COMPARISON OF METALLIZATION SYSTEMS FOR THIN FILM HYBRID MICROCIRCUITS
PART I: Fabrication and Lead Frame Bondability

By R. A. Hines and M. K. Raut

BDX-613-2332
Distribution Category
UC-38

Manuscript Submitted
2nd AES Design and Finishing of Printed Wiring and Hybrid Circuits Symposium
AES
January 15-17, 1980
San Francisco, CA

The Bendix Corporation
Kansas City Division
P. O. Box 1159
Kansas City, Missouri 64141

A prime contractor with the United States Department of Energy under Contract Number DE-AC04-76-DP00613

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ABSTRACT

Cr/Pd/Au and Ti/Pd/Au metallization systems with either evaporated or electroplated gold were evaluated relative to the currently used Cr/Au (evaporated) system. A description of the five systems and the process steps used to fabricate thin film networks are discussed. Over 7000 leads from thermocompression bonded lead frames were pull tested to determine the bondability and adhesion characteristics of the film.

Introduction

A Cr/Au metallization system currently is used by Bendix Kansas City to manufacture thin film hybrids designed by Sandia Laboratories. The initial Cr/Au development work by Sandia and Bendix showed that, as a result of Cr diffusion during resistor stabilization, a prebond Cr etch was necessary to remove Cr_2O_3 from the surface.[1,2] The Cr/Au process has been very successful at producing high reliability hybrids for weapon systems. No field failures caused by the thin film system have been detected during the extensive production history.

Recurring seasonal decreases in manufacturing yields caused by metallization adhesion rejects at lead frame bond acceptance testing have resulted in an effort to develop an improved metallization system for possible new production programs and development orders and as a backup for the Cr/Au system. The failures can result from the prebond Cr etch attacking the Cr "glue" layer through the porous evaporated Au or by iodine attack during processing.[3] Other factors, including humidity, affect the yields which historically are lower in the spring and summer.

*Operated for the U. S. Department of Energy by The Bendix Corporation, Kansas City Division under Contract No. DE-AC04-76-DP00613.

Electroplated gold has been studied as a possible replacement for evaporated gold. Dini (Sandia Laboratories Livermore) used electrochemical measurements to quantify the reduced porosity that can be obtained with electroplated gold.[4] Bendix investigated the possibility of substituting electroplated gold for the outer 5.5 microns of a 6-micron gold layer.[5] Although the electroplated Au may be helpful for reducing corrosion, infrequent but low strength ceramic-metallization failures were encountered on the Cr/Au (electroplated) system.

The use of an intermediate Pd layer for corrosion and diffusion protection was studied by Hampy.[3] Hampy found that 500 Å of Pd did not sufficiently reduce the diffusion of Cr to the surface but 2000 Å did reduce the amount of Cr at the surface below a concentration that would interfere with thermocompression bonding. As 2000 Å of Pd was needed, Hampy recommended that additional testing include a Ti/Pd/Au system that also uses 2000 Å of Pd. Ti/Pd/Au was recommended because palladium was reported to be an effective barrier for Ti diffusion[6] and because the Ti/Pd/Au system is widely used by others, including Bell Labs,[7] Western Electric,[8] and Collins Radio.[9]

Description of Conductor Metallization Systems

Three basic metallization systems were studied: Cr/Au, Cr/Pd/Au, and Ti/Pd/Au. The Cr/Au system, with evaporated Cr and Au, is the current Bendix production standard. A Cr/Au system using electroplated gold over a thin evaporated gold layer had previously been evaluated.[3,4] This study compares Cr/Pd/Au and Ti/Pd/Au, both with either evaporated Au or pattern electroplated Au, to the Cr/Au (evaporated) system.

The conductor metallization is deposited on a 99.5% Al_2O_3 substrate which may include a sputtered Ta_2N coating on one side. The optional Ta_2N layer is used to form thin film resistors. Some circuits also require backside metallization and vias through the ceramic to provide a conductive path between the backside metallization and the conductors on the patterned front side. Twelve combinations of ceramic-Ta_2N-via variables were evaluated with each of the five metallization systems. The deposition steps for each system are shown in Figure 1. Although not included in this study, the Cr/Au system using electroplated gold also is shown in Figure 1.

All the evaporation was done in a single evaporation system. The energy for evaporation was supplied by an electron beam for all the evaporation with the exception of Cr in the Cr/Au system. The production evaporation system uses a resistively heated boat for Cr evaporation. Both electron beam and resistively heated Cr were used to form the Cr/Au circuits for these tests. Cr evaporation was done at a rate of 1 Å/s to

