“Closed Loop” Study for Wire Bonding Process

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Abstract:

Presently, in standard and some fine pitch wire bonding applications, the methods for checking the bond quality during volume production still remains the same. The inspection methods used to determine the quality of the bonds have proven to be acceptable and reliable for many current industrial needs are ball shearing, measuring the ball diameter and wire pull measurement. These methods are acceptable, but as the semiconductor sector moves towards ultra fine pitch wire bonding, data obtained by these conventional methods may not be sufficient. As the bonded wires per device increases and the size of the bond decreases, the interaction between machine, bonding tool, material and method has become much more sensitive. This paper discusses the use of a “closed loop” wire bonding study to analyze this area.

Introduction:

The ultra fine pitch applications are commonly done on high frequency wire bonder, which produces smaller displacement but at higher cycle rate as compared to the conventional bonder. Depending on the power setting on the bonder, the ultrasonic energy in the form of vibration or displacement is transmitted directly from the transducer through the capillary to create the necessary ball deformation. Unlike bonding on non-fine pitch devices, which can accommodate a wide range of ball size variation due to the large pad opening, bonding on ultra fine pitch (UFP) devices required the ball size to be controlled within a much tighter tolerance. In most cases, a variation of +/-3µm of the eventual ball size is considered acceptable. Given the tight bonding process requirement, optimum capillary design and machine performance is necessary to achieve a reliable bond process control.

Objective:

The intent of this paper is to establish the feasibility of using a “closed loop” wire bonding study mainly for fine pitch and UFP bonding application. The study incorporates the use of a laser vibrometer, wire bonder, the bond process analyzer (BPA) and the physical quality checking of the bonds. By using the “closed loop” study, verification on design ideas, bonding set-up and conditions can be done at 3 different stages (pre bonding, during bonding and post bonding). These data obtained at different stages can used to justify the actual bond achieved.

Principle of “closed loop” studies:

The set-up of the monitoring system used for the studies is illustrated in Figure 1. It consists of a PC base laser vibrometer and a BPA connected to the output of the ultrasonic generator and the input to the transducer.

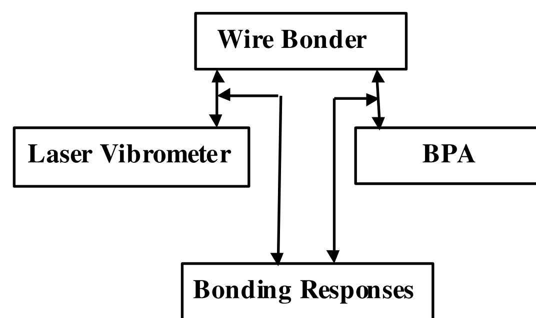

Figure 1: “Closed loop” monitoring system

Actual bonding was performed on an ESEC 3008 wire bonder using a 25µm Au wire. For the visual inspection and measurement, a high power microscope of 0.5µm resolution was used for ball height, and ball size measurement. Ball shear measurement was performed on the ball shear tester with a shear height of 3µm.

Laser Vibrometer

In wire bonding, the bonding tool vibration amplitude is the most important parameter which influences the energy delivered to the bond zone. The amplitude of such nano scale vibration is measured with a laser vibrometer (Figure 2), which utilizes a 3mW helium-neon laser and is aligned perpendicular to the bonding tool. Capillary movement during bonding is feed back to the system, which displays vibration amplitude directly as shown in Figure 3.

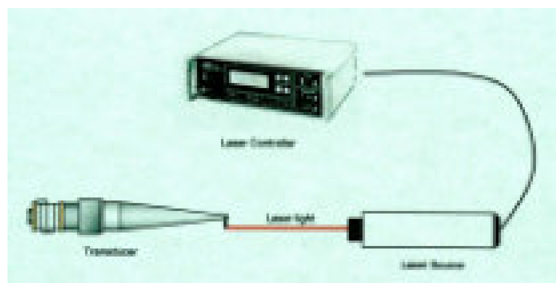

Figure 2: Laser vibrometer set-up

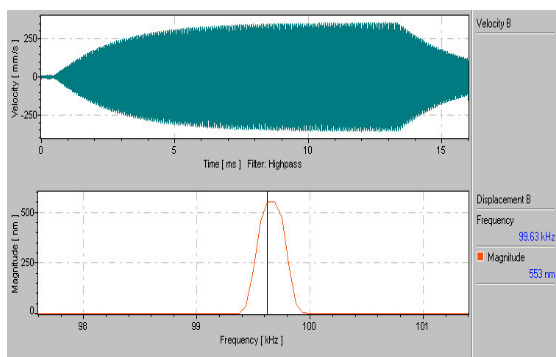

Figure 3: Ultrasonic displacement for a good waveform

Bond Process Analyzer

During bonding, the impedance at the bond surface changes continuous with time. Depending on the surface condition, the vibration characteristics of the capillary and transducer changes accordingly. The BPA can be used to read the changes in the ultrasonic impedance in real time during wire bonding. The system analyzes the bonding result and the change in the ultrasonic parameters statistically to accumulate the changes, and to determine the bond quality by the extent of the changes. The set-up for the equipment is shown in Figure 4.

