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Nondestructive Testing of Thermocompression Bonds

By G. M. Hale

Published February 1981

Final Report

P. A. Campbell, Project Leader

Prepared for the United States Department of Energy
Under Contract Number DE-AC04-76-DP00613.

Bendix Kansas City Division

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A Scanning Laser Acoustic Microscope (SLAM) was used to characterize hybrid microcircuit beam lead bonds formed on thin film networks by a thermocompression process. Results from subsequent pull testing show that the SLAM offered no significant advantage over visual inspection for detecting bad bonds. Infrared microscopy and resistance measurements were also reviewed and rejected as being ineffective inspection methods.

DC/drb

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

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SUMMARY

A nondestructive product test other than visual inspection was sought for rapid evaluation of the quality of thermocompression bonds connecting beam lead semiconductor chips to hybrid microcircuit substrates.

Bond characterization using a scanning laser acoustic microscope (SLAM) was of particular interest. Samples prepared at Bendix were sent to an outside contracting laboratory for SLAM characterization, then returned for destructive pull tests. Comparison between results of the two methods indicated that the SLAM technique offered no reliable advantage for detecting bad mechanical bonds.

Infrared microscopy and resistance measurements were also reviewed and rejected as being ineffective inspection methods. No other techniques were suggested or evaluated.

DISCUSSION

SCOPE AND PURPOSE

The purpose of this project was to develop an improved test method to evaluate the quality of thermocompression bonds (formed between the beam leads of active devices and thin film networks) in the manufacture of hybrid microcircuits. Emphasis was on nondestructive techniques for evaluating bond strength.

Devices attached to the thin film networks in this study have four or 24 beam leads and range in width from 0.465 to 2.095 mm (0.018 to 0.082 inches). The bonds between the leads and the network are formed by a thermocompression process using a Kulicke & Soffa Model 576 Wobble Bonder. The process is controlled by monitoring the force, time, and temperature of the tool and substrate. Visual examination of the bond area is used to assure that the proper deformation (shape and size) of the beam lead was achieved. These controls do not verify that an adequate intermetallic bond was formed between the beam lead and the network. Pull tests are used on monitor parts to evaluate the process; however, these destructive tests cannot be used on the product. A test method is needed that will assure that satisfactory bonds are formed on the product. The method should be comparable in time to visual inspection, but should be sensitive to poor bonds that cannot be observed visually.

A questionnaire was distributed to the engineers responsible for thermocompression bonds (both Engineering and Quality divisions) to establish the information and direction needed to plan this project. Their replies have been incorporated in the project definition. As a result of the questionnaire and a preliminary literature search, two new instruments were selected as showing promise for nondestructive characterization of beam-lead bonds: the scanning laser acoustic microscope (SLAM) and the scanning laser infrared microscope (SLIM). A feasibility study for the SLAM technique was set up using an outside contracting lab to characterize the bonds on Bendix Kansas City-furnished samples which were subsequently returned and pull-tested. This has been the major undertaking under this project and the results do not warrant further development. The SLIM technique and a related technology herein termed Infrared Emission Microscopy were examined and abandoned. An attempt to probe the bonds by direct resistance measurements was also deemed impractical and not worthy of pursuit. No other techniques were suggested or evaluated.

ACTIVITY

Hybrid Microcircuits and Thermocompression Wobble Bonding

A hybrid microcircuit (HMC) is the interconnection of semiconductor chips on a ceramic substrate by a thin metal film deposited on the substrate surface. The semiconductor chips are beam lead devices (BLDs), meaning that the surface metallization imparted during fabrication of the chip extends beyond the edges of the chip in the form of cantilever beams that can support the device and provide electrical connection. The beam leads are bonded to the HMC substrate by a thermocompression (TC) technique called wobble bonding. Temperature and pressure are applied to the bond zone by heating the thin-film network through a work stage and by heating the beams of the chip through the bonding tool to which the chip is held by a vacuum. An operator aligns the beams with the thin film bonding pattern. The tool and chip descend vertically to the substrate. After touching the substrate, the bonding tool tilts off-normal, wobbles twice around the periphery of the chip, rolling over all leads in rapid succession, and then returns to the start position. The process is repeated for each BLD to be attached into the HMC.

The beam lead is deformed from pressure applied through the heated bonding tool. The allowable deformation can be determined nondestructively by measuring the foot-pad shape of the bond zone and the distance from the bottom of the device to the substrate (bugging).

Visual appearance will also reveal non-attached pads or broken leads, but satisfactory appearance does not ensure bond integrity.

Surface properties, interfacial temperature, beam hardness and grain microstructure, tool pressure and contact time all affect the integrity of the bond. During TC bonding gases absorbed on the surfaces normally are removed when the parts are heated before bonding, and interfacial gaps are closed by plastic flow of the hot deformed metal. However, inclusion of foreign material or an oxide layer would still be detrimental to bond integrity and these must be chemically removed prior to bonding. Monometallic gold interconnects reduce effects of environments and eliminate intermetallic problems.

The HMC described in this report (Figure 1) has a substrate composed of 99 percent Al_2O_3, 650 to 725 μm thick, coated with a 0.5 μm tantalum nitride resistor network, 0.2 μm chromium and finally a 6-μm-gold layer. Chromium oxide contamination produced at the substrate surface by chromium diffusion during a 300°C air bake used to stabilize the tantalum-nitride is removed by etchant prior to bonding. The leads of the BLDs are electroplated gold.

Scanning Laser Acoustic Microscopy

Acoustic microscopy is a technique for visually revealing on a microscopic level localized changes in elastic properties of materials. The physical properties which govern sound propagation, namely, the modulus of elasticity, mass density, viscosity and viscoelasticity, are translated into acoustic micrographs revealing point-by-point reactions of a material to a periodic stress wave. Internal structures are visualized by variations in the acoustic index of refraction of materials in a manner not unlike the formation of optical images by variations in electromagnetic properties. The acoustic waves are reflected, refracted, absorbed, and scattered in passing through interfaces, structures, and inclusions where mechanical characteristics are perturbed. Because the physical properties responsible for the acoustic image are different from those responsible for images obtained using waves from the electromagnetic spectrum, the information revealed is different. Many optically opaque substances are transparent to ultrasonic energy.

In contrast to electromagnetic radiation such as light, acoustic waves require a transporting medium. Coupling between that medium, the object to be observed, the ultrasonic transducer, and the detector is of crucial importance. Liquid water is often used as a transporting and coupling medium and was the medium in which samples were immersed in this study. An ultrasonic transducer attached to a wall of the liquid cell insonifies the sample.

Imaging is normally composed from waves reflected from or passing through a sample. Reflected waves define surface features and shapes, whereas transmitted waves reveal internal features of the sample. The acoustic microscope used in this study uses transmitted sound to probe characteristics of the bond interface.

