Performance Study of an Ultrasonic Transducer used for Wire Bonding

S.W. Or [1,2,*], *Member, IEEE*, H.L.W. Chan [1], V.C. Lo[1], *Member, IEEE*, and C.W. Yuen [2]

[1] Department of Applied Physics and Materials Research Centre
The Hong Kong Polytechnic University, Hunghom, Kowloon, Hong Kong.
[2] ASM Assembly Automation Ltd.
12/F, Watson Centre, 16 Kung Yip Street, Kwai Chung, Hong Kong.
[*] Corresponding author: E-mail: swor@asmpt.com

Abstract --- In-situ studies on the performance of an ultrasonic wire-bonding transducer (about 60 kHz) are presented and discussed in this paper in order to optimize the bonding process. The resonant frequencies and vibration mode shapes of the transducer were computed using finite element method (FEM) and were compared with the experimental resonant frequencies and displacement distributions. Good agreements between the computed and experimental results were obtained. The desirable second axial mode was found and proven to be the dominant mode of the transducer that facilitates the bonding process. Characteristics of the transducer under different input power were also studied. Results show that its performance is good and high quality bonds can be formed.

I. INTRODUCTION

In microelectronic packaging, wire bonding is classified as the first level packaging. It is the most widely used method that provides electrical interconnections from the terminals on an IC chip to those on a chip carrier using fine metal wires. Ultrasonic bonding is one of the major techniques for wire bonding. It is a lower power intensity process based on the proper transmittal of ultrasonic vibrational energy under pressure to plasticize the metallic bonding surfaces by means of an ultrasonic transducer.

As a tool of bonding, an understanding of the behavior of the transducer is necessary as the overall bonding performance depends significantly on the characteristics and proper use of this device. Some earlier works on the transducers in this class have been reported [1-5]. They are useful for predicting general characteristics, but are incapable of describing detailed behavior, especially if the transducer is mounted on the wire bonder. With improved measurement and modeling techniques, however, more detailed information can be obtained to optimize the bonding process.

In this paper, studies on the performance of an ultrasonic transducer currently used in wire-bonding industry are carried out by first computing its resonant frequencies and vibration mode shapes and then comparing the results with experimental measurements. The paper also includes measurements of its electrical and vibrational characteristics. We have reported some work in this area [6-9]. Presented here are some details on this particular type of transducer.

II. THE ULTRASONIC WIRE-BONDING TRANSDUCER

The ultrasonic transducer (nominal resonant frequency is 62.1 – 63.0 kHz) used in the present study was an Uthe 70-PTL wedge transducer (comprises a piezoelectric driver, a concentrator, and a barrel) with attached bonding tool (Fig. 1).

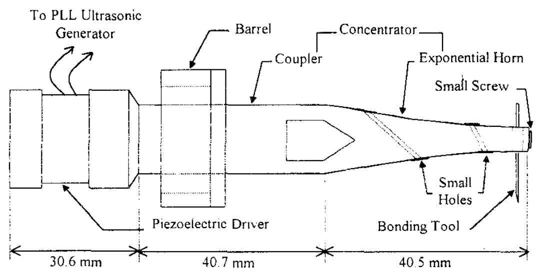

Fig. 1. Schematic diagram of the ultrasonic wire-bonding transducer.

The piezoelectric driver at the rear part of the transducer is a 30.6 mm thick bolt-clamped Langevin type sandwich transducer that converts electrical energy generated by a phase-locked-loop (PLL) ultrasonic generator into mechanical axial vibration based on converse piezoelectric effect. The 81.2 mm long concentrator couples and amplifies the vibration (displacement or particle velocity) of the driver to the bonding tool. It is made of aluminium (Al) alloy and consists of two sections. The section next to the driver is a 40.7 mm long cylindrical solid rod without any taper (called coupler) and the second is a 40.5 mm long solid exponential horn designed to amplify the axial motion with maximum amplitude at its small (front) end at which the 21 mm long tungsten carbide bonding tool is being clamped at an optimal position by a small screw (See reference [9] for details on the determination of this optimal position). The wave motion in the bonding tool is flexural and is transmitted to the bond interface during the bonding process. The barrel, which is used for mounting the whole transducer into the wire bonder, is attached rigidly, ideally at a nodal point, on the coupler to avoid energy loss and transmission inconsistency. There are two small holes in the concentrator, drilled at angles of 60° and 30°, respectively, for threading the Al wires in

(0-7803-4932-6/98/$10.00 1998 IEEE)

the wire bonder.