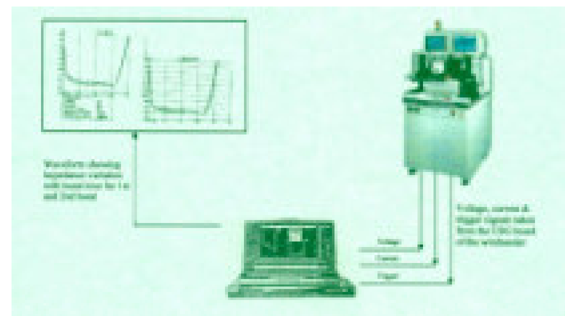

Figure 4: Schematic Diagram for BPA set-up

Capillary Optimization:

During the formation of the ball bond, many factors influence the consistency of the ball deformation. Factors such as machine parameters, capillary material and design have a significant effect on the desirable ball size. Traditionally, capillary selection was based on device type and wire size. In most wire bonding applications, a cone shape ceramic capillary with a taper angle of 20 or 30deg has been utilized and deemed suitable for most devices. With the increase demand for UFP bonding application, which requires a small and consistent ball deformation, current capillary material and design configuration has to be re-defined and optimized.

Initial studies have indicated that the main taper angle (MTA) of the capillary has the most significant effect on the bond stability and consistency. Although other factors, such as tip diameter (T) and bottleneck angle (BNA) can also influence the capillary

characteristic, this is normally dictated by the bond pad pitch (BPP) of the device.

Figure 5: Profile of a Bottleneck Capillary

To further understand the characteristics of the capillary used for UFP bonding, interaction between the laser vibrometer and the wire bonder was set-up. In this experiment, the ultrasonic behavior of Cap A (20 MTA) and Cap B (50MTA) was investigated with real time bonding. Bonding parameters was set at, Force=140mN, Time=10msec, Power=9.4%. This parameter setting was based on the actual bonding characterization on a 60µm BPP. platform.

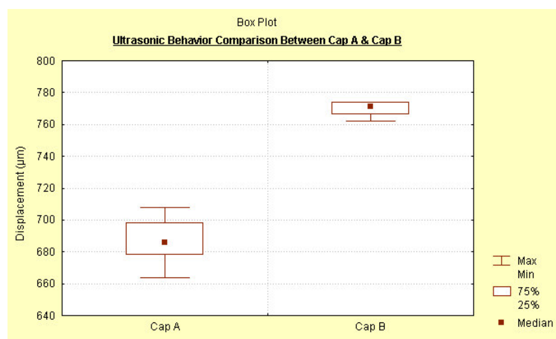

Figure 6: Ultrasonic behavior comparison between Cap A and Cap B

In wire bonding, it is necessary to ensure that maximum ultrasonic vibration occurs at the tip of the bonding tool for optimum performance. In addition, a consistent ultrasonic displacement with a minimum standard deviation (SD) is necessary for consistent ball deformation. In actual fact, the intent is have a stable bonding response insensitive to a wide range of process variables. From Figure 7, it can be seen that lower ultrasonic displacement was obtained for Cap A design as compared to Cap B. The higher SD observed was verified from the actual bonding responses, which indicates a higher ball shear fluctuation. Lower ball shear reading was obtained for units bonded with Cap A with higher occurrence of ball lifted failure mode. This observation correlates with the lower ultrasonic displacement seen earlier. During bonding, a 3% ball non-stick was also noticed with smaller ball deformation as shown in Figure 8.

	Cap A	**Cap B**
Ultrasonic displacement, nm SD, nm	688 14.4	770 4.6
Ball size, µm SD, µm	42.1 0.6	43.0 0.5
Ball height, µm SD, µm	10.0 1.0	10.4 0.9
Ball Shear Reading, gmf SD, gmf	16.6 2.4	19.2 1.6
Failure mode: Ball Shear Ball Lift	 58% 42%	 73% 27%