The detected image can be the result of focused sound probing a small scanned sample volume or the result of unfocused sound exhibiting interference effects on a scanned surface. In the first case, a lens and transducer combination collect transmitted sound for display as image intensity on a cathode ray tube (CRT) while the sample is rapidly moved in a scan sequence relative to the focused "spot." In the second case, plane wavefronts passing through a sample volume are altered in passing and strike a flat boundary beyond. Presence of the sample disturbs the uniform

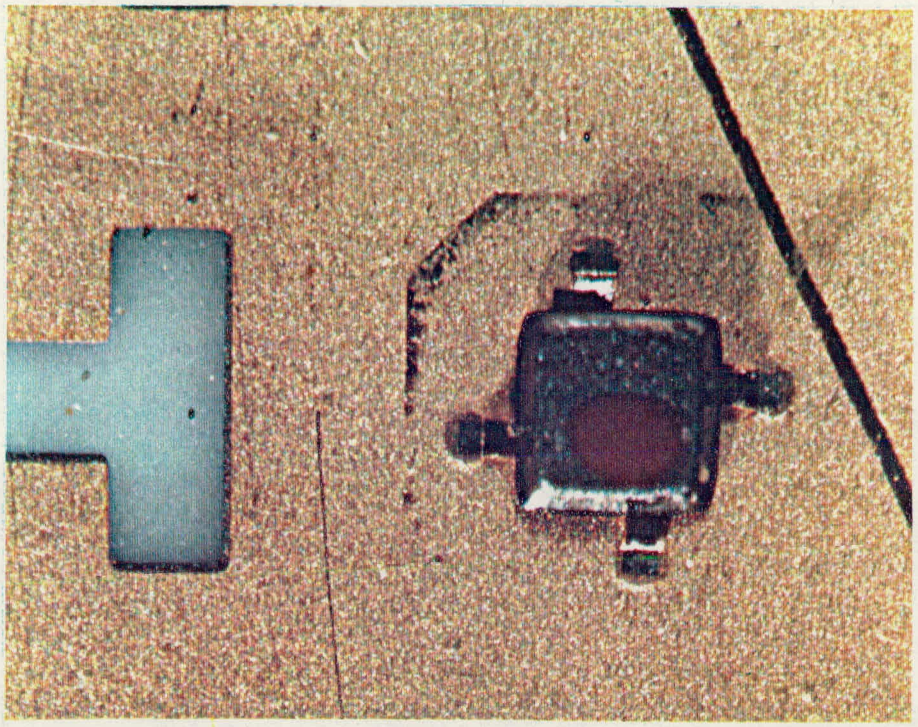


Figure 1. Thermocompression Bonded F-25 Format Device

interference pattern that would otherwise prevail at the boundary. The interference pattern exists as an amplitude variation at the boundary and the mechanical energy variations deform the boundary. This deformation is picked up as a variation in optical reflection for a narrow light beam scanned across the boundary and reflected into an opto-acoustic receiver. (Figure 2) When this light beam is a laser, the system is designated a Scanning Laser Acoustic Microscope, or SLAM. The detected signal is displayed on a CRT.

SLAM Characterization of Thermocompression Bonds

Two sets of Bendix supplied samples were sent to Sonoscan, Inc. for characterization of the gold to gold lead/pad bonds of HMC beam lead devices. A designated goal was to develop parameters which can be used to non-destructively evaluate bond quality.

The instrument used in Sonoscan's investigation was the Sonomicroscope 100, which operates at an ultrasonic frequency of approximately 100 MHz. The acoustic image is displayed on a TV monitor where the white regions of the micrographs correspond to areas of the sample with good acoustic transmission, while the darker areas are regions of higher ultrasonic attenuation. There are 40,000 image points per micrograph. A mirrored coverslip is

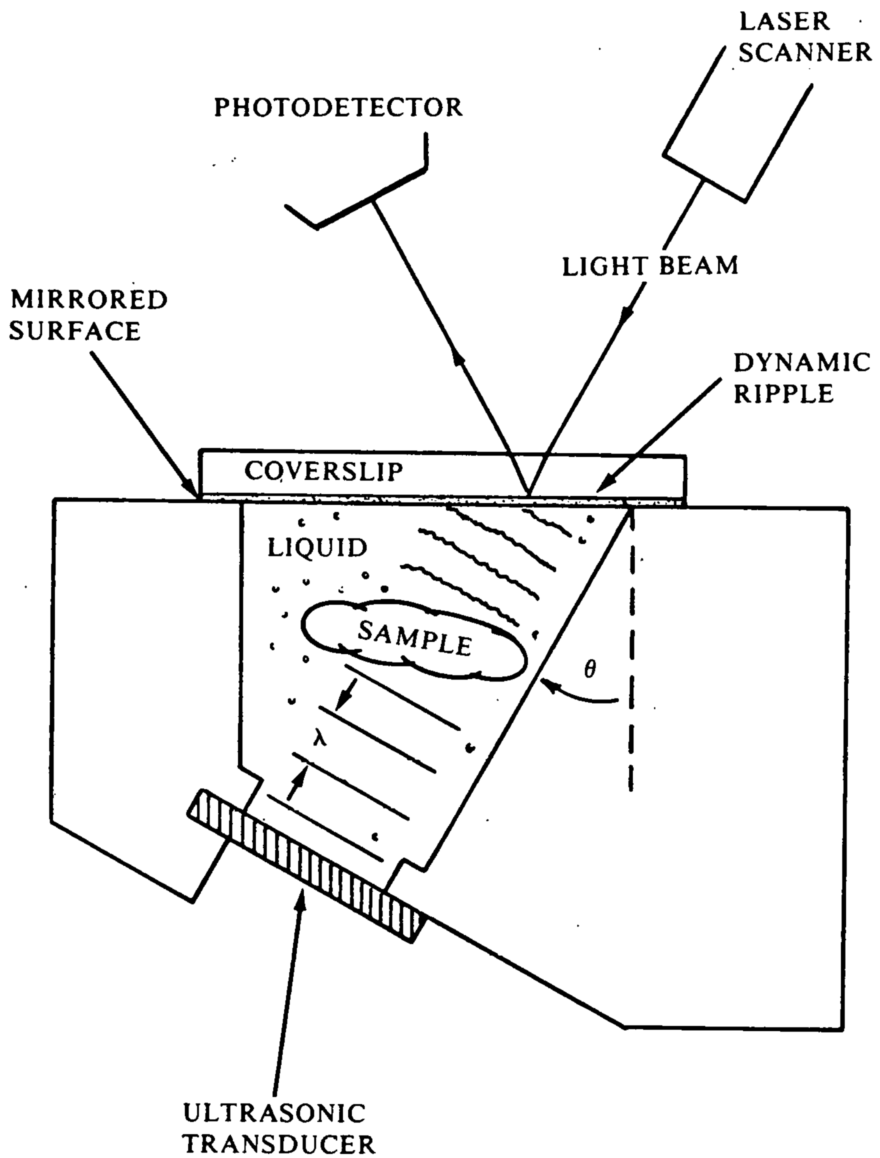


Figure 2. Representation of SLAM Imaging Technique

placed in acoustic contact with the top surface of the sample cell and light reflected from the coverslip is used to form the acoustic image, as described previously.

