts off with a Freon degrease; then the substrates go through a peroxide clean, followed by a D.I. water rinse, and finally a nitrogen dry. The alternate clean is a Freon degrease, an Igepal (surfactant) scrub, a D.I. water rinse,

two peroxide cleans, two ultrasonic D.I. water cleans, then four D.I. water rinses, and finally a nitrogen tunnel dry.

The wire pull strength test used in these experiments consisted of cleaning the substrates as required, then printing them with Ferro 31-012 Pt/Au conductor material using the KCD conductor test pattern. These substrates next had wires soldered to them; the wires were then pulled on an Instron pull tester.

AlN substrates were subjected to individual portions of the cleans described above and then to the full process to ensure that there would be no adverse interactions with the chemicals or equipment involved. No adverse interactions occurred.

Next, the wire pull strength of AlN processed with these two cleans and how it compared to no clean was investigated. It was found that the wire pull strength exceeded the 2 pound pull strength specification for all three conditions. The best results were obtained with the standard clean; then came the alternate clean and no clean (see Table 2).

Finally, the interval between cleaning and printing was examined to determine its effect on wire pull strength. Several substrates were cleaned, and a group was printed each day for 10 days. The wire pull strength for these substrates oscillated over this time period but never developed a clear upward or downward trend. (See Figures A-1 and A-2 in the Appendix of this report.)

To summarize, AlN substrates were found to be compatible to the present KCD cleaning chemicals and equipment. Wire pull strengths for substrates cleaned using the present processes exceeded specifications. Finally, a timing specification is not required between cleaning and printing of AlN substrates.

Analysis of Assembly Techniques

Thermosonic Gold Wire Bonding

Sample substrates that were single-printed with gold conductor (30-010, which is suitable for gold wire bonding) were populated with 1-mil gold jumper wires. Standard parameters were used during the wire bonding process. Subsequent pull testing of the wires to destruction yielded normal pull strengths (average = 7.5 grams, standard deviation = 1.17 grams, minimum = 5 grams).

Ribbon Bonding

During the thermosonic bonding of 2 X 5 mil gold ribbons to single-printed gold conductor, metallization peeling occurred in over 50% of the bond sites (see Figure 6). Subsequent bonding and pull testing of double-printed gold conductors showed a much more stable bond zone and normal pull strengths (average = 126.5 grams, standard deviation = 14.8 grams, minimum = 80 grams).

Conductive and Nonconductive Epoxies

Samples of a 230 mil square semiconductor die were attached to thick film gold conductors (30-010) using both a conductive and a nonconductive epoxy. Shear tests of the die revealed that all shear strengths were over 19.6 kilograms and that there were no metallization lifts.

Analysis of Laser Scribing/Machining Techniques

Laser Scribing

The YAG laser scribe in the Micro-miniature Electronic Assembly Department

Figure 6. Metal Adhesion Failures

at KCD does a fine job of scribing AlN ceramic substrates. Many substrates have been scribed and broken. The results have been excellent. The AlN ceramic breaks in a perpendicular fashion along the scribe lines. The breaks are very clean and accurate. The only drawback is that the scribe lines have a conductive aluminum track from the top of the ceramic surface to the bottom of the scribe (7 to 8 mils deep). If this conductive track is a problem on the front side, the substrates could be scribed on the back side with little or no accuracy loss.

Laser Drilling

A CO₂ laser is more likely to cause thermal damage to AlN than to aluminum oxide because of the high absorption coefficient of AlN. Also, CO₂ laser machining has to be performed with a cover gas (O₂) to limit the formation of aluminum. Because of the high absorption coefficient of AlN, the distance between holes must be doubled compared to machining aluminum oxide. The minimum hole diameter possible with a CO₂ laser is 0.005 in. A hole cannot be placed as close to the edge of an AlN substrate as an aluminum oxide substrate because the AlN substrate may crack.

The CO₂ laser driller in the Microminiature Electronic Assembly Department (400 watts) does a marginal job of drilling vias and cutouts in AlN. Many holes ranging from 5 mils upward have been drilled. The problem with this laser is that to get the power to do a good job on 25 mil thick AlN, the laser must be pulsed at 5000 Hz. The laser manufacturer says that this laser should only be pulsed to 2000 Hz maximum. Pulsing the laser faster than 2000 Hz could lead to premature failure in certain components in the laser, but the exact details of what would fail and when are not known. It has been observed that sometimes when pulsing at 5000 Hz, one of the laser tubes loses power, causing a

power output drop. When this occurs, the AlN may crack. A method for preventing this occurrence has been discovered, but this may not be a final solution for this problem. A new lens and the addition of oxygen as a nozzle cover gas have both helped this process, but not enough to overcome the lack of power of the laser.

