NBS TECHNICAL NOTE 785

Scanning Electron Microscope Examination of Wire Bonds from High-Reliability Devices

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Kathryn O. Leedy

Electronic Technology Division
Institute for Applied Technology
National Bureau of Standards
Washington, D.C. 20234

U.S. DEPARTMENT OF COMMERCE, Frederick B. Dent, *Secretary*
NATIONAL BUREAU OF STANDARDS, Richard W. Roberts, *Director*

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K. O. Leedy

ABSTRACT

An examination with a scanning electron microscope was made of the wire bonds of over 75 high-reliability microelectronic devices. The device interconnects were ultrasonically bonded aluminum wires. Of primary interest were the bonds themselves; their appearance and its significance are described. Also described is the appearance of the metallization and the wire. Comments and explanations are given where the phenomena are understood. Although the devices studied had passed preliminary electrical tests and pre-encapsulation visual examinations, many potential reliability problems were identified such as weak bonds, electrical shorts and contamination.

Key Words: Aluminum wire; high reliability; integrated circuit; metallization; scanning electron microscope; transistor; ultrasonic bonding; wire bonding.

SCANNING ELECTRON MICROSCOPE EXAMINATION OF WIRE BONDS FROM HIGH-RELIABILITY DEVICES

K. O. Leedy

1. INTRODUCTION

Wire bonds in a variety of integrated circuits and transistors from production lines dedicated to the production of high-reliability devices were examined with a scanning electron microscope (SEM). The study was undertaken initially to observe differences in appearance of bonds produced by 14 supposedly identical ultrasonic bonding machines on three controlled production lines. Subsequently, many devices from other high-reliability production lines were examined and found to have similar characteristics.

A variety of the commonly used package types and many different circuit types were represented among the more than 75 devices examined. All devices were ultrasonically bonded with 0.001-in. (25-μm) diameter, 99-percent aluminum 1-percent silicon wire. The bonding pads were metallized with aluminum while the package leads had either aluminum or gold metallization. The devices examined had all passed preliminary electrical tests and pre-encapsulation visual examinations but were removed from the production lines before they were capped, sealed, or environmentally tested. Each of the devices examined would probably have functioned as intended in the final tests if allowed to continue down the production line.

Although this examination was not a study of failed devices, many potential reliability problems were observed. Comments and explanations are given where the phenomena are understood; in other areas the observations are merely reported. In addition, even though the study primarily centered on wire bonding, several other device defects were observed; these are illustrated in the last section of the report.

Of the several hundred SEM photographs made, the examples shown were selected to be indicative of particular faults. It is not intended to suggest that the faults illustrated are unique to a particular device type, production line, or circuit configuration. In fact, most of the faults were observed to some extent in all types of the devices investigated.

2. BACKGROUND

In order to obtain perspective of the problem and to define some terms, let us look first at the devices and see why the wire bond is important. In Figure 1 are shown an integrated circuit (a) and a transistor (b) representative of the device types studied. Wire bonds are made to connect the bonding pad on the circuit chip electrically to the external lead: a post or finger of the package in which the chip is held. The welded interface between the wire and the pad, post, or finger, under the flattened areas at the ends of the wire, are the bonds. The bond which is made first is called the first bond. The second bond then completes the bond loop. The weld is formed by the combination of a force applied by the bonding tool on the wire and by the application of ultrasonic vibration of the tool in the direction parallel to the wire axis.* The welding that occurs at the wire-metallization interface can be seen in Figure 2 which shows the lift-off pattern of a partially removed bond which was made under laboratory conditions. A similar pattern can be seen on both the pad and the wire. The center portion of the wire-metallization interface is not welded.

Figure 3 shows a schematic illustration of the bonding operation. The wire is fed through a hole in the tool and passes under the foot of the tool. The foot is the part of the tool that exerts a static force on the wire during the bonding process. The front edge of the foot is rounded to prevent damage to the wire, but the back edge is sharp to facilitate the cut-off of the wire after the second bond is produced.

There are many differences in appearance and in structure between the first and second bonds. Some of these may be seen in Figure 4 where the first bond is shown in (a) and the second bond in (b). The most obvious difference between the two bonds in the figure is in the shape of the toe or free end of the bonding wire. The second bond exhibits evidence of the cut-off operation which occurred after it was made. The first bond shows the tail, the unflattened portion of the free end of the wire which extended beyond the foot during bonding. A more important difference is in the heel of the bond, the juncture between the undeformed wire and the bonded portion. The sharp heel of the tool, which provides for cut-off at the second bond, causes an indentation or crack. in the heel of the first bond. This will be discussed in more detail below. In most of the devices examined, the first bond was made on the external lead (a post) and the second was on the pad. This accounts for the different appearances of the metallization in Figures 4a and 4b.

