Acoustic Metrology for Fine Pitch Microbumps in 3DIC

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***Abstract* – The continuing shift to 3D integration requires formation of electrical interconnects between multiple vertically stacked Si devices to enable high speed, high bandwidth connections. Microbumps and through silicon vias (TSV) enable the high-density interconnects for die-to-die and die-to-wafer stacking for different applications. In this paper, we present acoustic metrology techniques for the measurement of multi-layer microbumps. One of the techniques, PULSE™ technology, is a very well-established mature solution for metal film thickness measurements. Repeatability and accuracy of the measurements more than adequately meets the process requirements. We also present a second nondestructive acoustic metrology for measuring taller copper pillars (> 30µm).**

Keywords: microbump, acoustic metrology, picosecond ultrasonics, advanced packaging

I. Introduction

With the approaching limitation of Moore's law scaling, the semiconductor industry has turned to advanced packaging technologies to meet high-performance computing needs. 3D integration and formation of electrical interconnects between multiple vertically stacked Si devices have enabled high speed, high bandwidth connections. Microbumps and through silicon vias (TSV) are the key architectural elements for die-to-die and die-to-wafer stacking as they improve performance of the complete system. Typical solder height is 15-30µm in Cu pillars and it is expected to scale down to less than 10µm in 20µm pitch interconnections. Solder based, fine pitch, microbump connections are preferred mainly due to lower bonding temperature compared with Cu-to-Cu thermo-compression bonding. However, with reducing bump dimensions, several critical reliability issues arise such as the small solder volume transformation and conversion to complete intermetallic compound (IMC), during thermocompression bonding. Studies have also shown that for a 20µm microbump the current density can reach values that are significantly higher than the threshold value of Sn electromigration (EM) and the failure mechanism in microbumps are different from traditional flip chip bump. Two main EM failure mechanisms are reported: void propagation along the IMC/solder interface and the dissolution of under-bump-metallization (UBM) [1-4].

From a bump processing standpoint, it is common to plate multi-metal films on the same equipment to minimize oxidation between metal depositions as well as to increase production flexibility and minimize risks due to equipment downtimes. Thickness information on microbumps (<30µm) are currently obtained from either step height measurements, X-ray techniques or cross-section microscopy. While these tools provide information in the form of indirect thickness, or Ag concentration in solder, they cannot be adopted for in-line monitoring in a high-volume manufacturing environment. The scaling microbumps also require a technology with a small measurement spot size to be able to position and measure on individual microbumps. Small spot (~10µm) picosecond ultrasonics (PULSE™) is well established in wafer fabs for metal film thickness measurement. The capability of the technique to measure UBM and redistribution layers (RDL) has been previously reported [6]. In this paper, we review microbump characterization using this technique. Additionally, we also used a second independent acoustic metrology tool to validate the results in this thickness regime and as an extension of capability of the technique for taller pillars.

II. Methodology

Picosecond ultrasonic metrology is a pump-probe technique. We have previously [6] discussed at length the underlying principle and measurement setup of the standard configuration. Interested readers are referred to those publications. In the standard configuration, the pump beam is modulated at 5.5MHz, probe beam is unmodulated and the signal is demodulated at the same frequency as the pump beam modulation frequency. The rough surface of the films scatter the measurement beams excessively, thus increasing the noise and reducing the overall signal to noise ratio (SNR). To overcome some of the challenges of the rough surface in the standard configuration, site averaging is performed by adding additional measurement sites (mini maps) to average the local surface roughness with impact to throughput. In this study, we used a dual modulation setup (Fig 1). The pump beam was modulated at 5MHz, the probe beam was modulated at 0.5MHz and the signal demodulated at 5.5MHz. Any scattering from both pump and probe beams was filtered out. The technique is currently capable of measuring films from 40Å to 30µm, depending on materials. This method is well suited for measuring the microbumps, because of the small spot size. Feasibility of further reducing the measurement spot size has been tested, hence making it attractive as microbumps undergo further scaling.