There are two types of acoustic amplitude pictures. The first is an amplitude picture made at a single ultrasonic frequency. These acoustic micrographs generally are characterized by high contrast; at times, the micrographs are subject to coherent speckles. The amount of speckle is related to the degree of scattering in the specimens. This phenomenon provides an indication of both the mode of acoustic losses and the elastic microstructure of the material.

The second type of amplitude picture is obtained by continuously sweeping the frequency over a variable bandwidth around 100 MHz. This eliminates the coherent speckle and may reveal low contrast features which the speckle masked.

An acoustic "interference" mode of operation also is incorporated into the SLAM. Here, the waves pass through the specimen and are combined with an electronic reference signal. The image that is produced, the interferogram, consists of a series of vertical alternating light and dark bands, or interference fringes. For acoustically homogeneous samples, these bands are parallel to one another and are equally spaced. For samples that are elastically inhomogeneous, the interference lines will be distorted by localized variations in the sound velocity and/or sample thickness.

Samples

Both sets of samples contained HMC Beam Lead Devices bonded to a one-inch-square, gold coated alumina substrate. One sample set consisted of F-25 (1-mm-square) BLD, each attached to the substrate by four lead bonds. The other set consisted of F-70 (2.5-mm-square) BLDs, each attached to the substrate by 24 lead bonds.

Each set of devices had been bonded using three sets of bonder parameters. These parameters were selected to produce a wide range in the quality of the gold-gold beam lead bonds. Substrate temperatures ranged from 100 to 250°C and the tool temperatures ranged from 100 to 450°C. The following parameters were used for each group.

Format 25			Format 70		
Group	Tt°C	Ts°C	Group	Tt°C	Ts°C
IA	100	100	IIA	400	250
IB	300	150	IIB	250	150
IC	450	250	IIC	100	100

The highest combination of tool and substrate temperatures produce the highest interface temperatures and the best bonds. The lowest temperatures produced very poor bonds and in some cases the devices fell completely off the substrate. As received by Sonoscan, none of the group IA BLDs were left attached to the substrate, only half of the IB BLDs were still attached, and one of the IIC BLDs was missing.

Procedure

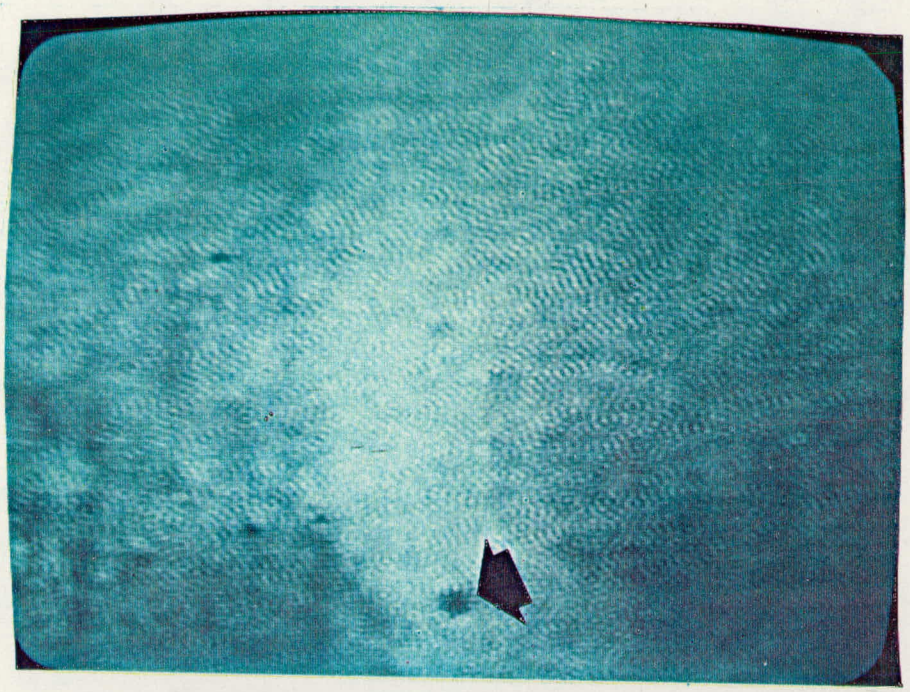
Each attached BLD and its leads were examined using the Sonomicroscope 100 SLAM operating at 100 MHz. A 10° angular insonification was used with water serving as the coupling medium. Each device was photodocumented. Orientation of the pads in the micrographs was recorded so that individual leads could be identified. Results were tabulated and transmitted to Bendix. The sample sets were returned to Bendix for pull test comparisons.

Characterization of Substrate

Acoustic microstructure of the substrate serves as a background for the pads and their leads. An abundance of very small (<50 μm), high contrast structure is evenly distributed throughout each substrate. (Figure 3) This fine structure is attributed by Sonoscan to the nature of the gold/alumina interphase region. Except for this fine structure, the acoustic transmission and sonic velocity were found to be relatively uniform. The only non-uniformities found in the substrate material are circular (100 μm diameter), more highly attenuating regions (Figures 3 through 5). These structures could represent near surface inclusions or void-like regions in the alumina substrate, precipitates in the coatings, or surface contaminants. They do not necessarily represent a feature that has a 100 μm dimension, however. Diffractional effects set the limit to the smallest detail that can be resolved at approximately one half of the ultrasonic wavelength. Typical wavelengths at 100 MHz for compressional waves and shear waves are listed below. Note that the diffraction limit must vary with the material.

Material	Compressional Waves	Shear Waves
Water	15 μ	
Solid Polymers	22-32	10-15 μ
Glasses	40-65	18-30
Metals	40-65	18-30
Ceramics	50-122	26-70

The velocity (v) of sound in bulk material is related to the frequency (f) and wavelength (λ) by: $v = f\lambda$.



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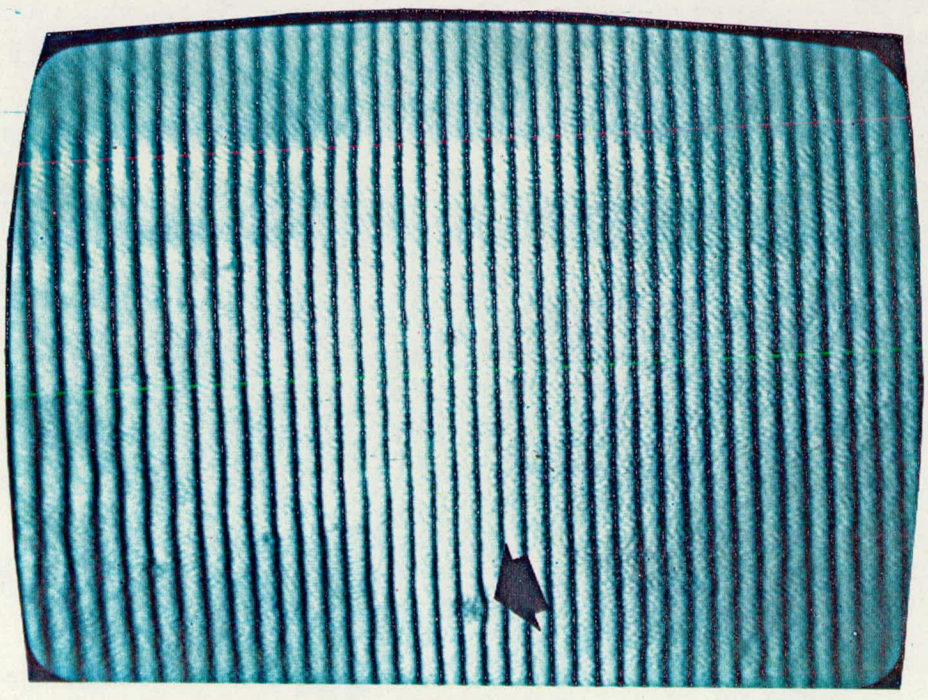