3. BOND APPEARANCE

A comparison of the devices showed significant differences in bond appearance. Bonds differ mainly in the amount of deformation of the

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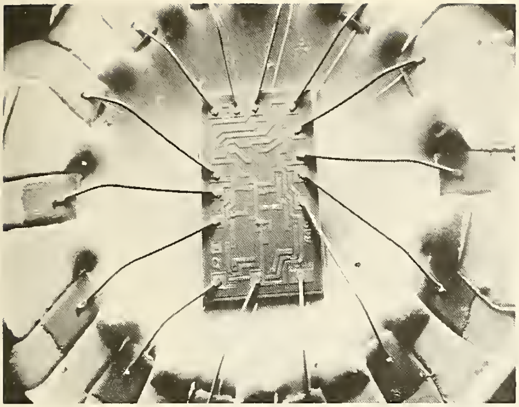
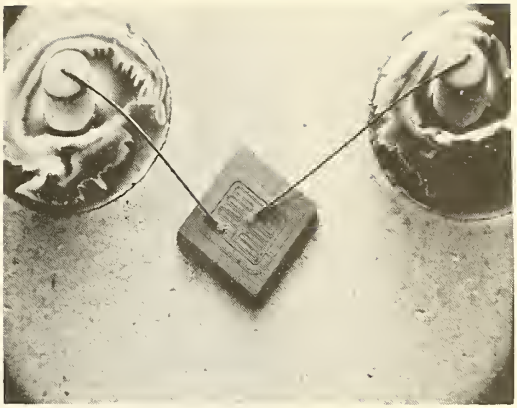
*All bonds examined in this study were formed ultrasonically. However ultrasonic bonding is not the only wire bonding technique. The other common wire bonding technique is thermocompression bonding, which combines pressure and heat to form the weld. It is used primarily with gold wire and, in some special cases, aluminum wire. In addition there are other techniques for making interconnections such as flip-chip and beam-lead bonding which do not include the use of wires.



a Magnification: 22X



b Magnification: 22X

Figure 1. Typical devices examined. An integrated circuit is shown in (a) and a transistor in (b).

Magnification: 540X

Figure 2. The lift-off pattern of a partially removed bond made under laboratory conditions. A similar pattern can be observed on both the wire and the pad. The center portion of the wire-metallization interface was not welded.

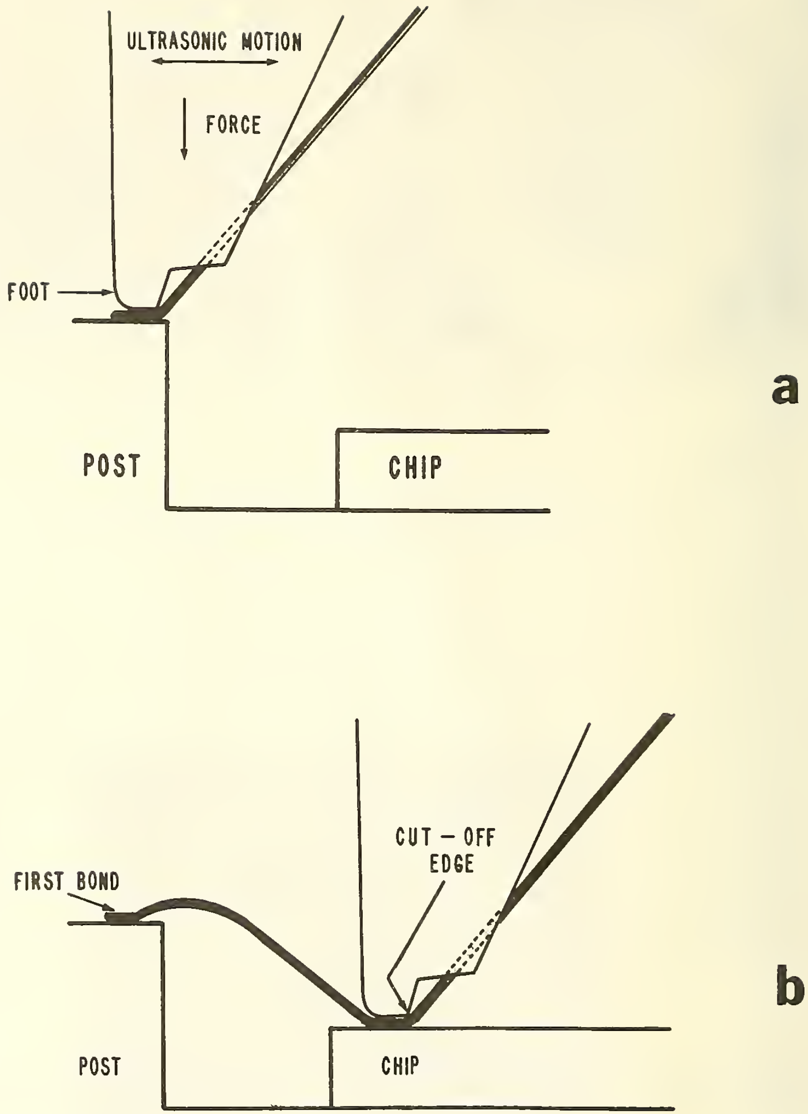
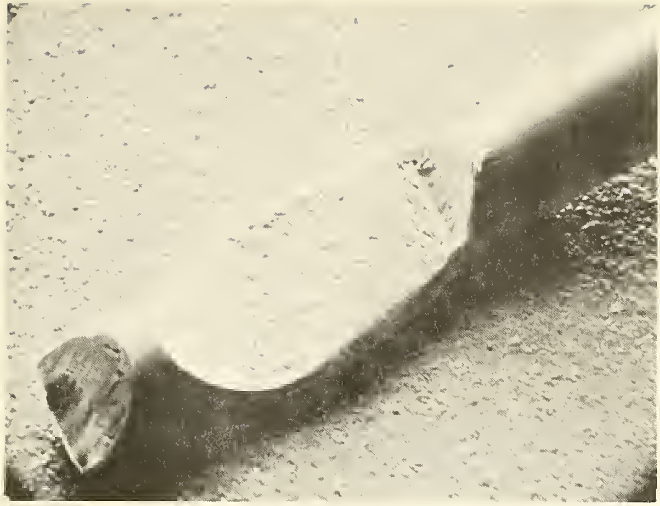