III. Finite Element Method Analysis

A. The Ultrasonic Transducer Model

A commercial FE package ANSYS version 5.2 was used in this analysis. The FE model of the transducer is shown in Fig. 2. In order to emphasis on the concentrator, simplifications are made to both the piezoelectric driver and the bonding tool. Thus, the model is incapable of describing the detailed behavior of these two parts. A cylinder is used to describe the driver and is assumed to have the same stiffness as that of the concentrator. Piezoelectric properties are ignored. Similarly, a cylindrical beam is used to describe the bonding tool. But each of them is assumed to have density that gives its the correct total mass of the actual driver and the bonding tool, respectively.

Moreover, all small holes and many small fillets in the concentrator are ignored because of difficulty in meshing. Due to the same reason, the small screw at the front of the horn for clamping the bonding tool is also ignored. Perfect mechanical couplings between all parts in the assembly are assumed. The cylindrical surface of the barrel is assumed to be fixed in all directions instead of the three-lines clamping.

All the elements used are 3-D structural elements solid 92 (10-node tetrahedral) [10]. About 17911 elements and 29501 nodes are used in the analysis. In order to model the highly curved volumes, the h-method [11] is applied and meshing is restricted by the length of element sizes. The length is set to 0.8 - 1.4 mm depending on the volume of interest and the shape of the model.

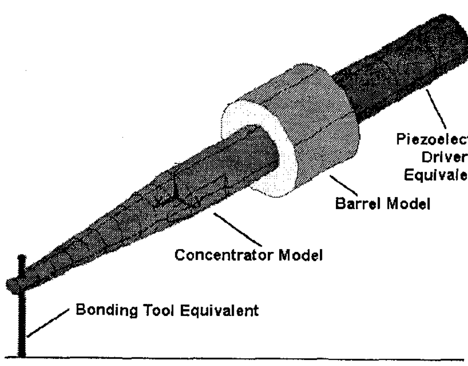

Fig. 2. The Ultrasonic Transducer Model.

B. Results and Discussions

The lowest 120 resonant frequencies and vibration mode shapes of the model were computed and well-converged results (that were confirmed by running the model several times) were obtained.

The axial motion is the most desirable motion in wedge bonding as it causes the tip of the bonding tool to move in a direction parallel to the axis of the concentrator (X-axis) and the wire to be bonded, and it should be the working mode of the transducer. The computed working frequency of the transducer for the axial mode is at 62.2 kHz (Mode 59). It is in good agreement with the manufacturer's value of 62.1 – 63.0 kHz. This axial mode is the second axial mode.

The amplitude distributions for the second axial mode are shown in Fig. 3. At about 0 mm (Fig. 3a) where the transducer is clamped by the bracket, the axial vibration amplitude is zero. Amplification of axial amplitude by about three times at the horn end can be observed. If we interpolate the axial distribution along the length of the transducer (Figs. 1, 2, & 3a), it is found that the length of the whole transducer is equal to 1.5 wavelengths at 62.2 kHz, in which the driver and the concentrator correspond to 0.5 and 1 wavelength, respectively. It can also be seen from Fig. 3 that other non-axial components (±Y and ±Z) are out of phase with the axial one. Due to the Poisson's effect [12], the axial vibration causes stress distributions that cause displacement distributions in the radial direction. These non-axial distributions are, in general, proportional to the deverative of the axial motion.