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Figure 3. Effect of Substrate Non-Uniformity on SLAM Method

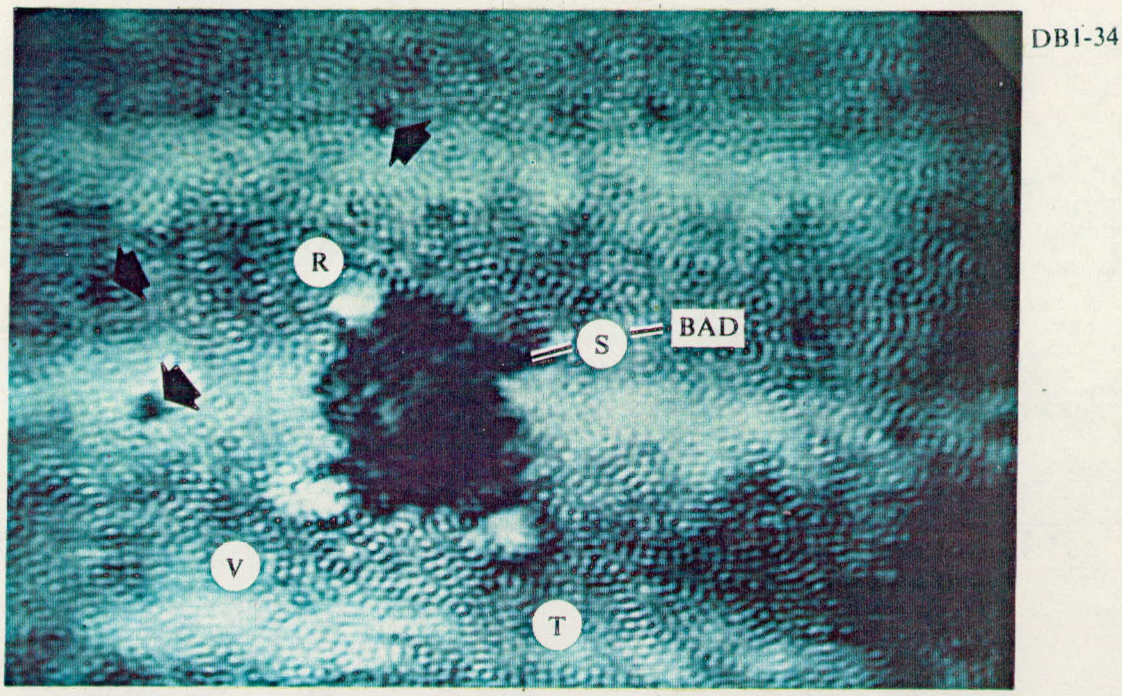


Figure 4. SLAM Picture Illustrating Both Good and Bad Bonds

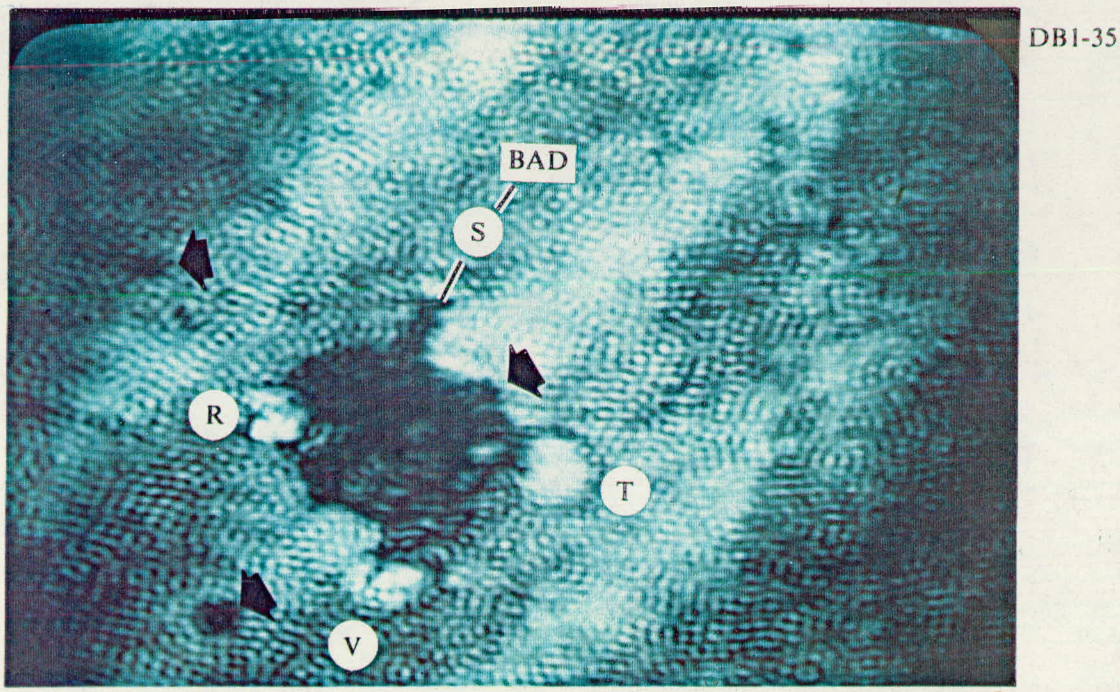


Figure 5. Same Sample Rotated Counterclockwise 60°

Typical sound velocities in bulk material at 25°C are listed below.

Material	Density	Longitudinal Velocity	Shear Velocity
Gold	19.7 gm/ml	3420 m/s	1200 m/s
Fused Silica	2.2	5968	3764
Distilled Water	0.998	1498	
Dry Air	0.00129	331	

Note that the velocity divided by 10^8/sec (100 MHz, the central microscope frequency) gives the wavelength in any particular medium. Because the wavelength and velocity vary between media, diffraction and refractive variations will determine the image size and definition produced at the coverslip boundary. The acoustic shadow produced there could have been either magnified or reduced in transit, with edges blurred by diffraction.

