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BEAM LEAD TESTING, HANDLING,
AND FAILURE ANALYSIS

PDO 6984775, Final Report

L. W. Brown, Project Leader

Project Team:
J. C. Rustman
W. O. Watson

September 1974

Prepared for the
United States Atomic Energy Commission
Under Contract Number AT(29-1)-613 USAEC

**Kansas City
Division**

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**Kansas City
Division**

BEAM LEAD TESTING, HANDLING, AND FAILURE ANALYSIS

BDX-613-975 (Rev.) Final Report, September 1974

Prepared by L. W. Brown, D/863, under PDO 6984775

Handling, testing, and failure analysis of individual beam lead devices (BLD) were investigated with specially-created fixturing and equipment. Devices were safely removed from closely-spaced (as-etched) arrays, and the arrays reprobed; and boundary conditions were established for each task.

THE BENDIX CORPORATION

KANSAS CITY DIVISION

KANSAS CITY, MISSOURI

A prime contractor for the
Atomic Energy Commission
Contract Number AT(29-1)-613 USAEC

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SUMMARY

Testing, handling, and failure analysis processes for beam lead semiconductor devices (BLD) were investigated. Experimental BLD reprobng was successful. Limits on probe force and number of reprobes were established for automatic probe equipment. A TO-5 size test header was developed to perform destructive sample testing and was subsequently used to perform qualification testing on devices for a high volume production program. A repeatable process for removal of BLD from "as-etched" arrays without moving or harming adjacent devices was established for sample removal on lots of purchased BLD. Special techniques were developed for failure analysis of BLD, including removal from circuit paths, probing loose chips for failure verification, mounting for metallurgical cross sectioning, and mounting for scanning electron microscope studies.

DISCUSSION

SCOPE AND PURPOSE

The objective of this process development project is to explore new testing, handling, and failure analysis techniques needed because of small device size and beam lead semiconductor fabrication technology.

The scope of this project included these items, some of which appeared as recommendations in a short term process development project.

- Establish beam lead device failure analysis techniques.
- Establish non-destructive test techniques for beam lead devices.
- Establish the capability to precondition devices.
- Define shipping methods for BLDs.
- Achieve accurate removal of BLDs from "as-etched" arrays.

PRIOR WORK

A short term process development project completed in September, 1970, in which initial studies of BLD handling and testing requirements were undertaken, established areas for future investigation. Some recommendations subsequently were incorporated into the project objectives. Areas specified for further investigation were a BLD handler capability, interfacing of tester and handler, high and low temperature non-destructive testing, developing substrates for life test, burn-in, and High Temperature Reverse Bias (HTRB) and manual test capability for BLDs.

ACTIVITY

Electrical Testing (Destructive and Preconditioning)

To evaluate BLD performance at environmental extremes, an oven door was constructed with front switching to contact any one of 56 devices. The devices were mounted to one-inch-square (2.54 cm) ceramic substrates with metalization patterns for six devices; each was then plugged into an edge connector wired to the switching arrangement. The wiring included Kelvin contacting (separate wires for sense and signal) from the switches to the test equipment, but not from the switches to the devices under test.

Fifty-four beam lead diodes and seventy-seven beam lead transistors were electrically tested at 25, -55, and 75°C with a Fairchild 600 tester and adapter. Contact resistances within the test adapter system in the non-Kelvin contacted portion caused two transistor tests and one diode test to consistently give readings over the normal limit. Since the readings agreed with each other, failure indications were based on the remaining tests.

Eight diodes failed to meet specification requirements in addition to forward voltage drop (V_F) because of system contact resistance. Seven of the eight diode failures were for reverse leakage current (I_R) higher than the 100 nanoampere limit. The readings for the diode leakage failures ranged between 123 nanoamps and 263 nanoamps. The leakage failures were caused by surface contamination on the device or the ceramic substrate.

One open circuit diode failure was recorded at 25 and -55°C, but operated normally at 75°C. Subsequent curve tracer testing of the "open" diode indicated that it was not open, but had a reverse leakage current (I_R) greater than 100 nanoamps. Inadequate thermocompression bonding of the beam leads to the palladium-gold thick film metallization pads was found to be causing intermittent contact between beam and metallization. Microscopic examination of the "open" diode revealed uneven "bugging"--that is, the bonding raised the chip more on one side than on the other. The open diode was visually identical to a transistor which had one open collector beam.

Eight transistors failed to meet specification requirements in addition to collector-emitter saturation voltage ($V_{CE\text{ Sat}}$) and base-emitter saturation voltage ($V_{BE\text{ Sat}}$), which were shifted to higher values because of contact resistances within the test adapter system.

Five of the transistor failures exhibited collector-base leakage currents ($ICBO$) in excess of the 100 nanoamp limit, and three of the five also showed very high collector-emitter leakage currents ($ICEO$); these failures were caused by surface contamination. The three additional transistor failures included two which gave open circuit indications and one which indicated a short circuit. Investigations into the three catastrophic transistor failures revealed the following.

- The shorted transistor exhibited normal performance characteristics when first tested for failure confirmation, but again exhibited short circuit indications on subsequent re-testing. The intermittent nature of this transistor failure suggests the existence of a conductive particle under the chip, or some crack or break between the beams and the chip.

- One of the transistors which indicated an open circuit was not observed to fail when confirmation of the failure was attempted. It is likely that poor contacting at some point within the test adapter system caused this failure.
- The second device which exhibited open circuit indications was verified as an open beam lead bond of one collector beam to the metallization pad. The beam was in such close proximity to the metallization pad that the open circuit could not be verified optically with absolute assurance. The beam lead had not, however, separated from the chip. This failure would not have occurred had the two collector beams been shorted together as is often the case. In this case, Kelvin contacting was being employed by using one collector lead for sense and the other for signal. Removal of either signal or sense from the Fairchild 600 is sufficient to give a failure indication.

Optical microscope inspection of the bonding pads, at a location where a transistor was missing, showed no indication of bonding--a prime reason that open bond indications were pursued. This is not an indictment of the bonding operation in general, but is rather an indication that bonding schedules may not be as easily defined for thick film metallization as are the bonding schedules for thin film chrome-gold metallization used more commonly at Bendix Kansas City.

Approximately 120 beam lead transistors and diodes were attached to TO-5 headers (Figure 1) fabricated at Bendix Kansas City. The devices were used to evaluate the individual transistor approach as opposed to the plug-in substrate which holds six devices. If acceptable, this method is better adaptable to proven test equipment fixturing and individual handling for special testing or failure analysis.

Nineteen beam lead 2N2222 transistors were tested. Two devices had defective bonds which apparently resulted from the ceramic wafer being mounted at a slight angle, causing more force to be applied to some beams during thermocompression wobble bonding.

Electrical test results at 25°C, -55°C, and 75°C were acceptable.

Seventy-four beam lead 2N2484 transistors (which experienced a much more significant problem during bonding) had twelve failures because of short circuits on either one or both junctions. Many of the functional devices also exhibited breakdown voltages below the specification limit of 60 volts by a range of 3 volts to 13 volts.