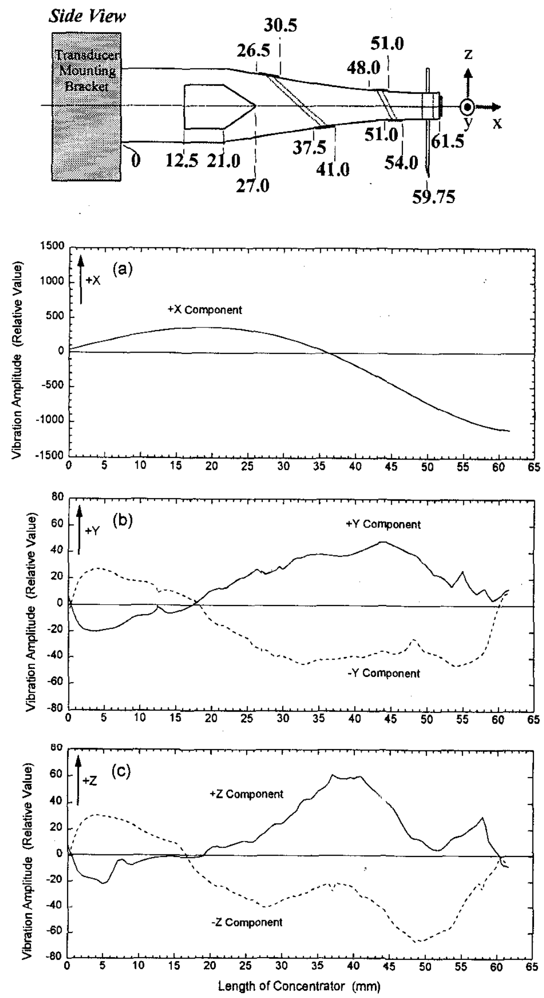

Fig. 3. Relative amplitude distributions of the second axial mode at 62.2 kHz computed by FEM. (a) Axial (+X) component; (b) ±Y components; and (c) ±Z components.

IV. Experimental Measurements

A. Electrical Impedance and Phase Angle as a Function of Frequency

At normal bonding power of about 0.1 W, the electrical impedance and phase angle as a function of frequency for the transducer mounted in the wire bonder was measured using a HP 4194A Impedance / Gain Phase Analyzer and the result is shown in Fig. 4.

The result shows that the resonance characteristics of the transducer are very complex. There are a number of allowable resonant modes in the transducer. It is found that some of the computed modes in section III are absent from this spectrum, and those modes are the modes excluded by the electrical boundary conditions. The strongest minimum impedance resonance is observed at about 62.5 kHz. This is the resonant frequency of the transducer as it agrees well with the manufacturer's specification (62.1 – 63.0 kHz) and the FEM result (62.2 kHz, agreed to 0.5%). Coupling between adjacent modes and a number of weaker resonances, including the higher frequency harmonics to the fundamental, can also be observed. In order to maintain the bond quality, therefore, the PLL ultrasonic generator should be capable of locking at this mode of vibration during bonding.

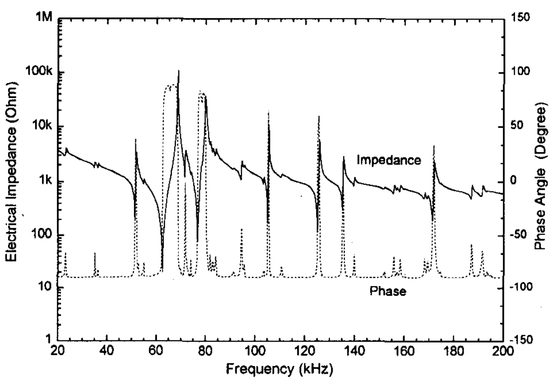

Fig. 4. Electrical impedance and phase angle as a function of frequency for the transducer.

B. Displacement Distributions along the Concentrator

The in-situ vibration displacement distributions along the concentrator were measured using a Mach-Zehnder type heterodyne interferometer (SH-120 from B. M. Industries in Frances) connected to a spectrum analyzer (HP 3589A). Four displacement distributions produced by scanning along the length of the concentrator in ±Y and ±Z directions (Fig. 2) were obtained at 62.5 kHz (the measured resonant frequency of the transducer), in steps of 0.5 mm. In order to maintain the transducer at resonance during measurement, a PLL ultrasonic generator was employed to drive it. Normal bonding power of about 0.1 W was used.

The measured distributions are shown in Fig. 5. The results show that the rod waves excited in the transducer give rise to many nodes and anti-nodes on the concentrator surface. Since the interferometer measures the absolute vibration displacement amplitude normal to the transducer surface (out-of-plane component), it cannot directly measure the axial mode of vibration. Instead, the axial mode vibration is measured indirectly by measuring the stress distributions. Thus, if we compare the measured distributions to those computed by FEM in Fig. 3b&c, good agreement is obtained, with the main nodes and anti-nodes being located at more or less similar locations. The agreement proves that the second axial is the dominant mode of the transducer and it facilitates the bonding process.