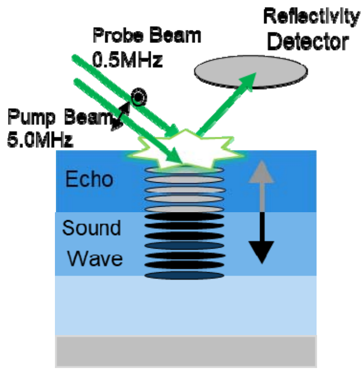

Fig. 1. Modified picosecond ultrasonic configuration with dual modulation.

The PULSE technique is currently limited to 30µm. However, to measure taller pillar bumps >30µm up to 100µm or so requires a different configuration. In an earlier paper [5, 6], we described an alternate in-line acoustic technique using the SONUS™ System for measurement of copper pillar thickness as well as void detection in TSV. Briefly, in the second set up, a pulsed laser source, 532nm, is used to excite high frequency ultrasound on the pillar samples. Optical absorption leads to heating of the pillar surface and subsequent thermoelastic expansion produces ultrasound waves that propagate through the structure and couple into resonant vibrational modes. A Michelson interferometer with a continuous wave laser operating at a wavelength of 660nm detects the displacement of the pillar surface following laser excitation. The detected signal is post-processed using Fourier Transform to determine the vibrational mode frequencies. These frequencies are sensitive to pillar geometry (diameter and layer thicknesses) and the mechanical properties of the layers. Using time domain finite element modeling (FEM) with the PZFlex code (Weidlinger Associates, Mountain View, CA) we were able to relate the measured vibrational mode frequencies to pillar parameters. The inline solution is not expected to involve running the FEM modeling in-line. FEM is only used to provide relationship between the modes identified in the measurement and parameters of the pillar.

We measured the current set of samples on a second experimental setup to establish the capability of that technique for such measurements and to bridge the capability between the two techniques. Microbump samples consisting of a skew of bilayer thickness of SnAg/Cu and SnAg/Ni with 1:1 ratio of bump diameter to thickness was investigated. Tri-layer (SnAg/Ni/Cu) microbump samples, ranging in total thickness from 3µm to 30µm were used for the study.

III. Results

A. Analysis of data from PULSE Measurements

Shown in Fig. 2a and 2b is signal from bi-layer SnAg/Cu films from pillars with diameter of 22µm. Each measurement is collected from a single pillar. The positioning accuracy is better than 1µm. Figures to the left (2a) (top and bottom) represent the raw data with corresponding modeled data to the right (2b). In Fig. 2b top graph echo position ~490ps corresponds to SnAg thickness of 2.3µm and echo ~1400ps corresponds to a Cu thickness of ~2.1µm, respectively. In Fig. 2b bottom graph, SnAg and Cu echoes are ~1400ps and ~3800ps and the corresponding thicknesses are 4µm and 5.1µm, respectively. Shown in Fig. 3a is raw data from the trilayer microbump from pillars with 16µm diameter. Echoes corresponding to SnAg, Cu and Ni (indicated by arrows in that order) are identified in Fig. 3b. Thickness of SnAg, Cu and Ni are ~ 2.2µm, 0.5µm and 1µm, respectively.

In addition to the data presented in Fig. 2a and b even thicker bilayer samples were measured using both PULSE and SONUS techniques for comparison. Measurements were carried out on individual pillars first using the PULSE technique and then the same exact pillars were measured using the SONUS system. The target thicknesses for these pillars are 6µm for SnAg and 10µm for Cu.

Typical load/unload repeatability is 3sigma <2% for each of the layers at site-level. Within wafer repeatability (averaged over 9 pillars) performance is much tighter at <1%. Repeatability is the average of 10 measurements on the same pillar with wafer unloaded and reloaded in between measurements. Fig. 4a shows the data from thick bilayer (SnAg ~6um and Cu ~10um) and Fig. 4b shows data from the microbump trilayer sample. The signal SNR from trilayer microbump sample was better than that from the bilayer sample due to differences in surface roughness.