Figure 3. Sketch of the ultrasonic bonding cycle. The first bond is formed, as shown in (a), by the combination of a tool force down on the wire and an ultrasonic motion parallel to the wire. A loop is then made, as shown in (b) and the second bond is made in the same manner as the first. The wire is then cut off by a pull of the wire by the wire clamp so that the machine is ready to repeat the process.



a Magnification: 550X

b Magnification: 525X

Figure 4. A comparison of a first (a) and second bond (b). They differ in appearance mainly in the nature of the toe of the bond (since the effect of the cut-off is evidenced there on the second bond) and in the condition of the heel of the bond.

wire. The appearance of the heel of the bond depends on the amount of deformation. For example, Figure 4 shows bonds typical of those examined from one manufacturer compared with those of another manufacturer shown in Figures 5a and 5b. The fact that there is a great difference in bond deformation results from the different combinations of force, ultrasonic power and time that are used in bonding on these production lines. These adjustments of the bonding machine (the bonding schedule) involve a compromise. Setting combinations that yield a small deformation result in a small crack at the heel leaving the wire itself as strong as possible. However, if the deformation is very small, the bond is frequently weak due to lack of welding at the interface. This is called underbonding. In the extreme, the wire does not stick at all; it lifts off. More welding at the interface can be attained by increasing one of the settings in the bonding schedule. This will also result in increased deformation so that the heel will be thinner and weaker. In extreme cases the wire will be nearly severed at the heel. This is called overbonding. The optimum bonding schedule would be a compromise between underbonding and overbonding.

Typical examples of the variation in heel cracks with different deformations are shown in Figure 6 which shows two first bonds from devices from two different production lines. The bond in Figure 6a is less deformed than the one in Figure 6b so that it has a considerably smaller crack in the heel. It should be noted that the bonding machine which made the bond in Figure 6a had a malfunction in its cycle (the tool was allowed to bounce on initial impact) which caused the indentation in the wire above the heel. The indentation in the bond surface below the crack is probably due to build-up of aluminum in a small region of the bonding surface of the tool.

There can also exist a variation in the amount of deformation from bond to bond on a single device. The amount of this variation is usually (but not always) less than the variation described as existing from production line to production line. Two examples are shown in Figure 7. In Figure 7a, which shows eight of the bonds on a device, there is seen a large difference in deformation particularly visible in the two bonds marked A and B. These variations are easily observable with ordinary optical microscopes. Figures 7b and 7c show two consecutively made first bonds on another device. There is a significant difference in deformation between the two bonds. These bond-to-bond deformation differences are characteristic of unwanted motion between the tool and the work stage during bonding.[1] This motion can be caused by many different factors such as movement caused by the operator, building vibrations, or just the normal motion or vibration of the bonder itself as it goes through the bonding cycle. This kind of motion is significant because it can result in the type of occasional bond lift-off which has not otherwise been explained. Relative motions of 0.00025 in. (about 6 μm) or smaller between the tool and the work stage are large enough to be significant. In addition to deformation differences there are other aspects of the bond appearance which give indication of unwanted motion during bonding. Figure 8 shows a bond which suffered from gross motion of the tool as

