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Wire Bonding – A Closer Look

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ABSTRACT

Just like soldering, wire bonding appears to be a simple process and is frequently taken for granted. People tend to think all that is required to have a high quality bonding process is a simple wire pull test to monitor and control the process. But like soldering, this process is complex and requires a thorough understanding of the metallurgy, thermodynamics, and surface chemistry involved.

This paper will report on a study of the wire bonding which is representative of the semiconductor industry from the aspect of the materials involved, the metallurgy of the resultant bonds, and techniques of monitoring the bond quality. It will also present information on the ability of a bond to withstand various aging conditions and the most effective manner to monitor bond quality.

INTRODUCTION

The expanding use of electronics in automotive applications, with the requirements for long life and high reliability in the harsh environment of the car, has highlighted several problems not normally observed. The use of plastic packaged state of the art integrated circuits and microprocessors in these applications generated information on their performance that had not been readily available before. In particular, failure analysis data became available which showed lifted wire bonds as a significant cause for unsatisfactory performance. Tremendous progress had been made in improving the quality and reliability of the semiconductor chip, but the quality of the interconnects seemed to be overlooked and lagged behind the progress in other areas. Reviewing the failure analysis data of various suppliers, it became apparent that some suppliers were showing superior performance in the area of wire bonds. This information triggered this study of wire bonding.

THE EVALUATION OF SUPERIOR WIRE BONDS

In this evaluation, a characterization of the significant differences between a supplier with superior bonds and suppliers with normal bonding quality was made in an attempt to understand the reasons for differences in bond failure rates. This characterization evaluated the following:

- o Shape and size of the ball bond
- o Form of the wire loop
- o Bond position on bond pad
- o Die bonding technique
- o Device metallization.
- o Metallurgical characteristics of the ball bond.

Reviewing the findings from this evaluation showed several interesting facts:

1. The shape of the ball bond of the best wire bond supplier showed some interesting differences. Ball bonds made with the same size wire were consistently larger in diameter with more set down, see Figure 1. This larger ball diameter provided a significantly larger bond area and a potentially stronger bond.

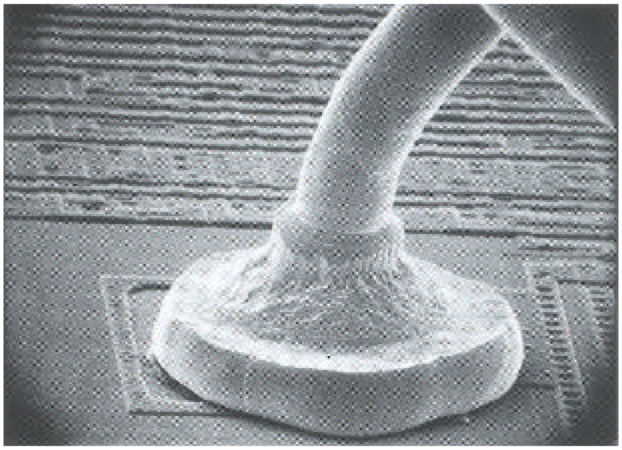

Figure 1 Ball bond shape. Note size of the ball.

2. The loop of the bond wires, which is very important in preventing shorting between the bond wire and the edge of the chip, was essentially the same for all suppliers, see Figure 2.
3. The location of the wire bond on the bond pad is obviously extremely important and the best suppliers maintained very good control on bond positioning.
4. Various types of die bonding from eutectic bonds to epoxy bonds were found, but this did not appear to be a significant factor in bond quality.
5. Suppliers making the highest quality bonds were bonding to aluminum or aluminum/silicon metallization.

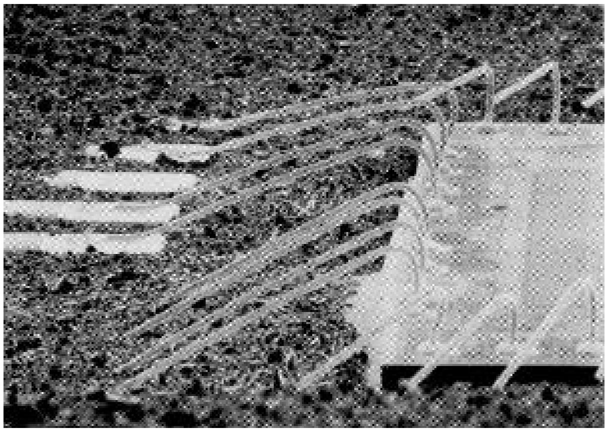

Figure 2 Typical gold bond wire loop from the chip to the lead frame.