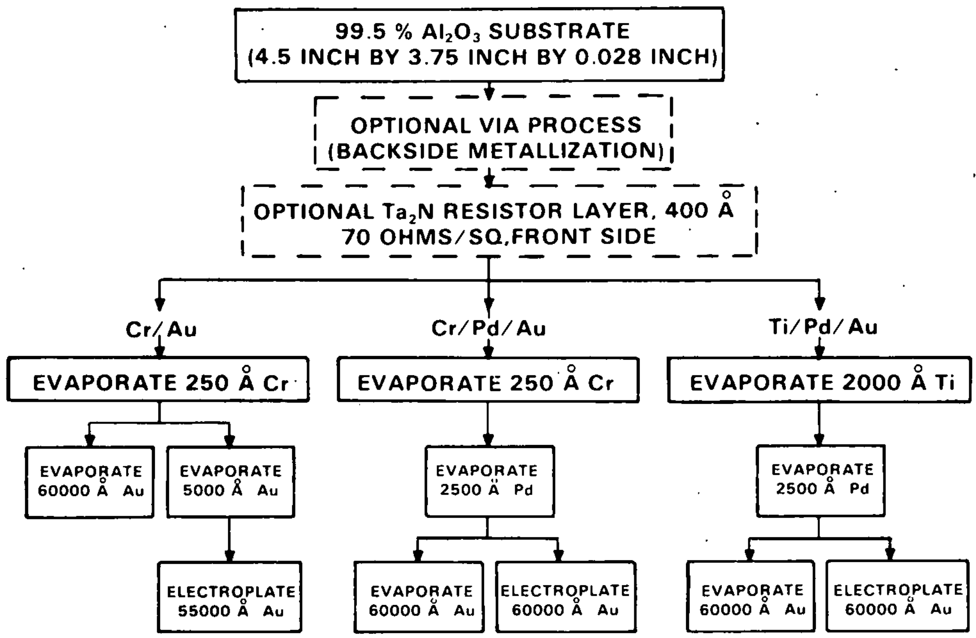


Figure 1. Description of Metallization Systems

a total thickness of 250 Å. Pd and Ti were deposited at a rate of 10 Å/s; 2500 Å of Pd and 2000 Å of Ti were used. Gold was deposited in the evaporation system at a rate of 60 Å/s to a thickness of 60,000 Å. Gold pattern plating on Pd was done using a gold cyanide-phosphonic acid solution to deposit a pure, soft gold at a rate of approximately 18 Å/s.

Substrates and Metallization Combinations Tested

Previous evaluations of new metallization systems and production experience indicated that lead frame bond results could vary as a function of ceramic or Ta_2N processing variables. Three types of ceramic processing and four types of Ta_2N were tested with each of five metallization systems. The three types of ceramic (all from a common vendor lot) that were studied are shown below.

> 800°C--standard blank or nonvia ceramic processing which includes an 800°C firing operation.
>
> Via (1400°C)--standard via processing which includes coating, drilling, peening, cleaning, and a 1400°C refire operation.
>
> 1400°C--standard nonvia processing plus a 1400°C refire.

Production Hermans containing vias are processed through several more operations than nonvia Hermans. The via Hermans are coated, drilled, glass bead peened, and refired at 1400°C; an additional cleaning operation also is included.

The four Ta_2N variables were Ta_2N from each of three sputtering systems and no Ta_2N. The no-Ta_2N Hermans had the metallization deposited directly on the bare ceramic. The no-Ta_2N Hermans are similar to the back side of production via Hermans which have metallization directly on the ceramic. Two nearly identical batch sputtering systems (B I and B II), which coat six Hermans per pumpdown, were used. These two systems and a larger, continuous processing machine which coats Hermans at a rate of one every 40 seconds were used to sputter Ta_2N for this evaluation. All 12 combinations of ceramic-Ta_2N variables were evaluated for each of the five metallization systems. Three Cr/Au (evaporation), two Cr/Pd/Au (evaporation), one Cr/Pd/Au (electroplated), one Ti/Pd/Au (evaporation), and one Ti/Pd/Au (electroplated) metallization runs were made.

Circuit Fabrication

Fabrication of thin film resistor-conductor networks from the Cr/Pd/Au and the Ti/Pd/Au systems required development of several process steps that differed from the production Cr/Au process. The processing steps for each metallization system are shown in Figure 2. The initial processing steps through Ta_2N sputtering are independent of the conductor metallization system used. Processing steps from resistor photolithography through lead frame bonding are the same for all systems with two exceptions. A prebond Cr etch using ceric ammonium nitrate solution (CAN) was used only on the Cr/Au circuits. The stripping of Ti from above the resistors can be done either directly before or after resistor photolithography. The Ti was stripped from the top of the resistors after resistor photolithography on the Ti/Pd/Au (evaporated) system. The Ti was removed prior to resistor photolithography on the Ti/Pd/Au (electroplated) system. The timing of the Ti etch had no measurable effect on the final product.

The three systems that used evaporated Au required a Au etch step to form the conductors. The conductors on the electroplated system were pattern Au plated. The pattern plated systems have the advantage of not exposing the circuits to the iodine-containing Au etch. Pattern plating reduces Au salvage costs by eliminating the deposition of Au on the bell jar walls and on nonconductor areas of the substrate. A new etch solution was developed at Sandia to etch Au and Pd in a single step. The production Au etchant used on the Cr/Au circuits is a 1.2 normal KI/1 normal I_2 solution. This solution did attack Pd but at a slow rate, resulting in excessive gold etch when tested as a combined Au-Pd etch. Sandia found that increasing the concentrations to 4 normal KI/1.5 normal I_2

PROCESS STEPS \ METALLIZATION SYSTEM	Cr/Au EVAPORATED	Cr/Pd/Au EVAPORATED	Cr/Pd/Au ELECTROPLATED	Ti/Pd/Au EVAPORATED	Ti/Pd/Au ELECTROPLATED
PHOTOLITH (DRY FILM)	X	X		X	
PHOTOLITH, PATTERN PLATE & STRIP RESIST			X		X
Au ETCH (1. 2/1 KI/I_2) & Cr ETCH WITH CAN	X				
Au & Pd ETCH (4/1.5 KI/I_2)		X		X	
Cr ETCH WITH CAN		X			
STRIP DRY FILM RESIST	X	X		X	
STRIP Pd (ANODIC OR $FeCl_3$)			X		X
ANODIC STRIP Cr			X		
STRIP Ti (1 % HF)					X
PHOTOPROCESS RESISTORS	X	X	X	X	X
STRIP Ti (1 % HF)				X	
LASER SCRIBE AND NUMBER	X	X	X	X	X
STABILIZE	X	X	X	X	X
PREBOND CAN ETCH	X				
CLEAN, BOND & PULL TEST LEAD FRAMES	X	X	X	X	X