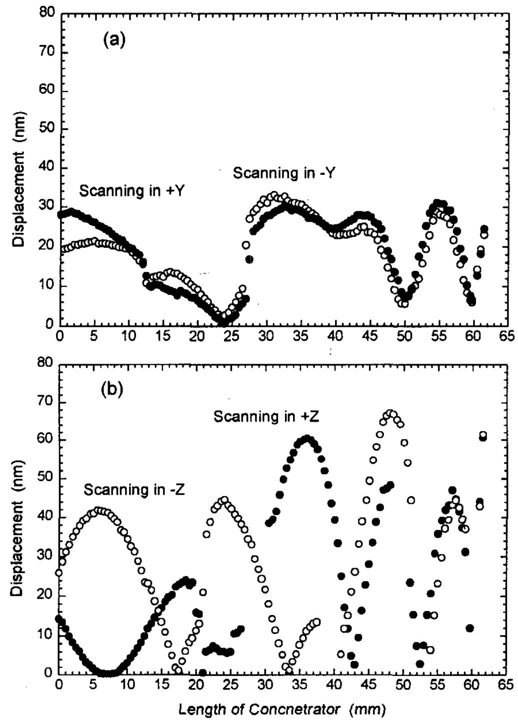

Fig. 5. Vibration displacement distributions along the concentrator. Scanning in (a) ±Y directions; and (b) ±Z directions.

C. Displacement Distribution along the Bonding Tool

The displacement distribution along the bonding tool in the +X direction (Fig. 2) was also measured to reinforce our pervious findings. For large vibration amplitude measurement (> 0.1 μm), a laser Doppler vibrometer (Polytec OFV-303) was used with an oscilloscope (HP 54504) and a spectrum analyzer (HP 3589A). The result is shown in Fig. 6. It should be noted that scanning was performed in steps of 0.25 mm and the displacement values are calculated from the measured velocity amplitudes using the following relationship

$$\mathbf{u} = \nu / \omega$$

where **u** is the displacement amplitude; ν is the velocity amplitude; and ω is the angular frequency.

Four anti-nodes and three nodes are observed along the length of the tool, with the largest displacement being located at the tip of the tool, i.e. 0 mm. That is, the bonding tool driven by the axial motion of the transducer, vibrates in the second free-free flexural mode. Displacement at the tip of the tool is found to be about 1.5 um that is about two times that at the end of the horn.

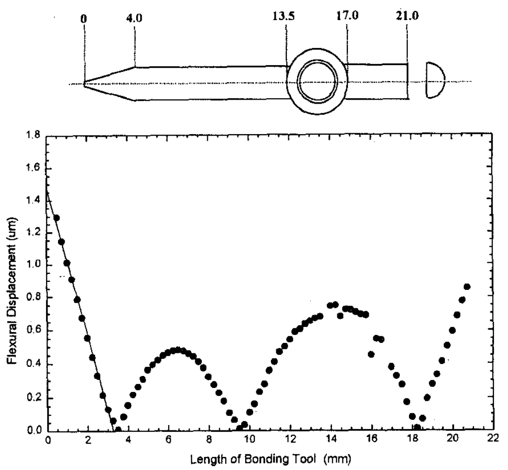

Fig. 6. Flexural displacement distribution along the bonding tool. The solid circles and the solid line are the measured values and the fitted line, respectively.

D. Characteristics at Different Input Power

The frequency, electrical impedance, Q factor, and axial displacement amplitudes, including those at the end of the horn and near the tip of the bonding tool (0.5 mm from tip), of the transducer at resonance were measured at different input power and are shown in Fig. 7.