The holes made in the AlN by this laser appear free of aluminum, mostly because of the addition of the O₂ cover gas. The holes have been observed under the scanning electron microscope and no radial cracking was evident.

In conclusion, this 400-watt CO₂ laser is underpowered for this job. It has shown that it can do a good job when it is working right. However, the possibility of causing a breakdown from over driving it is also a consideration. It is recommended that this laser be used only in emergency situations on small runs and that standard jobs be sent to an outside laser machining source.

Analysis of Resistors

Stability

At this time, two conclusions can be reached: (1) the resistors made from 100 ohms/square paste (89-007) are not stable enough to meet anticipated tolerances, and (2) the resistors made from 50 ohm/square paste (89-005) cannot have a tight tolerance (< 5%).

The graphs in Figure 7 show the average differences in stability, during accelerated aging, for untrimmed resistors made from 1, 50, 100, 1,000, and 10,000 ohms/square paste. In addition, the difference in stability because of firing profiles is compared.

Test samples for each resistor paste decade were prepared and fired using the standard profile (60 minute profile with an 850°C peak for 10 minutes). The value of

a. FOR 50 AND 100 OHMS/SQ

b. FOR 1, 1000, AND 10,000 OHMS/SQ

Figure 7. Stability Versus Furnace Profiles

each resistor on the sample was measured and recorded. Each untrimmed test sample was subjected to the following tests: 24 hour drift, temperature shock (25 to 268 to 25°C), temperature cycle (-40 to 125°C for 10 cycles), and a 1,000 hour thermal aging test at 150°C. The values of the resistors were measured after each test, and the percent change in value from the initial value was calculated. As can be seen in Figure 7, there is a considerable difference in stability between the 100 and 50 ohms/square pastes and the other pastes. This was not an expected result. The vendor suggested using a shorter firing profile.

Additional test samples were prepared, approximately 500 resistors for each paste decade. They were fired using the profile suggested by the vendor (see Figure 2). The same tests were performed on this group as before. The resulting percent change in resistor value is shown in Figure 7 for each paste. The results of the testing show an improvement in stability for 50, 100, 1,000, and 10,000 ohms/square resistors.

A comparison in average stability for 1, 50, 100, 1,000, and 10,000 ohms/square untrimmed resistors fired with the suggested profile is shown in Figure 8. As can be seen, there is a large difference between the 100 ohms/square resistors and resistors made with the other paste decades. This data indicated, based on anticipated resistor tolerances, that resistors made with 100 ohms/square paste are not acceptable for use. The stability of the 50 ohms/square paste also limits the resistor tolerance for resistors made with this paste. Figure 9 further supports these conclusions. The average percent change, as well as the 3 sigma distribution, is shown for each paste decade for each test.

Laser Trimming

It is possible to YAG laser trim AlN resistors, but it is difficult in that the laser parameter range necessary to achieve a visually acceptable cut is very narrow compared to the trimming range for aluminum oxide resistors.

Figure 10 shows the difference in stability between trimmed 10,000 ohm resistors and untrimmed 10,000 ohm resistors. For YAG laser trimming of AlN resistors, no substrate penetration should occur. Kerf width should be slightly wider than 50 μm . A cover gas is not used when trimming AlN resistors. It is recommended that a minimum resistor width be specified at 40 mils.

Auger electron spectroscopy profiles that were run at different points along the resistor kerf determined that no metallic aluminum could be detected. The points examined were all aluminum oxide when the profiles were terminated at a 12,000 angstrom depth.

Percent Coefficient of Variation

Four hundred thirty-two resistors were printed at $25 \pm 2 \mu\text{m}$ dried thickness (108 resistors for each paste decade) to determine the percent coefficient of variation. The resistors had a width of 50 mils and a length of 100 mils. See Figures A-3 through A-10 in the Appendix.

The percent coefficient of variation gives a comparative number for the variance in resistivity caused by the paste itself.

The percent coefficient of variation was calculated by dividing the standard deviation by the mean (see Table 5). The % CV for 89-001 = 11%, 89-005 = 14%, 89-008 = 7%, and 89-009 = 12%.

