FAILURE ANALYSIS OF A HYBRID DEVICE EXHIBITING COPPER DENDRITE GROWTH ON THICK FILM RESISTORS

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ABSTRACT

The subject of this paper is the failure analysis performed on several hybrid devices submitted to Oneida Research Services, Inc. (ORS).

The analysis was initiated because of electrical testing failures -- a voltage divider exhibited an out-of-specification value during burn-in at elevated temperature. This voltage divider compared the outputs of two thick film resistors.

Analysis of the hybrid failures revealed a copper dendritic growth propagating across the laser trims in the thick film resistor.

We describe the hybrid materials construction, environmental testing, and electrical testing performed in examining the factors which led to the dendrite growth and overall failure of the hybrids. A detailed description of the analytical equipment and methodology used in identifying the cause of the "copper" dendrite growth as a result of processing is also presented. We conclude with a discussion of the corrective actions proposed as a result of the failure analysis.

METAL MIGRATION IS A COMMON FAILURE MODE in Microelectronics(1, 2, 3), and may cause increases in electrical current leakage, dielectric breakdown, and electrical shorting. It is most common in silver and silver alloys, but does occur in other metals such as aluminum, lead, copper, zinc, and gold.

We have observed copper dendritic growth failure in a laser trim on a thick film resistor. The source of the copper was identified as the thick film gold conductor on the hybrid. (Thick film conductor pastes typically contain a small amount of CuO to promote adhesion between the conductor and substrate(4).)

An important reliability problem in the hybrid manufacturing process has been identified. The object of our failure analysis was to determine the mechanisms related to the corrosion and to propose corrosion mechanisms so that recommendations might be made to prevent the future occurrence of similar failures.

Two mechanisms are proposed for the deposition of the dendrites. Both involve an electrochemical corrosion reaction of CuO with the constituents in the atmosphere of the package(5). The mechanisms differ in the way that copper migrates from the surface of the thick film conductor material to the laser trim. It is possible that both mechanisms contribute to the electrochemical deposition of the dendrite in the laser trim.

In Mechanism 1 a thin layer of moisture combines with adsorbed ammonia and chlorine on the surface of the resistor to form an electrolyte. Copper-bearing ions form at a resistor termination conductor and migrate across the surface of the resistor to the laser trim under the influence of the potential difference across the resistor.

In Mechanism 2 volatile copper-bearing complexes form through a reaction of the constituents in the package (*i.e.*, chlorine, ammonia, and moisture) with the CuO on the surface of the thick film conductor material. These complexes condense in the laser trim where electrochemical deposition of copper occurs, and copper is transported from the thick film conductor material to the kerf *via* a gas-phase process. This mechanism is consistent with the observation of copper on all internal surfaces of the hybrid.

The internal atmosphere of the hybrid was analyzed by Residual Gas Analysis (RGA). Internal inspection of the package was conducted through Optical Microscopy and Scanning Electron Microscopy/Energy Dispersive X-ray Microanalysis (SEM/EDX). The materials on the surfaces of the hybrid package's components were analyzed through Auger Electron Spectroscopy (AES). The source of the corrosion was correlated with the manufacturing process.

FAILURE VERIFICATION

The hybrid failure was identified as a shift in a voltage divider network during burn-in at elevated temperatures. The outputs of a 10 kΩ and a 1 kΩ resistor were compared in a voltage divider circuit which was used to check a reference voltage within the hybrid. The reference voltage, resistor values, and applied voltage are related:

$$V_{ref} = [R_1/(R_1 + R_2)]V \quad (1)$$

where R_1 = 1 kΩ and R_2 = 10 kΩ.

Internal inspection of the hybrid after delidding revealed a copper coloration in the kerfs of some of the 10 kΩ thick film resistors, particularly in R_2. The coloration was in the region of the kerf parallel to the resistor terminations. The electrical parameters returned to acceptable values when the package was opened to the atmosphere at elevated temperatures. Increasing exposure to ambient temperature caused a depletion in the number of dendrites that were visible in the kerf. These facts suggested that volatile metallic complexes might have formed.

All failed hybrids contained substrates from the same lot. Because hybrids assembled in the same time frame from a different substrate lot did not exhibit failures, it is logical to assume that the failure mechanism was related to the materials used in this particular substrate lot.

FAILURE ANALYSIS

INTERNAL ATMOSPHERE - The first step in our failure analysis was to compare the internal atmosphere of failed and "good" hybrids. Residual Gas Analysis (RGA) in accordance with MIL-STD 883/Method 1018/Procedure 1[6] was performed. The RGA results for failed and good hybrids are given in Table 1.

RGA did not reveal significant differences between the failed and good hybrids, an indication that the critical factor for the electrical failure was not exclusively related to the internal atmosphere. RGA did show the presence of constituents used in the manufacture of the device. The ammonia is a by-product of the substrate attach epoxy cure. Freon® TF, methylene chloride, and cyclopentane are constituents of a final cleaning solvent. (It is helpful in the testing process if information concerning the cleaning solvents and epoxies used in the manufacturing process accompanies parts submitted for RGA testing.)

INTERNAL INSPECTION - The failed and good hybrids were delidded and underwent light microscopy and SEM inspection. Light photographs of the laser trim in the failed devices show the copper-colored material across the laser trim (Figure 1). The laser trims exhibited a narrowing of the kerf in the region of the copper-colored material. Comparative photographs from a "good" device in Figure 2 show no narrowing and a trim region devoid of the copper-colored material.

