BDX-613-1762

CONF-770513--2

FAILURE MECHANISMS IN BEAM LEAD SEMICONDUCTORS

J. R. Sim and U. C. Brown
The Bendix Corporation
Kansas City Division
Kansas City, Missouri 64141

SUMMARY

Hybrid microcircuits (HMCs) designed for the Energy Research and Development Administration by Sandia Laboratory in Albuquerque, New Mexico, and manufactured by the Kansas City Division of the Bendix Corporation use beam lead devices as active components.

The HMCs consist of sputtered tantalum-nitride (Ta_2N) resistors and evaporated chromium-gold (Cr-Au) conductors on alumina substrates with applique components and thermocompression bonded ribbons, lead frames, fine wires, and beam lead devices.

During recent testing of HMCs for a new program, failures of beam lead devices (BLDs) resulted in unacceptable yields and increased rework. These BLD failures showed up primarily as increased leakage failures, intermittent failures that repeated on a random basis, and in worst cases, as direct device shorts.

NOTICE
This report was prepared as an account of work sponsored by the United States Government. Neither the United States nor the United States Energy Research and Development Administration, nor any of their employees, nor any of their contractors, subcontractors, or their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness or usefulness of any information, apparatus, product or process disclosed, or represents that its use would not infringe privately owned rights.

DISTRIBUTION OF THIS DOCUMENT IS UNLIMITED

DISCLAIMER

This report was prepared as an account of work sponsored by an agency of the United States Government. Neither the United States Government nor any agency Thereof, nor any of their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof.

DISCLAIMER

Portions of this document may be illegible in electronic image products. Images are produced from the best available original document.

An investigation of the problem showed that cracks often appear on the edge of the silicon and on the silicon nitride lip that overhangs the edge of the beam. These cracks appear at various phases of the processing but primarily during BLD bonding. High temperature reverse bias (HTRB) tests of diodes and transistors and analysis of the devices that failed during these tests indicated that gold in the cracks was a primary cause of failures. The gold in the cracks is the result of gold "relocation" or migration from the gold beams on the semiconductor.

↖ The gold was detected by EDAX and electron-beam induced-current methods. Gold was observed on the silicon cracks above the beams and in silicon nitride cracks on either side of the beams.

Gold resistive leakage paths of this type have been observed ^{ONLY} in devices such as PNP transistors and P+ silicon substrate zener diodes where one of the gold beams is more than ^{0.142} ~~15~~ V positive with respect to the body of the silicon chip. This indicates that the gold leakage paths are formed by electro-migration of gold from the beam to the silicon

chip. Results of HTRB tests on NP* diffused zener diodes, PN diffused zener diodes, and NPN transistors are consistent with the gold electromigration theory.

Several conditions theoretically are required for gold electromigration of this type: the gold beam must be positive with respect to the silicon chip ~~SOME MINIMUM VOLTAGE; (THE GOLD POTENTIAL IS 42 VOLTS)~~ by more than ~~1.5 volts~~; there must be a crack in the silicon nitride, or at the intersection of the beam and a chip, or a crack in the silicon above the beam; and an electrolyte such as moisture-containing halogen ions must be present in the crack.

Vacuum baking of HMCs after cleaning and just before electrical testing, the elimination of water as a cleaning agent, and the elimination of trichloroethylene at final assembly cleaning have solved the leakage problem caused by gold electromigration in the devices.

*NP describes an N-type material diffused into P-type silicon, while PN describes a P-type material diffused into N-type silicon.

INTRODUCTION

Hybrid microcircuits manufactured at Bendix Kansas City are produced on aluminum oxide substrates. A layer of tantalum nitride is sputtered onto the substrates after they are cleaned and then vacuum evaporated layers of chromium and gold are applied.

Photoprocessing and etching techniques are used to define the thin film resistor and conductor network. The resistors are thermally stabilized in air. Large substrates are separated into smaller substrates called thin film networks (TFNs) by using laser scribing. Resistors are adjusted to their final values with an automatic YAG laser trimming system.

HMCs are assembled using applique components, including beam lead devices, lead frames, crossovers, and capacitors. Beam lead devices, gold ribbon crossovers, and lead frames are attached using thermocompression bonding techniques. Capacitors and inductors are soldered using a nonactivated flux and 50Pb-50In solder followed by a cleaning procedure to remove flux residue. At this point,

the HMCs are temperature cycled, centrifuged, tested, and inspected before final lidding and testing.

It has been shown by several authors how gold electromigration can occur on the active surfaces of semiconductor devices or on the surface of hybrid substrates.^{1,2} The conditions necessary to form migrated gold resistive shorts (MGRS) were shown to be reactive chemicals, water, bias, and time.³ Migrated gold was primarily noted on flat surfaces between adjacent gold or conductor strips. The type of migration reported in this paper deals with the electrolysis of gold in process-induced cracks on beam lead devices. Electromigration in cracks appeared to occur before flat surface type migration. This may be the result of smaller anode-cathode spacings and the affinity of cracks for ~~collecting~~ water and halogens.