Twenty-seven beam lead 1N914 diodes were electrically tested at 25°C, -55°C, and 75°C. Most results were within specified limits, but three devices ex-

Figure 1. Beam Lead TO-5 Test Header

hibited open circuit readings on reverse junction measurements, and were similar to other devices on forward characteristics, which is indicative of erratic contacting. Most of the devices also exhibited forward voltage drops slightly greater than the 0.85 volts maximum allowed at 25°C, but fell within their specification limits at 75°C and -55°C.

With every type of device tested, difficulty was encountered in meeting very low limit leakage current requirements if any light fell on the back of the chip. This was overcome by using a fixtured oven door inserted in the oven, even for room temperature measurements. The difficulty remains during probing of unmounted devices; special precautions will be necessary when probe testing production quantities of beam lead devices.

The use of the TO-5 size ceramic header proved acceptable, and since it would plug directly into any TO-5 socket, the capability to perform device preconditioning was realized. The TO-5 test vehicle was used for sample HTRB testing of development device lots for and then as the vehicle for qualification testing for final "SA" types.

Device Handling and Non-Destructive Electrical Testing

As evaluation testing and failure analysis activities proceeded, it became apparent that a sophisticated approach to testing and handling was necessary. This necessity became obvious because of the extreme difficulty encountered in picking up, orienting, and positioning a discrete BLD chip.

The pickup tool, designed and completed early in the study, was made of machineable ceramic and was fired for hardening after machining. The tip has a square depression into which a BLD will fit, and a vacuum inlet hole, which runs through the center of the tool.

To precisely use the pickup tool, a tester-handler mechanism was designed (Figure 2) using a maximum of commercially available hardware items.

General operation was planned as follows.

- Beam lead devices are placed on a dice tray at Position 1 under the pickup tool.
- A beam lead device is aligned with the pickup tool using the mirror and a microscope (not shown).
- The mirror is then swung aside and the pickup tool lowered so that the vacuum will pickup the BLD.
- The pickup tool is raised slightly and the table is moved to the test position (Position 2).
- The pickup tool is lowered to the test pattern and the BLD is held with enough force to make good electrical contact. (The test pattern location is pre-aligned so that alignment is not needed after initial setup.)
- Electrical testing is done using accessory equipment.
- The BLD may be replaced in its original position by reversing these procedures.

This tester-handler was intended primarily for use as a non-destructive electrical test vehicle for this process development program. It was experimental and was intended as a model for improvement and change so that information gained from it might later be used to assist in specifying capital equipment.

A manually operated probe test station (Figure 3) was acquired for non-destructive electrical testing and failure analysis. The station uses pre-aligned probes on a printed circuit. The cards are aligned for precise simultaneous contacting of all probe tips to the four beams of a Format 25 beam lead device (Figure 4).

This station may be used with such existing test systems as curve tracers, Fairchild 500, and Fairchild 600. With the acquisition of probe cards for

Figure 2. Beam Lead Device Tester-Handler (Microscope not Shown)

Figure 3. Manual Probe Test Station With Card in Place

Figure 4. Probes Contacting Beams on Beam Lead Transistor

probing integrated circuits, the station will also be adaptable to the Fairchild 4000 and 5000 systems.

At first, it was difficult to test the devices with the manual station if the devices were not tightly bound to the carrier glass. Loose devices (held by Vaseline only) would move as the probe force was increased. Damage to the beams would result if care were not exercised. After some experimentation, however, a non-destructive sample test probe capability was established. The x-y stage and rotating vacuum chuck allowed positioning of any device for test.

Probe station testing proved sufficient, so the tester-handler was dropped from planning. This approach was taken because the cost of building the tester-handler appeared excessive.

Failure Analysis

Several beam lead transistors (TI 2N3829) in ceramic TO-5 cans which had experienced electrical failures were acquired for use in evolving failure analysis techniques and procedures. All of the devices on which initial work was done were shorted emitter to collector. Failure verification was carried out on the Tektronix 576 transistor curve tracer. Since the beam lead devices were in TO-5 cans, electrical contacting was no different from the conventional transistors now in use. There are, however, two factors which cause the BLD to differ considerably at this point.

- The semiconductor chip is bonded face down onto a minute printed circuit path. This rules out viewing the active face (including metallization) which is common among conventional transistors.
- Since BLDs will be used in hybrid microcircuits, failure verification will be required at the chip level.

In view of both of these points, after determining that there were no visible external short circuits, attention was focused on removing the BLDs from the headers. The small beam size dictated use of a microtool with a knife edge to sever the beams from the chip to facilitate removal. Thirty power magnification was used to view removal. This method proved marginally adequate, but should be considered destructive to the circuit path to which the BLD is bonded. BLD removal tools for circuit rework are available, and some measure of success in removal of BLD chips without breakage has been reported. The level of destruction is dependent upon the removal method, and one suggestion which offers great promise is a wobble bonding tool with very narrow walls which could be used in a beam lead bonder for controlled removal.

In this kind of testing, the BLD chip must now be handled and tested as a separate item. Reverification of the failure is necessary to determine if the device suffered damage during removal or if the chip is again "normal" -- that is, with a failure mechanism external to the chip.

The BLDs under analysis were probed using equipment then available. The probe tooling was not adequate for testing without risk of considerable damage, but two samples were successfully probed and were found to still have the same electrical characteristics as they had before removal. At least one sample was damaged by the probes past the point of meaningful analysis.

The BLDs successfully probed were subjected to angle cross-sectioning to determine the cause of the short circuits. To allow sectioning of so small a device, a small amount of epoxy was applied to the chip to increase its size for handling. This piece of epoxy was then potted in the larger lapping block. This worked quite well and should be a readily usable technique subject only to refinements.

The probe test station was required partially for failure analysis. Because BLDs are used in hybrid circuits, failure verification must be done on BLD chips. The failed BLDs will have been removed from substrates and will almost certainly have no beam lead extending beyond the chip edge. The necessity of "face up" probing to the anchor pad area is then evident. A probe card was acquired which allows probing to the anchor pad area. The anchor pad is an enlarged section of the beam lead which attaches the beam lead to the silicon chip. Figure 5 is a photo of the probe tips of the probe card contacting a "face up" BLD in the anchor pad areas.

Failure analysis of TI 2N3829 beam lead transistors continued with the refined probing equipment to evolve techniques for failure analysis. Efforts with additional devices having emitter-collector shorts again revealed the difficulty of removing the chip from the substrate intact. Only one of four removed could be further analysed. The metal was etched partly off with aqua regia. All gold was removed, but some of the platinum remained. Microscopic examination did not reveal the region of the short circuit, but further etching was not attempted. The device was then mounted in clear plastic potting compound for metallurgical cross-sectioning, which revealed a small region of burn-through from the emitter finger through to the collector region (Figure 6).

A method of mounting beam lead devices for visual inspection was devised: a thin layer of conductive epoxy was rolled onto the surface of a 3/8-inch-

Figure 5. Probes Contacting Anchor Pads on Beam Lead Transistor

square (1 cm) metal wafer, and then the beam lead devices were placed on the epoxy with a vacuum tweezer (Figure 7). A conductive medium was needed to make it easier to view the devices with the scanning electron microscope. Since this work was done, it was discovered that good results could be obtained by placing devices on a brass cylinder with a very small amount of Vaseline on the surface to hold the devices in place.

