Wire Bonding: The Ultrasonic Bonding Mechanism

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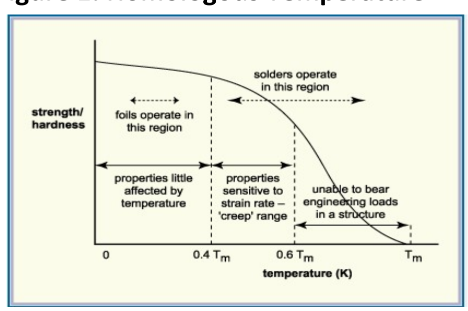
Abstract

Wire bonding is a welding process. During both ball and wedge bonding, wire and bond pad are massively deformed between the bond tool and the anvil of the bond pad or substrate. The dominant variables affecting deformation are ultrasonic energy, temperature, bond force and bond time. Deformation exposes new surface material that is clean and has not been exposed to atmospheric contamination and oxidation. As the new wire and bond pad surfaces mix, they form diffusion couples that grow and transform into the intermetallic weld nugget. The initial mixing is not at equilibrium in that it does not initially form the compounds described by the equilibrium phase diagram, but temperature and time very quickly allows diffusion to relax the initial mixture into the equilibrium phase diagram compounds. This paper will discuss the mechanisms behind the formation of ball and wedge bonds.

Deformation Normalization- The Homologous Temperature[1]

Deformation in a metal occurs by dislocations moving (slipping) along preferred crystallographic planes within the crystal lattice. Deformation behavior across the spectrum of metals is described by the Homologous Temperature[1] (the % of the melting temperature in Kelvin degrees). Below 40% of the melting temperature metals are rigid, between 40% and 60% they are subject to creep (slow deformation under a load), above 60% of the melting temperature they are unable to support loading. The four main bonding wires are copper, gold, aluminum and silver. Figure 1

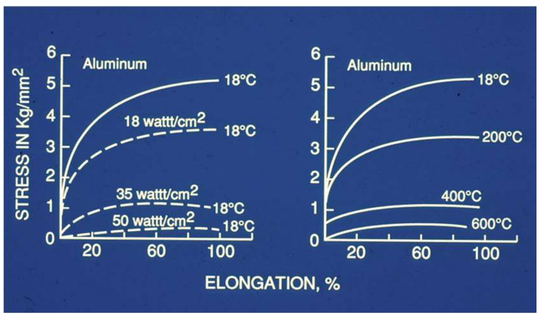
Figure 1. Homologous Temperature



Ultrasonics allows "easier" deformation by unlocking dislocation movement mechanisms, adding energy analogous to increasing temperature

shows a graph of the Homologous Temperature. It explains why we bond Al wire at room temperature and gold, copper at approximately 150^{0}C. In each case bonding is at approximately 30% of their respective melting temperatures and the metals have similar deformation properties. Ultrasonic energy provides the additional energy required for deformation and welding.

Figure 2 Langenecker Experiment

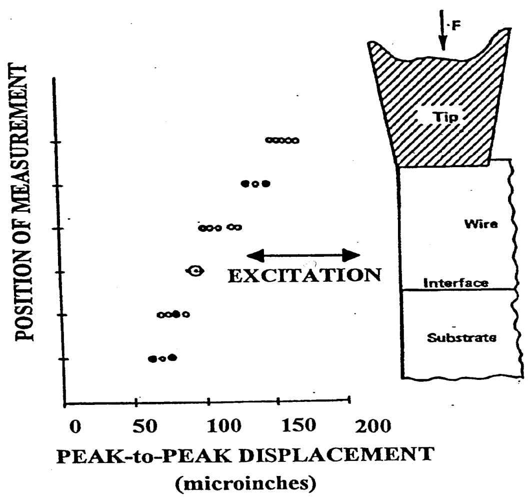


Ultrasonics- Langenecker[2] and Joshi[3]

Early work on the effect of ultrasonic energy on metal deformation was by Langenecker[2]. Using dog-legged Aluminum Instron tensile bars he mechanically deformed them over both a range of temperature and over a range of ultrasonic energy (room temperature). Figure 2 shows the effect. Langenecker showed that ultrasonic energy was analogous to the effect of heat on deformation, but the temperature did not increase. Langenecker showed that ultrasonic energy increased dislocation density allowing "easy slip" of dislocation planes. A load (force) was still required but it was significantly less than that required for the same deformation at room temperature.