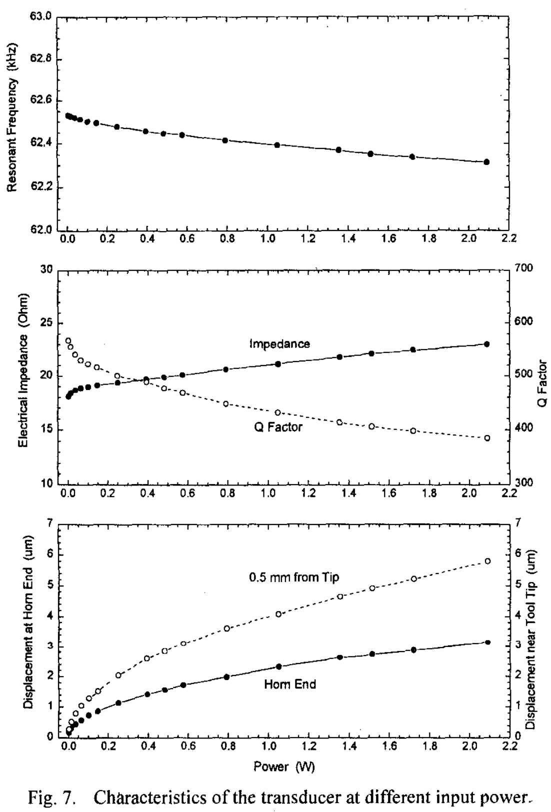

Fig. 7. Characteristics of the transducer at different input power.

It is observed that the resonant frequency and Q factor decrease gradually as input power increases, whereas the electrical impedance increases slightly with input power. Both displacements are proportional to the square root of the power. When the bonder is operated at different power, these changes in transducer characteristics should be taken into account in order to produce high quality bonds although the changes are not very significant.

V. Conclusions

The performance of a commercial grade ultrasonic wire-bonding transducer has been evaluated in-situ to optimize the bonding process. Good agreements have been established between the computed and experimental results. The desirable second axial mode has been found and proven to be the working mode of the transducer. With the transducer being operated in this mode, it can consistently produce optimal characteristics for the formation of high quality bonds.

Acknowledgment

Financial support from The Hong Kong Polytechnic University is acknowledged.

References

[1] N.M. Bilgutay, X. Li and M. McBrearty, "Development of non-destructive Bond Monitoring Techniques for Ultrasonic Bonders", *Ultrasonics*, vol. 24, pp. 307-317, 1986.

[2] M. McBrearty, L.H. Kim and N.M. Bilgutay, "Analysis of Impedance Loading in Ultrasonic Transducer Systems," *Proceedings IEEE Ultrasonics Symposium,* vol. 1, pp. 497-502, 1988.

[3] L.G. Markulov and A.V. Kharitonov, "Theory and Analysis of Sectional Concentrators," *Soviet Physics - Acoustics,* vol. 5, pp. 183-190, 1959.

[4] S. Lin and F. Zhang, "Study of Vibrational Characteristics for Piezoelectric Sandwich Ultrasonic Transducer", *Ultrasonics*, vol. 32, No. 1, pp. 39-42, 1994.

[5] Z. Yan and Z. Lin, "Optimum Design for Sandwich Transducer - By Analyzing Effects of Structure and Material Parameters of Transducer on its Performance", *Acta Acustica*, vol. 20, No. 1, pp. 18-25, 1995.

[6] S.W. Or, H.L.W. Chan, V.C. Lo and C.W. Yuen, "Dynamics of an Ultrasonic Transducer used for Wire Bonding", *IEEE Transactions on Ultrasonics, Ferroelectrics, and Frequency Control*, in press.

[7] S.W. Or, H.L.W. Chan, V.C. Lo and C.W. Yuen, "Ultrasonic Wire-bond Quality Monitoring using Piezoelectric Sensor", *Sensors and Actuators A: Physical*, vol. 65, pp. 69-75, 1998.

[8] S.W. Or, H.L.W. Chan, V.C. Lo and C.W. Yuen, "Sensors for Automatic Process Control of Wire Bonding", *Proceedings 10th IEEE International Symposium on the Applications of Ferroelectrics (ISAF '96)*, vol. 2, pp. 991-994, 1996.

[9] S.W. Or, H.L.W. Chan, K.C. Cheng, Y.M. Cheung, C.W. Yuen and P.C.K. Liu, "Effect of Tool Drop on the Performance of a High Frequency Piezoelectric Wire-bonding Transducer", Abstract submitted to *2nd Asia Meeting on Ferroelectrics, International (AMF-2)*, Dec. 8-11, 1998, Singapore.

[10] P.C. Kohnke, *ANSYS 5.2 User's Manual*, ANSYS Inc., 1995.

[11] R.D. Cook, *Finite Element Modeling for Stress Analysis*, John Wiley & Sons, Inc., 1995.

[12] F. Graff, *Wave Motion in Elastic Solids*, Clarendon Press, Oxford, UK, 1975.