SEM inspection of the morphology of the copper-colored material indicated that it was dendritic growth (Figure 3). The dendrites show a granular structure rather than the more typical dendritic fern structure.

AUGER ELECTRON SPECTROSCOPY (AES) - AES was particularly useful in this failure analysis because of its high surface sensitivity and its ability to perform depth profiles. The top 5-30 Å of the surface were analyzed in the elemental surveys. Depth profiles allowed a comparison of contamination and oxide thickness between samples.

Three regions of the failed and good hybrids were targeted to determine the elemental constituents in the dendrites and the extent of material migration. The regions of interest were the kerfs in the thick film resistors, the thick film gold conductor, and other components on the assembled hybrids. The results are discussed in the following subsections. The elements identified in the elemental surveys are listed in Table 2. The Auger transition energies of the elements detected are listed in Table 3.

Laser Trims (Kerfs) Failed Hybrid - A representative elemental survey of the copper-colored material in the laser trim is shown in Figure

Table 1 - RGA Results for Failed and Good Hybrids

Detected	Failed		Good
Nitrogen (%)	79.4	76.9	81.0
Oxygen (ppm)	ND	6245	ND
Argon (ppm)	494	658	531
Carbon dioxide (%)	2.03	1.73	1.53
Moisture (ppm)	3995	6588	2860
Hydrogen (ppm)	3815	3596	1761
Helium (%)	15.3	15.4	12.4
Fluorocarbons (ppm)	ND	ND	ND
Ammonia (%)	1.39	2.96	2.83
Cyclopentane (ppm)	1215	1915	2591
Methylene chloride (ppm)	292	346	<100
Freon® TF (%)	0.89	1.04	1.49

4. High levels of chlorine and copper were detected in this region of the kerf, demonstrating that the copper-colored material is associated with the deposition of copper in the kerf.

Laser Trims (Kerfs) Good Hybrid - Elemental surveys were collected in a region of a kerf analogous to that analyzed in the failed hybrid. A representative survey showed levels of chlorine typically associated with handling contamination (Figure 5). Copper is detected in this region, but at a level just above the noise level, indicating that copper migration had occurred in the good device, but not to the same extent as in the failed hybrid.

Thick Film Gold Conductors Failed Hybrid (Assembled) - A survey of the conductor showed that significant levels of copper are detected on its surface (Figure 6). The thickness of the copper is approximately 400 Å. The amount of oxygen was much lower than that observed in the depth profile of the conductor material on the failed substrate lot prior to assembly and burn-in. The copper-to-gold ratio in the depth profile of the assembled hybrid is lower than in the hybrid prior to assembly (Figure 7).

Failed Substrate Lot (Unassembled) - A survey of the conductor showed significant levels of copper and oxygen on the surface of the gold (Figure 8). The depth profile shows that the copper thickness is very similar to that on the failed hybrid conductor (Figure 9). The copper is, however, associated with oxygen on the unassembled substrate and appears to be in greater abundance relative to the assembled hybrid. The presence of CuO on the surface of the conductor prior to burn-in and the absence of CuO following burn-in is consistent with the hypothesis that CuO was removed by an electrochemical corrosion reaction.

Good Substrate Lot (Unassembled) - A survey of the conductor shows copper and oxygen on the surface (Figure 10). The depth profile revealed a much thinner copper layer relative to the failed substrate lot (Figure 11). (This profile was collected using the same ion gun parameters used on the failed substrates.) The oxygen is assumed to be associated with the copper since both follow similar elemental trends in the profile.

Other Components (Failed Hybrid) - Elemental surveys were collected on the package lid and on a ball bond to determine the extent of copper migration (Figures 12 and 13). Both surveys show copper and chlorine contamination, illustrating the large extent of the copper migration within the failed hybrid.

Other Components (Good Hybrid) - Elemental surveys were collected on the package lid and on the die attach fillet to determine the extent of copper migration (Figures 14 and 15). Copper was not detected on the surface of the package lid. Copper was detected in the die attach fillet, but elevated levels of chlorine were not observed. This indicated a much lower migration of copper within the good hybrid.

FAILURE MECHANISM

Two mechanisms have been postulated to explain how the CuO on the surface of the thick film conductor material migrated from the conductor into the laser trim region of the 10 kΩ resistors. In both mechanisms the dendritic growth resulted from an electrochemical deposition process.

