Understanding the Role of Ultrasonic Welding in Wire Bonding

Lee Levine
Process Solutions Consulting, Inc.
8009 George Road
New Tripoli, PA 18066
Ph: 610-248-2002
Email: levilr@ptd.net

Abstract

Wire bonding is the dominant chip interconnection method. Ultrasonic energy is the most important bonding parameter effecting the quality and the reliability of the intermetallic weld. Understanding the mechanism enabling weld formation is a key factor in maintaining the reliability and productivity that wire bonding provides.

Key words

Wire Bonding, Interconnects, ultrasonic bonding, ball bonding, wedge bonding, ultrasonic welding

I. Introduction

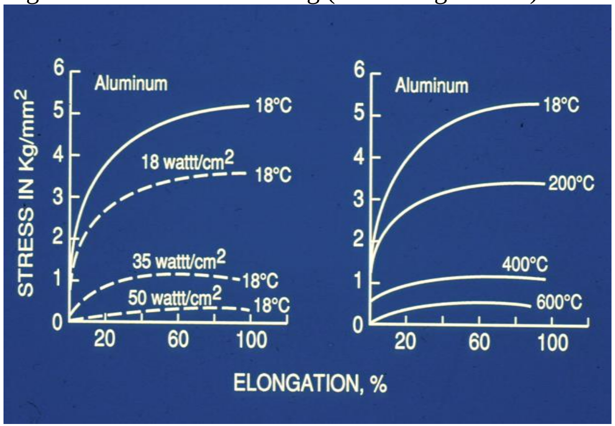
Wire bonding is a high-speed ultrasonic welding process that produces almost 90% of all chip interconnections. More than 15 trillion wires are bonded annually. Copper, palladium coated copper and silver wires will capture 51% of the market share in 2015. The transition away from gold wire continues and it is unlikely that the industry will return to gold usage for the majority of devices. Ultrasonic energy is the principal process parameter affecting the deformation of the ball and the bond pad or substrate[1, 2]. Deformation of both the ball and the bond pad are required to form the intermetallic weld. Understanding of the process and the effect of ultrasonic energy on the deformation behavior of the materials is a key to achieving high-yield, high-reliability interconnections.

In welding, materials are joined to form an alloy composed of the materials to be joined. In the case of a wire bond, the wire and the bond pad are joined to form the intermetallic alloy. Intermetallics are normally stronger than either of the constituent materials. Once they achieve equilibrium their chemistry can be described by phase diagrams (describing the distribution of stable compounds (phases) that can be formed) and their thermal-mechanical history dictates the transformation reactions of these phases.

II. Discussion

Ultrasonic energy changes a materials mechanical properties. Figure 1 shows a series of experiments using standard aluminum tensile test bars[3]. In each case an aluminum tensile bar was exposed to either elevated temperature or ultrasonic energy. The samples exposed to ultrasonic energy were held at room temperature during the test. The experiments showed that increasing ultrasonic energy allowed deformation at reduced stress. This was analogous to the materials behavior when heated, however, the material remained at room temperature. Ultrasonic energy is absorbed preferentially at dislocations (defects) in the crystal lattice increasing both the density and mobility of dislocations. The movement of dislocations within the lattice enables a material to deform. When the ultrasonic energy is turned off the material returns to its original state. Hardness is a measure of a materials resistance to deformation. Deformation can also strain harden a material.

Figure 1 Ultrasonic Softening (from Langenecker)



The material can behave as if additional deformation had occurred and retain the additional hardness. Hardening of bond pad metallization during first pass bonding often makes attempts at rework fail, more power is required to form the weld on the hardened location.