Figure 8. Average Stability (new furnace profile)

Thermal Performance Results

To experimentally verify the aluminum nitride substrate thermal performance in the actual T/R Module housing, two modules were built using logic assemblies made from aluminum nitride and alumina substrates. The substrate material thickness in both units was 25 mils. The logic assembly uses gold wire based chip and wire construction with solder attachment of all heat-generating components and conductive epoxy attachment of the remaining components.

To ensure that the same electrical loads were present in both units, precision 1% wire-wound resistors were used to simulate power demand of the RF assemblies that

would normally be present in the T/R Module assembly. The power resistors were conductive epoxy bonded to the housing on the RF side to ensure that the heat generated by the resistors was conducted back into the housing. The load on the + 8 volt transmitter regulator was set to 3.5 amperes (pulsed, 40 microsecond pulse width, 30% duty factor), the + 5 volt receiver regulator load was 170 milli-amperes (pulsed, 60 microsecond pulse width, 70% duty factor), and the -2.5 volt gate bias regulator load was 2.0 milli-amperes.

To start data collection, the thermal chuck on the tester was set to + 65°C and a hand-held noncontact infrared thermal probe was used to measure the

Figure 9. Stability at Different Stages of Testing

Figure 10. 10,000 Ohm Resistor Stability (trimmed versus untrimmed)

temperature of the thermal chuck and the unit. The unit was placed on the preheated chuck, and its warmup characteristics were observed as the unit warmed to +65°C from room temperature. The unit was not powered during this sequence.

The aluminum nitride based logic assembly had worse case thermal gradients of 3°C across the face of the substrate during warmup. The alumina based logic assembly had gradients in the 15°C range. The lower gradients for AlN

mean less mechanical stress on the surface mount parts during temperature transitions.

Using the thermal probe, the temperature on the top of the transmitter (Tx) regulator (U1) was measured as the DC power was applied to the unit. The final stabilized temperature of the regulator was recorded for each type of substrate material. The actual test temperatures measured on the units are summarized in Figure 11.

Table 5. Percent Coefficient of Variation

Paste	Average Dry Thickness (μm)	Resistance for Two Squares ($X-\Omega$)	Standard Deviation	Coefficient of Variation (percent)
1 $\Omega/\text{Sq.}$	25 $\pm$ 2	2.5	0.282	11
50 $\Omega/\text{Sq.}$	25 $\pm$ 2	85.0	11.985	14
1,000 $\Omega/\text{Sq.}$	25 $\pm$ 2	1,500	0.110	7
10,000 $\Omega/\text{Sq.}$	25 $\pm$ 2	9,600	1.128	12

Aluminum Nitride Substrate

Tx Regulator Temperature = + 73°C
 Thermal Chuck Temperature = + 67°C
 Temperature Difference = + 6°C

Alumina Substrate

Tx Regulator Temperature = + 95°C
 Thermal Chuck Temperature = + 65°C
 Temperature Difference = + 30°C

Temperature Reduction Using AlN = 24°C (80% reduction in operating temperature).

Figure 11. Actual Test Temperatures

The technical requirement details for AlN thick film hybrid materials are displayed in Table A-1 in the Appendix.

Accomplishments

A new substrate material and 11 new inks were analyzed to determine their suitability for use in the manufacturing of high-power microcircuits with efficient thermal properties. Preliminary data indicated satisfactory results with most of the new materials. However, the capability to print resistors was abandoned because of the

wide variation experienced in resistor values.

In addition to these determinations, this study also achieved the following results.

- Circuit operating temperature was shown to decrease by 24°C when the new substrate material was substituted for the standard substrate material in a complex thick film multilayer circuit.
- A technical partnership was successfully formed with two outside companies.

- Technical requirements were established for AlN thick film materials.
- A preliminary characterization of laser trimming on a new series of resistor pastes was performed.
- Aging characteristics of the new resistor pastes were completed for 1,000 hours on 1, 50, 100, 1,000, and 10,000 ohms/square resistor materials at 150°C.
- Assembly techniques used on standard thick films were evaluated for AlN materials.

Overall, it was found that the properties of the new AlN resistor pastes were not as good as the properties of standard thick film resistors.

Future Work

Future activities should include additional AlN resistor evaluations. The Ferro Corporation is currently developing a more stable 100 ohm/square paste. Also, there was a design-related problem with the resistors on the Logic Networks that kept the resistors from being printed at controllable thicknesses. In addition to stability, parameters of interest should include sheet resistivity, temperature coefficient of resistance, percent coefficient of variation, and laser trimmability to nominal within a specified tolerance.