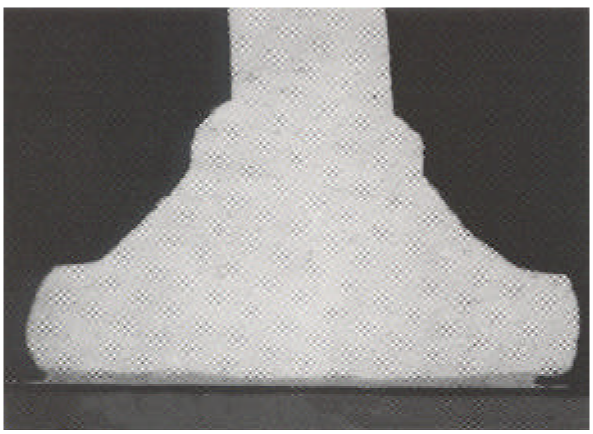

Figure 3 Metallurgical characteristics of a quality wire bond, Notice the uniform gold-aluminum intermetallic layer,

6. Metallurgical studies of the high quality bonds showed an almost perfectly formed intermetallic present at the gold aluminum interface, see Figure 3. Cross sections of the poorer quality bonds showed a spotty to non-existent intermetallic layer.

VISUAL EXAMINATION OF BALL BONDS TO DIFFERENT METALLIZATIONS

Based on the above findings, a thorough visual analysis of ball bonds made to different metallizations was performed. In this evaluation, bonds made to aluminum, aluminum/silicon(I %), aluminum/copper(1%),and aluminum/copper(1%)/silicon(1%) were studied using the scanning electron microscope. The bonds studied were in the "as molded condition' and had not been exposed to any testing. The results of this evaluation showed that bonds made to aluminum and aluminum/silicon all showed an extrusion of metallization from the bond interface, see Figure 4. Bonds made to aluminum/copper and aluminum-copper/silicon showed slight to no indication of extrusion from the bond interface. This lack of

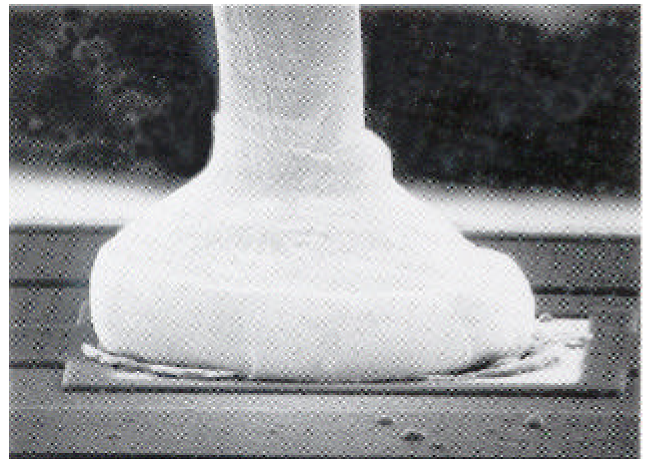

Figure 4 Wire bond to Al or Al/Si metallization. Notice aluminum extruded from bond interface.