Figure 2. Process Steps

increased the palladium etch rate relative to the gold etch rate. The concentrated solution was used on the two systems containing Pd and evaporated Au with satisfactory results. Palladium was removed from the pattern plated systems using an immersion etch in an $FeCl_3$ solution or by anodic stripping in an ethylene glycol solution containing 0.5 molar LiCl and 0.2 molar $Mg(ClO_4)_2$. Both methods for stripping Pd in the presence of Au were satisfactory, but the $FeCl_3$ solution was faster and did not require any special equipment. The $FeCl_3$ solution will be used in the future for Pd etching. Cr was anodically stripped from the Cr/Pd/Au system using a 100 g/L K_2CO_3 solution.

Anodic stripping was used to avoid exposing the circuits to CAN etch. Ti was stripped from the Ti/Pd/Au system using a 1% HF solution. The 1% HF strips the Ti in about 20 seconds with no measurable damage to the Ta_2N resistors.

Mod III Monitor

The circuit pattern used exclusively for this study is shown in Figure 3. The Mod III monitor normally is used at the four corners of a production Herman (4.5- by 3.75-inch ceramic substrate) for quality control testing. For this study, the Mod III monitor pattern was repeated 49 times on a Herman. The bond sites (19 along each 1-inch side), vias, and the control and series shorted resistor are the primary features of the monitor used in this study. Part I of this paper involves only the bond sites. Two types of bond pads on the monitor were used. One of the 1-inch sides of the monitor contains four checkboard bond pads and 15 standard bond sites. The standard pads are at least 0.040 inches square. The checkerboard pads are made up of alternately metallized and unmetallized 0.005-inch-square areas. The checkerboard pads provide half the metallized area to support lead frame bonding. The checkerboard pads were designed to force a failure at some point other than the lead to help identify the weak point in the metallization.

Bond Parameters and Pull Testing

Bare (unplated) Cu lead frames were thermocompression bonded to the Mod III monitors and individual leads were bent 90° and pulled to failure. The load at failure and the failure mode is recorded. The lead frame contains 19 individual leads that have a rectangular cross section of 0.007 by 0.015 inch. Bare copper leads are used for adhesion acceptance testing of thin films in production and were used to collect all the lead frame bond data reported here. Gold plated leads are used for electrical connection to production circuits and were used for some elevated temperature testing of circuits produced in this study. Although the number of gold-plated leads pulled in this study was about 5% of the total, the trends were the same as reported here for bare copper leads.

The production copper lead frame bond schedule was used for all bare copper lead frame bonding. No attempt was made to optimize the bond schedule for each metallization system. Nineteen leads were bonded at a time, using a tool with a rail 0.014 inch wide at 620°C for 30 seconds with a load of 17.3 pounds.

The data reported here were collected on the front side of fully processed monitors. Lead frame bonding and testing were done on unpatterned mirrors and on the back side of some