Concerning the AlN substrates, future activities should include additional studies on lot-to-lot effect on metallization adhesion to the substrate.

References

¹ Department of Defense Memorandum for Industry Distribution, "Request for Suitable Substitutes for Beryllium Oxide," February 6, 1989.

² S. W. Bandler and L. H. Perdieu, Thick Film Multilayer AlN Power Hybrid Circuit. ISHM Proceedings, Dallas, TX, 1993.

³ K. Allison, A. Shaikh, D. Leandri, M. Raymond, G. Ackerman, and D. Hankey, Thick Film Materials For Applications On Aluminum Nitride Substrates. IMC Proceedings, Tokyo, 1988.

⁴ Y. Kurihara, S. Takahashi, K. Yamada, T. Endoh, and K. Kanai, Thick Film Resistors for AlN Ceramics, IEEE Transactions on Components, Hybrids, and Manufacturing Technology, Vol. 14, No. 1, March 1991.

Appendix

Test Data for AlN Microcircuits

Figure A-1. Pull Strength Versus Days After Cleaning

Figure A-2. Pull Strength Versus Days After Cleaning, After Thermal Aging

TSD TEST RESULT DISTRIBUTION ANALYSIS

Plot dates: 11-DEC-92

50-mil Wide

Plot 1 of 1

Part : 89-001
 Lot ID : 2 lot collection -#2241-2-2261
 Insertion :
 Sublot :
 Test Dates: 11-DEC-92 11-DEC-92

POPULATION Minimum : None
 LIMITS Maximum : None
 Underflows : 0
 Overflows : 0

PLOT Minimum : Automatic
 LIMITS Maximum : Automatic
 Underflows : 0
 Overflows : 0
 Y Maximum : Automatic

DATA	Minimum	:	2.073		
STATISTICS	Maximum	:	3.219		
	Cells plotted	:	40	+3 Sigma :	3.2850
	Cell width	:	0.0310	+2 Sigma :	3.1031
	Total Tested	:	27	+1 Sigma :	2.9213
	N	:	108	Mean :	2.5295
	Mean	:	2.5395	-1 Sigma :	2.3477
	Mode cell	:	2.357	-2 Sigma :	2.1658
	Std. Deviation	:	0.28185	-3 Sigma :	1.9839

Included failed tests : 108
 Included alarmed tests : 0

CV = 0.1109864 = 11%
 Dry Thickness = 25 ±2 microns

Figure A-3. CV Data for 1 Ohm/Square Material

Each * represents 0.148 % of the data within the population limits.

Test units : 0					
Cell Lower Bound	Cell %	Distribution			
Plot Underflow	0.00	0%	1.85%	3.70%	5.56%
		+	+	+	+
2.047		-----			
2.078	2.78				
2.109	1.85	*****			
2.140	1.85	*****			
2.171	2.78	*****			
2.202	3.70	*****			
2.233	3.70	*****			
2.264	2.78	*****			
2.295	3.70	*****			
2.326	5.56	*****			
2.357	7.41	*****			
2.388	3.70	*****			
2.419	5.56	*****			
2.450	6.48	*****			
2.481	5.56	*****			
2.512	1.85	*****			
2.543	0.93	*****			
2.574	6.48	*****			
2.605	1.85	*****			
2.636	2.78	*****			
2.667	1.85	*****			
2.698	0.93	*****			
2.729	0.93	*****			
2.760	2.78	*****			
2.791					
2.822	0.93	*****			
2.853	3.70	*****			
2.884	1.85	*****			
2.915	5.56	*****			
2.946	1.85	*****			
2.977	1.85	*****			
3.008	0.93	*****			
3.039	0.93	*****			
3.070	1.85	*****			
3.101	0.93	*****			
3.132					
3.163	0.93	*****			
3.194	0.93	*****			
3.225					
3.256					
Plot Underflow	0.00	-----			
Overflow					

Figure A-4. Histogram for CV Data for 1 Ohm/Square Material

TSD TEST RESULT DISTRIBUTION ANALYSIS

50-mil Wide

Plot date: 11-DEC-91

Plot 1 of 1

Part : 89-005
 Lot ID : 000001 -#2260-1-2261
 Insertion :
 Sublot :
 Test Dates: 14-DEC-92