Ultrasonic vibration (amplitude) is transmitted from a stack of piezo-electric crystals (piezo-electric crystals convert an ultrasonic electrical current to a mechanical vibration) through a tapered horn (the taper provides mechanical amplification) to the bond tool.

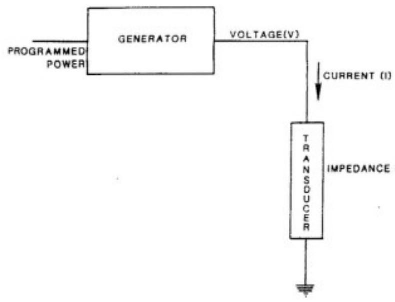
Figure 3 Joshi[3]: Laser Interferometry



- **No Displacement Discontinuity at bond Interface**
- **The interface "PINS" almost immediately, bonding is not friction welding**

Early work by Joshi[3] using laser interferometry looking for displacement discontinuities from a wedge bond tool tip to the bond interface explained "ultrasonic scrub". Joshi determined that at the tool/top of wire interface there was a discontinuity. The tool "scrubs" the top surface of the wire. At the wire/substrate interface the motion was different. Almost immediately (<2msec) the two surfaces pinned and there was no net difference in motion. There was no "scrubbing" at the bond interface. Once the surfaces "pin" together Langenecker's explanation that the two surfaces deform and mix together to form the intermetallic weld is applicable[4,5,6].

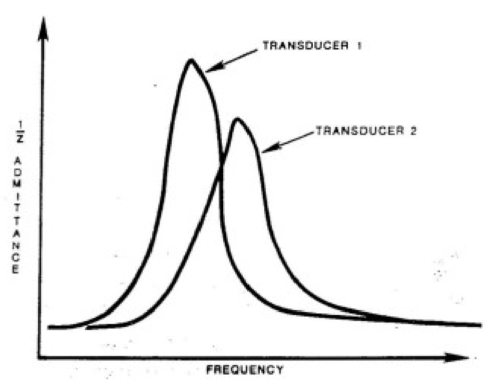
Figure 4 Ultrasonic Block Diagram



Ultrasonic Frequency

Langenecker[1] provides an equation for acoustic stress induced by an ultrasonic system, Stress is directly proportional with ultrasonic frequency. However, the realities of available ultrasonic systems also generate a significantly smaller ultrasonic amplitude at higher frequency. Ramsey[7], et al., found that significantly shorter bonding times could be used for equivalent bond strength. In general, the transition from 60kHz to 120kHz has been implemented. Normal ball bonding times have been reduced from 15-25mS with 60kHz systems to 10-15mS for 120kHz systems. A more important finding is that equivalent bond strength could be achieved with less deformation at the 120kHz system. Where 60-80% deformation was the standard for wedge bonding with 60kHz systems, 20%is now the standard for 120kHz. In ball bonding below 50µm bonded ball diameters 60kHz systems were unable to achieve tightly controlled deformation and achieve high reliability production. Most recent high-speed automatic wire bonders allow selection of 60 or 120kHz ultrasonics for individual bonds. It is possible to select 120kHz for ball bonds and 60kHz for second bonds.