MECHANISM 1: SURFACE MIGRATION - Mechanism 1 postulates the migration of copper complexes from the conductor to the laser trim across the surface of the resistor. Hydrophyllic SiO_2 was present on the surface of the resistor as a result of the firing process(7). An electrochemical cell was established which consisted of a thin film of electrolytic fluid on the resistor surface, a CuO layer on the thick film conductor (the anode), the side of the laser trim where dendrites were deposited (the cathode), and the applied voltage across the resistor. Consideration of the solvent rinse used and the RGA test results indicate that chlorine and moisture could have formed a thin layer of solution on the surface of the resistor. The presence of chlorine in an aqueous medium under the influence of an applied voltage

Table 2. Materials Analysis by Auger Electron Spectroscopy

Description	Elements Detected	Figure
Laser Trims		
Failed Hybrid	S, Cl, C, N, O, Cu, Si	4
Normal Hybrid	Pb, S, Cl, C, Ca, N, O, F, Cu, Al, Si	5
Thick Film Conductor		
Failed Hybrid (Assembled)	S, Cl, C, N, O, Cu, Au	6
Failed Substrate Lot (Unassembled)	S, Cl, C, N, O, Cu, Au	8
Good Substrate Lot (Unassembled)	S, Cl, C, N, O, Cu, Au	10
Other Components		
Package Lid Metallization/Failed Hybrid	S, Cl, C, N, O, Cu, Si, Au	12
Ball Bond on Die/Failed Hybrid	S, Cl, C, N, O, Cu, Au	13
Package Lid Metallization/Good Hybrid	S., Cl, C, O, Cu, Si, Au	14

formed ionic copper complexes which migrated across the resistor surface. The solubility of the CuO in aqueous solutions is an important factor in the electrochemical cell reaction. These complexes were reduced at the cathode where copper deposition occurred. The dendritic growth required the presence of suitable cathode sites which have the appropriate electrostatic and chemical properties for dendrite growth to occur(8). The rough morphology and composition of the detritus material on the side of the laser trim provided favorable conditions for dendritic growth.

MECHANISM 2: GAS-PHASE MIGRATION - Mechanism 2 postulates the formation of volatile copper complexes through a reaction of the constituents in the package (*i.e.*, chlorine, ammonia, and moisture) with the CuO on the surface of the thick film conductor material. These complexes condensed in the laser trim where the electrochemical cell reaction occurred. The presence of condensed copper complexes, reactive chemicals, moisture, and a potential difference across the laser trim provides the conditions necessary for an electrochemical deposition of copper-containing dendrites. The two sides of the laser trim served as the anode and the cathode. Mechanism 2 is consistent with the observation of copper on all internal surfaces of the hybrid, and with the disappearance of the dendrites following delidding.

SUMMARY AND CONCLUSIONS

The significant results of the failure analysis are summarized. (1) The electrical leakage current failure was caused by resistive shorts in the laser trims of the 10 kΩ thick film resistor ink. (2) The resistive shorts in the laser trims were associated with dendritic growth of copper. (3) Abnormally high levels of CuO were detected on the conductor material of the unassembled substrate from the lot associated with the hybrid failures. (4) CuO on the surface of the thick film conductor material reacted with constituents in the hybrid package atmosphere, and this CuO was the source of the copper for dendritic growth. (5) The reaction of the CuO is shown in the comparison of the depth profiles of unassembled *vs.* assembled failed samples. No oxide is associated with the copper on the failed hybrid. Copper levels relative to gold appear to be lower on the failed hybrid. (6) Copper migration was observed to be significantly less on the electrically good device, apparently because of the lower availability of surface copper on the thick film conductor. (7) Copper was observed throughout the interior of the failed hybrid packages except on the alumina substrate. (8) Dendritic growth occurred because of an electrochemical corrosion reaction of the constituents of the package. This corrosion reaction was driven by the elevated temperatures at burn-in.

RECOMMENDATIONS

To prevent similar failures with hybrid devices we recommend that: (1) Auger depth profiles be performed on representative samples of raw substrates prior to assembly to screen for bad ink lots; (2) the halogens in cleaning solvents be properly removed so that they do not contribute to the formation of an electrochemical cell. Vacuum bake procedures should be developed for effective removal of residual process materials, and evaluated by RGA testing.

Table 3. Auger Electron Peak Identification Energies.

Element	Primary Peaks (ev)	Secondary Peaks (ev)
C	272	---
N	379	---
O	503	---
F	651	---
Na	990	---
MgO	1174	---
Al_2O_3	1378	51
SiO_2	1606	76
S	152	---
Cl	181	---
K	252	---
Ca	291	318
Mn	589	636
Ni	848	783, 716
Cu	920	849, 776
Zn	994	1017, 916
Au	2024	1838, 1772, 1523, 69
Pb	94	1910

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Figure 1. Light micrograph of a laser trim on a failed hybrid.

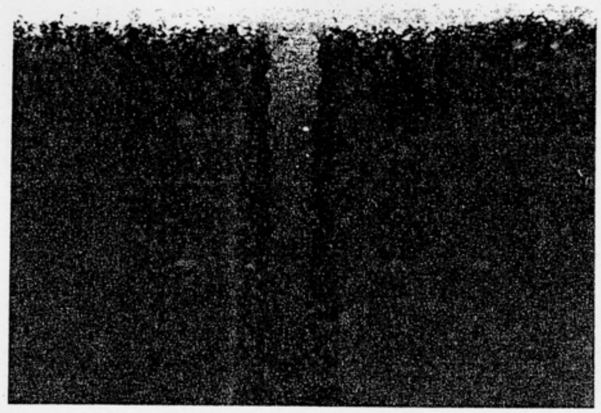

Figure 2. Light micrograph of a laser trim on a "good" hybrid.