POPULATION	Minimum	:	None
LIMITS	Maximum	:	None
	Underflows	:	0
	Overflows	:	0

PLOT	Minimum	:	Automatic
LIMITS	Maximum	:	Automatic
	Underflows	:	0
	Overflows	:	0
	Y Maximum	:	Automatic

DATA	Minimum	:	64.60		
STATISTICS	Maximum	:	113.15		
	Cells plotted	:	40	+3 Sigma :	120.907
	Cell width	:	1.280	+2 Sigma :	108.922
	Total Tested	:	27	+1 Sigma :	96.937
	N	:	108	Mean :	84.953
	Mean	:	84.953	-1 Sigma :	72.948
	Mode cell	:	78.67	-2 Sigma :	60.932
	Std. Deviation	:	11.9846	-3 Sigma :	48.927

Included failed tests : 108
 Included alarmed tests : 0

CV = 0.1417792 = 14%
 Dry Thickness = 25 ±2 microns

Figure A-5. CV Data for 50 Ohms/Square Material

Each * represents 0.167 % of the data within the population limits.

Test units : 0						
Cell Lower Bound	Cell %	Distribution				
Plot Underflow	0.00	0%	2.08%	4.17%	6.25%	8.33%
		+	+	+	+	+
63.31						
64.59	1.85	*****				
65.07	0.93	*****				
67.15	1.85	*****				
68.43	2.78	*****				
69.71	1.85	*****				
70.99	2.78	*****				
72.27	4.63	*****				
73.55	7.41	*****				
74.83	2.78	*****				
76.11	5.56	*****				
77.39	4.63	*****				
78.67	8.33	*****				
79.95	1.85	*****				
81.23						
82.51	6.48	*****				
83.79	2.78	*****				
85.07	6.48	*****				
86.35	2.78	*****				
87.63	2.78	*****				
88.91	1.85	*****				
90.19	0.93	*****				
91.47	0.93	*****				
92.75	0.93	*****				
94.03	1.85	*****				
95.31	1.85	*****				
96.59	0.93	*****				
97.87	4.63	*****				
99.15	3.70	*****				
100.43	3.70	*****				
101.71	1.85	*****				
102.99						
104.27	1.85	*****				
105.55	1.85	*****				
106.83	1.85	*****				
108.11						
109.39	0.93	*****				
110.67	0.93	*****				
111.95	0.93	*****				
113.23						
Plot Overflow	0.00					

Figure A-6. Histogram for CV Data for 50 Ohms/Square Material

TSD TEST RESULT DISTRIBUTION ANALYSIS

50-mil Wide

Plot date: 11 DEC 82

Plot 1 of 1

Part : 89-008
 Lot ID : 000002 -#2237-2-2239
 Insertion :
 Sublot :
 Test Dates: 11-DEC-92

POPULATION Minimum : None
 LIMITS Maximum : None
 Underflows : 0
 Overflows : 0

PLOT Minimum : Automatic
 LIMITS Maximum : Automatic
 Underflows : 0
 Overflows : 0
 Y Maximum : Automatic

DATA	Minimum	:	1.228		
STATISTICS	Maximum	:	1.807		
	Cells plotted	:	39	+3 Sigma :	1.8541
	Cell width	:	0.0160	+2 Sigma :	1.7142
	Total Tested	:	27	+1 Sigma :	1.6342
	N	:	100	Mean :	1.5243
	Mean	:	1.5243	-1 Sigma :	1.3140
	Mode cell	:	1.580	-2 Sigma :	1.3014
	Std. Deviation	:	0.10795	-3 Sigma :	1.1044

Included failed tests : 108
 Included alarmed tests : 0

CV = 0.0721315 = 7%
 Dry Thickness = 25 ±2 microns

Figure A-7. CV Data for 1,000 Ohms/Square Material

Each * represents 0.185 % of the data within the population limits.