As Figure 8 shows, scanning electron microscope rendition was quite good. The light edge along the sides of the chip is where the silicon nitride lip extended past the silicon. This white is indicative of an insulating material as is expected from silicon nitride.

Scanning electron microscope inspection at 450X (Figure 9) revealed a region around a collector pad of a B2T2222 (SA2215-130) which had a fogged non-conductive appearance. Some peeling of the material can be seen in one area. A visual examination with a metallurgical microscope found unre-
 moved photo resist which showed up as green spots in the otherwise red oxide-nitride at the interface between the fogged and unfogged area.

A third device, B2T2907 (SA2217-130), was found to have a particle across the emitter-base junction which appeared non-conductive. An X-ray spectrographic inspection indicated the presence of gold, silver, and aluminum. The mass may have been from the conductive epoxy used for device mounting. The collector beam can be seen contacting the collector pad at the right of Figure 10. Note that the gold beam extends over the pad because of overplating.

Figure 6. Cross-Section of Beam Lead Transistor Showing Point of E-C Short

Figure 7. Metal Wafer 0.375-Inch Square (9.52 mm) With Four Beam Lead Devices Mounted for Viewing

Figure 8. Full View Scanning Electron Microscope (SEM) Photograph of B2T2484 (SA2211-130)

Excellent results were obtained here and have been obtained since on both optical presentations and X-ray spectrographic analysis from the scanning electron microscope. The SEM has shown its value as a failure analysis tool for beam lead devices.

Physical characteristics of beam lead devices such as beam hardness, beam thickness, and gold plating grain size were investigated by the Materials Test Lab. As expected, gold beam hardness testing proved impractical on hardness testing machines capable of no less than a 25 gram load such as is available in the Bendix Kansas City Quality Division test labs. In addition, the porosity and the gold plate grain size can affect results to a significant degree.

Special hardness testing equipment capable of loading the indenter with less than 10 grams is necessary to make measurements of hardness on the very small areas of pure gold found in the beams of beam lead devices measuring 0.003 by 0.005 inch (80 by 130 μm).

Gold grain size measurements fared somewhat better with some correlation between X-ray diffraction and optical microscopic measurements being obtained. Optical measurements found a grain size range from 0.15 mil (3.8 μm) to 0.4 mil (10.1 μm) and the X-ray diffraction showed an average grain size of approximately 0.4 mil.

Figure 9. B2T2222 (SA2215-130) SEM View of Contamination Around Collector Pad at 450X

Figure 10. B2T2907 (SA2217) SEM View of Foreign Particle and Metallization Paths at 600X

Beam thickness was checked by metallurgical cross sectioning and differential microscope focusing techniques. The cross sectioning method, while quite accurate, is very slow, as well as being a destructive test technique. Differential focusing is fairly rapid, non-destructive, and while not as accurate as cross sectioning is well within the presently set tolerances for beam thickness.

Shipping Methods

Major beam lead device manufacturers were visited to determine available methods of procuring devices. These methods were available from Texas Instruments and Motorola Semiconductor.

- Electrically and visually good devices are manually placed on glass discs and held in place by a silicone or organic grease coating.
- All devices, both good and reject, from the original silicon slice are held in place, face down, on a sapphire disc in a precisely spaced matrix. Electrical probe testing is performed by contacting the backs of the beam leads.

These methods were available from Raytheon Semiconductor.

- Electrically and visually good devices are manually placed on glass discs and held in place by a silicone grease coating.
- All devices, both good and reject, from the original silicon slice are held in place, face up, by a plaster of paris holding media, in a precisely spaced matrix. Electrical probe testing is performed by contacting the gold beam leads in the anchor pad region over the silicon die.

The shipment method offered by Texas Instruments and Motorola Semiconductor--a precisely spaced matrix of beam lead devices face down on sapphire--was deemed superior and met the requirements of PDO 6984765 (High Volume Probing System) while presenting the devices in a better system for further handling. Raytheon Semiconductor was requested to investigate the impact of modifying their system to be compatible with other available systems. Although they had special problems caused by the temperature required for separation etch, the problems were overcome sufficiently to adopt the face down "etch separated array" electrical testing and shipment method.

BLD Reprobe Study

The mechanical damage effects of reprobing beam lead devices were studied to determine the effect of repeated probing, so that a level of risk in reprobing might be established.

The material system, on which the supplier's initial electrical probe testing and the proposed reprobing is done, consists of beam lead devices face down on a sapphire or glass disc held firmly in place by an organic wax. Such an "etch separated array" composed of mechanical samples, procured from Texas Instruments, was used to conduct this evaluation. This array meets the requirements set forth in PDO 6984765 (High Volume Probing System).

The individual probes on the probe cards were characterized in grams of force per 0.001 inch of vertical displacement (Table 1).

The etch-separated oriented array was then probed systematically to include units probed 1, 2, 3, and 4 times and vertical displacement of probes of 0.001 through 0.005 inch (25.4 through 127 μm). Table 2 presents the test conditions applied to given quantities of devices.

Approximately 800 devices on the wafer were not included in the study because of previous probing for information purposes along one side of the chip and because an area devoid of gold beam plating fell across six rows along that same side. The devices devoid of gold plating would easily fall out in a visual inspection and were by-passed for convenience since punctures would be caused in probing. Figure 11 shows a device without gold plating following probing. As will be seen in subsequent photographs, no damage of this type occurs on properly plated devices.

Devices probed one time at 0.001 through 0.005 inch (25.4 through 127 μm) vertical probe displacement were not recorded on film since subsequent reprobes would show the results of both, and actual devices would always be probed once with minimal damage. The 0.001 inch vertical probe displacement samples showed such slight indentations that reprobes at that pressure were not investigated. The additional reason is that 0.001 inch of displacement is extremely difficult to control. Visual results of repeated probing presented here will be of samples probed 2, 3, and 4 times with probe displacements of 0.002, 0.003, 0.004, and 0.005 inch (50.8, 76.2, 101.6, and 127 μm). In all cases, the beam with the worst depression is picked to establish worst case damage conditions.

Table 1. Pre-Aligned Probe-Card Probe-Force Profile

Vertical Displacement (Inch)	Force (g)			
	Probe 1	Probe 2	Probe 3	Probe 4
0.001	2.8	2.8	2.7	2.8
0.002	4.4	4.9	4.8	4.5
0.003	6.6	7.2	7.0	6.2
0.004	8.0	8.9	8.8	7.9
0.005	9.8	10.2	10.5	9.6

Table 2. Device Reprobe Schedule

Times Probed	Displacement (Inches)(μ m)	Quantity Probed
1	0.001 (25.4)	55
1	0.005 (127)	111
1	0.004 (101.6)	114
1	0.003 (76.2)	114
1	0.002 (50.8)	57
2	0.005 (127)	114
2	0.004 (101.6)	114
2	0.003 (76.2)	57
2	0.002 (50.8)	114
3	0.005 (127)	111
3	0.004 (101.6)	110
3	0.003 (76.2)	106
3	0.002 (50.8)	103
4	0.005 (127)	99
4	0.004 (101.6)	93
4	0.003 (76.2)	96
4	0.002 (50.8)	80

Figure 11. Beam Lead Device Without Gold Beam Plating Showing Beam Punctures

The first condition is that of a device probed 2 times with 0.002 inch ($50.8 \mu\text{m}$) of overtravel (vertical probe displacement) as shown in Figure 12. Two separate scraped depressions may be seen, neither of which went through the platinum layer. This depicts what would probably be seen if both the supplier and buyer probed the array properly.