a Magnification: 500X

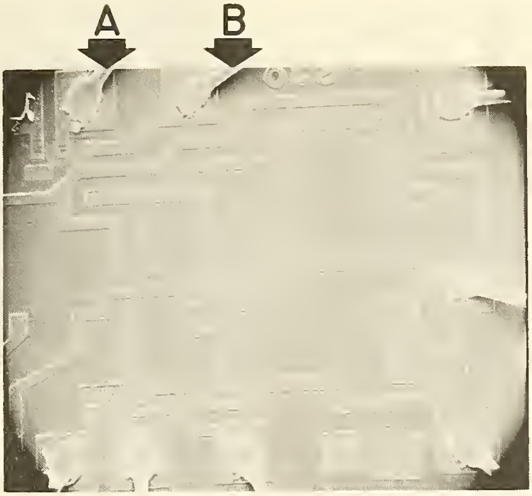
b Magnification: 550X

Figure 5. First and second bonds from another production line. These first and second bonds, shown in (a) and (b) respectively, differ from those of Figure 4 mainly in the amount of deformation of the bond and in the shape and size of the crack in the heel of the first bond.

a Magnification: 490X

b Magnification: 500X

Figure 6. Examples of different types of first-bond heel cracks. The type of crack depends primarily on the amount of deformation of the wire during bonding. Small deformation yields a small crack as shown in (a), while a bond with greater deformation has a larger crack as shown in (b).



a Magnification 95X

b Magnification 575X

c Magnification 650X

Figure 7. Variation in bond deformation from bond to bond on a single device. In (a), there is a variation in the width of the bonds that is particularly noticeable between those marked "A" and "B". Two consecutively made bonds from a different device are shown in (b) and (c). While that in (c) is underbonded, the bond in (b) is not.

evidenced by the lateral deformation. An example of a much smaller motion is shown in Figure 9. The wiggle marks seen in the heel are due to motion between the bonding tool and the post as the tool lowers to form the bond.

During the bonding process, aluminum is often extruded from under the wire to appear as little curls on either side of the bond. This is illustrated in Figure 10. The extruded material is part of the aluminum metallization that is pushed up as the bond is made. Extrusions usually occur when the metallization is too soft. Variation in the amount of this extrusion and in its relative position on either or both sides of the bond from bond-to-bond on a device is another indication of unwanted motion during bonding. The bonds in Figure 7a illustrate these variations. These variations can be seen with an optical microscope.

Differences in surface texture of the deformed wire were also observed. These differences are primarily due to the surface condition of the foot of the bonding tool. A clean tool will give a smooth bond appearance as can be seen in Figure 4a. A tool becomes rough as a result of aluminum build-up on its bonding surface. The bond in Figure 11a is one produced with a generally rough tool while those in Figures 11b and 11c were made by a tool that had only small areas of aluminum build-up similar to that which made the bond in Figure 6a. When these surface indentations were observed, the same pattern was generally repeated on all the bonds of a particular device. It is not known at this time if the presence of aluminum on the tool affects the quality of the bond produced.

Figure 12 illustrates the unusual appearance found on the bonds of one device. The tail has been flattened. Since the surface appearance of the flattened area is similar to that of the wire-bond surface, it was probably subjected to a force by the tool. One would suspect malfunction in the bonding cycle of this particular bonder.

4. WIRE APPEARANCE

Large indentations have been observed on the sides of the wire in some bonds. The worst example is shown in Figure 13a with the area indicated shown at higher magnification in Figure 13b. It has been determined that these marks are produced by the jaws of the clamping system through which the wire is fed from the spool to the bonding tool. In addition to marring the surface finish, these imprints work-harden the wire and thus affect the bonding conditions. Occasionally the wire twists 90 degrees after passing through the clamping system, and the indented portion then becomes a part of the actual wire-metallization interface. Figure 14 shows a bond in which this twisting has taken place. Indentations are formed on opposing surfaces of the wire by the clamp so that marks similar to those seen on the top also appear on the underside of the wire. Of particular concern is the possibility of contaminants on the clamp becoming embedded in the wire and directly interfering with the bonding process. This combination of events may cause an occasional, weak bond which can not be detected by the usual inspection.