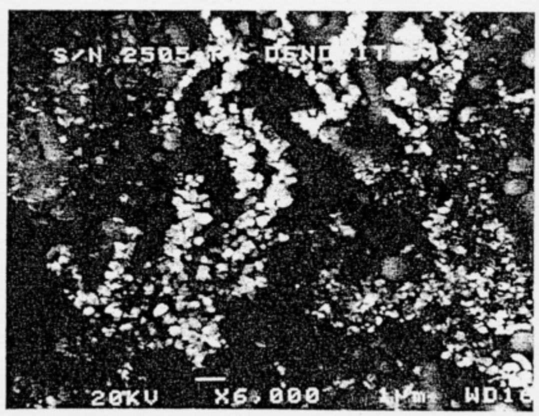

Figure 3. SEM photograph of dendrites.

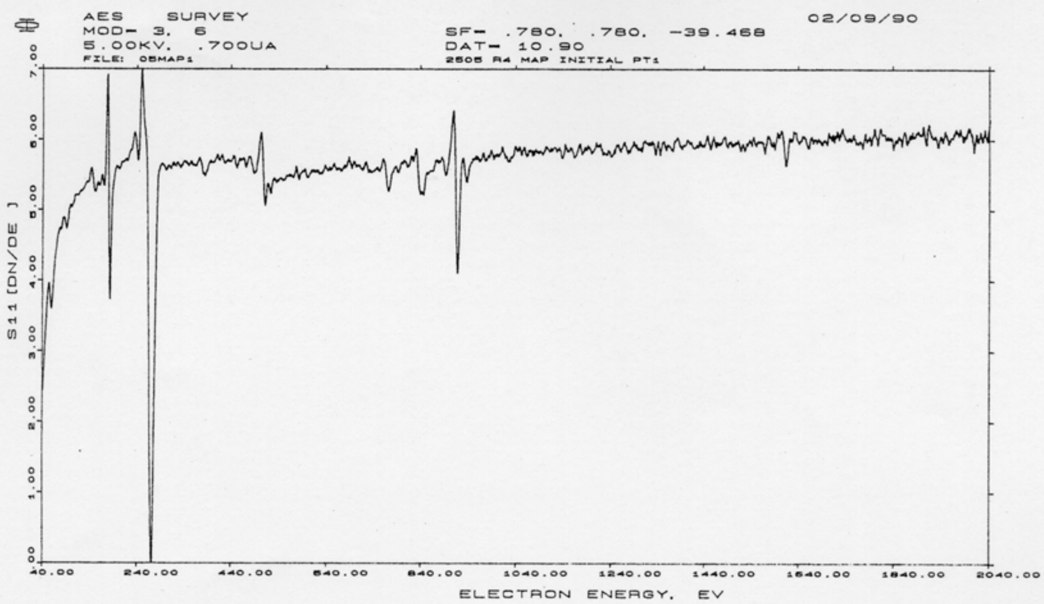

Figure 4. Auger elemental survey of material in failed hybrid laser trim.

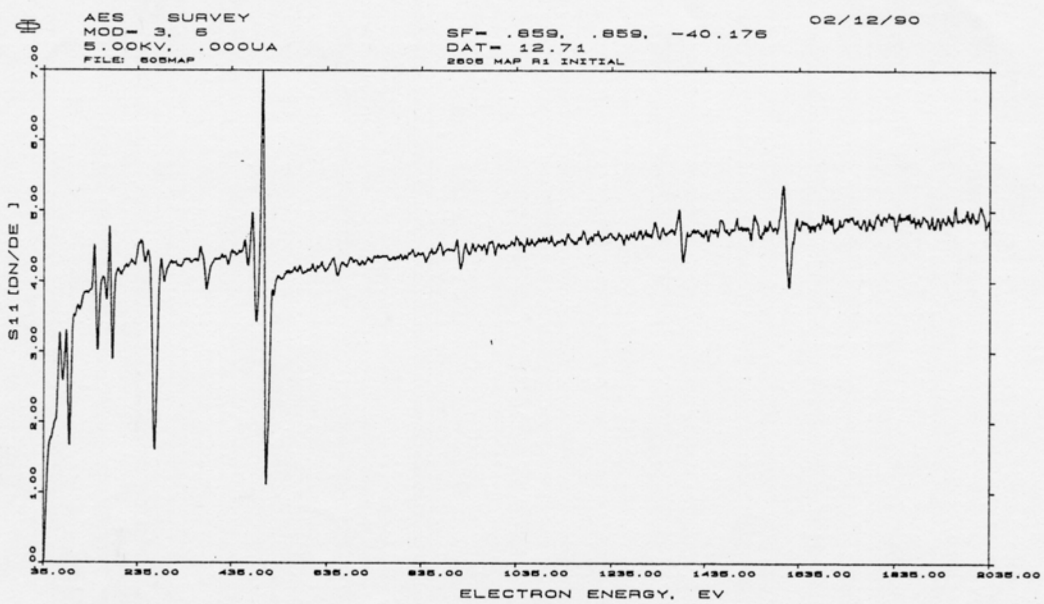

Figure 5. Auger elemental survey of material in "good" hybrid laser trim.