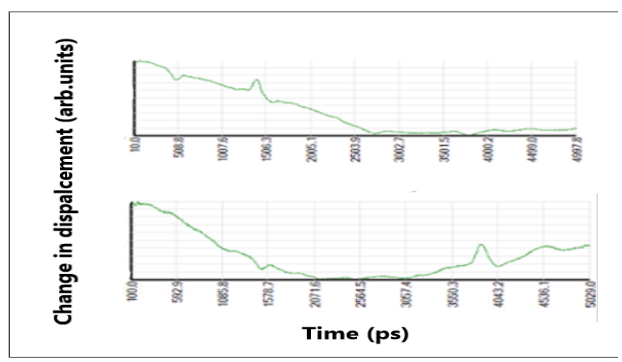

Fig. 2a. Raw data from SnAg/Cu films. Top and bottom figures correspond to different samples in the skew.

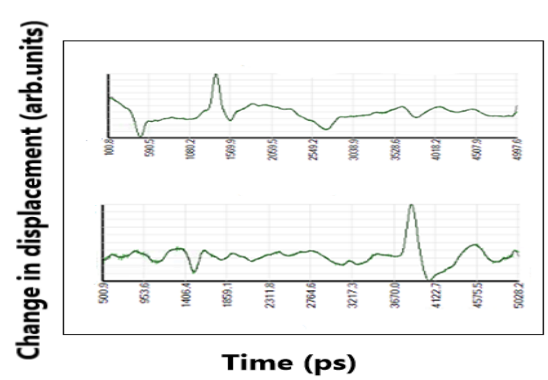

Fig. 2b. Thermal background-subtracted data from the bi-layer films. Modeled fit (black) to measured data (green) shown.

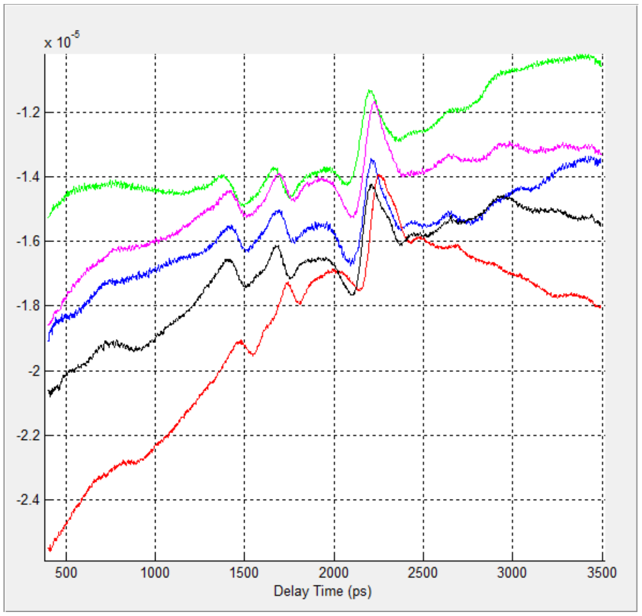

Fig. 3a. Raw data from tri-layer bump stack. The different traces represent multiple sites across the wafer. Variations in echo positions correspond to cross wafer variation.

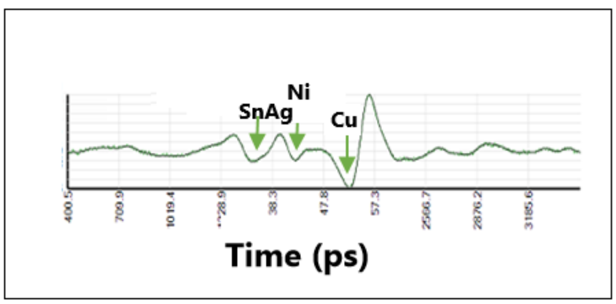

Fig. 3b. Thermal background subtracted data with echo positions from the tri-layer identified. The three arrows correspond to SnAg/Ni/Cu, respectively.