Figure 2. Block Diagram of the Ultrasonic System

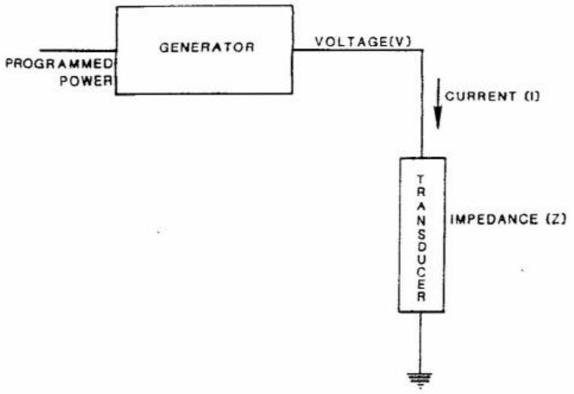
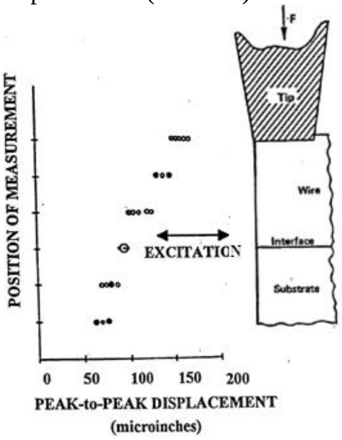


Figure 2 is a block diagram of an ultrasonic system[4]. The generators on all modern wire bonders are Phase Locked Loop (PLL) designs which latch the ultrasonic generators resonance to the resonance frequency of the transducer. Driving the system with a frequency shift of as little as 36 Hz between the generator output frequency and the transducer resonance frequency can result in a loss of over 15% of the energy output. They must work together at their peak admittance for proper functionality. Today transducer and generator design is well controlled in order to achieve uniform performance across large factories with many bonders. Transducers are designed using FEM (Finite Element Analysis) to control resonance frequency (or multiple resonance frequencies in some frequency switchable designs). The displacement of the transducer tip is designed to act along a single axis. Double resonances and amplitude components that bounce or twist the transducer during bonding are unacceptable. The generator-transducer-tool system is recalibrated at every tool change to control the system impedance. The calibrated impedance is used to achieve uniform output across the factory. Tools are benched against a fixed stop built into the transducer and the tool clamping screw is tightened with a torque watch to control system impedance. Slight differences in tool mounting and tightening would result in excess process variation. In facilities where all machines are required to operate with a narrow process window this would be unacceptable.

Figure 3 Laser Interferometer Measurements of Displacement (K. Joshi)



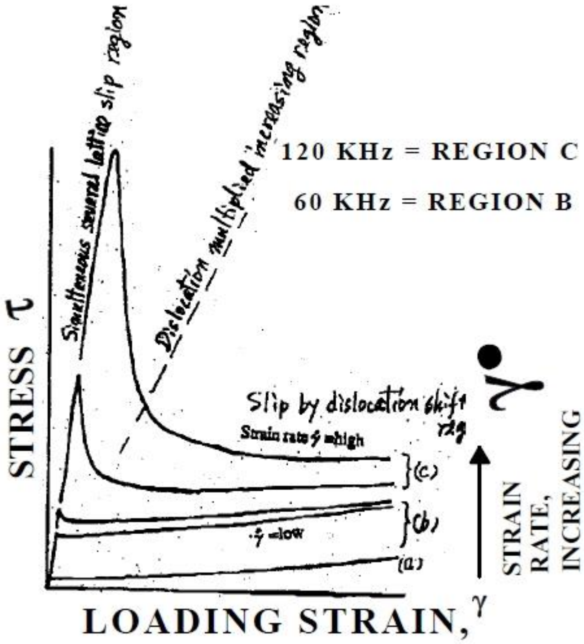
Note- No Displacement Discontinuity at Interface