extruded material in bonds to metallization containing copper appears to be related to the hardness of the metallization. Although there are various factors in the metal deposition process that can affect this hardness, the presence of copper would have a tendency to precipitate in the aluminum matrix causing a harder metallization. Whatever the cause, the hardness of the metallization appears to be an important variable in the wire bonding process. The first step in achieving a good bond is to expose a fresh, unoxidized surface capable of being bonded. This is especially true for aluminum with its oxidized surface which must be deformed to expose unoxidized aluminum for bonding **[1]**. The lack of visual evidence of significant deformation in the Al/Cu and Al/Cu/Si metallization suggests that it is difficult to remove the oxide film (very little of the oxide layer was broken up by the ultrasonic scrubbing action) from these systems and thus it is more difficult to achieve a high quality bond to these systems. Cross sections of bonds made to these various metallization systems clearly show the differences in bondability, see Figures 5, 6, 7. The cross sections of bonds made to the harder metallizations (Al/Cu) systems showed a poorly developed or almost non-existent spotty intermetallic. John Devaney stated 'This results in a bond interface which is characterized by regions of reaction between ball metal and pad aluminum and areas where no reaction has occurred. These unbonded regions are merely areas of compressed aluminum. These spotty intermetallic sites grow quickly on exposure to temperature resulting in bond failure" **[1]**. Our studies suggest that many of these spots represent areas of trapped aluminum oxide or other contaminants trapped at the interface which never changed and resulted in low strength bonds. Bonds made to the softer metallization systems (Al and Al/Si) show a desirable uniform intermetallic across the complete bond interface.

After review of the intermetallic seen in the bonds shown in Figures 5, 6, and 7, it might be concluded that only aluminum or aluminum/silicon metallization can be bonded with a high degree of reliability. This is in fact not true. The initial evaluation tended to indicate this because the copper containing aluminum metal systems were being bonded without proper bond schedule development. In the case of metal systems without copper, bond schedules which showed good wire pull values (the bond wire broke) also had good metallurgical bonds because it was very easy to form an

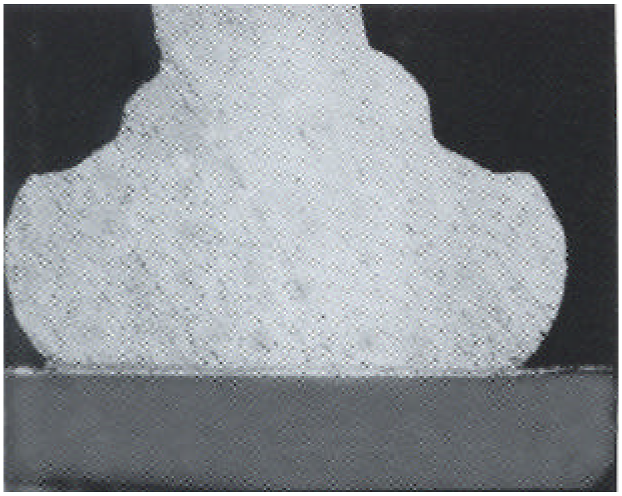

Figure 5 Metallurgical characteristics of wire bond to aluminum metallization. Notice uniform intermetallic layer.

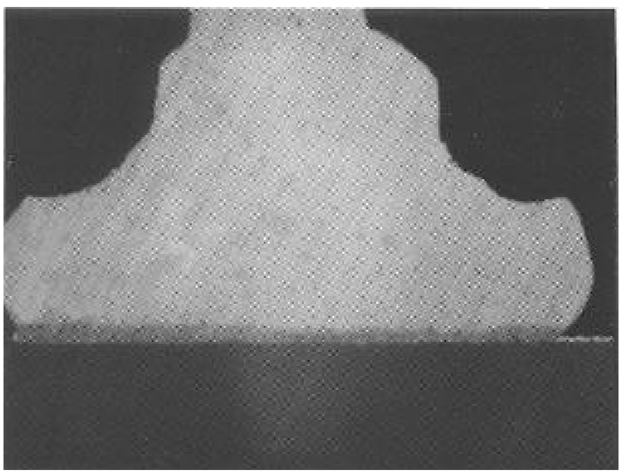

Figure 6 Wire bond to aluminum/silicon metallization. Notice uniform intermetallic.

intermetallic at the bond joint in these systems. With the use of copper in the metallization, it became much more difficult to form a metallurgical bond. Development of proper bonding schedules for copper containing metallizations will result in the formation of a uniform intermetallic at the bond interface as shown in Figure 8. Comparing Figures 7 (typical bond made with old bonding schedule) to Figure 8, it is easy to see improved metallurgical characteristics (uniform intermetallic).

T'ESTING OF BONDS WITH POORLY FORMED INTERMETALLICS

Testing **[2]** was performed to evaluate the effectiveness of the following:

o Wire pull as an indicator of wire bond quality.
o The effects of wire bond metallurgy on bond performance.
o The effectiveness of temperature cycling as an indicator of wire bond quality.