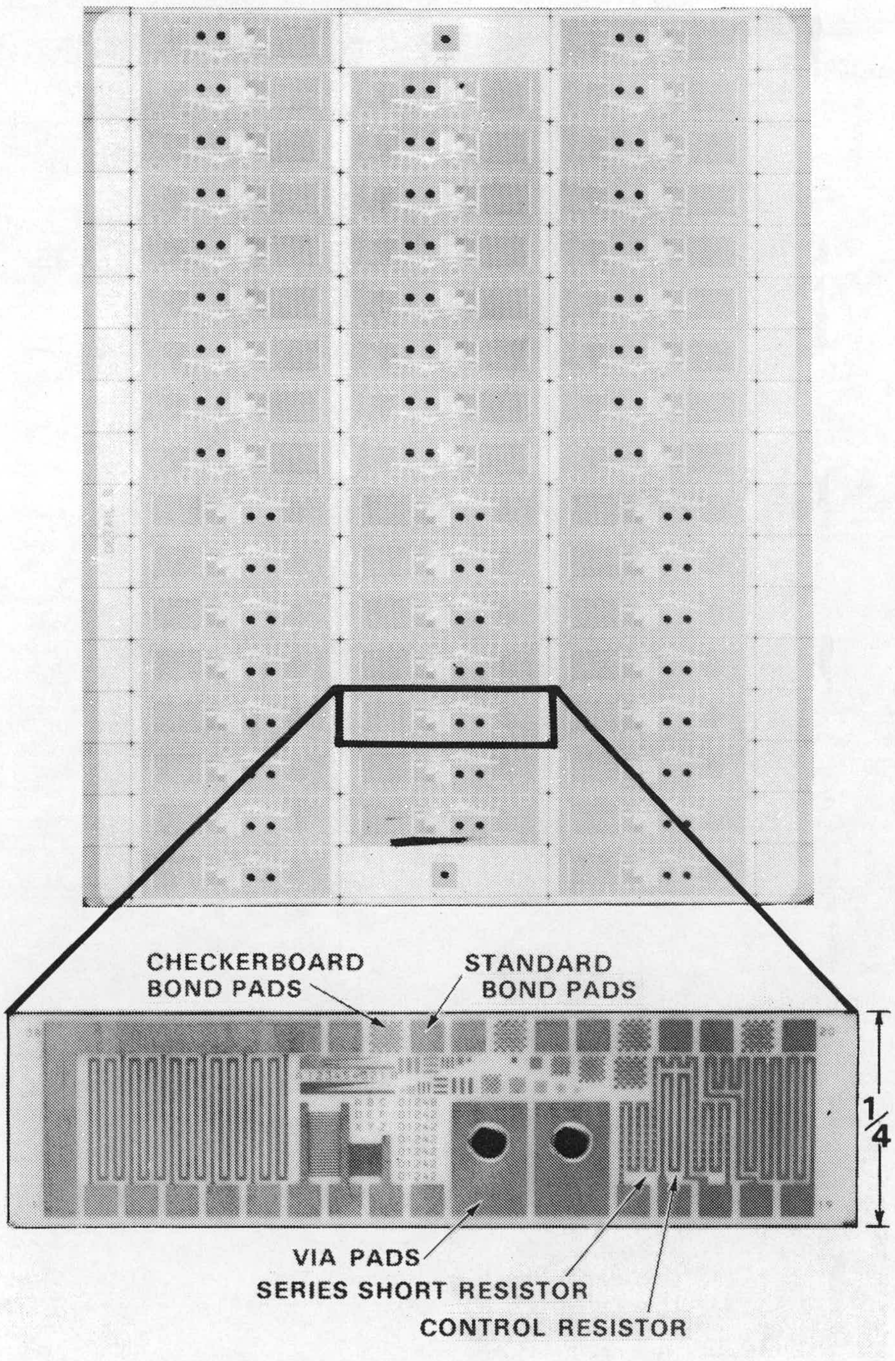


Figure 3. Mod III Monitor

monitors to help determine if the failure modes and strength measured on the processed front sides were caused by processing or were a function of the basic metallization system. No processing problems were found, and the trends on the unprocessed mirrors and on the back side test were the same as those reported here.

Over 7,000 leads were pull tested. Every other lead on the checkerboard side of each monitor tested was pulled, which resulted in pulling leads from eight standard pads and two checkerboard pads. Five monitors from a Herman representing each of the twelve ceramic-TA_2N variables was tested from each of the eight conductor metallization runs.

(10 leads)* (5 monitors)*(12 Hermans)*(8 runs) = 4800 leads tested.

An evaluation of gold plated leads, back side metallization, mirrors, and elevated temperature aging increased the number of leads tested to over 7,000.

A series of interactive computer programs were written to aid lead frame bond data reduction. Strength and failure modes are interactively entered into a data base along with identification Herman, monitor, and lead numbers. Other programs access the data base and sort by any combination of Hermans, monitors, or leads. The selected set of data is reduced to average, maximum, minimum, σ, and percent of each failure mode. Other programs use the data base to display the data in graphic form.

Four basic failure modes were encountered on leads pulled from the substrates. The failure modes are shown schematically in Figure 4. Of the four failure modes the most desirable is a Type B failure, heel break, which is a lead failure and indicates a sound thermocompression bond and a sound metallization system. A Type C failure, bond delamination, indicates a thermocompression bonding problem. The other two failure modes are more direct indicators of the relative quality of the metallization system. Type M failure, metallization failure, is pull out of the metallization which typically exposes some non-gold underlying metal. Type E failures are delaminations at the ceramic substrate.

The E failure rate historically has been less than 2 percent on production Cr/Au edge monitors. Initial evaluations of electroplated gold on Cr/Au systems found a 20 to 50 percent E failure rate.[5]

This study is the first use of checkerboard bond site to aid in the evaluation of metallization systems. Because the checkerboard bond sites almost always produce non-B failures they reveal the "weak link" in the metallization system instead of just establishing that metallization is "stronger" than the lead. The stress distribution during lead frame gold testing from checkerboard pads is different from that on standard bond pads; therefore, additional experience will be necessary before the significance of failure modes on checkerboard pads can be determined.

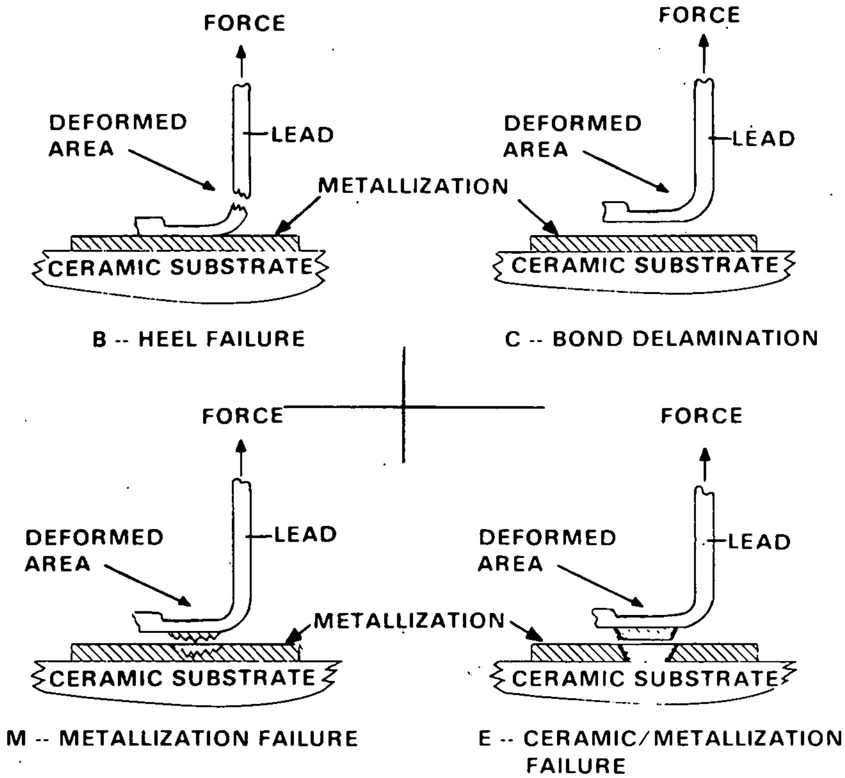


Figure 4. Lead Frame Bond Failure Classification

Bond Results

Figures 5 through 10 display the strength and failure modes measured during lead frame pull testing. The data have been organized to show trends as a function of ceramic-Ta_2N type, metallization system, and time-temperature aging for each system.