The interface "PINS" almost immediately, bonding is not friction welding

Most modern wire bonders allow programmable ultrasonic control modes. For an impedance based system Ohms Law translates as Voltage = I (current) * Z (total system impedance). Control systems are normally run in either constant current or constant voltage modes. The best predictor of bond strength is ultrasonic amplitude, the displacement of the tool tip. Amplitude is proportional to current. Impedance (Z) changes during the bonding cycle. It increases as the two surfaces pin together and the bond size grows. In constant current mode the ultrasonic generator output is a constant current, as Z changes the current is held constant therefore V increases as Z increases, keeping displacement of the tool tip constant. In constant Voltage mode as Z increases I decreases. Displacement of the tool tip decreases as the bond forms. For fine pitch ball bonds with very small diameter balls constant current gives better control of ball deformation and results in less ball size variation. Constant voltage mode is sometimes useful for second bond. Lower amplitude as bonding progresses helps reduce breakage of the bond at the heel of second bond reducing machine stoppages for short tails. Newer machines allow programming ultrasonic mode for each bond. In addition some newer machines have been designed so that the transducer has dual frequency modes (both 60 kHz and 120 kHz are an example). The user can program each bond independently for the desired frequency and control mode. The software will drive the transducer to resonate according to the programmed choice.

The term "ultrasonic scrub" is often used incorrectly to describe the motion of the ball or wire on the pad. The image of rubbing your hands together and feeling heat from the friction is a bad analogy for the action at the bond interface. Figure 3 is from early laser interferometer work published by K. Joshi[5]. He measured the motion of tool and wire as the beam moved down a polished wedge and across the face of the wire to the die edge, looking for a discontinuity at each interface. A discontinuity would mean that there was independent movement at each side of the

Figure 4 The Effect of Strain Rate (K. Otsuka)



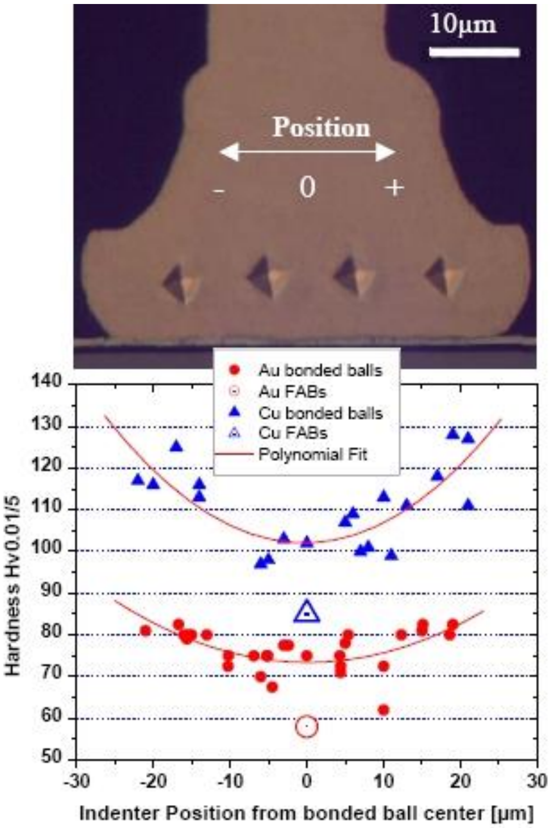
interface. No discontinuity meant that the two surfaces were moving together. Joshi demonstrated that at the tool-wire interface there was discontinuity. The tool was moving independently, scrubbing the top surface of the ball or wire. At the wire-die interface the two surfaces pinned almost immediately (<2ms). After pinning the two surfaces continued to move but they were pinned together.

There has been much discussion over the optimum bonding frequency. Langenecker gives us the equation for ultrasonically induced stress as directly proportional to frequency and intensity (amplitude). However, most high frequency transducers also have significantly lower displacement amplitude. The result is that the energy output is approximately equal. In Figure 4 Otsuka[6] explains that strain rate for a high frequency ultrasonic systems is significantly higher than for low frequency systems. Materials subject to high strain rate deformation exhibit much higher yield/flow stress. For fine pitch bonding, where the ultrasonic energy needs to transfer to the wire/bond pad interface in order to deform the bond pad and produce a weld nugget the higher frequency ultrasonic energy has a benefit. For both wedge and ball bonding, smaller full strength bonds can be produced with high frequency ultrasonics (120kHz) than can be produced by lower (60kHz) ultrasonics. For wedge bonding high frequency bonds with bond width 1.2x wire diameter will have full strength. Low frequency bonds will require approximately 1.75 x wire diameter to achieve the same strength.