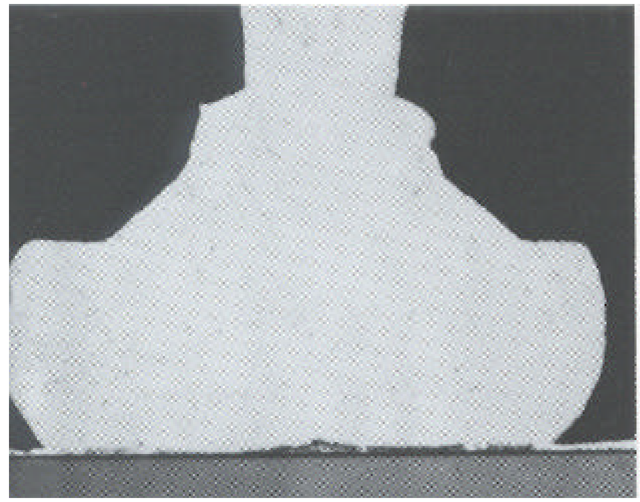

Figure 7 Wire bond to Al/Si/Cu metallization using the old bonding schedule. Notice spotty non-uniform intermetallic.

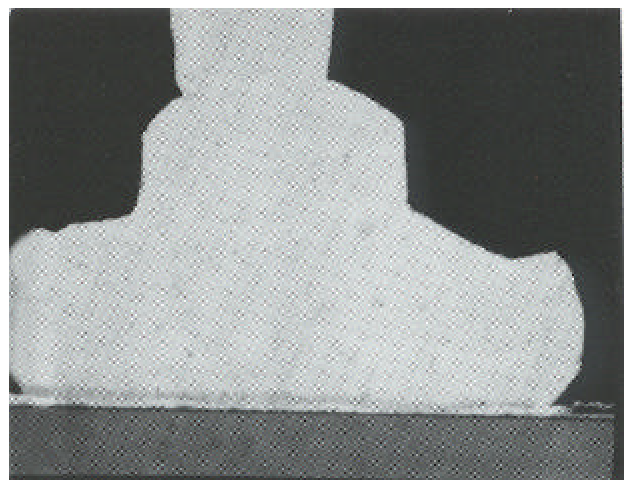

Figure 8 Wire bond to Al/Si/Cu metallization using the revised bonding schedule. Notice much more uniform intermetallic formation than seen in Figure 7.

o The effect of molded package stresses on wire bond performance.

The specimens selected for this evaluation were Delco manufactured ICs made with Al/Si metallization and Al/Cu/Si metallization. The die were adhesively bonded to copper lead frames and wire bonded using 1.3 mil gold wire. The bond schedules used were known to produce bonds with varying metallurgical characteristics which would pass wire pull testing. The bonds made to Al/Si metallization showed a very uniform intermetallic, while the bonds made to Al/Cu/Si showed a non-uniform or spotty formation of intermetallic. The bonds were sampled to insure that the bonding process was producing bonds that passed wire bond pull testing. This testing showed no ball lifts and the wire broke in all cases. Half of each group of parts were then plastic molded and the remaining parts were placed in strip carriers (fixtures which supported the bonded lead frame strips). The molded and unmolded parts were then placed on -50° to + 150°C

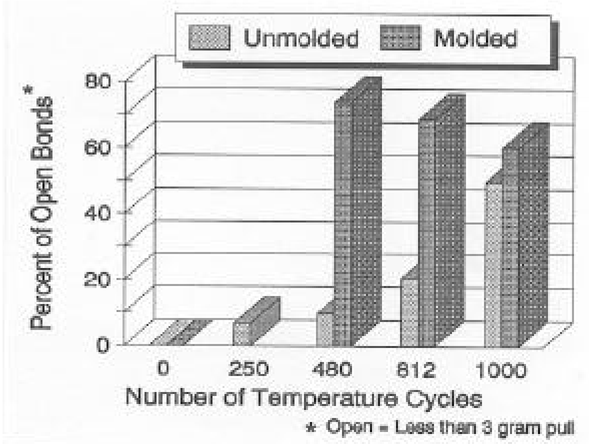

Figure 9 Graph showing results from wire pull testing of molded and unmolded parts through various periods of temperature cycling.