Figure 8. A bond which has suffered from gross unwanted tool-to-substrate motion during bonding as evidenced by the large side-to-side indentations.

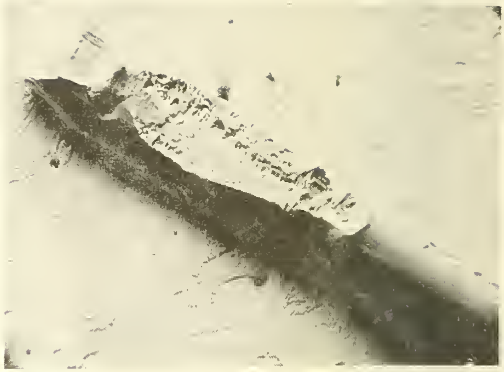
Magnification: 610X

Figure 9. A bond which exhibits small unwanted tool-to-substrate motion during bonding as indicated by the small "wiggle" marks (indicated by the arrow) seen on the crack in the heel. The marks on the wire above the bond are due to impressions of the wire-feed clamp.

Magnification: 1500X

Figure 10. Aluminum extruded from under the wire during bonding. The extruded material appears as little curls (indicated by the arrows) on either side of the bond. Magnification: 300X

a Magnification: 580X



b Magnification: 540X

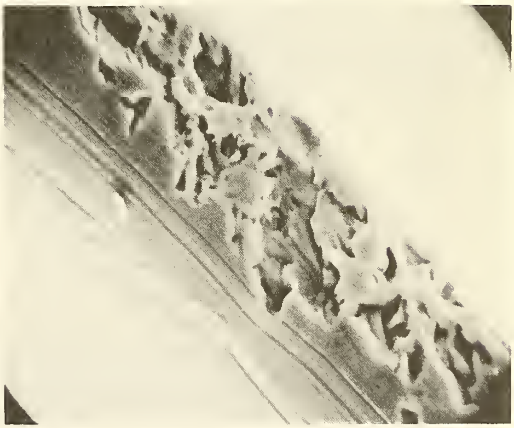
c Magnification: 540X

Figure 11. Differences in surface texture of the deformed wire. In (a), the bond was made with a tool having significant aluminum build-up over its surface. Those in (b) and (c) had small areas of build-up which produced a pattern of indentations on the surface of the bond which was repeated for all the bonds on the device.

a Magnification: 510X

Figure 12. A bond presumably produced by a malfunctioning machine. The flattened toe of the bond is indicated by the arrow.

a Magnification: 520X



b Magnification: 2100X

Figure 13. An extreme example of marks left on the wire by the wirefeed clamps. The bond and wire are shown in (a) with the part of the wire indicated by the arrow shown at greater magnification in (b).

Another defect that has been observed on the surface of the wire is a scrape or scratch mark. An example of this can be seen on the top part of the wire shown in Figure 13b. These scrapes or scratches can be due to rubbing of the soft aluminum wire against a hard surface somewhere along its path from the wire spool to the bond, such as guides on the wire feedhole of the tool itself. Since there is the possibility that damage of this type may induce stress or introduce contamination in the wire and thus affect the bonding process, these marks may be significant.

5. METALLIZATION APPEARANCE

A mark often found on the bonding pad metallization is the indentation due to the probe used during the electrical testing of the circuit. A typical example of such a mark is shown in Figure 15. It is possible for the probe to completely scrape away the metallization as is shown in Figure 16. In any case the metallization may be scraped quite thin by the probe so that bonding should not be attempted over probe marks. Since probes are usually aimed at the center of bonding pads, it often becomes difficult, particularly on small pads, to find enough space for placing the bond on an unprobed area of the pad. As a result, there are many cases of bonding over probe marks as in Figure 17a or of bonding partially off the pad as shown in Figure 17b.

Another type of mark found on the metallization which may be similar to a probe mark is the lift-off mark (the mark left on the metallization when a bond does not stick, necessitating rebonding of the pad or post).[2] Examples of rebonded posts are shown in Figure 18 and examples of rebonded pads are shown in Figure 19. In Figures 19a and 19b, the marks to the left of the bonds are probe marks and those to the right are lift-off marks. In Figure 19a, lift-off was due to underbonding; the combination of power, time and pressure did not yield enough welding at the interface for the bond to stick. In fact, the successful bond which was subsequently made is also underbonded. In Figure 19b, lift-off could be due to unwanted motion during bonding. In Figure 19c, the initial bond attempt was over a probe mark as indicated by the arrow to the left of the lift-off mark. In this case lift-off might be due to overbonding or to poor metallization. Figure 19c illustrates the bond placement problems which result from rebonding. In the small area available for bonding, there is not enough room for two attempts without having one of them be partially off the pad, over a probe mark, or over a lift-off mark.