Figure 5 displays lead frame bond data for each of the twelve ceramic-Ta_2N types. The data are reduced from data from all five metallization systems. Some of the correlations between ceramic-Ta_2N type and bond results apply to only certain metallization systems. In other words, some of the metallization systems were relatively insensitive to ceramic-Ta_2N types. This point will be emphasized in the following discussion. From Figure 5, one can see that the E failure rate is much higher and the average strengths are lower on the no-Ta_2N Herman. The continuous processing machine resulted in a higher E failure rate than the two batch sputtering machines. Also, when the E failure rate is significant some zero strength values are measured. No significant differences can be attributed to ceramic processing.

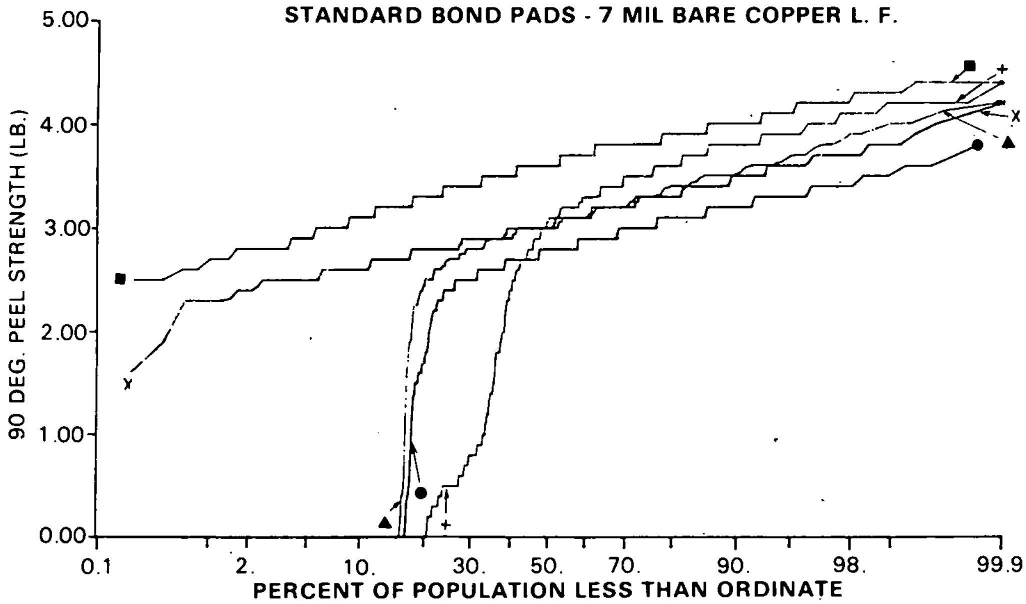
STANDARDS PADS, BARE Cu L.F.

Al_2O_3 \ Ta_2N		C.P.	B I	B II	NO Ta_2N
800°C	#LEADS	319	319	320	320
	$\bar{X}$ (LB)	2.78	3.19	3.03	1.40
	MAX. (LB)	4.2	4.4	4.3	4.2
	MIN. (LB)	0.0	1.2	0.0	0.0
	σ (LB)	.99	.42	.66	1.61
	% B	86.8	96.2	82.5	42.5
	% C	.6	.3	.9	0.0
	% M	.3	1.6	12.5	0.0
	% E	12.2	1.9	4.1	57.5
VIA (1400°C)	# LEADS	319	312	312	280
	$\bar{X}$ (LB)	2.99	3.15	2.98	1.20
	MAX. (LB)	4.3	4.4	4.4	4.1
	MIN. (LB)	0.0	0.0	0.0	0.0
	σ (LB)	.68	.55	.71	1.51
	% B	83.1	97.8	78.5	33.9
	% C	0.0	0.0	0.0	0.0
	% M	11.9	.3	12.8	0.0
	% E	5.0	1.9	8.7	66.1
1400°C	# LEADS	312	320	312	320
	$\bar{X}$ (LB)	2.89	3.09	3.01	1.47
	MAX. (LB)	4.4	4.2	4.3	4.2
	MIN. (LB)	0.0	1.0	0.0	0.0
	σ (LB)	.68	.42	.58	1.55
	% B	91.7	85.6	88.1	37.5
	% C	.6	.6	.6	0.0
	% M	.3	13.8	7.4	0.0
	% E	7.4	0.0	3.9	62.5