Samples probed 2 times at 0.003 inch ($76.2 \mu\text{m}$) overtravel were only slightly more indented than those probed at 0.002 inch ($50.8 \mu\text{m}$) with a small amount of gold showing through the platinum layer (Figure 13).

The devices probed 3 times did not show significantly greater mechanical damage when probed at 0.002 inch overtravel than did units probed 2 times. Devices probed 3 times at 0.003 inch overtravel, however, showed a greater degree of worst case damage than similar devices probed twice. Figure 14 shows a beam in which a small area of gold is visible through the platinum layer. This area is approximately 0.0008 by 0.0001 inch ($20.3 \mu\text{m}$ by $2.54 \mu\text{m}$). The better devices showed no gold through the platinum and looked little worse than devices probed twice at 0.002 inch overtravel.

Devices probed 3 times at 0.004 inch ($101.6 \mu\text{m}$) overtravel showed signs that the beams were bent in the process of probing, as shown by shadows present around the probe marks at low magnification.

Figure 12. Beam Lead Probed Twice With 0.002 Inch ($50.8 \mu\text{m}$) Overtravel

Figure 13. Beam Lead Probed Twice With 0.003 Inch ($76.2 \mu\text{m}$) Overtravel

Figure 15 is a view of the whole chip showing all four beams seen as a worst case of 3 times probed at 0.004 inch probe overtravel. Gold was revealed through the platinum in an area approximately 0.001 inch square ($25.4\ \mu\text{m}$) on one beam, which was as bad as was seen. The silicon nitride layer had been masked slightly off center causing the emitter beams to contact the nitride layer of the adjacent device, and resulting in nitride damage if the beam was probed at the very end. This off-center mask condition would not be acceptable on active devices.

The less severely damaged beams on other chips were still quite acceptable; the devices that sustained damage similar to Figure 15 were probably not in hard contact with the sapphire disc, but had a thin layer of wax between the beams and sapphire.

Figure 14. Beam Lead Probed Three Times With 0.003 Inch ($76.2\ \mu\text{m}$) Overtravel

Devices probed at 0.005 inch ($127\ \mu\text{m}$) overtravel all showed gold through the platinum layer, and many had slightly bent beams as seen with the 0.004 inch overtravel probed devices. Since devices probed at 0.004 inch or more overtravel sustained some beam degrading damage, further views of additional probings at high forces are not shown.

Devices probed 4 times at 0.003 inch ($76.2\ \mu\text{m}$) overtravel had beams which exhibited gold through the platinum layer, but none were bent or otherwise

Figure 15. Beam Lead Device Probed Three Times With 0.004 Inch (101.6 μ m) Overtravel

damaged to a degree which should interfere with bonding. Figure 16 shows a representative worst case beam. Only two of the four beams on the device were scraped deeply enough to reveal gold; the other two looked no worse than devices probed 2 times with 0.002 inch (50.8 μ m) overtravel.

Part of the damage sustained on some of the devices appears to have been caused by the devices not being tightly in contact with the sapphire disc. This comment is pertinent in that devices located in a different area of the wafer did not suffer such critical lead damage as those which were around the device shown in Figure 15.

The visual evidence obtained in the beam lead reprobe study, as applied to number of times reprobed and probe forces used, indicates a safe level for reprobing. Probe damage was acceptable until a probe overtravel of 0.004 inch was used. This overtravel represented individual forces of probes against beams of 8.0 grams, 8.9 grams, 8.8 grams, and 7.9 grams. The devices probed at 0.003 inch of overtravel, or about 1.8 grams less per beam, yielded acceptable levels of beam degradation even when probed four times. The conclusion of the study is that beam lead devices may be reprobed up to 3 times at probe forces of 6.1 grams or less without causing undue visual damage to the beams.

Figure 16. Beam Lead Probed Four Times With 0.003 Inch (76.2 μm) Overtravel

To determine if probe pressure affected contact resistance to a significant degree, measurements of contact resistance were made at 0.001, 0.002, 0.003, 0.004, and 0.005 inch (25.4, 50.8, 76.2, 101.6, and 127 μm) of probe overtravel.

The contact resistance of most beams went down as force was increased in three of four devices probed. The resistance seen when the probes contacted the platinum-titanium film on the backs of the beam leads appeared to be approximately 100 milliohms higher than when the probes directly contact gold. The maximum series resistance to be expected through two probes contacting the backs of the beams should be 500 milliohms with most values being near 350 milliohms.

Non-Disruptive Removal of BLDs From "As-Etched Arrays"

A study designed to determine the necessary equipment requirements for the removal of beam leaded devices from waxed-down, as-etched arrays was instituted. Required boundary conditions at the completion of this operation are that devices adjacent to those removed should not have been disturbed and the remaining array can be probed on automatic test equipment.

Initial attempts to achieve the desired removal were unsuccessful. They were made with a cold pickup tool (collet) lowered and raised by a pivoted arm controlled through a spring-loaded block and level assembly. A substrate heater held the array at a predetermined temperature, because devices could not be picked up at temperatures below the softening point of the wax-holding medium. Temperatures well in excess of that softening point were required to achieve device pickup. The pickup collet exhibited a serious problem in use, however; the tip would "walk" on the back of the device because of the single pivot arm motion.

The manual pickup machine's replacement was a K&S beam lead bonder. The reason for this decision was the stability of the tip, the collet heater, and the better control of all parameters.

Adequate temperature control in the desired range of 40 to 70°C (104 to 158°F) could not be maintained by the standard substrate heater accompanying the bonder. The table used in the manual pickup machine was modified to fit the K&S bonder, allowing temperature control of $\pm 3^\circ\text{C}$ (5°F), in a temperature range from 25 to 100°C (77 to 212°F).

Wax clogging the collet tip created a problem. A pressure valve was installed in the collet vacuum line so the collet vacuum could be turned on and off, while positive nitrogen pressure could be turned on and off independently. Excess wax could then be blown from the vacuum hole in the collet. For reliable pickup it was discovered that a short blast of nitrogen should be sent through the collet after each device removal.

A major problem in removing chips from an¹as-etched array is that of allowing air to replace the wax under the chip. Since the wax surface tension is relatively high, and the viscosity at the temperature considered is also high, the replacement of wax by air under the chip took more time than anticipated. In addition to a dwell time, it became apparent that pickup time--defined as the time from the start of lift until the chip is clear of the wax--was a critical variable. With the K&S bonder, pickup time was controlled by the manual operation of the pickup height adjustment. This causes some loss of tip stability but, with care, the sacrifice is not significant.