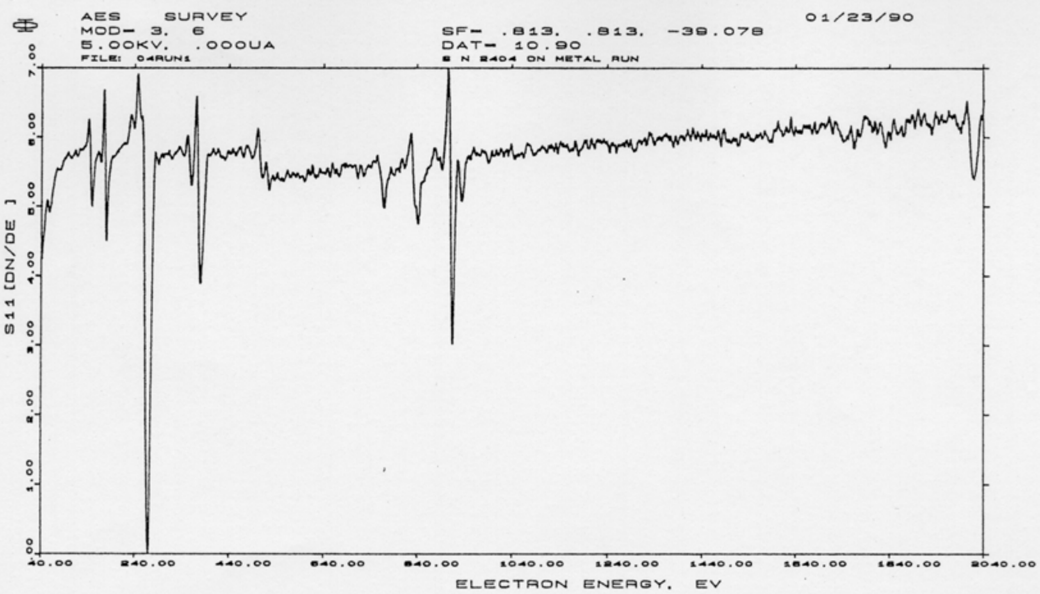

Figure 6. Auger elemental survey of a thick film conductor on a failed hybrid substrate (assembled).

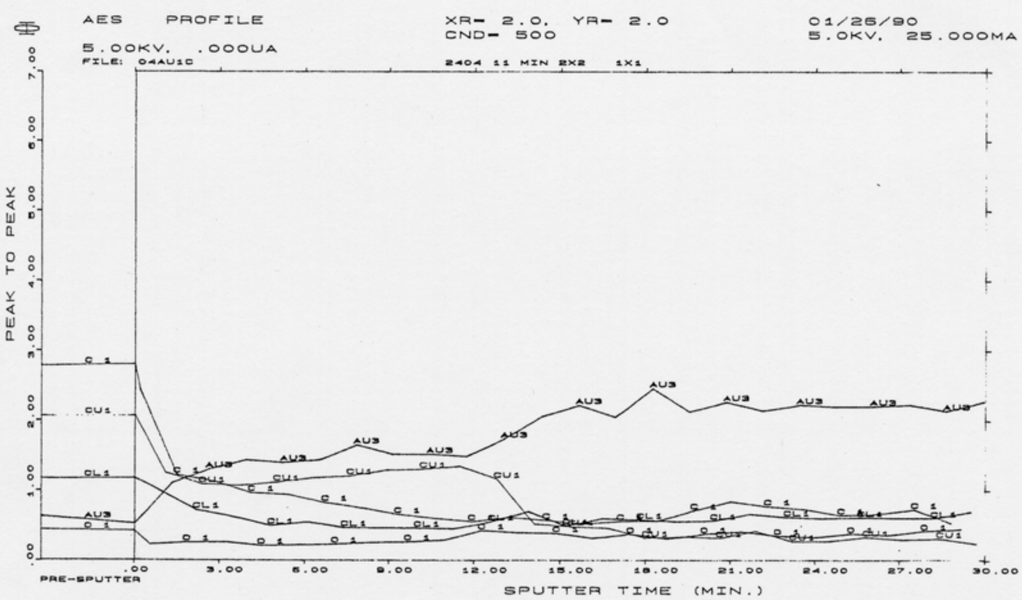

Figure 7. Auger depth profile of a thick film conductor on a failed hybrid substrate (assembled).