What can be ascertained from non-uniformities in the image of the substrate is that some non-uniformity among the layers of the substrate did exist. The more highly attenuating (i.e. darker) circular structure noted by the arrow in Figure 3, is commonly found dispersed throughout the substrate. The acoustic interferogram fringes are parallel, straight, and continuous, indicative of uniform sonic velocity, except near this structure. The shift to the right indicates a region of higher sonic velocity.

Characterization of Bonds

In the previous section we illustrated the acoustic transmission characteristics of the substrate material. In this section, results are presented on the bonded pads. The acoustic transmission characteristics in the vicinity of the beam are influenced by the sample architecture, as well as orientation. In the next few pages, acoustic characteristics of the pad regions are presented, along with interpretations of the structures seen.

The following micrographs illustrate the influence of the sample architecture and orientation on the acoustic characteristics of the pad regions.

MICROGRAPH DESIGNATION	SAMPLE	DESCRIPTION
DB1-34	IB6	Note the presence of the darker, circular structures (green arrow), which are typically found in both

substrates. The dark/light pattern seen running horizontally in the micrographs is a result of sound reverberation between the coverslip and the substrate surface. The pad is darker (blue arrow) because of increased acoustic losses. The four lead bonds are labeled R, S, T and V. Three of the bonds, R, T, and V appear acoustically bright, indicating good mechanical contact. One, S is more attenuating indicating poor mechanical contact.

DB1-35
After sample rotation counter-clockwise 60°

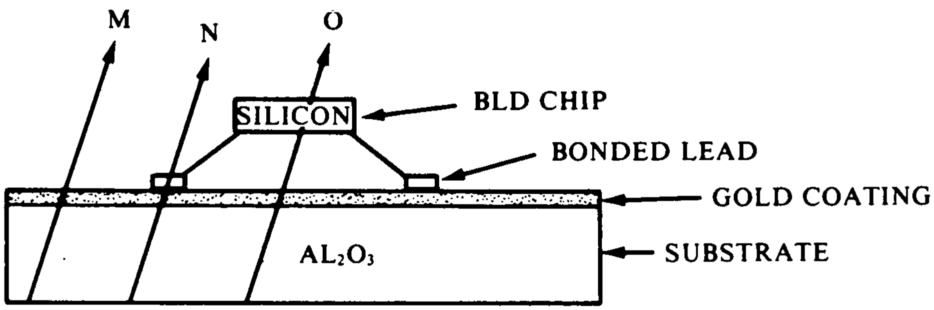
This is the same sample pictured in DB1-34; however, this sample has been rotated 60° in a counter-clockwise fashion. Notice how the T and V leads' acoustic characteristics have changed. The change in acoustic characteristics is attributed to sample orientation effects. All beams were examined in at least two orientations to ensure that the results are not a product of sample orientation.

NOTE: The small device (4 leads) was used for illustration; however, the same arguments hold true for pads on the larger F-70 device.

The acoustic structure observed in the vicinity of the bonded pad can be understood with the aid of Figure 6.

First, consider the more highly attenuating characteristics of the BLDs with respect to the substrate. The acoustic transmission path M, through the substrate, includes propagation across an alumina/gold interphase and a gold/water interphase. Whereas, the acoustic transmission through the chip (path O) involves propagation across two additional interphases: silicon/water and water/silicon. The higher attenuation through the chip results from acoustic energy losses at these additional interphases. Furthermore, transmission through the BLD may be disrupted because of inadequate coupling, i.e., air bubble between the chip and the substrate in which case the chip will appear opaque.

It is also noticed that the acoustic transmission through the 'good' lead/substrate bonds is better (brighter) than the transmission through the substrate (see micrograph DB1-34). Path M



M - ACOUSTIC PROPAGATION PATH THROUGH SUBSTRATE
N - ACOUSTIC PROPAGATION PATH THROUGH BONDED LEAD
O - ACOUSTIC PROPAGATION PATH THROUGH BEAM LEAD DEVICE

Figure 6. Diagram on Acoustic Attenuation

and path N are similar in that both involve propagation across alumina/gold and gold/water interphases. The higher transmission through the well bonded leads can be attributed to microstructural changes in the gold--e.g. decreased porosity or grain size changes, as a result of thermocompression bond formation.

A second aspect which needs to be addressed is the effect of sample orientation with respect to the insonification source. This can be illustrated by comparing micrograph DB1-34 with DB1-35. These are micrographs of the same chip, but the latter was obtained by rotating the sample approximately 60° counterclockwise. The primary features of the image are the same in each case, but minor variations are observed in the chip and bonded leads. These variations are attributed to changes in the insonification angle of the bonded leads and are illustrated schematically in Figure 7.

For each pad, there are three orientations of the leads with respect to the sound field: For one set, the acoustic energy intersects the lead from the 'front,' in the second set the acoustic energy intersects the lead from the 'side,' finally, the energy intersects from the 'back' (Figure 7). These different sample orientations can lead to some differences in the acoustic characteristics. This geometrical effect did not effect the results of the work presented because each pad was examined in several orientations (i.e. rotation about Z axis) to confirm results.

In this study, bonds were classified into only two groups based on their acoustic transmission properties. Only bonds exhibiting complete attenuation were classified as bad; others, showing complete or paritial transmission, were classified as good. Substantial variation existed in the acoustic transmission properties of the good bonds.