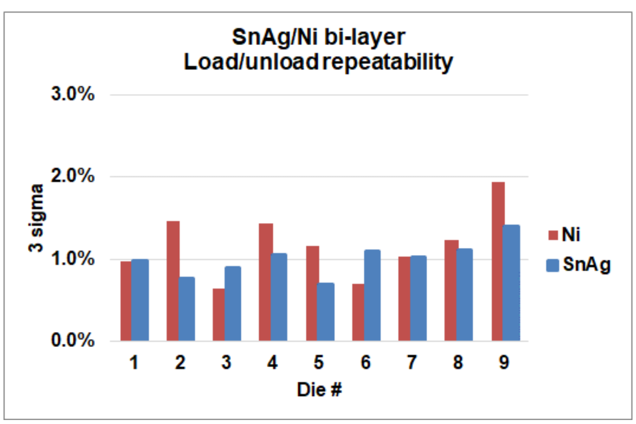

Fig. 4a. Load/unload repeatability of bi-layer measurements.

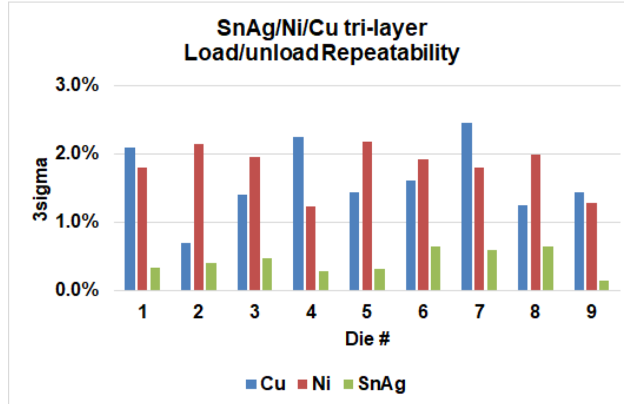

Fig. 4b. Load/unload repeatability of tri-layer measured simultaneously.

B. Analysis of data from the SONUS System

Shown in Fig. 5a is the time domain measurement signals from the SnAg/Cu microbumps and Fig. 5b is the Fourier transformation of the signal. Frequencies of interest are identified based on simulations. The signals are complex and contain information about different modes and are sensitive to thickness, pillar diameter and mechanical properties of the materials. In order to minimize the number of parameters to iterate and avoid trade-offs, the pillar diameter was measured using the vision system. Material properties were set to values previously used in Ref. [5]. Our models assume perfect interfaces. At the frequency modes that we are working with the sensitivity is probably small.

Initial results indicated that the fit error using material properties previously obtained were higher than expected and the difference between the measured and modeled peaks were relatively higher. Also, the thickness results were not consistent with PULSE data analysis that assumed same previous values for the sound velocities to convert echo times to the thickness values. Additional analysis and optimization was performed, floating material properties. We also used echo times for Cu and SnAg from the PULSE measurements as additional constraining parameters in the optimization. It was found that better fit to the modes frequencies at different pillars was achieved with SnAg longitudinal speed of sound to be ~9% higher than previously used value and other sound velocities remained unchanged. This could be attributed to the differences in SnAs composition and/or grain size/inhomogeneity of the material between these samples and those used in Ref. [5]. The agreement between SnAg thickness values obtained from the PULSE and SONUS measurements for each pillar also improved. In Fig. 6 is the correlation between the PULSE and SONUS data obtained at the site-level for one of the samples which uses the adjusted SnAg longitudinal sound velocity for both cases and material properties from Ref. [5] and [6]. The agreement is significantly better and some of the smaller variations observed is also likely due to placement errors and high surface roughness that may contribute to ~>1um variation in PULSE measurement.

As an extension of our studies on microbumps, we are currently focused on the next generation of microbumps (<10µm) where the consumption of Cu by Sn and formation of intermetallic compound poses considerable reliability issues. Sensitivity of the technique for monitoring the evolution of IMC is also being investigated.