Figure 7: Bonding behavior comparison between Cap A and Cap B

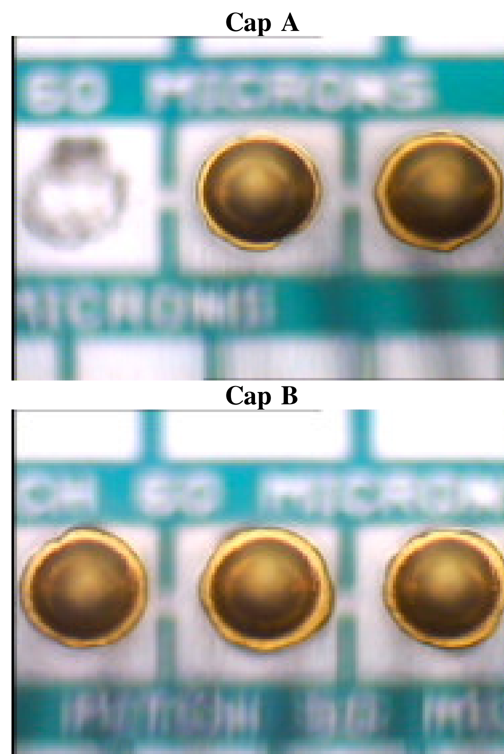

Figure 8: Ball size comparison

Process Optimization:

In wire bonding it is important to achieve a robust operating window. This means that there should not be any drastic change in the response within the specified parameter range. Currently, the only way to observe this is after bonding (during the ball size measurements). However, the situation can be improved by incorporating the laser vibrometer as a monitoring system to study the displacement of the capillary during bonding.

Again, the study was based on the characterization report done for the 60µm BPP by SPT. Only the response of the ball bond was monitored and the optimized ball bond parameters are:

Bond Power : 8.4 - 10.0%
Bond Force : 140 - 170mN
Capillary Type : Cap B

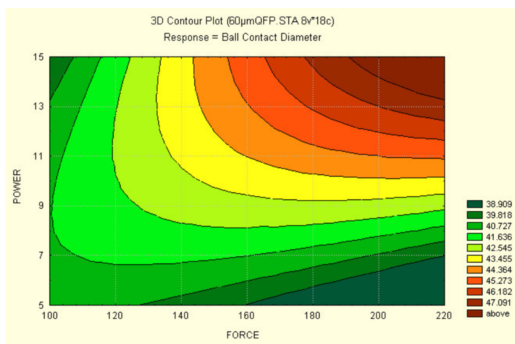

Figure 9: Contour plot for bond force and power

From the optimized parameter range, the responses were monitored with the result as shown in Figure 10. Results obtained shows that for all the possible combinations for bond force and bond power, there is no drastic change in the displacement. This indicates that the selected process window is situated in the stable region.

Bond Force : 140mN	Displacement (nm)
Bond Power : 8.6%	
Average	684.4
Std Dev.	1.7
Bond Power : 9.0%	
Average	725.2
Std Dev.	1.8
Bond Power : 9.4%	
Average	768.0
Std Dev.	1.1
Bond Power : 9.8%	
Average	809.2
Std Dev.	2.3

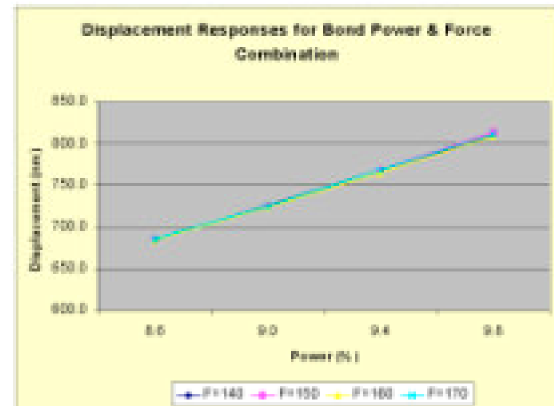

Figure 10: Displacement comparison for different bond power and force combination

This method of monitoring can be extended for bonder to bonder portability and compatibility. Theoretically, by getting the same ultrasonic displacement as a function of bond power and bond force, the ball deformation should be similar even though the machine settings might be different.

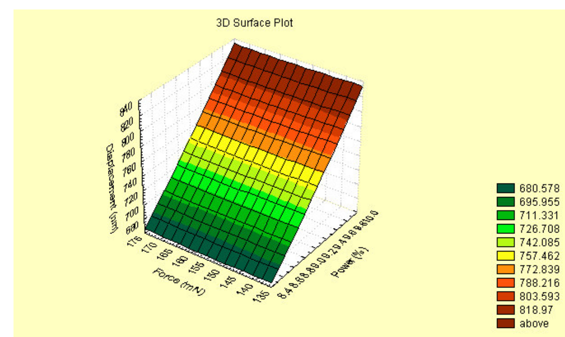

Figure 11: Relationship between bond power, bond force and ultrasonic displacement

In Process Monitoring:

In the industry, bond quality measurement has all along been accessed through visual inspection and destruction test and ball shear is

the predominant method used for such test to determine the bond strength. A good bond can be defined as one that has a high shear value with Au residue left on the bond pad after the ball shear test. As the bond pad pitch and ball size requirements becomes smaller, process robustness decreases as the process variables and other uncontrolled factors become more sensitive. These wide ranges of variables can affect the ball size and ball shear readings resulting in unreliable bonds. In some cases, failure at the bond interface is only noticed during the reliability test.