Test units : KO					
Cell Lower Bound	Cell %	Distribution			
		Cumulative %			
Plot Underflow	0.00	0%	2.31%	4.63%	6.94%
		+	+	+	+
1.212					
1.228	1.85	*****			1.85
1.244					
1.260	0.93	*****			2.78
1.276					
1.292					
1.308					
1.324	3.70	*****			6.48
1.340	0.93	*****			7.41
1.356					
1.372	2.78	*****			10.19
1.388	0.93	*****			11.11
1.404	1.85	*****			12.96
1.420	2.78	*****			15.74
1.436	7.41	*****			23.15
1.452	2.78	*****			25.93
1.468	7.41	*****			33.34
1.484	6.48	*****			39.82
1.500	8.33	*****			48.15
1.516	8.33	*****			56.48
1.532	2.78	*****			59.26
1.548	6.48	*****			65.74
1.564	4.63	*****			70.37
1.580	9.26	*****			79.63
1.596	0.93	*****			80.56
1.612	3.70	*****			84.26
1.628	1.85	*****			86.11
1.644	1.85	*****			87.96
1.660	1.85	*****			89.81
1.676	3.70	*****			93.51
1.692	0.93	*****			94.44
1.708	1.85	*****			96.30
1.724	0.93	*****			97.22
1.740					
1.756	0.93	*****			98.15
1.772					
1.788	0.93	*****			99.07
1.804	0.93	*****			100.00
1.820					
Plot Overflow	0.00				100.00

Figure A-8. Histogram for CV Data for 1,000 Ohms/Square Material

TSD TEST RESULT DISTRIBUTION ANALYSIS
50-mil Wide

Plot date: 11-DEC-92
Plot 1 of 1

Part : 89-009
Lot ID : 000001 -#2269-2-2673
Insertion :
Sublot :
Test Dates: 11-DEC-92

POPULATION Minimum : None
LIMITS Maximum : None
Underflows : 0
Overflows : 0

PLOT Minimum : Automatic
LIMITS Maximum : Automatic
Underflows : 0
Overflows : 0
Y Maximum : Automatic

DATA	Minimum	:	7.110		
STATISTICS	Maximum	:	12.919		
	Cells plotted	:	40	+3 Sigma :	12.9915
	Cell width	:	0.1530	+2 Sigma :	11.8634
	Total Tested	:	27	+1 Sigma :	10.7354
	N	:	108	Mean :	9.6073
	Mean	:	9.6073	-1 Sigma :	8.4772
	Mode cell	:	8.793	-2 Sigma :	7.3511
	Std. Deviation	:	1.12808	-3 Sigma :	6.2230

Included failed tests : 108
Included alarmed tests : 0

CV = 0.117419 = 12%
Dry Thickness = 25 ±2 microns

Figure A-9. CV Data for 10,000 Ohms/Square Material

Each * represents 0.222 % of the data within the population limits.

Test units : K0

Cell Lower Bound	Cell %					Distribution Cumulative %
Plot Underflow	0.00	0%	2.78%	5.56%	8.33%	11.11%
		+	+	+	+	+
6.957						
7.110	0.93	****				0.22
7.263						
7.416						
7.569						
7.722						
7.875	3.70	*****				4.44
8.028	1.85	*****				5.33
8.181	3.70	*****				10.19
8.334	4.63	*****				14.81
8.487	4.63	*****				19.44
8.640	3.70	*****				23.15
8.793	11.11	*****				34.26
8.946	4.63	*****				38.89
9.099	3.70	*****				42.59
9.252	9.26	*****				51.85
9.405	5.56	*****				57.41
9.558	5.56	*****				62.97
9.711	0.93	****				63.90
9.864	2.78	*****				66.68
10.017	2.78	*****				69.46
10.170	5.56	*****				75.02
10.323	2.78	*****				77.80
10.476	1.85	*****				79.65
10.629	2.78	*****				82.43
10.782	4.63	*****				87.06
10.935	2.78	*****				89.84
11.088	1.85	*****				91.69
11.241						
11.394	2.78	*****				94.47
11.547						
11.700	0.93	****				95.40
11.853	0.93	****				96.33
12.006	0.93	****				97.26
12.159	0.93	****				98.19
12.312						
12.465						
12.618	0.93	****				99.12
12.771	0.93	****				100.00
12.924						
Plot Overflow	0.00					100.00