temperature cycling. At approximately 250 cycle intervals samples of molded and unmolded parts from each part type were removed from temperature cycling and wire pull tested. The results of these tests are shown in Figure 9. This testing showed:

1) Passing wire pull testing does not assure the bonds are high quality and will give reliable performance.
2) The stresses of a plastic molded package are not required to cause a poor bond to fail.
3) If a good metallurgical bond is not achieved during bonding, the stresses due to thermal expansion will cause a poor bond to fail.
4) Molded parts, with the added stress due to thermal expansion of the molding compound, will cause poor bonds to fail at a higher rate during temperature cycling **[3]**.

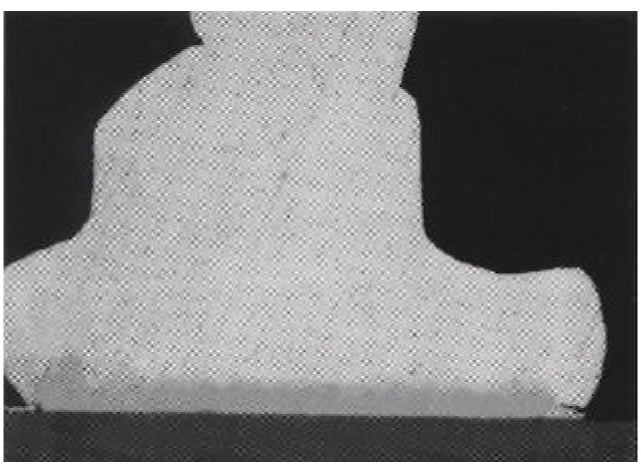

Figure 10 Cross-section of wire bond to aluminum metallization after 1000 hours of 150'C storage. Notice the growth of the intermetallic from Figure 5.

EFFECT OF EXTENDED EXPOSURE TO HIGH TEMPERATURE

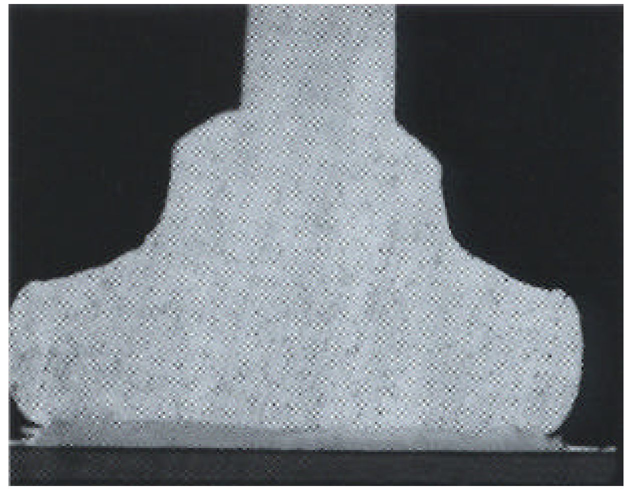

Figure 11 Cross-section of wire bond Al/Si metallization after 1000 hours of 150°C storage. Notice growth of intermetallic from Figure 6.

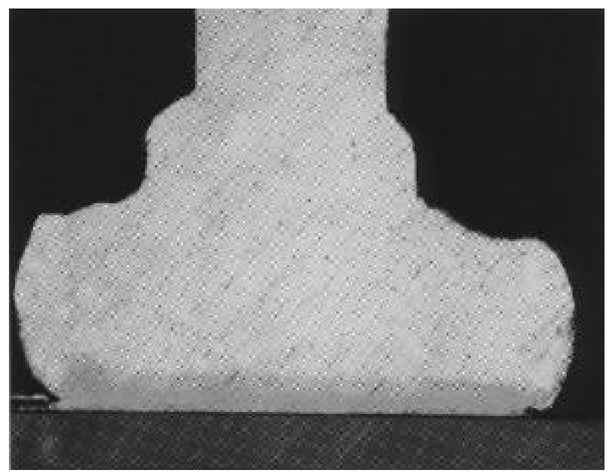

Figure 12 Cross-section of wire bond to Al/Si/Cu metallization using the revised bonding schedule after 1000 hours of 150°C storage. Notice growth of intermetallic from Figure 8.