Put this as last paragraph in this section.

At one point during the ~~development stages of a new manufacturing program at~~ manufacturing process at Bendix Kansas City, a significant number of HMCs were failing. Most of the failures were attributed to P-type silicon zener diodes and PNP transistors. The failure rate of these devices was more than ~~that~~ ^{that} five times of other devices. It was not uncommon

for failures to repeat on a random basis in the HMC. The suspect devices would be removed from the HMC and failure analyzed. A routine failure analysis would often reveal no device defect other than cracked nitride at the intersection of the gold beam and the silicon, or a crack in the silicon over the beam. An ensuing test and materials analysis program resulted in the conclusion that the failures were caused by the electromigration of gold from a gold beam to the silicon chip through a crack in the nitride or silicon.

TESTS TO DETERMINE SOURCE OF PROBLEM

← Put in 2nd paragraph from previous page.

BEAM LEAD DAMAGE VERSUS PROCESSING

Since cracks in beam lead devices were common to many of the failures, a test was conducted to determine the origin and magnitude of the cracks.

Two hundred beam lead devices were followed through normal HMC processes and the number and types of cracks were categorized before the devices were bonded, after they were bonded, after they were cleaned, and after they had undergone 10 temperature cycles from -40°C to +125°C.

The devices were visually inspected at 200X to detect the cracks. The cracks were identified and grouped (Figure 1) into five categories, ranging from a slight cracking on the silicon nitride lip that extended toward the silicon strip to U-shaped cracks extending through the silicon and onto the top of the beam.

Most of the severe cracks occur during the beam lead bonding process (Figure 2). Other processes, such as cleaning after soldering and ~~thermocycling~~ *thermal cycles*, produce few cracks compared to those that occur during beam lead bonding.

The beam lead bonding parameters used for this experiment included a 0.61 by 0.61 mm bonding tool, a substrate temperature of 200°C, a tool temperature of 450°C, and 500 grams force.

The 200 nm silicon nitride lip is highly susceptible to damage during all phases of inspection, handling and processing. A wide silicon nitride lip caused by over-etching during fabrication of the BLD is more likely to be damaged during processing than a narrow lip. Visual inspection criteria has been added to eliminate Type E and D damage from HMCs.

TYPE A

CRACK ON ONE SIDE OF
BEAM—EXTENDING TO
SILICON—NOT ON TOP OF
BEAM

TYPE B

NITRIDE CRACK ON BOTH
SIDES OF BEAM

TYPE C

NITRIDE CRACK ON TOP
OF BEAM

TYPE D

MISSING NITRIDE
EXTENDING TO SILICON—
EXPOSING PORTION OF
BEAM OR INTERFACE

TYPE E

CRACK IN SILICON
ADJACENT TO BEAM

Figure 1. Nitride Damage Classifications

Figure 2. Beam Lead Damage Versus Processing

Some beams contain multiple defects; for example, a single beam can have both Type D and Type E defects.

LONG TERM HTRB TRANSISTOR STUDY

A long term HTRB study was performed to establish whether BLD cracks, flux, flux cleaning, and temperature cycling have an adverse effect on beam lead NPN transistors. One hundred twenty devices were bonded to thick film ceramic headers, separated into 4 groups of 30 each, and subjected to 4 different processing steps.

- o Group 1 (Serial Numbers 1 through 30) was subjected to flux and temperature cycles.
- o Group 2 (Serial Numbers 31 through 36) was subjected to flux, cleaning, and temperature cycles.
- o Group 3 (Serial Numbers 61 through 90) was subjected to a temperature cycle only.
- o Group 4 (Serial Numbers 91 through 120) was subjected to a trichloroethylene wash.

All four groups had the silicon nitride and silicon cracks categorized and were then subjected to 336 hours of HTRB tests at 20 V and 175°C. Electrical end points were recorded at 25°C at various time intervals.

Three units failed during the HTRB test study.

- o Serial Number 39 had an I_{CBO} measurement of 216 μA after 48 hours. Failure analysis revealed a crack extending from the base beam through the silicon toward the left collector beam.
- o Serial Number 46 had an I_{CBO} measurement of 179 μA at 48 hours. The silicon was broken and appeared to be making contact with the base beam through a piece of cracked nitride.
- o Serial Number 23 had a short in the emitter-base junction. Failure analysis revealed a gold wire bridging gold.

← clarify that this isn't gold in a crack.

Since these devices were unsealed, the failures were attributed in one way or another to handling damage. However, the study did show that for NPN transistors ~~there were no failures related to~~ ^{the} ~~cracks and processing variations.~~ ^{were not correlatable to} or to the types of cracks.