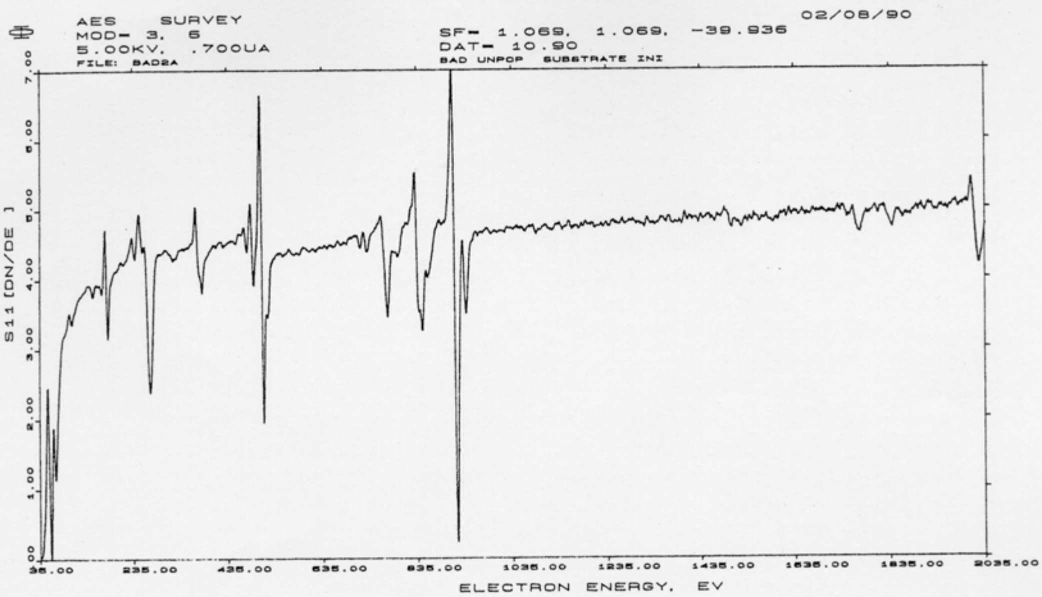

Figure 8. Auger elemental survey of a thick film conductor from the failed substrate lot (unassembled).

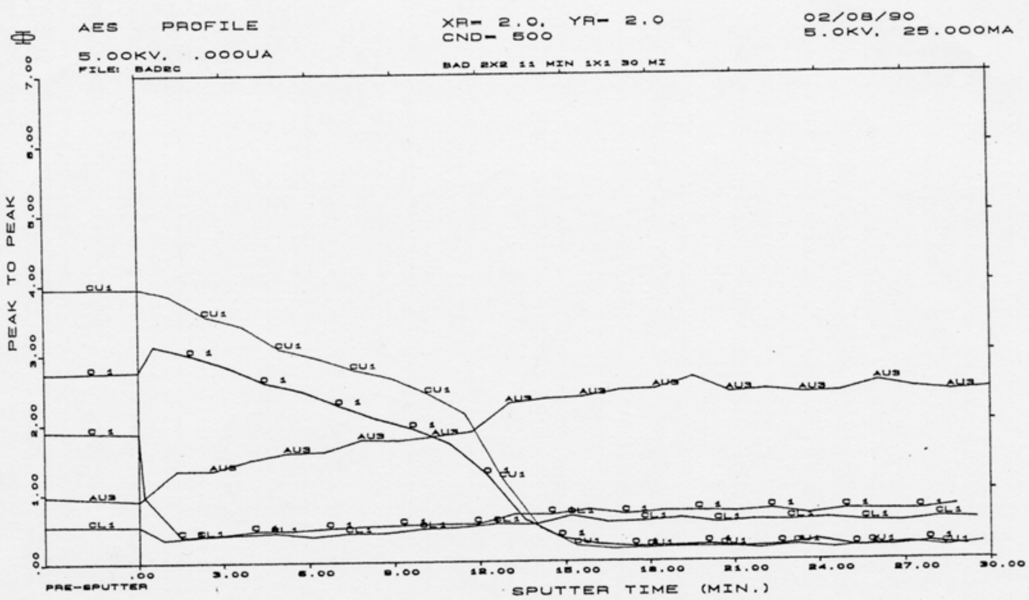

Figure 9. Auger depth profile of a thick film conductor from the failed substrate lot (unassembled).

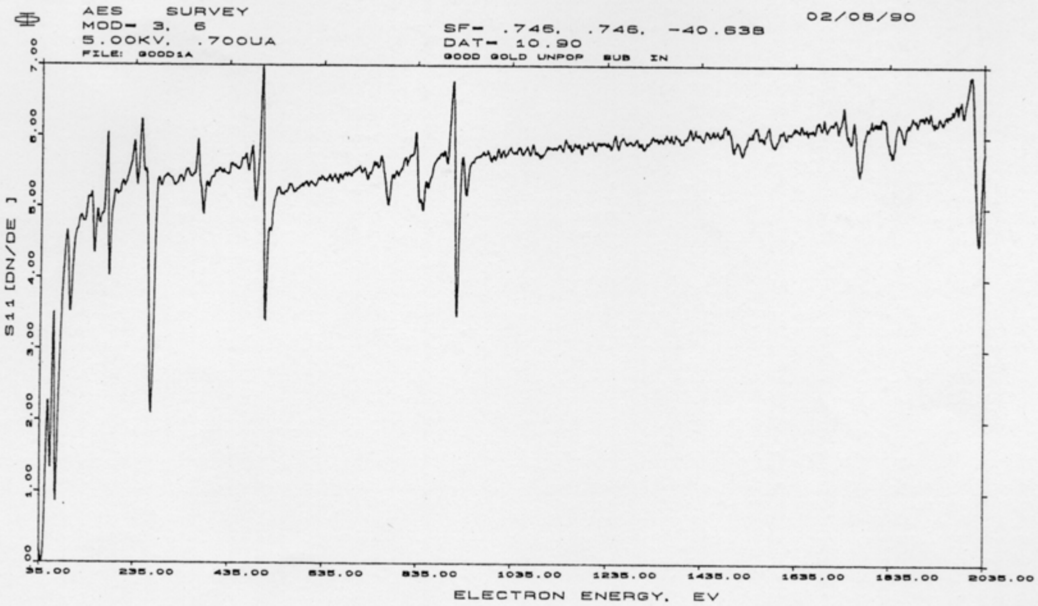

Figure 10. Auger elemental survey of a thick film conductor from the "good" substrate lot (unassembled).