Figure 5. Bond Results As A Function Of Ceramic-Ta_2N Type

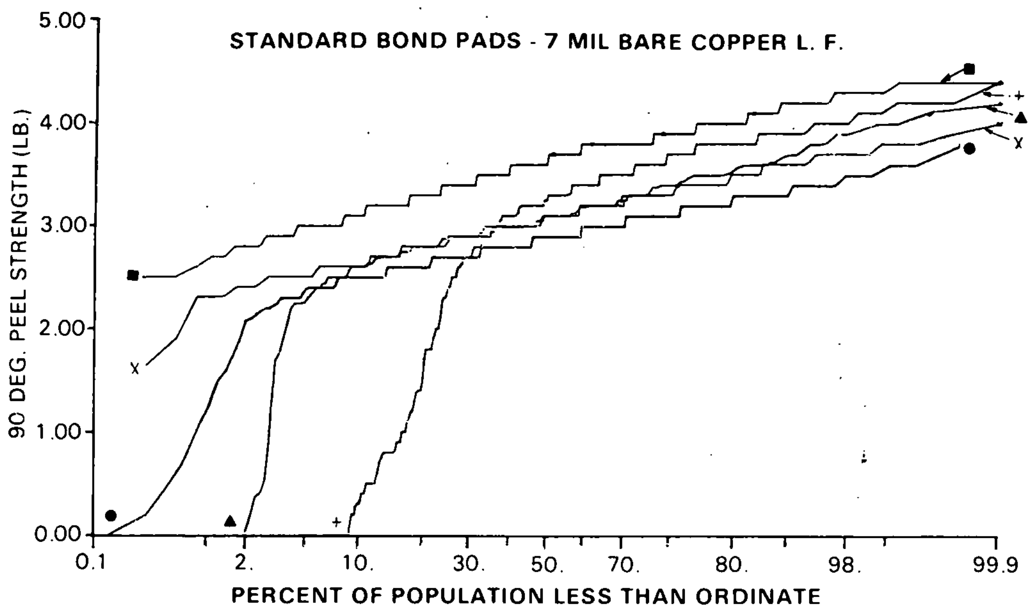
Figures 6, 7, and 8 display lead frame bond data, for different sets of data, in a similar format. The strength distribution for each metallization system is plotted. The peel strength is measured on the ordinate and a probability scale is used on the abscissa. The peel strength is plotted versus the percent of population having lower strength. If the strength values are a normal distribution, the plot will be a straight line with a slope inversely proportional to sigma. Each figure also includes a table showing the number of leads in the population, the average strength at failure, the standard deviation and the failure modes by percent for each system.

Figure 6 displays the bond data for each of the five metallization systems with data from all twelve ceramic-Ta_2N combinations included. These data are from standard bond pads. The Ti/Pd/Au (electroplated) system produced the best



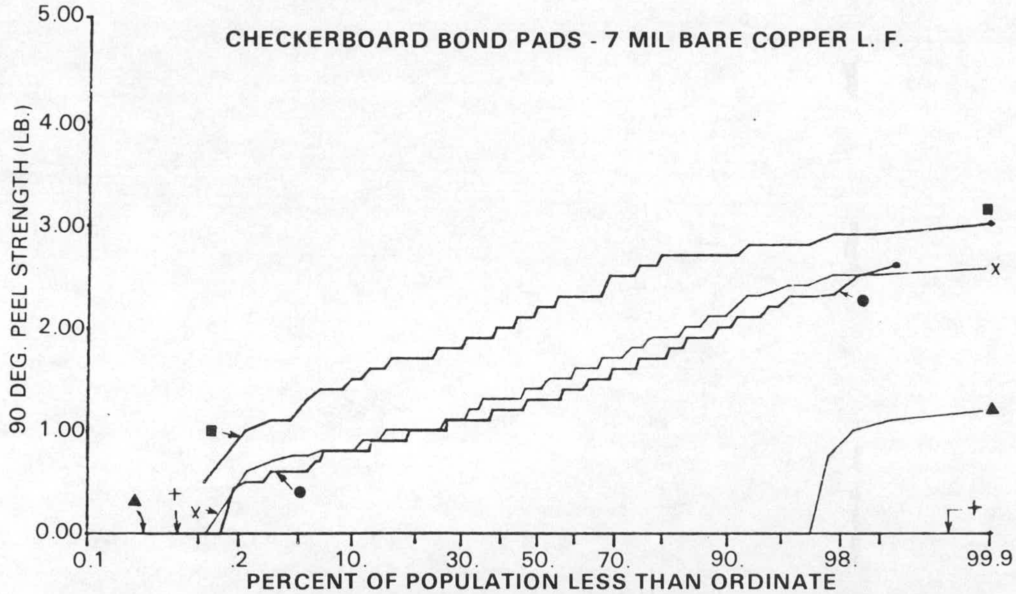
N	XBAR	SIGMA	%B	%C	%M	%E	SYSTEM
1398	2.33	1.13	65.8	0.36	12.8	21.0	● CR/AU (EVAP)
1232	2.50	1.21	80.6	0.32	0.00	19.1	▲ CR/PD/AU (EVAP)
463	2.24	1.54	55.7	0.00	2.81	41.5	+ CR/PD/AU (ELEC)
472	3.05	0.33	98.9	0.42	0.00	0.64	X TI/PD/AU (EVAP)
480	3.59	0.36	99.6	0.21	0.00	0.21	■ TI/PD/AU (ELEC)

Figure 6. Bond Results: 12 Substrate Types, Standard Pads



N	XBAR	SIGMA	%B	%C	%M	%E	SYSTEM
1078	2.86	0.39	81.3	0.46	16.7	1.58	● CR/AU (EVAP)
992	3.02	0.62	94.9	0.40	0.00	4.74	▲ CR/PD/AU (EVAP)
343	2.75	1.25	70.9	0.00	3.79	25.4	+ CR/PD/AU (ELEC)
352	3.07	0.33	99.6	0.57	0.00	0.85	X TI/PD/AU (EVAP)
360	3.61	0.36	98.4	0.28	0.00	0.28	■ TI/PD/AU (ELEC)