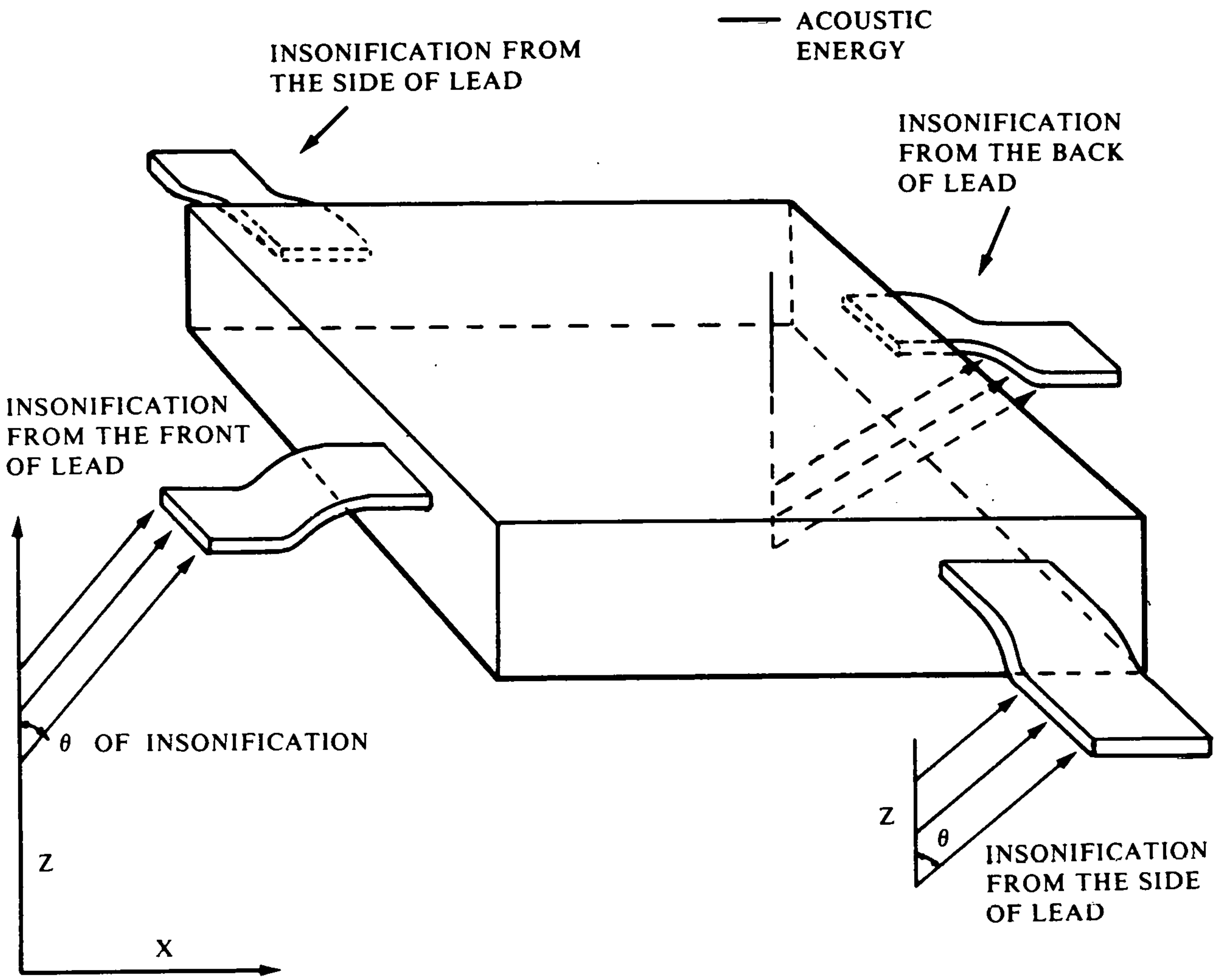


Figure 7. Diagram on Orientation Effect

Beam Lead Pull Tests

The mechanism used in pull testing is illustrated in Figure 8. The pull-test procedure involves the following steps:

1. On the top of a BLD, crystals are deposited that will melt into a uniform polyvinyl acetate glue upon heating;
2. Lower a heated current loop into the crystals, melting the glue to form a liquid mass in contact with the loop and the BLD;
3. Let the assembly cool to form a solid bonded unit;
4. Pull up on the loop and record the maximum force required to break all lead bonds.

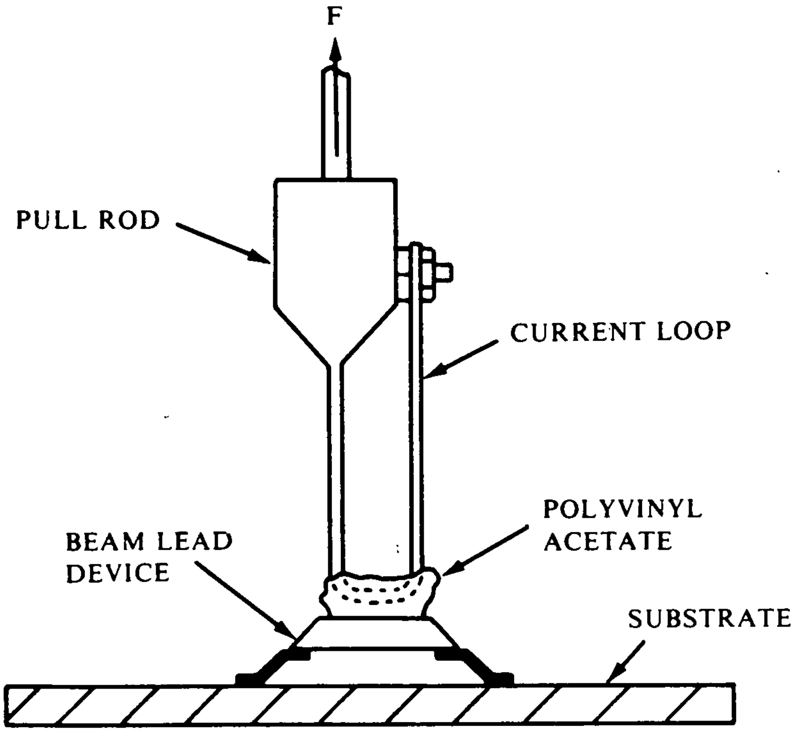


Figure 8. Diagram on Pull-Off Test

The maximum force recorded will be lower if either all bonds are weak or some bonds separate before others. Note that this procedure does not record the average force to separate all bonds on the device. Rather, there is an assumed correlation between average goodness of bonds and the maximum force recorded during the test.

Comparison Between Bendix Pull Tests and Sonoscan Evaluation of BLD Bonds

After Sonoscan characterized the beam lead bonds, some of the devices were pull tested at Bendix and the data was compared to the acoustic microscope results. The pull test results and the comparison of the failure modes with Sonoscan's data were tabulated and photodocumented with light microscopy. (Tables 1 and 2)

Of twelve Format 70 devices pull tested, six had bond delaminations (D's). Sonoscan predicted five devices would have D-failures; however, of these five devices predicted to have open bonds, two devices had no open bonds. One device had D-failures that were not predicted and another device pull-tested had not been examined with the acoustic microscope.

Table 1. Format 70

	Device	Sonoscan Prediction Number of Bad Beams	Bendix Bad Bonds (D's) Pull Test	Pull Strength (gms)
	1	1	0	68.7
IIA	2	0	0	129.4
Ts=250°C	3	0	0	99.8
Tt=400°C	6	0	0	117.8
	7	1	0	127.2
	1	17	16	30.0
IIB	2	4	10	51.5
Ts=150°C	3	2	1	115.7
Tt=250°C	7	0	7	62.0
	8	0	0	130.7
IIC	2	No Test	21	36.4
Ts=100°C	6	20	23	11.6
Tt=100°C				

Of seven Format 25 devices pull tested, two had D-failures, though only one device was predicted. Both failures occurred on devices bonded at T_s = 150°C and T_t = 300°C. (Devices bonded at T_s = 100°C and T_t = 100°C fell off of the substrate prior to testing.)

A tele-microscope photograph of the F-25 device labeled IB6 is shown in Figure 9. The image display mode is reversed (negative) in the photograph because this enhances the raised appearance of attached pads V and R. This is the same device illustrated in acoustic microscope Figures 4 and 5. The beam lead pad labeled T pulled loose even though it appears good in the acoustic image.

Visual examination through a light microscope of some of the hybrid microcircuits and substrates used for this study has revealed that the bonds characterized as bad by the acoustic microscopist are not necessarily the same bonds that failed during pull tests. There is also evidence (Figure 10) that unequal pressure was applied by the wobble bonder in attaching beam leads to thin film layers and that bonds receiving less pressure were those more likely to delaminate during pull testing.

