INTERMETALLIC COMPOUND FORMATION IN Au - Al BONDING SYSTEM

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Bonding is the term commonly used for the process of connecting wire leads from the semiconductor chip to the external leads of the package in semiconductor device and microcircuits fabrication. Au-Al thermocompression bonding system is most reliable if bonding process is controlled properly and the device is not subjected to long time storage at temperature exceeding 200°C, beyond which there is interaction between Au and Al forming intermetallic compound popularly called 'Purple Plague'. The various aspects of intermetallic compound has been discussed in this paper. Illustrations are given with two Scanning Electron Micrographs.

Introduction

In semiconductor electronic parts fabrication, various internal circuit elements of the chip are interconnected by Al metallization system. Normally Al is used as metallization system because it is (a) a low cost material, (b) available in high purity form, (c) has high electrical conductivity, (d) forms low resistance contact with silicon, (e) adheres well to SiO_2, (f) is readily bondable with Au or Al wire, and (g) provides a good contact surface for the bond connection. The periphery of the chip is provided with enlarged metallization area called bonding pad for bonding wire lead. The chip is mounted on the package such as DIP. TO5 or Flat pack by die bonding. The posts of the package are gold plated and they are connected to the bonding pads of the chips through thin Au or Al wires. The process of this inter-connection is called Wire Bonding. One wire lead uses two bonded joints, one for inter connection at the chip and another at the post.

There are two popular methods of bonding interconnect wire, thermocompression ball bonding of Au wire on Al pad and ultrasonic bonding of Al wire on Al pad. Thermocompression bonding process uses a pressure at a temperature below the melting point. Bonding parameters are temperature, pressure and time, and of the three, temperature has the greatest influence on final bond strength. Ultrasonic bonding is used where temperature is to be kept low. In this process, high frequency vibratory energy, is transmitted to the joint through a tip for a small interval. In this process important parameters are clamping force, vibratory energy and time, and metallurgical bonds can be made in any similar or disimilar metals ; either Au or Al wire can be bonded by this process on Al pad without applying external heat.

Al-Al Bonding

Al - Al ultrasonic bonding does not guarantee repetitive uniform distribution of vibratory energy clamping force and coupling between the tool, the wire and the bonding pad, and it is unreliable as a production method. To facilitate handling during device assembly, the Al wire must be hardened and for this purpose usually 1% Si or Mg is added in the wire. But due to manufacturing defect this is not distributed evenly over the wire length producing unevenness in hardness, which causes abrupt changes in cross section of the wire during bonding operation. This creates a significant reduction in wire fatigue strength and the wire usually breaks at this weakest point during vibration shock or acceleration. For any high reliability application, the device is screened on 100% basis and radiographic or X-ray inspection is carried out to examine the inside of the package without opening it. Al wire bond cannot be examined by X-ray test because the relatively low density of Al causes sufficient X-ray absorption and hence any break in the wire cannot be examined by X-ray test, but there is no such problem with Au wire. Al is susceptible to corrosion during the processing, whereas gold is non-corrosive.

Au-Al Thermocompression Bonding

The Au interconnect wire bonded on Al metallization pad is the most reliable if the device is not operated above 200°C. The bond made this way has bond strength greater than Al-Al ultrasonic bonding system and in all high reliability application Au-Al thermocompression bonding system is preferred. If the working temperature of 200°C is exceeded Au and Al interact and there is intermetallic compound formation which is popularly called 'purple plague' from colour of the principal Au-Al phase formed This intermetallic can be formed during the thermocompression bonding process if the temperature or time is not controlled properly or subsequent packaging operation at high temperature or during storage or application of the device at high temperature. This compound is brittle in nature and results in an increase in contact resistance, decrease in mechanical strength and ultimately open contact. The presence of intermetallic by itself is not the cause for bond failure. In fact strength of all

intermetallic which form between pure gold and pure Al is higher than that of the individual metals Al or Au and the failure in the intermetallic bonds does not occur within the body of the intermetallic. The weakest boundary is intermetallic interface ; this is where the fracture is initiated and mostly mechanical failure has been observed for this type of bond.