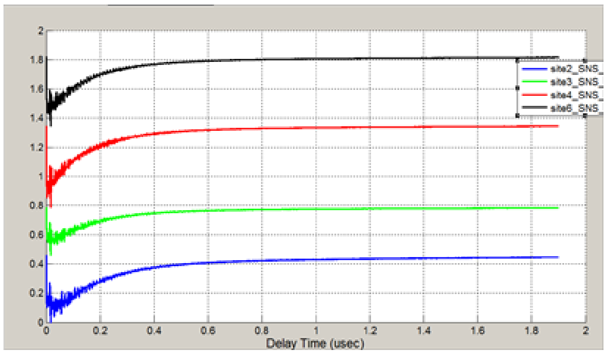

Fig. 5a. Time domain signal from the microbump samples. Signals carry thickness information as well as mechanical properties.

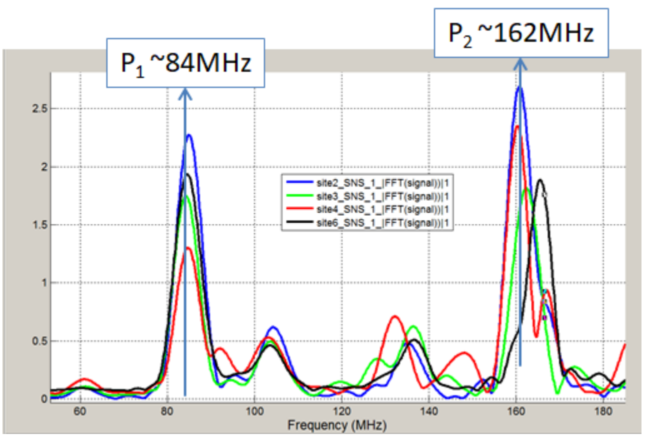

Fig. 5b. Fourier transformation of the raw data with peaks of interest identified.

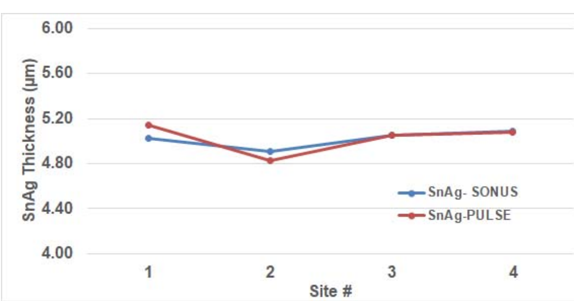

Fig. 6a. SnAg/Cu microbump. SnAg thickness correlation between PULSE and SONUS on different pillars.

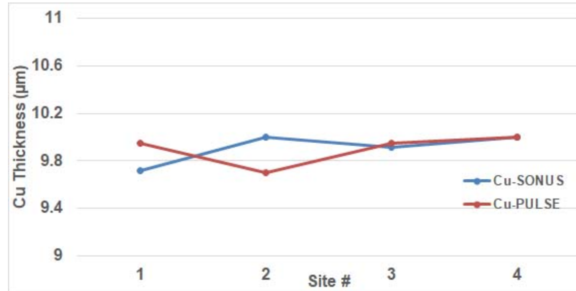

Fig. 6b. SnAg/Cu microbump. Cu thickness correlation between PULSE and SONUS on different pillars.

IV. Conclusion

The continued scaling of pillar bumps for high performance applications has led to the adoption of front-end metrology techniques to back-end packaging. We have presented acoustic metrology techniques as in-line tools for monitoring copper pillar bump process. Picosecond ultrasonic technique, which has been a workhorse in wafer fabs provides simultaneous characterization of the multi-layer metal bumps with excellent repeatability and accuracy. Repeatability measurements for within wafer average is 3sigma <1%. We have also shown that for taller copper pillar bumps (>30µm), using a complementary acoustic technique from the SONUS system, we can extend that capability [5, 6]. Both PULSE and SONUS techniques provide the unique capability of measuring individual layer thickness simultaneously as opposed to measuring only the total thickness with other techniques such as optical scanning. Combination of PULSE and SONUS can also provide sound velocities, which may be helpful to infer the layers' compositions. Both PULSE and SONUS would be helpful in the layer deposition of process control, rather than full wafer inspection.

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