Figure 5 Transducer Resonance



Control Mode

Figure 3 is a block diagram of the ultrasonic system. High frequency electrical signals are generated by the phase-locked loop ultrasonic board. Phase-locking is necessary because as small as a 5^0 difference in frequency off peak can result in a 95% loss in output. Figure 4 shows transducer Admittance (1/Impedance). Calibration of Impedance is required after every capillary change and if any part of the system is mechanically adjusted. Use of a calibrated torque gage is highly recommended. Designing a transducer to resonate cleanly at a specific frequency (or at frequency multiples such as 60 and 120kHz) without interference from stray modes requires significant FEM modeling.

Today most fine pitch bonding uses 120kHz systems and constant current control mode

Figure 6 Ultrasonic Control Mode

Constant Current or Constant Voltage?

- For impedance based systems Ohms Law is V=IZ where Z is the system impedance
- The best predictor of bond strength is ultrasonic amplitude, the displacement of the tip. Amplitude is proportional to I, the driving current

For Constant Current mode:
- During bonding Z increases as the bond pins to the surface and grows
- As Z increases the current stays constant therefore V also increases. Displacement is constant.

For Constant Voltage mode:
- During bonding Z increases as the bond pins to the surface and grows
- As Z increases Voltage is constant, therefore I must decrease. Displacement decreases as the bond forms.

- For fine pitch ball bonds constant current gives better control of the ball deformation and smaller bond variations.
- Some people believe that stitch bonding is better with constant voltage mode.
- Newer machines allow mode choice for each bond.

for driving ultrasonics. Figure 6 compares Constant Current vs Constant Voltage control modes. Constant current has proven to provide much better ball size control for very small ball bonds. Constant voltage is sometimes used for second bonds. They are operator selectable.

Cratering and deep level fractures

Cratering is fracture of the die and bond pad metallization. It can be a deep fracture that lifts a divot of Si die material or with multilayered bond pad metallization[8] it can be a small fracture several layers below the bond pad. Fractures below the surface are not immediately apparent and through electromigration can lead to device failure by “dark” currents and current leakage. Craters are revealed by etching the bonds from the die (KOH or NaOH for Al bond pads) and examining for cracks or wrinkles in the metallization. Multi-layered bond pads require more detailed procedures or FIB to determine the failure location.

The dominant variables effecting cratering are bond pad metallization[9] and ultrasonic energy. Aluminum- 1% Si bond pad metallization is not stable. Over time and at elevated temperature Si precipitates out of the matrix as pure nodules. In die that have a thermal SiO_2 layer directly below the bond pad the nodule welds itself to the thermal oxide layer. Any minor ultrasonic-vibration fractures the nodules attachment nucleating a fracture. Fracture growth requires much less energy than nucleation and results in a crater. Koch demonstrated that the use of thin, barrier metal layers like Ti, W, Ti-W between the thermal oxide layer and the Al-Si bond pad resolved the cratering problem. The Si nodules still precipitate but the barrier layer prevented attachment and fracture nucleation.

Of the programmable bonding parameters ultrasonic energy has the largest effect on cratering. Adjusting parameters to minimize ultrasonic energy (smaller bonded ball diameter, higher bond force, higher temperature, longer bond time, thicker bond pads) can help mitigate the effect of ultrasonic energy.

Conclusions and Guidelines

Although market share has been lost to Flip Chip over the past 10 years, wire bonding still represents the largest portion of semiconductor interconnection. Between 75-80% of all packages are wire bonded. It is a complex welding process, joining two metals to form an intermetallic (or mono-metallic in some cases) weld. Understanding the process requires knowledge of materials, mechanics and statistics. My guidelines for understanding a failure are:

1. Try to determine where within the bond cycle the process is failing.
2. Close examination by SEM with EDS is almost a necessity. Look at both sides of the failure.
3. Look for signs of mechanical damage along the wire loop.
4. Review pull test and shear test data. Pull testing[10] is all resolution of forces. If the pull test hook is placed above the ball, second bond is not adequately tested and may in fact be very weak.
5. Designed experiments are necessary for understanding the process. The principal parameters effecting bonding are: ultrasonics, bond force, temperature and bond time (in order of the strength of their effects). However, many other material, setup and mechanical factors can be critical.

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