Figure 7. Bond Results: 9 Ta_2N Substrate Types, Standard Pads



N	XBAR	SIGMA	%B	%C	%M	%E	SYSTEM
270	1.35	0.48	0.37	81.1	17.0	1.48	● CR/AU (EVAP)
248	.028	0.17	0.00	0.00	0.00	100.	▲ CR/PD/AU (EVAP)
86	0.00	0.00	0.00	0.00	98.8	1.16	+ CR/PD/AU (ELEC)
88	1.46	0.51	0.00	30.0	34.1	35.4	X TI/PD/AU (EVAP)
80	2.13	0.50	17.8	8.89	2.22	71.1	■ TI/PD/AU (ELEC)

Figure 8. Bond Results: 9 Ta_2N Substrate Types, Checkerboard Pads

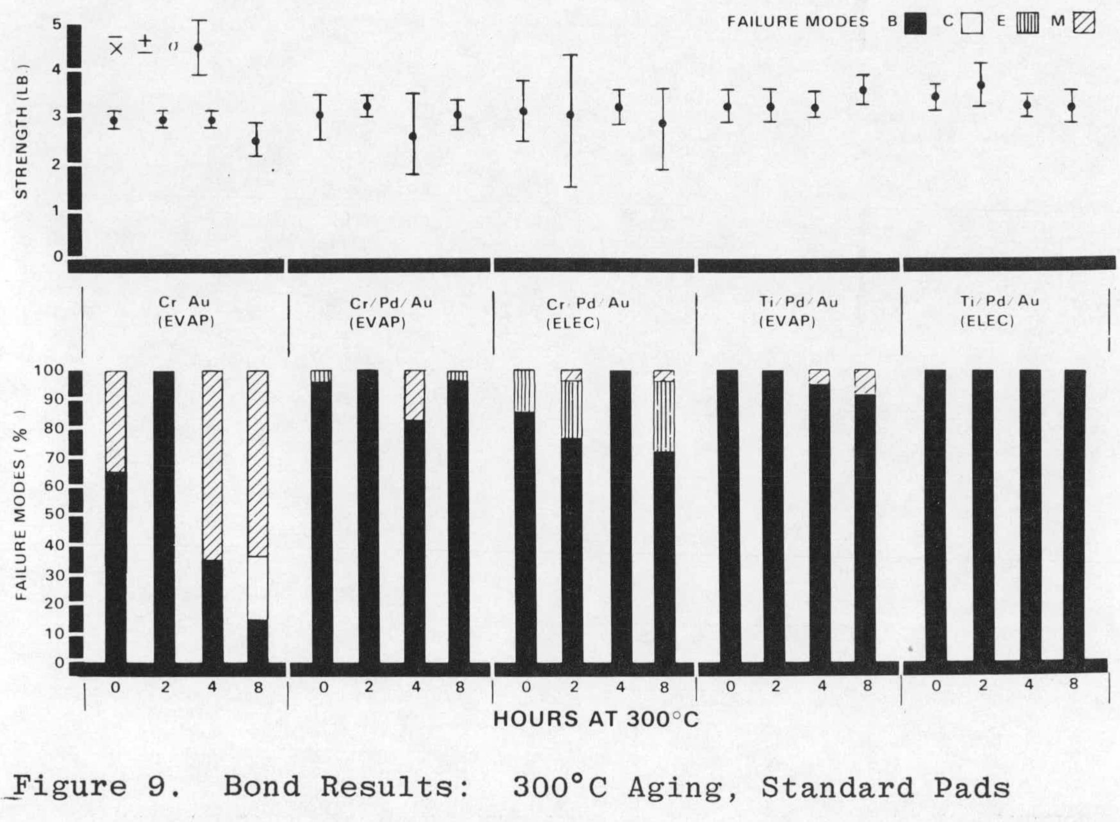


Figure 9. Bond Results: 300°C Aging, Standard Pads

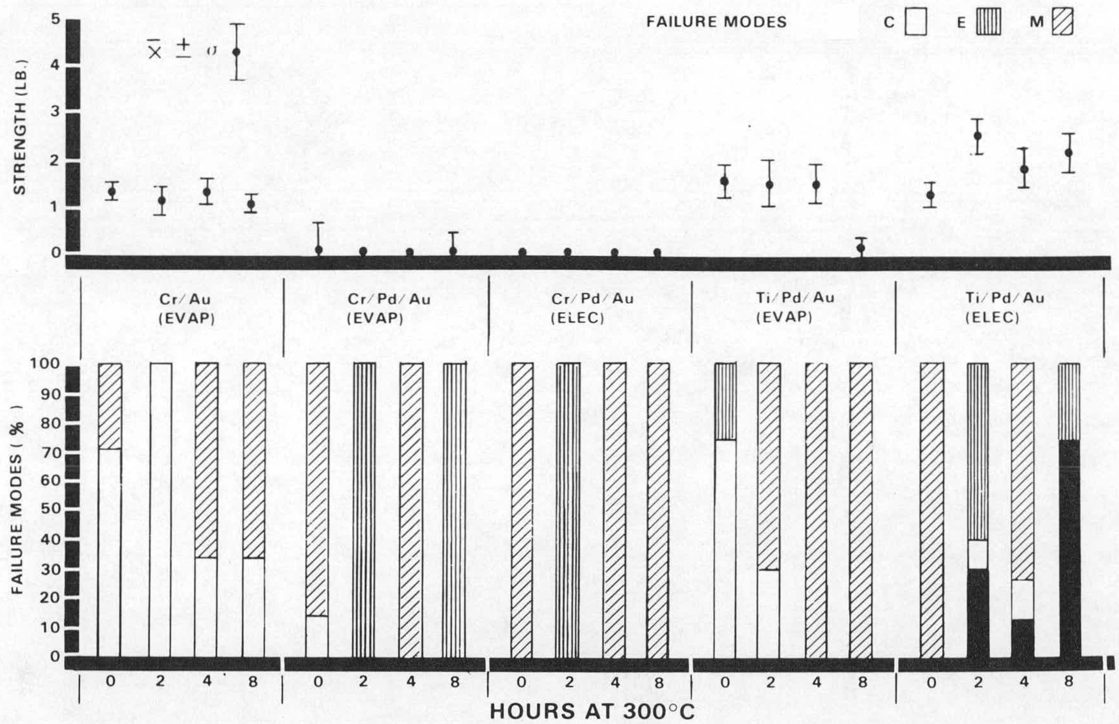


Figure 10. Bond Results: 300°C Aging, Checkerboard Pads

results, with an average strength of 3.54 pounds and a B failure rate of 99.6 percent. Data from the two Ti/Pd/Au systems closely follows a straight line with no zero strength failures. The other three systems have from 15 to 20 percent zero-strength failures.

Figure 7 displays a subset of the data given in Figure 6, omitting the no-Ta_2N data (only the data from the 9 ceramic-Ta_2N combinations containing Ta_2N are included). Most of the zero strength failures on the Cr/Au (evaporated) and the Cr/Pd/Au (evaporated) system occurred on substrates that contained no Ta_2N. The Cr/Pd/Au (electroplated) system still has a high percent of E-failures and zero strength E-failures that were not isolated to a particular set of ceramic-Ta_2N combinations. Data from both Ti/Pd/Au systems is nearly identical to the data displayed in Figure 6. The Ti/Pd/Au systems work equally well on bare ceramic or Ta_2N. In general, the Ti/Pd/Au bond results showed no correlation to ceramic-Ta_2N variables.

Figure 8 displays the checkerboard bond data from the same monitors used for Figure 7. Again, data from the no-Ta_2N substrates have been omitted. The checkerboard data tend to exaggerate the differences between the systems. The two Cr/Pd/Au systems show nearly 100% zero strength failures. The

Ti/Pd/Au (electroplated) system yielded the best results, with an average strength of 2.13 pounds and a B failure rate of 17.8%. Subsequent tests on other Ti/Pd/Au (electroplated) monitors have produced approximately 80% B failures on checkerboard bond pads.

The standard Bendix process for fabricating thin film networks containing Ta_2N resistors includes a 2-hour bake in air at 300°C to oxidize the Ta_2N and stabilize the resistor values. The previous data were collected on stabilized monitors. In the Cr/Au system, the stabilization results in the diffusion of Cr to the surface which necessitates a prebond Cr etch step to restore bondability. Monitors from each system were aged at 300°C to determine how sensitive the various systems were to elevated temperature aging. Baking at 300°C was conducted for 0, 2, 4, and 8 hours. The data are displayed