Another type of rebonding occurs where the wire breaks at the heel leaving the bond itself behind. It occurs for very highly deformed bonds which was usually not the case in the devices studied. In the example shown in Figure 20 there were at least two attempts before a successful connection was made.

The main reason for not rebonding on high reliability devices, particularly if more than two attempts are necessary, is the likelihood that if additional tries are needed it is indicative of a problem. It might

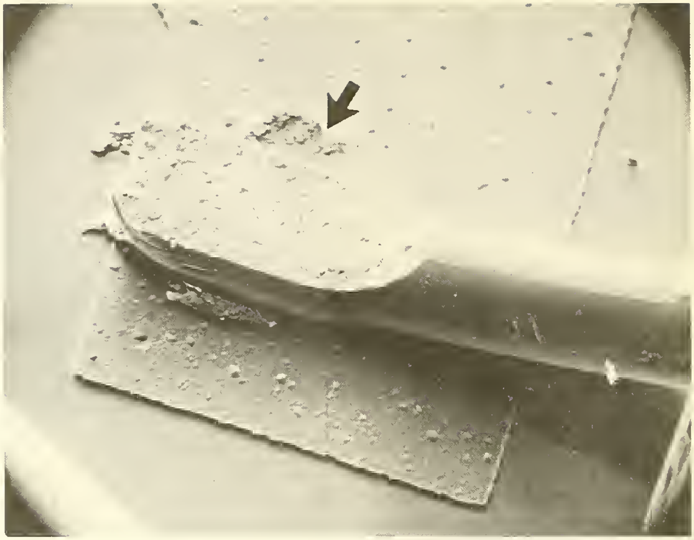
Figure 14. A bond showing the clamp marks on the top (and therefore also on the bottom instead of on the sides of the wire).

Magnification: 580X

Magnification: 510X

Figure 15. A probe mark on a bonding pad indicated by the arrow.

Figure 16. A probe mark on a bonding pad. Note where the probe has completely scraped through the metallization as indicated by the arrow. Magnification: 560X



a Magnification: 540X

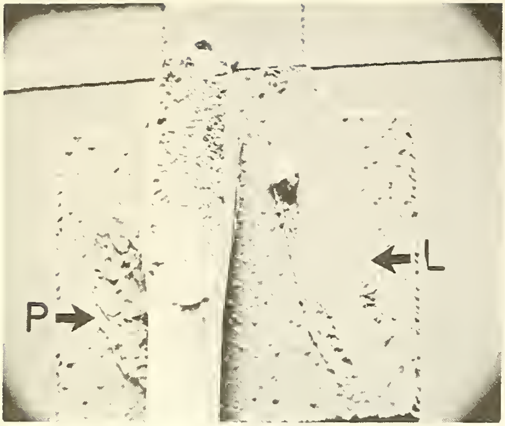
b Magnification: 510X

Figure 17. Examples of probe marks interfering with bonding. In (a), the bond is made over a probe mark and in (b), the bond was put partially off the pad to avoid bonding over the probe mark.

a Magnification: 465X

b Magnification: 190X

Figure 18. Rebonding on the package leads. The bond in (a) was the second attempt while that in (b) was the fourth.



a Magnification: 540X

b Magnification: 520X

c Magnification: 475X

Figure 19. Rebonding on the bonding pads on the circuit chip. The probe marks are indicated as (P) and the lift-off marks as (L). In (a), lift-off was due to underbonding while that in (b) seems to have been caused by unwanted motion during bonding. The bond which lifted-off in (c) was made over a probe mark.

be bad metallization on that particular pad or post, bad wire, excessive unwanted motion during the bonding cycle, or even an incorrect bonding schedule. The result is that even if there is enough room left on the pad and a bond can be made to stick, there would be no assurance that it will be a good bond.

Poor metallization was frequently observed on the package leads of the devices examined. Figure 21a shows the metallization of a finger on a flat-pack. The area in which the bond is placed is extremely rough. There is a wide variation in texture across the finger and in a portion the metallization has actually peeled off. While roughness in the metallization surface is not necessarily difficult to deal with in bonding, variation in this roughness from bond to bond or package to package is a problem. Since the proper bonding parameters (power, time, and pressure) depend strongly on the surface texture, they cannot be at optimum settings for both extremes in surface texture. Therefore as this texture varies from package to package there will be a resultant variation in the character of the bond.

Magnification: 600X

Figure 20. Rebonding following wire break-off at the heel.