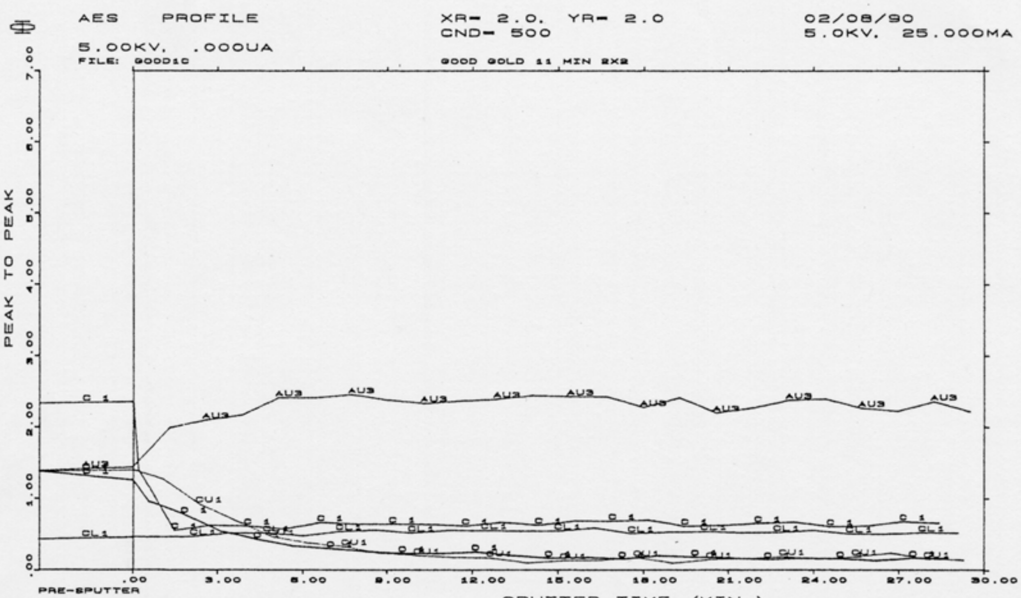

Figure 11. Auger depth profile of a thick film conductor from the "good" substrate lot (unassembled).

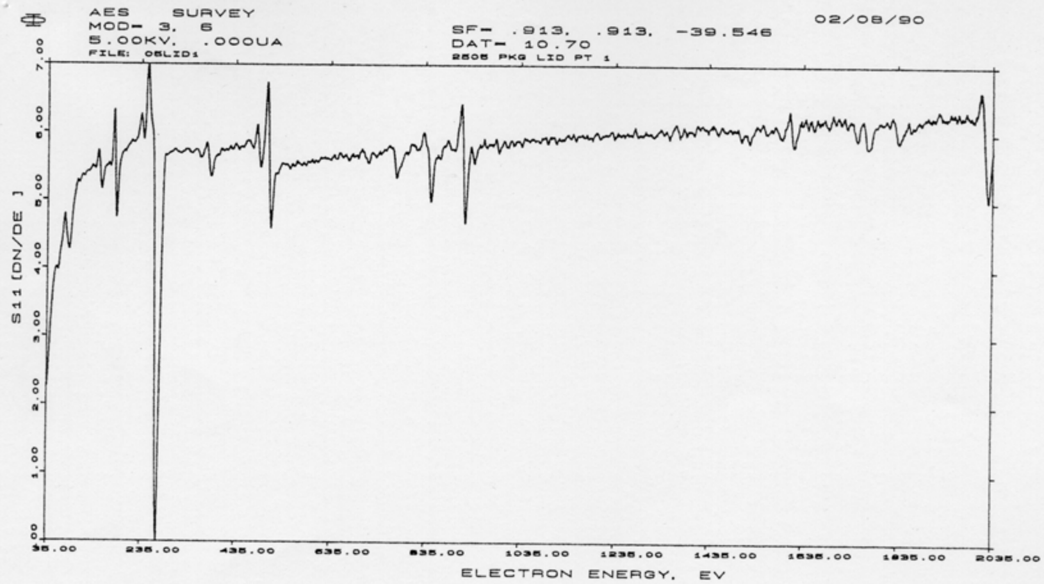

Figure 12. Auger elemental survey of a package lid from a failed hybrid.