Figure 11 shows an F-70 format device from Group IIB and the gold film substrate containing bonds broken after pull testing device 3 (Table 1). There is one delamination (arrow), though Sonoscan

Table 2. Format 25

	Device	Sonoscan Prediction Number of Bad Beams	Bendix Bad Beams (D's) Pull Test	Pull Strength (gms)
IB	6	1	2	6.6
Ts=150°C	10	0	2	6.6
Tt=300°C				
	6	0	0	18.6
IC	7	0	0	19.0
Ts=250°C	8	0	0	19.0
Tt=450°C	9	0	0	17.8
	10	0	0	25.0

predicted two. Photodocumentation in the form of color slides submitted by Sonoscan, however, show that the slide that Sonoscan has labeled IIB-3 (Figure 12) is probably an acoustic micrograph of device IIB-4, the BLD on the right side of Figure 11 that was not pull tested. It is unclear whether the tabulated result for IIB-3 actually refers to device 3 or 4. Problems such as this lend confusion to the report and cast doubt on the validity of some of the correlation determinations. Overall, however, there still does not appear to be sufficient correlation between the two test methods to support acoustic microscopy as a reliable predictor for poor mechanical bonds. Reliability of the destructive pull test for detecting bond and heel failures is well established.

Infrared Microscopy

The infrared microscope is similar to an optical microscope except that the optics are designed of materials suitable for transmitting and polarizing light in the near infrared region of the electromagnetic spectrum-wavelengths up to about 1.2 μm. Laser assisted infrared microscopy uses an argon-ion laser beam to locally heat the inspection region under a cryogenic IR microscope having a thermocouple output. We have dubbed this technique "SLIM" for Scanning Laser Infrared Microscopy. The technique is described in detail in a paper "A Laser-Assisted Infrared Scanning Technique for Evaluating Bonded Connections on Beam Lead Microcircuits" by B. C. Miao and J. Longfellow, Applied Optics 9, 669 (1970). However, a single unbonded lead in contact with the substrate is not detectable. Thus, this method appeared to show no advantage and has not been studied further.

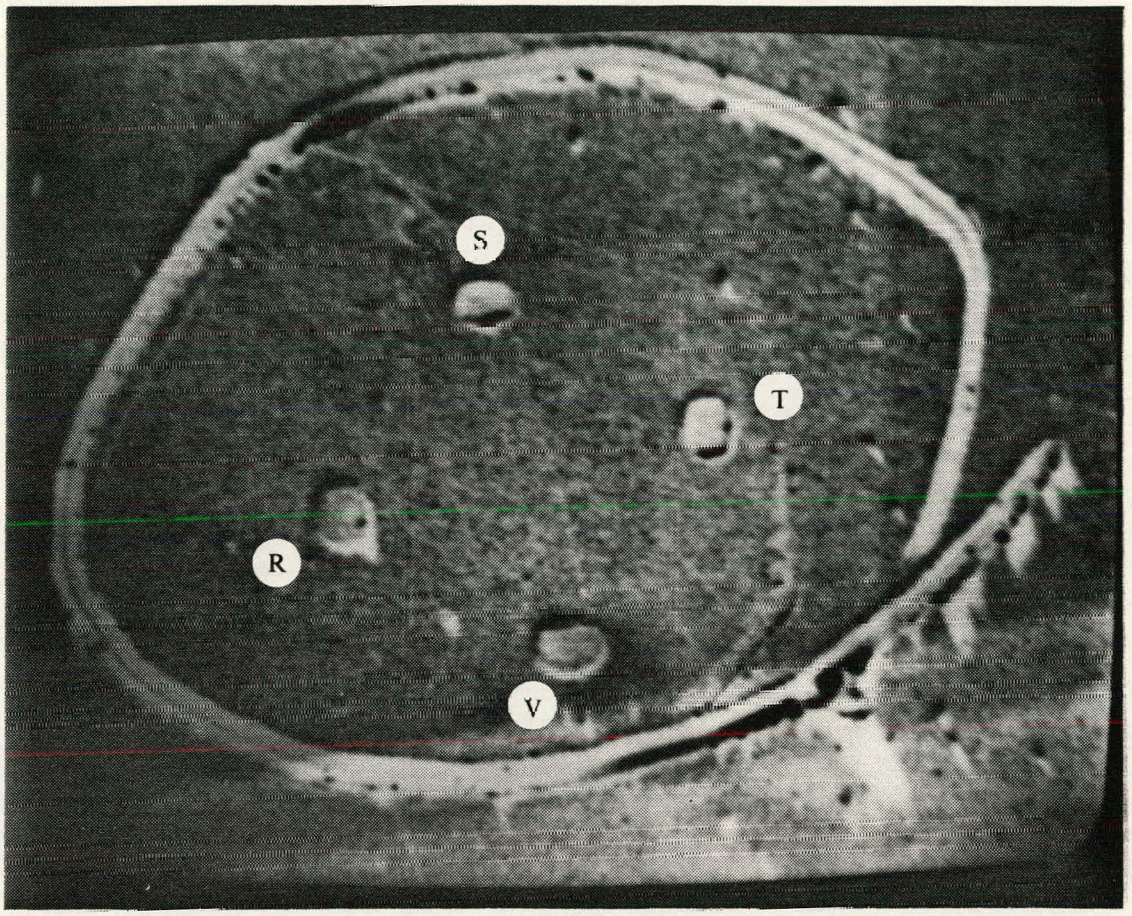


Figure 9. Tele-Microscope View of Device With D-Failures

Infrared Emission From an Active Circuit

By incorporating an infrared-to-visible converter tube, an infrared microscope image can be made visible, allowing visual inspection of the active regions of an energized circuit, with light intensity corresponding to current density, where joule heating results in increased infrared emission.

This technique was not studied because of the requirement that the circuit be energized.

Resistance Measurements

It is possible, in concept, to find a bad bond by a measurement of its increased resistance to the flow of current through the bond. Some trial measurements were performed to assess the feasibility of using such a direct measurement method. This