All temperature measurements were made with a fine wire [smaller than 30-mil (762 μm) wire] chromel-alumel thermocouple. An Omega-CJ temperature compensator and a Cimron digital voltmeter measured the thermocouple response, giving a very reliable collet temperature reading. All collet temperatures were taken with the vacuum and purge systems off.

A Teledyne TAC pickup machine was used later. This machine allowed rapid pickup and smooth operation, but it did not allow sufficient control of the variables.

A Teledyne TAC PS100 prober formed measurement reference in the non-disruptive portion of experimentation. This automatic prober used fixed probe cards with four probes.

Collet Geometry

Several kinds of tips were tried with the beam lead bonder. The first one used was 24 mils (609 μm) square with 6-mil (152 μm) walls. This tip was large enough to come into direct contact with the chip's beams, and the adjacent chips. Therefore, this variable was not considered important to non-disruptive-device removal, but rather served to give an idea of the variables required for chip removal with the substrate temperature below the softening point of the wax. Chips could be lifted with this 24-mils-square tip with the substrate temperature above and below the softening point of the wax. However, one problem was pointed up by this tip: because the tip came into contact with the beams, and because of the wax flow which then took place, it became difficult to release the chip after the vacuum was turned off. A low-pressure collet purging system was required to clear the chip from the end of the collet. The tip further suffered from severe wax clogging problems. It was deemed unsuitable.

The next tip, a used Format 25 bonding tip, was ground down to present a flat surface to the top of the chip. The tip edges were ground off to form a 19-mil (482 μm) outside diameter and contained a round 12-mil (304 μm) inside diameter vacuum hole. This tip made good physical contact with the top of the chip. The vacuum hole appeared to seal well. However, the tip did not seem to transfer heat efficiently to the beam leads when it rested on top of the chips. In fact, the majority of the heat transferred to the beam leads appeared to be by means of radiated energy. Lifting of the chips could be accomplished only by using long dwell times and slow lifting speeds. When the tip did lift, no problem was encountered in releasing the chip, nor was there any problem with the severe clogging experienced with the previous tip. It was thus concluded that these two problems were a result of the tip lying either in contact with, or in proximity to, the wax.

A round copper 19-mil tip was tried using approximately a half-second dwell time. This tip would lift chips only when the substrate was heated significantly above the softening point of the wax; it fell down over the edges of the chip, and failed to make a good vacuum seal (one of the most important variables).

A round copper 16-mil (406 μm) tip was then made to provide a better fit. This tip also fell down over the sides of the chip; however, it did make a much better vacuum seal. The vacuum hole was 10-mils (254 μm) inside diameter.

When this tip was tried at a five- to nine-second pickup time, pickup was achieved at substrate temperatures substantially below the softening point of the wax. Although the vacuum force was less than optimum because of lack of contact with this tip, devices were removed. A preliminary test of variables was made (Figure 17).

At this point the following conclusions were drawn:

- To lift a chip, the wax under the beams must be melted;
- By allowing the tip to contact only the back of the chip, little heat is conducted to the beam leads;
- With the larger tips, radiated heat warms the beams and melts the wax under the beam leads; and
- To insure easy removal of the chips from the collet, contact between the collet and wax should not be allowed.

A Format 25 bonding tip was ground down to a wall thickness of 1 mil ($25.4\ \mu\text{m}$) and a depth of 0.2 mils ($5.1\ \mu\text{m}$). The interior walls sloped at approximately a 45° angle to an interior vacuum hole of 12-mil ($305\ \mu\text{m}$) diameter. This tip promised to combine the advantages of low vacuum leakage, good radiation of heat to the beams, avoidance of contact with the beams or the nitride lip, and fine enough not to disturb adjacent chips.

Inspection of the tool showed the interior walls were too irregular to provide the desired vacuum seal. It was found that pickup could be accomplished on about 90 percent of the attempts on the previously mentioned array. However, the lifting force seemed to be too low to provide good reliability.

A new set of four tips was designed. These tips were square with various inside diameter vacuum holes, various outside diameters, and various depths of inside cavity. Figure 18 and Table 3 show a cross section of such a tip and the dimensions varied.

With these tips, pickup was attempted on a new array. Pickup appeared much smoother and much easier than previously experienced. Tip 2 appeared to work the most reliably, and still not injure the nitride lip. A test of variables with this tip, however, followed very closely to Figure 17. Because of the drastic change made in tip geometry, these results were viewed with some surprise. A re-check of parameters with the four newly-designed tips showed only a slight difference in any parameter measurement from the flat tip parameter measurements shown in Figure 18. This difference was so slight as to fall easily into the range of error of measurement.

Figure 17. Effect of Substrate Temperature on Pickup Success

Figure 18. Collect Tip Dimensions

Table 3. Collet Tip Dimensions

	A		B		C	
	<u>Inches</u>	<u>μm</u>	<u>Inches</u>	<u>μm</u>	<u>Inches</u>	<u>μm</u>
Tip 1	0.0021	533	0.016	406	0.016	406
Tip 2	0.0015	381	0.016	406	0.020	508
Tip 3	0.0015	381	0.012	305	0.016	406
Tip 4	0.0021	533	0.022	559	0.022	559

It was known at this time that the Teledyne TAC pick and place machine had difficulty operating below a temperature of 75°C (167°F) on the substrate. An investigation into the difference between the Teledyne method of pickup and the method used on the modified K&S bonder revealed that the significant difference lay in the timing and sequence of operations.

With the K&S bonder this was the sequence of operation:

1. Position the chip under the collet.
2. Lower the collet to contact the chip.
3. Turn on the vacuum.
4. Raise the chip.
5. Transport the chip to the receiving dish.
6. Set the chip down.
7. Release the vacuum.
8. Raise the collet.
9. Purge the system with a short blast of air or nitrogen.
10. Position another chip under the collet.

Using this sequence of operations with the K&S bonder and the square tip, pickup was accomplished on a new as-etched array of Format 25 devices. The substrate temperature for reliable pickup, a 90 percent success on the second try, was 51 to 58°C (124 to 136°F). A collet temperature of 190 to 200°C (374 to 392°F) was used. Pickup time was approximately six seconds. Increasing the table temperature to 55 to 60°C (131 to 140°F) made pickup all but a certainty using the same collet temperature. Collet temperature was lowered to 160 to 180°C (320 to 356°F) and approximately 5 percent of the attempted removals were successful.

The table temperature was lowered to 46 to 50°C (115 to 122°F). Approximately 20 percent of the devices attempted were removed. Collet temperature was 190 to 200°C (374 to 392°F). At any table temperature below this, essentially no devices were removed (Figure 19).

It would thus seem that this area would be an optimum operation region. The tip is not hot enough to cause damage to the devices, and the substrate may be kept at low enough temperatures to prevent the binding wax from flowing.

Using the above optimum temperature setting [substrate at 55 to 60°C (131 to 140°F) and collet at 190 to 200°C(374 to 392°F)], a grouping of eight devices

Figure 19. Effect of Substrate Temperature on Pickup Success-- Second Attempt

were removed about a single chip (Figure 20). Lowering the substrate to the temperature range of 51 to 58°C (124 to 136°F) a second square of eight devices was removed about a single chip (Figure 21).