Figure A-10. Histogram for CV Data for 10,000 Ohms/Square Material

Table A-1. Pre-established Requirements for AlN Thick Film Hybrid Materials

Anything not otherwise specified below will be tested to manufacturer's data sheet		
1	Conductor Line Resolution	5 mil lines and spaces After line has been printed and dried it must maintain width of ± 1 mil
2	Conductor Thickness	0.4 - 0.6 mil
3	Conductor Resistivity (1 mil fired thickness)	(Au) 3068N = 4.0 - 5.0 mohms/sq (Au) 3066 = 2.0 - 2.4 mohms/sq (Au) 30-010 = 3.0 - 4.0 mohms/sq (Au) 30-011 = 5.5 - 6.0 mohms/sq (Pt/Au) 31-012 = 20-25 mohms/sq (Pt/Au) 30-012 = 7-10 mohms/sq
4	Conductor Adhesion	Initial ≥ 6.0 lbs Aged ≥ 4.0 lbs
5	Must be able to coat vias walls	Through-hole resistance ≤ 4.5 lbs
6	Conductor Adhesion and Bondability Over Dielectric 31-009 (double printed) and 3066 and 3068N (single printed) over dielectric	Initial Adhesion ≥ 4.5 lbs Aged Adhesion ≥ 2.0 lbs
7	Compatibility with Cleaning Methods Used Prior to Bonding & Fluxless Solder. (1) Hydrogen Peroxide (Aqueous) (2) Plasma A) Oxygen B) Nitrogen/Hydrogen 97/3 C) Argon	
8	Solder Acceptance <div> <div>Mix</div> <div>Content</div> <div>Process Temp</div> </div> <div> <div>80/20</div> <div>Au/Sn</div> <div>345°C</div> </div> <div> <div>92.5/5/2.5</div> <div>Pb/Sn/Ag</div> <div>345°C</div> </div> <div> <div>50/50</div> <div>In/Pb</div> <div>250°C</div> </div> <div> <div>60/40</div> <div>In/Pb</div> <div>225°C</div> </div> <div> <div>70/30</div> <div>In/Pb</div> <div>210°C</div> </div> <div> <div>63/37</div> <div>Sn/Pb</div> <div>183°C</div> </div>	On AlN = 98% Wetting On Dielectric = 98% Wetting

Table A-1 Continued. Pre-established Requirements for AlN Thick Film Hybrid Materials

Anything not otherwise specified below will be tested to manufacturer's data sheet.		
9.	Bondability <ul style="list-style-type: none"> Metallization system(s) shall be capable of .001" pure gold wire bond strengths of 6 grams average, 3 grams minimum using a thermosonic ball bonding technique, using a substrate temperature of no more than 170°C. Loop profiles prior to pull testing shall be no more than .015" in height, and shall be no more than .025" in length (bond to bond). Parallel gap welding (lead frames) Metallization system(s) shall be capable of .001" and .002" aluminum (1% silicon) ultrasonic wire bonding. Strengths of 6 grams average and 2.5 grams average minimum for .001" and 15 grams average and 5.6 grams minimum for .002" wires. Loop profiles prior to pull testing shall be no more than .015" in height and shall be no more than .025" in length (bond to bond) for .001" and .050" in length (bond to bond) for .002" wire. Thermosonic gold ribbon bonding. Metallization system(s) shall be capable of epoxy attachment techniques using epoxies listed to the right. Curing profile shall be 160°C for 1.5 hours. Shear strengths shall be no less than 1000 #/square inch. 	1) Furane 7002 2) Furane 7200 3) Able Film 517 4) Able Film 550 5) Epo-Tek H20E 6) Epo-Tek H81 7) DuPont 5504 For the DuPont 5504 a 300°C for 1 hour temperature spike is added to the cure profile.
10.	Pt/Au and Au conductors can be used together on the same level and can overlap.	
11.	Resistor Stability (after trim) ⁴	Thermal Aging ≤ 1% Thermal Shock ≤ .5% Thermal Cycle ≤ 1%

Table A-1 Continued. Pre-established Requirements for AlN Thick Film Hybrid Materials

Anything not otherwise specified below will be tested to manufacturer's data sheet.		
12.	Dielectric Requirements: Insulation Resistance (200 VDC) Breakdown Voltage Dielectric Constant	$> 10^{11}$ $> 600 \text{ V/mil}$ 8.0 - 10.0
13.	Substrate Requirements: Dielectric Constant Volume Resistivity Dielectric Loss Thermal Conductivity TCE Density Grain Size Camber Surface Roughness Thickness Bending Strength	$8.6 \pm .1$ (at 1 MHz) $\geq 10^{14}$.0005 Max (at 1 MHz) $> 170 \text{ W/mK}$ $4.7 \times 10^{-6}/^{\circ}\text{C}$ 3.3 g/cm^3 3-5 micrometers $\leq .003"/\text{inch}$ $< 25 \text{ microinches}$ $25 \pm 2.5 \text{ mil}$ 276 MPa

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