III. Copper Wire Bonding

The past 5 years have seen a landslide transition from gold wire bonding dominating the wire bonding marketplace to copper ball bonding achieving > 50% market share. Copper is harder and stronger than gold. During the bonding process copper strain hardens (becomes more resistant to deformation) and requires more energy to continue deforming. Figure 5 is a photo of a deformed ball with Vickers hardness indications across its diameter[7]. Copper is harder than gold even in its undeformed state. The hardness of the Free Air Balls (FAB, undeformed balls) demonstrates this property. It can also be seen that the increase in hardness as distance increases from the ball center is much greater in copper than in gold (strain hardening). Increasing bonding energy by ramping up ultrasonic power and bond force is an important factor in copper bonding.

Figure 5 Strain Hardening During Ball Deformation (K&S)



IV. Process Mechanism Description

A description of the bonding process would be: The tool and wire (ball or wedge) move toward the bond pad and impact with the pad. Impact force is sufficient to deform the ball or wire and the pad, flattening them and pushing them into contact. Ultrasonic energy is switched on, the tool vibrates with the amplitude of the ultrasonic energy applied. Almost immediately the wire and pad surfaces are pinned together and there is no relative motion between them. Ultrasonic energy changes the materials properties of both, lowering the yield (flow) stress and allowing massive deformation at lower stress and lower temperature than would otherwise be possible. As the wire and pad deform massively new surface is generated. The new surface is clean and oxide free (oxides are trapped on the old surface between slip planes). Clean oxide free surfaces in intimate contact bond readily. Initially the bond is a mixture of the two materials. It does not have the stoichiometry and crystal structure of the equilibrium phase diagram, however very quickly transformations to the stable equilibrium phases occur.

V. Conclusion

Wire bonding will continue to be the dominant chip interconnection method for the foreseeable future because of its low cost, flexibility, reliability and large established infrastructure of equipment, people and knowledge, Ultrasonic bonding will not only continue as the principal driving energy of wire bonding but will be used to attach flip chip and other advanced packaging interconnections. Understanding the mechanism by which the interconnection is formed is vital to producing highly reliable and repeatable welds.

VI. References

[1] L. Levine, “The Ultrasonic Bonding Mechanism: Two Theories Converge” Proc. ISHM 1995, pp 242-246
[2] G. Harman, J. Albers, “The Ultrasonic Welding Mechanism as Applied to Aluminum-and Gold- Wire Bonding in Microelectronics”, IEEE Trans. Parts, Hybrids and Packaging, vol PHP13, No. 4, Dec. 1977
[3] B. Langenecker, “Effects of Ultrasound on Deformation Characteristics of Metals”, IEEE Transactions on Sonics and Ultrasonics, Vol. SU-13,1, March 1966
[4] G.N. Shah, L.R. Levine, D.I. Patel, “Advances in Wire Bonding Technology for High Lead Count, High-Density Devices, Proc. IEMT, Oct 1987
[5] K.C. Joshi, “The formation of ultrasonic bonds between metals”, Welding J, vol50, pp. 840-848, Dec 1971
[6] Y. Shirai, K. Otsuka, T. Araki, I. Seki, K. Kikuchi, N. Fujita, T. Miwa, “High Reliability Wire Bonding by the 120KHz Frequency of Ultrasonic”, ICEMM Proceedings, 1993, pp. 366-375
[7] F.W. Wulff, C. Breach, D. Stephan, Saraswati, K. Dittmer, Michel Garnier, “Further Characterisation of Intermetallic Growth in Copper and Gold Ball Bonds on Aluminum Metallization”, Proceedings Semicon Singapore, 2005