Teledyne's sequence of operations differ in that Step 9, in the previous operation sequence, is not accomplished with a short blast, but rather a continuous blast of nitrogen from the time the chip is released until the collet moves to drop onto the chip. At this time, the purge goes off and the vacuum comes on immediately.

The effect of the altered sequence is that air, or nitrogen, is constantly traveling through the collet cooling it. As the collet is dropped to the back of the chip, the rush of air around the chip cools the chip and the binding wax. This results in a reverse effect on chip removal.

To test this theory, an array of Format 25 devices was taken to the Teledyne TAC unit. Using the standard collet and a cylindrical flat bottomed tip, pickup was accomplished at a substrate temperature of 74°C to 76.5°C (165 to 170°F) and collet temperature in excess of 220°C (428°F) with no air flow through the collet. Pickup time was six seconds. Such a pattern is shown in Figure 10.

The nitrogen purge system was then manually operated such that it would only turn on for a short blast. The vacuum pump was manually switched on and off to provide vacuum only after the collet had been manually set down on the chip's back. With these modifications, the Teledyne machine removed devices from an array with a 90 percent reliability on second try at 55 to 60°C (131 to 140°F).

No effort was made to take extensive data using this system, because the number of manual operations needed to complete each device removal made it prohibitive. A grouping of four devices, however, was removed about a single device in a diamond pattern (Figure 22). It should be noted that the binding wax in Figure 22 still maintains the pattern of the device. It was not hot enough to flow back sufficiently to eliminate a clearly defined pattern. The close-up in Figure 22 shows the imprint of the front side metallization in the wax pattern. No such pattern is seen in Figure 28, which means the wax shown in Figure 28 was hot enough to tend to flow back to a smooth surface.

Device Removal

To show that devices could successfully be removed from as-etched arrays without disturbing adjacent devices, the Teledyne TAC pick and place machine was used in the normal operational mode. This provided easy removal of a large number of devices in selected patterns. Although this is not

Figure 20. Beam Lead Devices Removed About a Single Chip, With Substrate Temperature 55 to 60°C

Figure 21. Beam Lead Devices Removed About a Single Chip, With Substrate Temperature 51 to 58°C

the optimum removal method, if the adjacent devices are not disturbed by removal with this mechanism, then certainly they would not be disturbed at even lower substrate temperatures.

An array from which devices had been picked several times was used to determine the limiting variables. A cylindrical tip of 30 mils ($762\ \mu\text{m}$) diameter, a 14-mil ($356\ \mu\text{m}$) inside diameter (vacuum hole) and a flat bottom was used. This tip traveled down to within 1 mil ($25.4\ \mu\text{m}$) of the back of the chip, then lifted.

Figure 22. Beam Lead Devices (Left) and Close-up of Wax Pattern (Right) Removed Using a Teledyne TAC Pick And Place Machine, With Substrate Temperature 55 to 60°C

With all air flow off, the collet measured 220°C (428°F) minimum. A minimum setting was maintained. A vacuum of approximately 20 inches (67.7 kPa) of mercury was used. Pickup was first accomplished with the substrate at 73.6 to 75.6°C (164 to 168.1°F). At this temperature pickup proved reliable. Pickup time was varied from about 4 to 10 seconds to allow pickup. This set of variables has been determined to be the lowest settings, or the least disruptive settings, and still allow for reliable die removal.

A new as-etched array of Format 25 devices was probed with a Teledyne TAC PS100 automatic probing machine. This machine used a probe card with one probe per beam. After probing, the prober was removed from service to avoid a change in the machine setup.

The array was taken to the Teledyne TAC pick and place machine and set up to remove devices. The substrate temperature was started 10°C (18°F) below that at which pickup had been accomplished on the previous array [62°C (144°F)]. Collet temperature was maintained at a minimum [220°C (428°F)]. Slowly the table temperature was raised until devices could be removed. This temperature was 74 to 76.5°C (165 to 170°F). It should be noted here that this is similar to the reading found for the array used previously for set up, that had been heated several times.

If a device could not be removed on the first attempt, another attempt was made to remove it, using a longer pickup time. This would be repeated until the device was removed. Therefore, pickup times varied from four seconds to nine seconds.

Approximately 85 percent of the devices were removed by the second attempt. If a second attempt failed, very often it took up to 12 attempts to remove the devices. A number of these types of devices (Figure 23) were left in the setup area of the wafer to provide a sample for analysis of this problem.

Figure 23. Device Not Removed After Twelve Attempts

For comparison, an adjacent device was also photographed (Figure 24). It can only be assumed that Figure 24 represents those devices that will be easily removed. A measurement of the backside width of the device shown in Figure 23 at the narrowest point is 12.7 mils (323 μm). The length at the narrowest point is 13.4 mils (340 μm). The backside width of the device in Figure 24 at the narrowest point is 14.5 mils (368 μm). The backside length at the narrowest point is 13.9 mils (353 μm). From this it is concluded that if the backside dimensions allow a larger than normal flow of air about the chip, device removal becomes increasingly difficult. This excess air flow causes a loss of lifting force and introduces additional cooling. This effect was discussed in the section on collet geometry.

Figure 24. Beam Lead Device Assumed Removable By Use of Proper Technique

The wafer was subdivided into areas shown in Figure 25.

From the free area more than 190 devices were removed. The removal was done in the following order:

- Two rows of every other device, separated by two rows;
- One row of every device, four rows away from the preceeding step;

Figure 25. Experimental Wafer Subdivision for Study

- Four patterns of four devices about a single device in a diamond shape, three rows over from the preceding step;
- One pattern of eight devices about a single device, on the same rows as the preceding step; and
- One row of every other device, one row over from the preceding step.

This represented what should be considered a worst case in an automatic pickup mode. Figure 26 shows portions of the second, third and fifth steps.

At two points in removing the solid row described in Step 2, the pick and place machine had a mechanical jump. At these points the collet came down too far and shifted to the side, displacing three devices (Figure 26) later removed. This is not a part of the experiment.

In removing the eight devices described in Step 4, one device was extremely difficult to remove. It took more than twelve attempts to remove it. This represents a worst possible case, and one which would never have been seen with automatic machines. At no time during device removal would such a pattern of eight devices be removed consecutively from these three rows. The succession of eight devices about a single chip removed successively, with one chip requiring in excess of 12 successive attempts, would be in excess of worst case. This pattern is shown in Figure 27.

Figure 26. Three Patterns of Removal Using Teledyne TAC Pick-And-Place Machine

The row of every other device described in Step 5 is shown at a closer view in Figure 28.

This array was then taken back to the Teledyne TAC prober and, using the same setup as previously used, adjusting only the Z, X, and theta adjustments, the wafer was reprobbed.

Figure 29 now shows the center area of the wafer. No gross drifts may be seen in this photograph, and two probe marks are visible on a number of beams (two probe marks are present on all beams, but not visible in the photograph).

One device, found in the pattern described in Step 4, failed to be reproducible with the automatic machine. Beam Number 3 of the center device was merely grazed by the probe. Good electrical contact was not made.