*could not be
correlated*

LONG TERM HTRB ZENER DIODE STUDY

A second HTRB study was conducted to determine the effects of cracks and process variations on NP and PN diffused zener diodes.

A total of 195 NP diffused 6.4 V temperature compensated (TC) zener diodes and 100 PN diffused 6.4 V TC zener diodes were used for this study. All of the PN devices and 100 of the NP devices were bonded to T018 headers. A nonactivated flux was brushed on each device to simulate next assembly processing. Each device was then cleaned to remove the flux: the cleaning included a trichloroethylene wash followed by one isopropyl alcohol and three deionized water rinses. Finally, the devices were temperature cycled 10 times from -40°C to $+125^{\circ}\text{C}$ and hermetically sealed in 32 percent relative humidity.

The remaining 95 NP devices were bonded to T018 headers, temperature cycled 10 times from -40°C to $+125^{\circ}\text{C}$, and hermetically sealed in 32 percent relative humidity. These units serve as the control sample.

All 295 units were then subjected to HTRB tests at 5 V and 175°C for 336 hours. Electrical end points were recorded at 25°C at various time intervals.

None of the 100 PN devices and only 30 of the 195 NP devices failed. Of the 30 NP device failures, 16 were from the control sample. The failures showed up primarily as increased leakage failures, intermittent failures that repeated on a random basis, or, in worst cases, as direct device shorts (Figure 3).

Failure analysis results revealed that all failures had cracks in the silicon nitride or the silicon chip. These failures were sensitive to moisture as evidenced by intermittent V_z characteristics.

Vacuum bake would heal some, but not all, the failures containing moisture. Scanning electron microscope (SEM) analysis at up to 10,000X and EDAX

Figure 3. Curve tracer display of an intermittent NP diffused zener diode

~~Need some explanation?~~

analysis revealed that gold was present in the cracks on some devices. On one failure, a beam-induced-current technique was used to pinpoint the exact location within a silicon crack where the gold resistive short occurred.

Statistical data on 100 NP diffused devices subjected to flux, a subsequent cleaning process, and temperature cycling were as follows.

- o None failed prior to 96 hours.
- o 7 percent failed at 96 hours.
- o None failed at 168 hours. The fact that no failures occurred at this point is not well understood; however, one possible explanation is that the units may not have been tested within the time necessary to reflect the effects of the HTRB.
- o 6 percent failed at 336 hours.
- o 14 percent failed through HTRB testing and subsequent electrical testing.

The statistical data on the 95 units subjected only to temperature cycling were as follows.

- o None failed prior to 96 hours.
- o 3.1 percent failed at 96 hours.
- o None failed at 168 hours.
- o 14.7 percent failed at 336 hours.
- o 16.8 percent failed through HTRB testing and subsequent electrical testing.

GOLD ELECTROMIGRATION THEORY

During this study it was found that cracks in the silicon nitride and the silicon were common to many of the BLD failures. HTRB tests showed that electromigration occurred on NP devices and not on PN devices.

Analysis of NP diffused zener diodes which failed the HTRB test indicated that a primary cause of failure was gold in the cracks. These cracks were at the interface of the gold beam and the silicon.

Check this

~~by energy dispersive X-ray analysis~~
(EDAX)

The gold was detected with an SEM. Figures 4 and 5 show the gold present in the silicon nitride crack over the cathode beam and the resultant degraded zener characteristics. The gold provides a resistive leakage path between the body of the silicon chips and the beam. Gold leakage paths of this type have been observed only in devices where one of the gold beams is at a positive potential greater than ES with respect to the body of the silicon chip. This indicates that the gold leakage paths are formed by electromigration of gold from the beam to the silicon chip. Results of HTRB tests on NP diffused zener diodes, NPN transistors, and PN diffused zener diodes are consistent with this theory.

The gold was detected with an SEM and identified by energy dispersive X-ray analysis (EDAX).

1.42 V

For gold electroplating to occur through the crack, the gold beam must be positive by at least ES with respect to the silicon chip and an electrolyte must be present in the crack. Moisture containing halogen ions would be likely to be present as the electrolyte. Although electrochemical effects can

1.42 V

~~A4~~
GOLD

← This picture
is difficult to
interpret. How about
using the one attached.
~~Type H crack
arrow to gold~~

Figure 4. Inverted Optical View of Serial Number 77, Showing Gold Growth Through ~~Crack~~ an "A" type crack in the Silicon Nitride Over the Cathode Beam

Figure 5. Serial Number 77--Showing Cathode-Chip Zener Voltage Characteristic of Device Failing

also occur on the surface of the device between adjacent conductor paths, electromigration through cracks apparently occurs more readily. Figures 6 and 7 show gold in cracks. This likely results from the nitride lip being very thin (200 nm) and ~~the fact that moisture can easily condense in a crack through a process called capillary condensation.~~^{from moisture condensation} ^{the fact that moisture can easily condense in a crack through a process called capillary condensation.}

The normal bias configuration for a PNP device allows the chip to be negative with respect to the emitter and base. NPN devices are generally biased with the chip positive with respect to the emitter and base beams. The bias on PNP devices is in the proper direction for formation of a gold electrochemical cell.