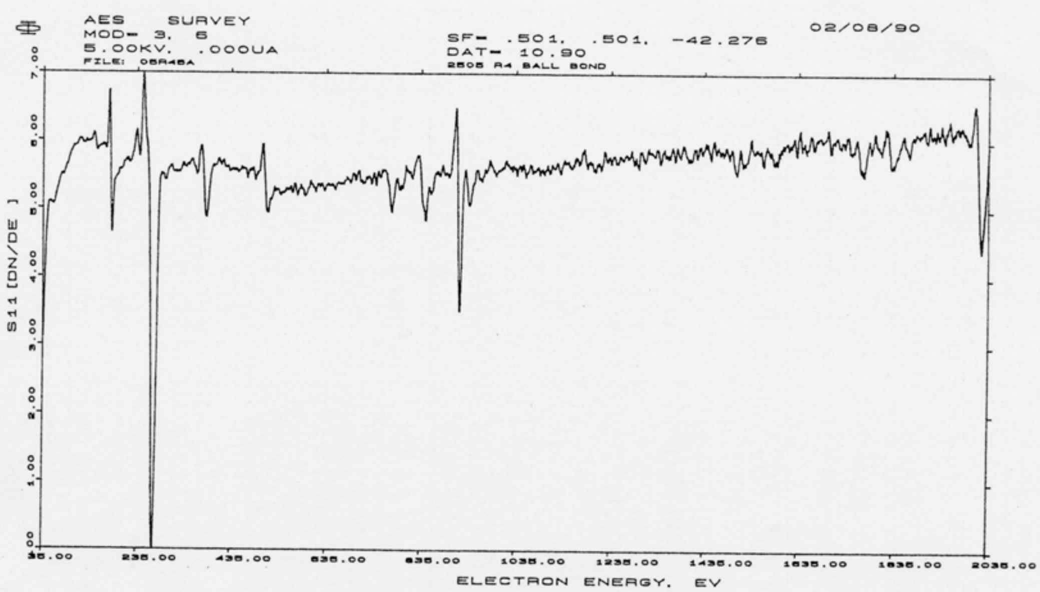

Figure 13. Auger elemental survey of a ball bond on a failed hybrid.

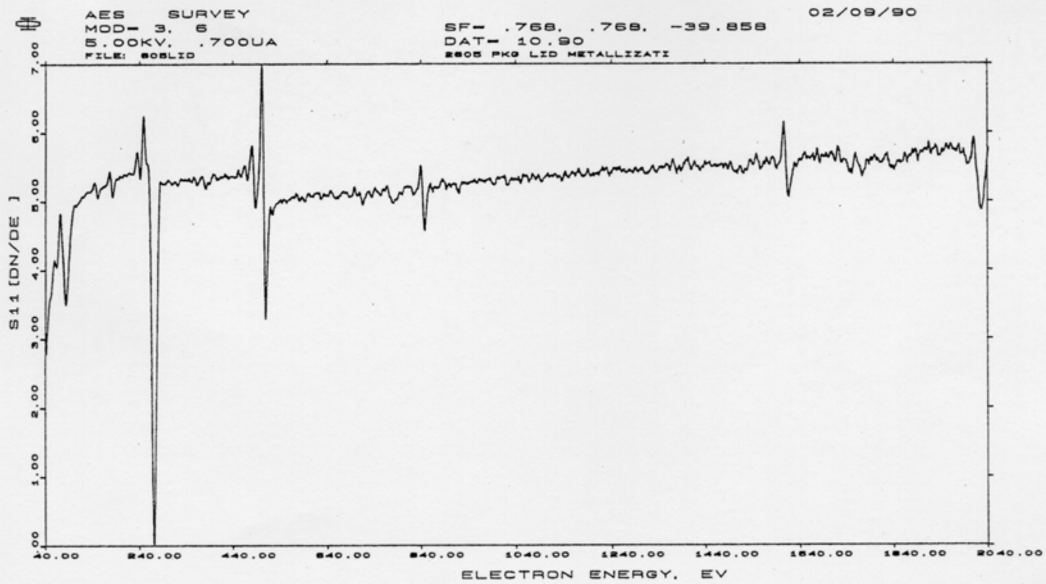

Figure 14. Auger elemental survey of a package lid from a "good" hybrid.

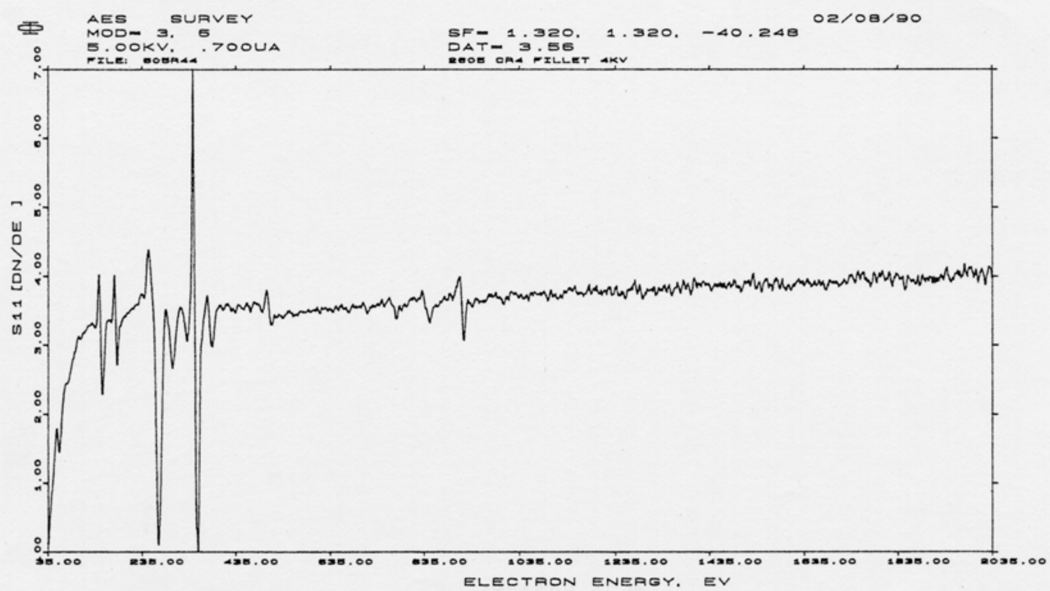

Figure 15. Auger elemental survey of a die attach fillet on a "good" hybrid.