Selected devices in the array were measured to determine the amount of drift caused by the pick and place operation. After correction for probe alignment error, device drift was found to be between 0.00 mil and 0.82 mil ($20.83 \mu\text{m}$) with an experimental accuracy of approximately 0.1 mil ($2.54 \mu\text{m}$) as shown in Appendix A, less than one-third the width of a beam lead in the worst case and, on the average, less than one-tenth the width of a beam lead. The non-disruptive removal of beam lead devices from an as-etched array proved feasible with the conditions stated, and has since been shown to be reproducible on a production program.

Figure 27. Pattern of Eight Devices About a Single Chip

Figure 28. Pattern of Every Other Device Removed

Figure 29. Center of Experimental Wafer

ACCOMPLISHMENTS

A safe level of probe force, as well as the maximum number of allowed reprobes, was established for BLD as-etched arrays.

Investigations proved BLDs must be tested in the dark because light induces current leakage.

A BLD removal method was established for failure analysis.

A way to best remove BLD samples non-destructively was found for manual and automatic pick and place machines.

A shipping method meeting PDO 6984765 requirements was obtained from all prospective BLD suppliers.

Test substrates were created for environmental testing and pre-conditioning, and were later used for qualification testing of multicode coded switch BLDs.

A non-destructive, manual (low volume) BLD probe contactor for electrical testing was defined and procured.

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Appendix A

DRIFT MEASUREMENT METHOD

Drift can be measured on the devices remaining after the systematic removal sequence. With eight rows of undisturbed devices, and two probe marks on each beam, a differential measurement may be set up using the coordinate system shown in Figure A-1. Two beams 90° to each other may be measured at a given device. Using the device beside the proper reference mark (A in Figure A-1), and another device on the opposite side of the wafer, a reference measurement may be made of the error in re-orienting the prober. The devices are oriented by coordinates defined in Figure A-2.

Figure A-1. Definition of Wafer Coordinate System

Two measurements were made per device, on beams marked 1 and 2 in Figure A-2. These measurements will provide the required Δx and Δy information (Figures A-3 through A-6).

Figure A-2. Definition of Device Coordinate System

Measuring Δx and Δy normalized to the beam width

Chip Designation	x (Inch) (mm)	y (Inch) (mm)	x Normalized (mil) (μm)	y Normalized (mil) (μm)
A	0.187 (4.76)	0.312 (7.93)	0.315 (8)	0.525 (13.34)
B	0.125 (3.175)	0.437 (11.11)	0.210 (5.3)	0.735 (18.67)
Difference			0.105 (2.67)	0.210 (5.33)

The total radius from the center of the wafer to device A or device B is 0.75 inch (19 mm), and devices A and B may be described as being equally 25° off the -y axis as shown in Figure A-1. Linear drift $\phi = \Delta x / \sin 25^\circ$. If the Δx normalized is considered a shift in probe patterns and a ϕ component, then (Δx normalized difference / 2) is the Δx in the above formula. From arc length measurements (assuming the linear drift is small compared to the arc length)

$$\frac{\Delta s}{r} = A^\circ / 180$$

where r is the radius of the arc, Δs is the arc length difference, and A is the angle difference. Therefore,

Figure A-3. X Drift at Approximately $X=90$, $Y=100$ (AX); Y Drift at Approximately $X=90$, $Y=100$ (AY)

Figure A-4. X Drift at Approximately $X=150$, $Y=100$ (AX); Y Drift at Approximately $X=150$, $Y=100$ (AY)

Figure A-5. X and Y Drift at the Midpoint of the Center Alternating Row

Figure A-6. X and Y Drift Beside the Center of the Solid Row Removed

$$180 (\Delta x / \sin 25^\circ) / \pi r = A$$

$$(180) (53 \times 10^{-6} / \sin 25^\circ) / \pi 0.75 = A$$

$$A = .4'$$

$$\begin{array}{r} \text{Then the x shift is } 0.315 \text{ (8 } \mu\text{m)} \\ \quad \quad \quad -0.053 \text{ (1.35 } \mu\text{m)} \\ \hline \quad \quad \quad 0.262 \text{ mil (6.65 } \mu\text{m)} \end{array}$$

$$\begin{array}{r} \text{and the y shift is } 0.735 \text{ (18.67 } \mu\text{m)} \\ \quad \quad \quad -0.105 \text{ (2.67 } \mu\text{m)} \\ \hline \quad \quad \quad 0.630 \text{ mil (16 } \mu\text{m)} \end{array}$$

Using similar calculations on the x axis, it is found that $\phi = 0^\circ 4'$

$$x = 0.25 \text{ mil (6.35 } \mu\text{m)}$$

$$y = 0.62 \text{ mil (15.75 } \mu\text{m)}$$

Hence, the calculation appears reasonable.

With this information at hand and the formula for translation and rotation of axis

$$x^1 = (x-h) \cos \theta + (y-k) \sin \theta$$

$$y^1 = (y-k) \cos \theta - (x-h) \sin \theta$$

$$\sin 4' = 0.000116$$

$$k = \Delta y = 0.63 \text{ mil (16 } \mu\text{m)}$$

$$\cos 4' = 1.0000$$

$$h = \Delta x = 0.26 \text{ mil (6.60 } \mu\text{m)}$$

Checking on four positions:

- Center of the center alternating row which is essentially the center of the wafer.
- Center beside the solid row, at $x = 0$ and $y = 0.25 \text{ inch (6.35 mm)}$.

- Four removed at 1 device, at $x = 0$ and $y = 0.125$ inch (3.17 mm).
- Eight devices removed about center device, at $x = 0.50$ inch (12.7 mm) and $y = 0.125$ inch (3.17 mm).

Figure A-7. X and Y Drift of Device With
Four Adjacent Devices Removed

Center of Center Alternating Row ($x = 0$, $y = 0$)

Using Beam 1 (Figure A-7), if the beam width is 3 mils ($76.2 \mu\text{m}$), a scale of 1.75 inch (44 mm) = 3 mils ($76 \mu\text{m}$) exists for the photograph. In this picture

$x' = 0.0625$ inch and $x = 0.105$ mil ($2.67 \mu\text{m}$)

$y' = 0.3125$ inch and $y = 0.525$ mil ($13.34 \mu\text{m}$)

Since this is at the center of the wafer any variation would only affect the x on this beam. This variation would be:

$x = (10 \text{ mils}) \sin 4' = (10 \text{ mils}) (0.000116) = 0.00116 \text{ mil} (29.4 \text{ nm})$

or essentially no variation at all.