in Figures 9 and 10. Figure 9 displays the lead frame bond data for standard bond pads. The strength data showed no clear trend as a function of time at 300°C. Most of the systems, particularly the Cr/Au system, showed a decrease in the number of B failures as the time at 300°C is increased. The Ti/Pd/Au (electroplated) system was the only one to produce 100% B failures at all times. Figure 10 displays checkerboard data from the same monitors. Again the checkerboards tend to exaggerate the differences between the systems. The only B failures measured were on the Ti/Pd/Au (electroplated) system.

Conclusions

The thermocompression lead frame bond results on the Ti/Pd/Au systems showed no dependence on ceramic or Ta_2N variables. The other systems produced poor results when deposited on bare ceramic. Of the three sputtering machines tested, the continuous processing machine produced a higher percentage of E failures. When E failures were encountered, some zero strength E failures were measured. No correlation was found between bond results and the three types of ceramic processing. The checkerboard bond pads exaggerate differences between the metal systems, and after some additional experience, a checkerboard bond test may be useful for quality control. The 2-hour, 300°C resistor stabilization did not degrade the bond results on any of the systems tested, and extended stabilization times to 8 hours had little effect. The smaller data base collected using gold plated lead frames shows no deviation from the above conclusions. Based on a judgement of lead frame bond strength distributions and failure modes, the best of the five metallization systems is the Ti/Pd/Au (electroplated), followed by Ti/Pd/Au (evaporated), Cr/Au (evaporated), Cr/Pd/Au (evaporated), and Cr/Pd/Au (electroplated).

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Acknowledgements

The authors wish to acknowledge the contribution of employees at Bendix Kansas City and Sandia Laboratories at Albuquerque and Livermore who contributed to the team effort to develop an improved metallization system. J. W. Dini (SLL) and A. R. Engquist (SLA) aided in the development of the gold electroplating process. R. C. Baxter and R. W. Pierce (Bendix) were responsible for the development of equipment and processes for evaporation. J. H. Pusch (Bendix) and D. P. Norwood (SLA) developed a photoresist process for pattern plating. P. V. Plunkett (SLA) and M. K. Raut (Bendix) evaluated anodic stripping and etching processes for the various metallization systems. R. J. Blazek and W. A. Piper (Bendix) did the failure mode evaluation. The contributions of others involved in bonding, pull testing, data collection, and software development for data reduction are appreciated.