To understand the effect of such variables on the bond quality, a BPA can be incorporated to the bonder, which captures the change in impedance during actual bonding. The representation of a good bond in time domain is shown in Figure 12. Point 1 indicates that at time 0, the impedance is at infinity. Point 2 indicates the diffusion of the Au ball with the Al pad with the application of power and force. Point 3 indicates a sudden drop in impedance when the voltage is cut off but the current remains.

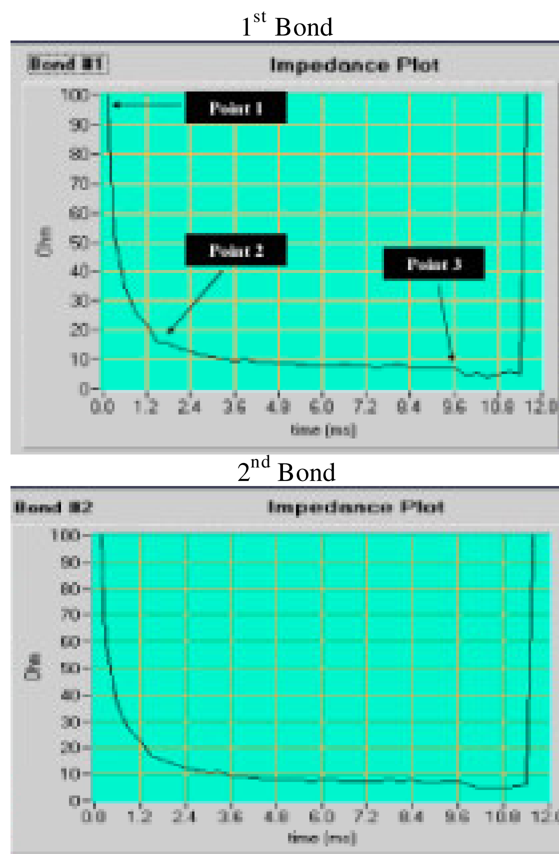

Figure 12: Wavefom for a good bond

To investigate the feasibility of using the BPA for in-process monitoring, data obtained from the BPA was correlated with the actual bonding responses. In this experiment, Cap B was selected based on the positive results obtained earlier and the bonding parameter was set at, Force=140mN, Time=10msec, Power=9.4%. To simulate the effect of bond surface variation due to contamination or other causes, bonding was carried out on different bond surface conditions (good and defective) and the impedance in time domain was recorded at 0.6, 2.4, 4.8, 7.2, and 9.6msec as shown in Figure 13.

	Good	**Defective**
Impedance at:		
0.6 msec		
Ave,Ω	46.3	44.3
SD, Ω	5.9	5.6
4.8 msec		
Ave,Ω	9.0	9.2
SD, Ω	0.2	0.3
9.6 msec		
Ave,Ω	7.2	7.3
SD, Ω	0.3	0.4
Ball Size		
Ave,µm	44.0	40.2
SD,µm	1.0	0.5
Ball Shear		
Ave,gmf	19.2	15.5
SD,gmf	0.8	2.2

Figure 13: Bonding behavior comparison between a good and defective bonding surface.

From Figure 13, it can be seen that the variation in impedance between the good and defective bond surface can affect the eventual ball size, ball shear, and SD readings. The change in impedance at the bond interface changes the vibration characteristic of the capillary resulting in different bonding responses.

Lower ball shear readings obtained for the defective surface is due to the non-uniform or poor intermetallic diffusion between the Au and Al pads. This was caused by the loss in ultrasonic power while trying to overcome the various oxide and contamination layers on the Al pad surface before any intermetallic can be occur.

For a reliable bond quality, it is important that the bond surface is free from contamination and other foreign material. Sources of contamination, such as oxidation of Al pad, epoxy out-gassing during curing, etc can degrade the bond quality. Although the source of contamination can be identified by analytical equipment such as the Energy Dispersive X-Ray Spectroscopy (EDS), it is not possible to incorporate such analysis for volume production. In this case, a BPA can be used for real time monitoring.

Conclusion:

With the use of the closed loop system, it has become possible to design and optimize a suitable capillary using the laser vibrometer and the actual bond monitoring through the BPA. Despite the fact that this technique has proven to be feasible, more in-depth study is needed to improve on the accuracy and robustness of the system.

Although the study is mainly focused on the ball bond, this can be extended to the stitch bond, which can be useful for machine set-up for leaded devices or material characterization for BGA substrate.

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