Looking back at the previously derived numbers:

$$\text{drift}_x = \frac{0.315 \text{ mil } (8 \mu\text{m})}{+0.105 \text{ mil } (2.67 \mu\text{m})} = 0.420 \text{ mil } (10.67 \mu\text{m})$$

$$\text{drift}_y = \frac{0.630 \text{ mil } (16 \mu\text{m})}{-0.525 \text{ mil } (13.35 \mu\text{m})} = 0.105 \text{ mil } (2.67 \mu\text{m})$$

Figure A-8. X and Y Drift of Device With
Eight Adjacent Devices Removed

Looking at Beam 2 (Figure A-8), assuming the same beam width and proceeding in the same manner:

- $\Delta y' = 0.3125 \text{ inch } (7.94 \text{ mm})$
- $\Delta x' = 0.1250 \text{ inch } (3.175 \text{ mm})$
- $\Delta y = 0.536 \text{ mil } (13.61 \mu\text{m})$
- $\Delta x = 0.214 \text{ mil } (5.44 \mu\text{m})$

- $x \text{ drift} = 0.094 \text{ mil } (2.38 \mu\text{m})$

- $y \text{ drift} = 0.048 \text{ mil } (1.22 \mu\text{m})$

Center Beside the Solid Row [$x = 0$, $y = -1/4''$ (6.35 mm)]

For Beam 1 (Figure A-9), these are the results:

Figure A-9. Y Drift Beside the Center of the Solid Row Removed

- $\Delta y' = 0.25 \text{ inch } (6.35 \text{ mm})$

- $\Delta x' = 0.125 \text{ inch } (3.175 \text{ mm})$

- $\Delta y = 0.43 \text{ mil } (10.92 \mu\text{m})$

- $\Delta x = 0.21 \text{ mil } (5.33 \mu\text{m})$

- $y \text{ drift} = 0.20 \text{ mil } (5.08 \mu\text{m})$

- $x \text{ drift} = 0.05 \text{ mil } (1.27 \mu\text{m})$

For Beam 2 (Figure A-10), these are the results:

Figure A-10. X Drift Beside the Center of the Solid Row Removed

- $\Delta y' = 0.3125$ inch (7.94 mm)
- $\Delta x' = 0.0312$ inch (0.79 mm)
- $\Delta y = 0.53$ mil (13.46 μm)
- $\Delta x = 0.053$ mil (1.35 μm)
- y drift = 0.10 mil (2.54 μm)
- x drift = 0.21 mil (5.33 μm)

But these numbers have not been θ corrected. For both beams θ correction amounts to a Δx correction,

$$\theta_x = (1/4)(\sin 4') = (0.25)(0.000116) = 0.000029 \text{ inches}$$

or

$$= 0.029 \text{ mils (0.725 } \mu\text{m)}$$

therefore,

	drift _x	drift _y
Beam 1	0.02 mil (0.5 μm)	0.17 mil (4.25 μm)
Beam 2	0.18 mil (4.5 μm)	0.07 mil (1.75 μm)

Four About One Device [$x = 0$, $y = 0.125$ inch (3.17 mm)]

Beams 1 and 2 are shown in Figures A-11 and A-12.

Figure A-11. Y Drift of Device With Four Adjacent Devices Removed

Again the θ correction need only be made in the Δx number:

$$\begin{aligned}\theta_x &= (1/8) \sin 4' = (0.125) (0.000116) = 0.0000145 \text{ inch (362 nm)} \\ &= 0.0145 \text{ mil} = 0.01 (0.36 \mu\text{m})\end{aligned}$$

For Beam 1, these are the results, corrected for θ :

- $\Delta x' = 0.0625$ inch (1.59 mm)
- $\Delta y' = 0.3125$ inch (7.93 mm)

Figure A-12. X Drift of Device With Four Adjacent Devices Removed

- $\Delta x = 0.105 \text{ mil } (2.69 \mu\text{m})$
- $\Delta y = 0.53 \text{ mil } (13.92 \mu\text{m})$
- $x \text{ drift} = 0.36 \text{ mil } (9.14 \mu\text{m})$
- $y \text{ drift} = 0.09 \text{ mil } (2.29 \mu\text{m})$

For Beam 2, these are the results, corrected for θ :

- $\Delta x' = 0.125 \text{ inch } (3.175 \text{ mm})$
- $\Delta y' = 0.375 \text{ inch } (9.53 \text{ mm})$
- $\Delta x = 0.21 \text{ mil } (5.33 \mu\text{m})$
- $\Delta y = 0.63 \text{ mil } (16 \mu\text{m})$
- $x \text{ drift} = 0.04 \text{ mil } (1.02 \mu\text{m})$
- $y \text{ drift} = 0 \text{ mil } (0 \mu\text{m})$

Eight About a Single Device [$x = 0.5$ inch (12.7 mm) and $Y = 0.125$ inch (3.17 mm)]

Beams 1 and 2 are shown below in Figures A-13 and A-14.

For Beam 1, these are the results:

- $\Delta x' = 0.25$ inch (6.35 mm)
- $\Delta y' = 0.281$ inch (7.14 mm)

Figure A-13. Y Drift of Device With Eight Adjacent Devices Removed

- $\Delta x = 0.43$ mil (10.98 μm)
- $\Delta y = 0.48$ mil (12.19 μm)
- x drift = 0.69 mil (17.52 μm)
- y drift = 0.15 mil (3.81 μm)

Figure A-14. X Drift of Device With Eight Adjacent Devices Removed

For Beam 2, these are the results:

- $\Delta x' = 0.50$ inch (12.7 mm)
- $\Delta y' = 0.125$ inch (3.175 mm)
- $\Delta x = 0.84$ mil (21.37 μm)
- $\Delta y = 0.21$ mil (5.33 μm)
- x drift = 1.1 mil (27.94 μm)
- y drift = 0.42 mil (10.67 μm)

In this case the influence of a θ rotation is not as clearly defined. The angle between a line from the device to the origin and the y axis is:

$$\phi = \tan^{-1} \frac{x}{y} = \tan^{-1} \frac{1/2}{1/8} = \tan^{-1} 4 = 76^\circ$$

The radius of the polar coordinate is: $[(1/2)^2 + (1/8)^2]^{1/2} = (1/2)$

The length of a chord subtending an angle θ is: $= 2r \sin 1/2\theta$

The x component of this chord is:

$$= (2 r \sin 1/2\theta) \cos 14^\circ$$

The y component of this chord is:

$$= (2 r \sin 1/2\theta) \sin 14^\circ$$

$$\theta_x = [(2) (1/2) (0.00029)] (0.97) = 0.00028 \text{ or } 0.28 \text{ mils } (7.11 \mu\text{m})$$

$$\theta_y = [(2) (1/2) (0.00029)] (0.24) = 0.0000695 = 0.00007 \text{ or } 0.07 \text{ mil } (1.78 \mu\text{m})$$

Putting these correction factors in:

	Drift _x	Drift _y
Beam 1	0.41 mil (10.41 μm)	0.07 mil (1.78 μm)
Beam 2	0.82 mil (20.82 μm)	0.35 mil (8.89 μm)

Summary of Measurement

No greater accuracy than 0.1-mil (2.54 μm) may be assumed for any final calculation. Looking at the drift terms now available:

	Drift _x Beam 1 (mil) (μm)	Drift _y Beam 1 (mil) (μm)	Drift _x Beam 2 (mil) (μm)	Drift _y Beam 2 (mil) (μm)
Test 1	0.41 (10.41)	0.105 (2.67)	0.048 (1.22)	0.094 (2.39)
Test 2	0.02 (0.508)	0.17 (4.32)	0.18 (4.57)	0.07 (1.78)
Test 3	0.36 (9.14)	0.09 (2.29)	0.04 (1.02)	0.00 (0)
Test 4	0.41 (10.41)	0.07 (1.78)	0.82 (20.83)	0.35 (8.89)

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