A typical environmental qualification test performed on parts at Delco Electronics is a high temperature storage (1000 hours at 150°C). Parts exposed to this environment were examined both visually (utilizing an SEM and cross sectioned to evaluate metallurgical changes. Scanning electron microscope evaluation showed no detectable indications of degradation as a result of the exposure (there were no signs of excessive interrnetallic growth or voiding). Cross sections of bonds made to the various metallization systems showed similar reactions at the interface. In all four metallization systems there was a significant growth of the intermetallic. Although other authors have reported voiding and a decrease in bond strength after extended periods of time at elevated temperature, our testing did not show excessive intermetallic growth (purple plague) or voiding after 1000 hours of 150°C storage **[4] [5**], see Figures 10, 11, 12. Mechanical testing of wire bonds showed no degradation in bond strength. Parts bonded with the proper Al/Si/Cu bond schedule were used in this experiment

DEVELOPMENT OF QUALITY WIRE BOND SCHEDULES

A method of evaluating the true strength of the ball bond was needed to set-up **a** quality wire bonding schedule. The wire pull test (with the limited stress it could apply to the joint) could not provide enough information about the true strength of the bond. Wire pull testing of bonds with a strength of greater than 12 to 15 grams just measure the strength of the bond wire. Cross sectioning could have been preformed to study the metallurgy, but because of the time involved and the fact that no one expected a problem, very little work was performed in this area. With the advent of the plastic quad packaged ICs and their high thermally induced stresses (especially on comer bonds) the weakness of these bonds quickly became a primary concern. At this point, other techniques for evaluating wire bonds were investigated. The most promising technique was ball shear **[6]**, see Figure 13. This technique records the stress required to shear a bond from the IC. The problem with the initial equipment available for doing ball shear was that it was extremely operator dependent which all but eliminated this method from consideration. At about this time, a new development in ball shear equipment related to automatic positioning of the shear tool a controlled distance above the surface of the die became available. This capability made it possible to get repeatable shear values without operator dependence. This development provided a true indicator of bond strength and a method for developing reliable bond schedules for copper containing metallizations. Cross sectioning has confirmed the effectiveness of ball shear in determining the presence of a uniform intermetallic in the bond. These bonds have also shown the ability to pass 1000 temperature cycles (-50° to + 150°C) and maintain a mechanical connection between the ball bond and the bond pad.

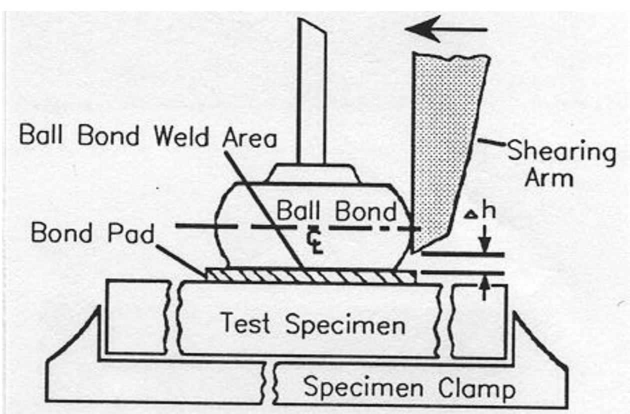

Figure 13 Sketch showing typical set-up for ball shear testing

CONCLUSIONS

The work discussed in this paper has lead to the following conclusions about wire bonding:

- o The presence of copper in the aluminum metallization creates a harder metallization which is more difficult to bond to than aluminum or aluminum/silicon metallization.
- o Bonding to copper containing metallization requires tighter bonding schedules so that a uniform metallurgical bond can be achieved.
- o Significant Au/Al intermetallic growth was seen on all metallization systems as a result of 1000 hours of 150°C storage, but no voiding, loss of bond strength, or other degradation was noted.
- o Bonds with a uniform intermetallic formation had a stronger bond shear strength than bonds with spotty or non-uniform intermetallic.
- o Thermal expansion of IC molding compounds places a significant stress on ball bonds during temperature cycling and can cause poor bonds to fail.
- o Wire pull testing does not assure that wire bonds are high quality and will be reliable.
- o Ball shear testing appears to provide a true indication of bond strength and can be used as a reliable method for developing bond schedules.

References

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