On P-type silicon substrates, an electrochemical cell can be created between the positively biased gold beams and the silicon chip. If the theoretical conditions necessary to cause gold migration are present, this migration takes the shortest path from the gold beam (positive cell) to the silicon chip (negative cell). This explains why gold has been observed in silicon nitride and silicon cracks near the edge of the positively biased gold beam

Figure 6. SEM Showing Cracks in the Nitride and Silicon of Serial Number 18; Foreign Material, Identified as Gold, Can be Seen Near the Edge of the Cathode Beam and the Chip

Magnified view of figure 6

Figure 7. ~~SEM~~ Showing Silicon, Titanium, and Gold in a Crack Along a Portion of the Edge of the Beam and the Silicon (Serial Number 18)

and the silicon chip. The gold often remains invisible until it is magnified approximately 10,000 times. This makes it virtually impossible to screen for this condition during receiving inspection or next assembly inspection.

OTHER FAILURE MODES

Ten basic BLD failure modes have been observed frequently during manufacturing steps at Bendix Kansas City.⁵

<u>Item</u>	<u>Mode</u>
1	Device meets electrical specifications
2	Cracked silicon
3	Cracked nitride under anchor pads
4	Device out of specification; no visible defects
5	Surface contamination or leakage
6	Electrical overstress
7	Nitride or oxide defects
8	Wrong device in assembly
9	Target bridging gold
10	Excessive gold bridging or smearing on chip

CORRECTIVE ACTION

To minimize the effects of the gold electrolysis and moisture associated with the gold migration, ~~the following processing conditions are now required or planned~~ *for the* ~~several changes have been made in the processes~~ *ing of* ~~used to manufacture HMCs at Bendix~~

- o All beam lead devices will be manufactured with a stress-relief point in the beam to minimize the flexing of the silicon nitride over the beam. By inducing the stress relief point, the beam will bend in front of the silicon nitride lip, thus minimizing the effect of the beam lead bonding operation.
- o HMCs will be stored in dry nitrogen cabinets when not undergoing processing or electrical testing during manufacturing. This step is designed to minimize the absorption of moisture on the surface and in cracks of the devices.
- o At various points in the process following cleaning and soldering, vacuum bakes have been added to dry out the HMCs before any electrical tests are run. The bakes are from 1 to 2 hours at 100°C in a vacuum oven.

- o Water has been eliminated as a cleaning agent.
- o The inspection criteria has been revised to include a minimum 100X magnification to spot and remove the most damaging Type D and E silicon nitride and silicon cracks.
- o The trichloroethylene spray previously used for final assembly cleaning has been changed to an isopropyl alcohol spray. In addition, consideration is being given to removing trichloroethylene from other cleaning steps to prevent the release of free chlorine which ~~is~~ ^{would accelerate} ~~needed as a constituent in~~ the electrolytic formation of gold.
- o The size of the beam lead bonding tool has been increased where feasible. Previously, a 0.61 by 0.61 mm bonding tool was used for Format 25 devices. This has been changed to a 0.63 by 0.63 mm tool. A larger bonding tool will move the bond zone further away from the chip edge, thus minimizing the beam flexure.

CONCLUSIONS

Based on the data from the various studies, it can be shown that NP diffused diodes and PNP transistors are susceptible to gold electromigration. The gold migrates from the gold beam to the silicon chip through cracks in the silicon nitride or silicon. This problem can be solved by eliminating condensed moisture and halogens, and by minimizing cracks in beam lead devices. The study also ^{showed} ~~pointed out~~ that PN diffused diodes and NPN transistors are not prone to this type of migration.

REFERENCES

- ¹F. J. Grunthaner, *et al*, "Migratory Gold Resistive Shorts: Chemical Aspects of a Failure Mechanism," *Proceedings of the Thirteenth Annual Reliability Physics Conference*, 1975.
- ²J. J. Mazenko, "Failure Modes in Beam Lead Integrated Circuits," *ISHM Proceedings*, 1975.

³A. Shumka and R. R. Piety, "Migrated Gold Resistive Shorts in Microcircuits," *Proceedings of the Thirteenth Annual Reliability Physics Conference*, 1975.

⁴S. Brunauer, *Adsorption of Gases and Vapors*, Princeton University Press and Oxford University Press, 1945, PP120-139.

⁵J. H. Swafford, "Failure Modes of Beam Lead Semiconductors in Thin Film Hybrid Microcircuits," *ISHM Proceedings*, 1975.