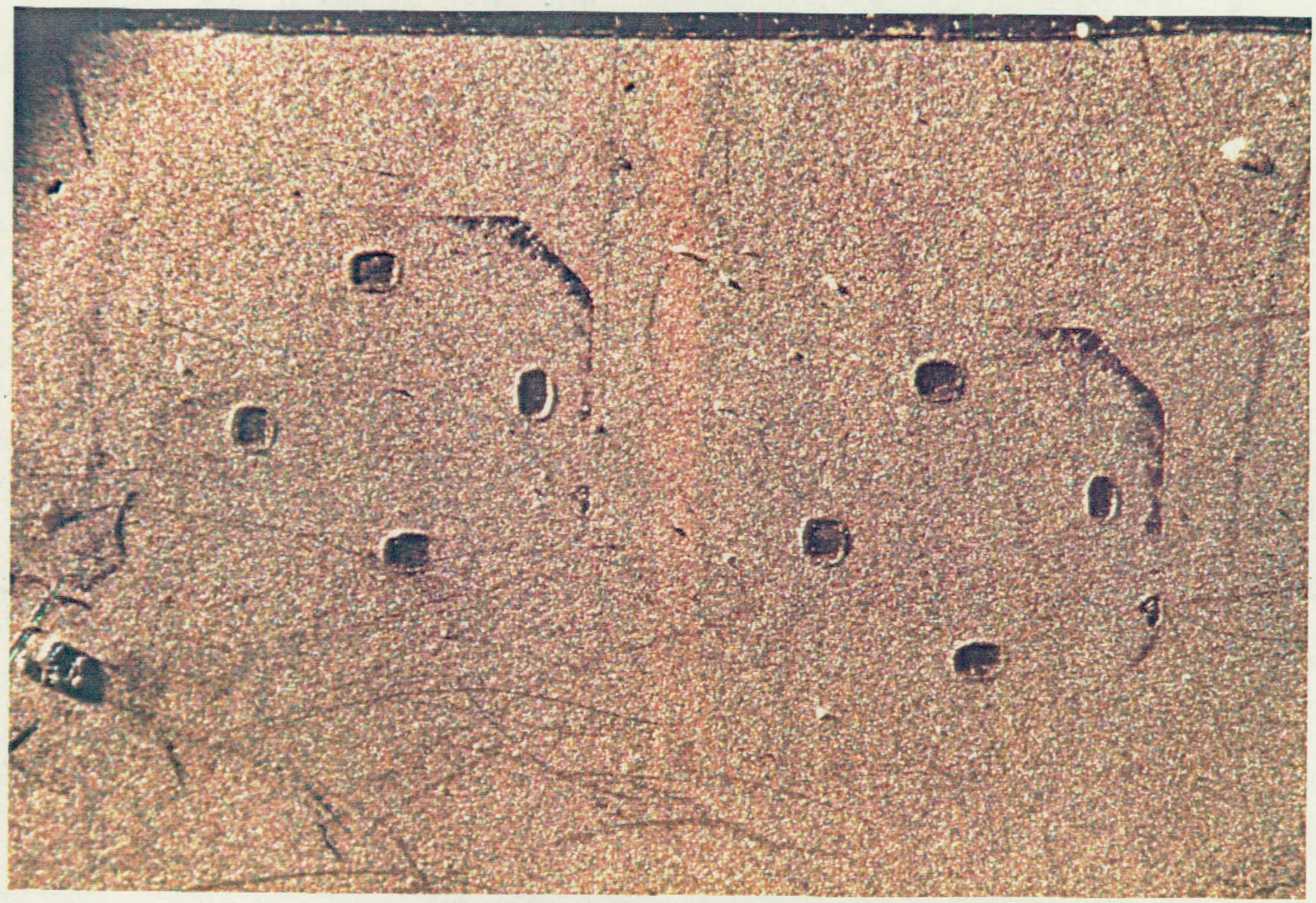


Figure 10. Evidence of Uneven Wobble Bonder Pressure

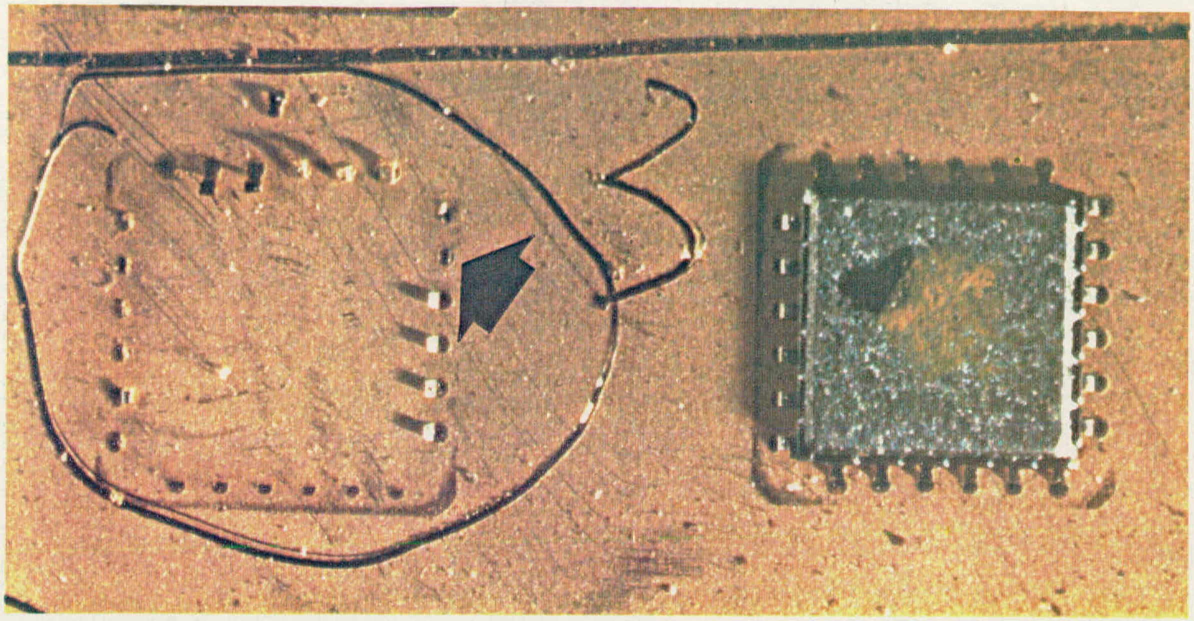


Figure 11. F-70 Format Device Before and After Pull Testing

method was not practical. The mechanical probe could force contact where no bond otherwise existed. And once a gold-gold contact existed, the variation in resistance across bonds was below the limits of detection.

ACCOMPLISHMENTS

No inspection technique better than visual inspection was developed during this study. A number of possible techniques for characterizing bad bonds were searched and found to be lacking in accuracy. Neither scanning laser acoustic microscopy nor scanning laser infrared microscopy appear to be sufficiently sensitive to provide any advantage over visual inspection at this time.

RECOMMENDATIONS

The instrument of greatest interest--the acoustic microscope--is not capable of improving the bond inspection process until its imaging properties are better defined. Acoustic microscopy has a distinct disadvantage in that the circuit to be studied must be submersed.

Figure 12. Acoustic Micrograph of F-70 Device

There are several new emerging technologies which show some promise for combination into a BLD bond inspection technique. These will be described briefly, but it is recommended that they be the object of a separate study: Infrared holography might be used to detect poor mechanical bonds. Through an infrared microscope, a hologram would be obtained of a bond assembly prior to heating with a laser beam. A second hologram would then be recorded after the bond is heated. Because the poor bond will show expansion characteristics different from a good bond, a fringe pattern will be evident in the processed hologram that might be distinct enough to characterize the bond as bad. Holography as an inspection technique is slowed by the photographic process normally used to record the hologram. But it might be possible to use a scanned infrared sensor to record enough information to store the holograms digitally in a computer memory for comparison. Illumination with a pulsed laser for the image exposure should reduce the need for a rock-steady imaging system for holography. There is nothing about this process peculiar to beam lead devices, so it should be applicable to emerging bonding technologies as well.

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