The variation in surface quality of the bonding areas of the packages was greater for the transistor-type packages examined than it was for the flat-packs and other integrated circuit packages. The integrated circuit frames were normally coated with evaporated aluminum which tends to be more uniform than the tumble plated gold on the transistor posts. Figures 21b and 21c show the gold plated post metallization of two transistor packages. In Figure 21b the metallization is very rough and hard. So hard, in fact, that instead of the bond being formed by the mutual deformation of the wire and the metallization, the wire was merely mashed flat over the irregular metallization. This can be seen in the surface texture of the bond which shows cracks with angles which are similar to the angular features of the metallization below. In Figure 21c there are many holes in the surface of the metallization. This was also true for the other post of this package and, to a lesser degree, for several other transistors examined. Since these holes affect the texture of the metallization, they would seem to be detrimental to wire bonding. Also, since they exist to some extent on the rest of the package surfaces, such as under the die, they might also present a problem during die bonding because the holes could entrap gas as the bond was being made.

6. OTHER OBSERVATIONS

The primary purpose of this investigation was to study the wire bonds of the devices examined. However, occasional examples of other possible reliability problems were observed. Some of these have an indirect bearing on wire bonding. The metallization faults encountered were primarily scraping or scratching of metallization stripes. The area marked with an "S" in Figure 22a exhibits evidence of scraping and that which is marked "E" shows holes in the metallization where material was etched away. The dielectrically isolated circuit shown in Figure 22b illustrates the difficulty in running a metallization stripe over a raised area. The damage to the metallization may have occurred when the wafer was broken into individual circuit dice since it is then that the die surface often comes into contact with a hard surface. Figure 23a shows another example of a metallization stripe 0.001 in (25 μm) where some of the material has been etched away, but here the stripe is almost etched entirely away at one point. It is shown in a higher magnified view in Figure 23b. Also illustrated in Figure 23 is the thinning in the metallization placed over a step in the oxide. The obvious problem with any of such imperfections in metallization interconnections is the possibility of electrical open-circuits. Another metallization defect, shown in Figure 24, is the presence of small metal pieces which could become loose after packaging and could possibly cause an electrical short between two metallization stripes.

Improper placement of the die during die bonding can cause difficulties when the device is wire bonded. Figure 25 shows a case where the wires are unnecessarily long and where there exists the possibility of the wires touching one another. Bad placement of the wire bonds on a transistor could also cause an electrical short. Figure 26a shows a

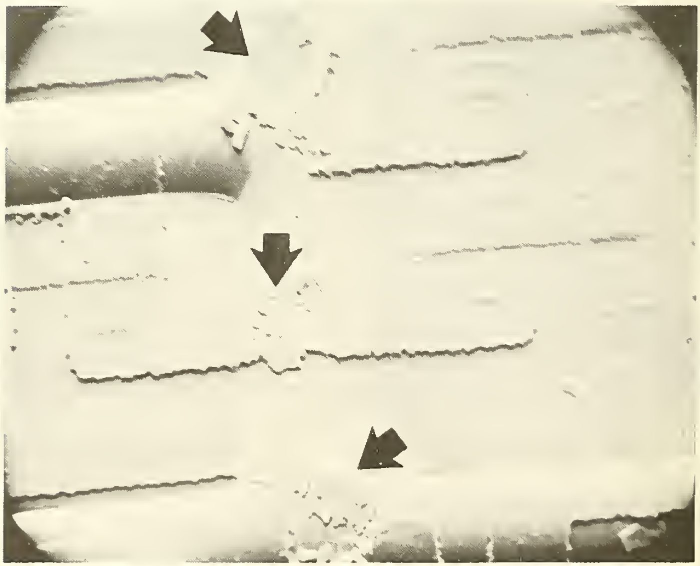
a Magnification: 60X

b Magnification: 660X

c Magnification: 555X

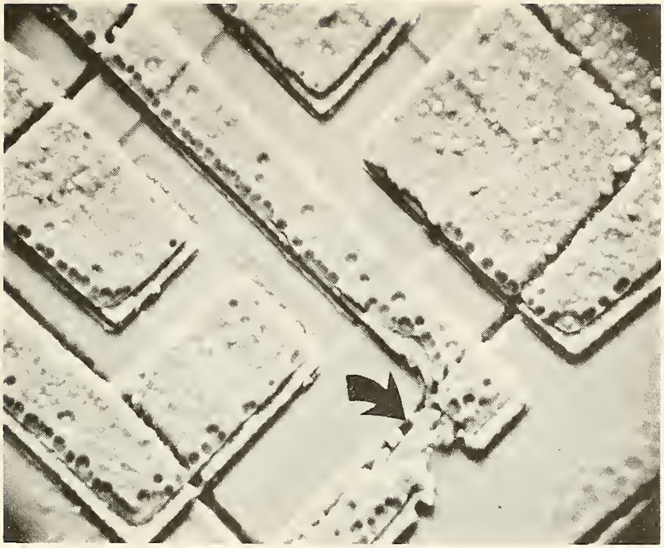
Figure 21. Defective package metallization. In (a) the metallization is actually peeling off of the finger of a flat-pack. In addition there is a great variation in the texture of the metallization across the lead. The examples in (b) and (c) are posts of transistor-type packages. The metallization in (b) is very hard and irregular as indicated by the impressions extending through the bond. The metallization in (c) is full of holes.