Five intermetallic phases have been found out (5) such as Au Al_2, Au Al, Au_2 Al. Au_5 Al_2 and Au_4 Al, but among them Au_5 Al_2 is the most dominant and majority of the intermetallic formation is Au_5 Al_2, regardless of time and temperature. At a temperature around 250°C kept for a long time all five phases appear. All intermetallics are stronger than Au or Al, but voiding occur in Au_5 Al_2 after longtime storage at a temperature above 300°C and in Au Al_2 after longtime storage above 400°C ; voiding also occurs in these phases at lower temperature if aged for a very long time and even in a shorter time if the aging is intermittent or there is thermal cycling. The thermal cycling process causes stresses due to thermal expansion differences between intermetallics, Au & Al, resulting in a microcrack at a region of high stress at the interfaces of intermetallics which enlarges on more thermal cycling and results in a void called Kirkendall void. This void is formed due to solid state diffusion at high temperature. In this reaction, Al diffuses faster than Au producing void at the interfaces and resulting in high resistance contact and weak bonds. The mechanical stresses such as vibration, shock and acceleration are very effective in detachment of the bond from the intermetallic interface. In all semiconductor electronic parts fabrication, a little amount of silicon is always present which works as a catalyst and increases the intermetallic formation and rapid degradation of bond strength. The purity of gold plating also makes the difference in intermetallic formation ; the impurities increases the susceptibility of failure mode due to intermetallic.

Results & Discussion

All the devices for space application are screened in VSSC and whenever failure is observed, investigation is carried out to detect what caused the device to fail. The Scanning Electron Microscope is an invaluable tool for failure analysis. During the analysis, failure in semiconductor electronic components has frequently been found to be caused by faulty open or intermittent circuit due to faulty bonds. Intermetallic compound formation is one of the contributor to bond failure. Figure 1 is the Scanning Electron Micrograph of a bond pad of a



Figure No. 1

Scanning Electron Micrograph of a bonding pad with intermetallic compound formation due to which the interconnect Au wire has flown off from the pad during constant acceleration test.

transistor without the interconnect wire, showing intermetallic formation at the pad. This transistor had undergone various screening tests such as stabilisation bake for 24 hours, thermal cycle test and Burn-in test for 168 hours and finally failed in constant acceleration test at 20,000 g. For this bond pad, intermetallic must have been formed during the bonding operation or subsequent packaging operation at high temperature. The stabilisation bake, Burn-in and thermal cycle resulted in microcrack and subsequently void formation at the interface of intermetallic and Au, and the constant acceleration test resulted in the detachment of the interconnect wire from the bond pad. Figure 2 is the high magnification Scanning Electron Micrograph of a bond of a transistor with intermetallic formation. The bottom portion of the figure is the Al pad, top portion is the Au bond wire and in between the two is the inter-



Figure No. 2

The high magnification Scanning Electron Micrograph of the Intermetallic Compound of another bond. Top portion is the AU ball bond and the portion seen as globules is the intermetallic. Towards the bottom portion of the intermetallic a fine line of microcrack is seen.

metallic which is seen as globules. Towards the Al pad, a fine line of microcrack is also been and this bond was showing open contact. This transistor had also undergone stabilisation bake, thermal cycle and Burn—in tests and failed in constant acceleration test.

If the device is hermetically sealed, the life of the bond will be more even if it operates at a temperature greater than 200°C. So, for a high reliability device it is necessary to have good sealing to avoid failure due to intermetallic and hence metal can or ceramic package is preferrable. Plastic package will not be suitable because the chip is completely embedded in the plastic material and any high temperature environment will be instantly experienced by the chip.

The best way to eliminate intermetallic is to use a single metal system either gold metallization and gold wire or Al metallization and Al wire. Due to cost constraints gold metallization cannot be used and Al has been found to be best suited for this application. By using Al pad and Al wire, intermetallic can be avoided at the chip end but at the gold plated post of the package, intermetallic is formed. By ultrasonic bonding Au wire on Al pad, intermetallic can be avoided during bonding process but if such a bond is stored at high temperature intermetallic is formed. The life test conducted by Horsting[7] has shown that for 1000 hour shelf life at 200°C for Au-Al ultrasonic bond, the bond wire lifts off from the pad with slight force and in many cases even without any force and this type of bond is unreliable.

The Au-Al thermocompression bonding is the most reliable, and during this process, temperature and time have to be controlled properly and during packaging storage and application of the device also the environmental temperature should not exceed 200°C. To detect the formation of intermetallic in bond, it is necessary to observe the bond at high magnification with good depth of focus and good resolution and for this purpose SEM is the most useful tool. After bonding a sample of the devices from a lot must be inspected with SEM for any intermetallic formation and any such defect during manufacturing process can be subsequently eliminated by improved and controlled manufacturing process.

Conclusion

1. Reliable Au-Al bonds can be made if the cumulative temperature and time product experienced by the device, both during fabrication and application, is kept to a minimum. The safe storage temperature for such bonds is less than 200°C.

2. The strength of all intermetallics is higher than individual metals, Au or Al, and the presence of intermetallic by itself does not cause bond failure. Due to high temperature storage and thermal cycle, microcrack and then void is formed at the interfaces of intermetallic which results in detached bond. The vibration, shock and acceleration are most effective in detachment of such bond.

3. The presence of silicon accelerates the intermetallic formation. The impurities in the gold plating also increases the susceptibillty of intermetallic formation.

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