a Magnification: 210X



b Magnification: 540X

Figure 22. Examples of damaged metallization. In (a) some metallization seems to have been scraped away (S) while some other seems to have been etched away (E). In (b) the metallization over the humps in a dielectrically isolated device has been damaged.



a Magnification: 550X

b Magnification: 1100X

Figure 23. Over-etching of a metallization stripe. A portion of a circuit is shown in (a) with the region indicated by the arrow shown at greater magnification in (b).

Magnification: 560X

Figure 24. Small metal particles observed on the metallization.

Magnification: 20X

Figure 25. Improper die placement resulting in wire bonding problems.

a Magnification: 60X

b Magnification: 660X

c Magnification: 555X

Figure 26. Improper placement of wire bonds on transistor chips. The bond indicated by the arrow in (a) is shown at greater magnification in (b). It is possible that the placement of this bond could cause an electrical short circuit. Another example of bad placement is shown in (c).

transistor; and in Figure 26b the emitter wire bond of the transistor is shown at greater magnification. Because of the way the bond is placed, the wire crosses very close to the base metallization. Another example of this is shown in Figure 26c.

An unusual situation observed on one device, shown in Figure 27, was caused by poor masking. This is shown by the fact that while the alignment was correct in finger A of the transistor, quite near, at finger B, the alignment was off by nearly one-third of the width of the finger. The bonding pad in this example is very small, illustrating another type of difficult bond placement that is often encountered.

Magnification: 515X

Figure 27. Misalignment caused by poor mask. Finger "A" is properly aligned but "B" is not. Note how the small bonding pad makes it difficult to find a suitable location for the bond.

Extraneous material was observed at the surface of some of the metallization, on a few of the bonds, and on one piece of wire. Figure 28a shows such material on the metallization of one of the bonding pads. In Figure 28b, there is a bond with material on its surface that we have not identified. At the top of the picture, what appear to be corrosion products cover portions of the wire. This is shown at greater magnification in Figure 28c. No identification was made of this extraneous material.

a Magnification: 510X

b Magnification: 530X

c Magnification: 1075X

Figure 28. Examples of extraneous material. The arrow in (a) indicates unidentified material seen on a bonding pad. In (b) the bonded area of a wire is covered with some foreign material. The material on the undeformed wire indicated by the arrow is shown in (c) at higher magnification.

7. SUMMARY

The results of an SEM examination of a large number of microelectronic devices, intended for use in systems demanding high reliability, have been described. The appearance of the bonds themselves has been discussed, including differences between first and second bonds, cracks in the heel of the first bond, variation in bond deformation, indications of unwanted tool-to-substrate motion and differences in bond surface texture. The surface condition of the wire above the bond has been noted. Also included are descriptions of the appearance of the metallization (package and die) on which the bond is made. This includes probe marks, lift-off marks, other indications of rebonding, as well as poor or damaged metallization. Miscellaneous observations were presented which covered improper die placement, improper bond placement, and the existance of extraneous material.

Comments and explanations have been given where phenomena are understood. It is not to be construed that all, or indeed any, of the observations noted would cause a device to fail. It is merely noted that a careful examination of a device can reveal many areas of potential difficulty. In addition, even though this examination was made with an SEM since it can be used to observe details not seen with an optical microscope, many of the defects could have been observed with an optical microscope.

8. REFERENCES

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16. ABSTRACT (A 200-word or less factual summary of most significant information. If document includes a significant bibliography or literature survey, mention it here.)

An examination with a scanning electron microscope was made of the wire bonds of over 75 high-reliability microelectronic devices. The device interconnects were ultrasonically bonded aluminum wires. Of primary interest were the bonds themselves; their appearance and its significance are described. Also described is the appearance of the metallization and the wire. Comments and explanations are given where the phenomena are understood. Although the devices studied had passed preliminary electrical tests and pre-encapsulation visual examinations, many potential reliability problems were identified such as weak bonds, electrical shorts and contamination.

17. KEY WORDS (Alphabetical order, separated by semicolons)
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