

Metrology of Thin Layers in IC Packages using an Acoustic Microprobe: Bondline Thickness

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Abstract

A nondestructive technique is demonstrated for the metrology of adhesive layers that are considerably thinner than a single wavelength of ultrasound in that material. The acoustic microprobe technique discussed here is capable of measuring the thickness and elastic properties of a thin layer sandwiched between two relatively thicker layers. Real time measurements over a 50 μm diameter spot are possible with this technique. The particular case of a silicone adhesive layer between an aluminum lid and die in a flip chip package is discussed here and layer thickness was measured down to 5 μm . The minimum measurable thickness limit of the acoustic microprobe technique is several times better (smaller) than that of time based techniques using the same transducer.

Introduction

The thickness of bond layers encountered in an IC package can play an important role in controlling the reliability of the package. For example, consider the thermally enhanced flip chip package shown schematically in Figure 1. The thickness of the adhesive layer between the lid and die could have a direct influence on the thermal resistance due to the relatively low thermal conductivity of the adhesive. This in turn has a strong bearing on the heat removal rate and on the successful operation of the device. In addition to the thickness, the elastic properties of the adhesive could also influence the build up of thermal stresses.

Thus, there is a need to measure the thickness and elastic properties of thin layers accurately and nondestructively both for purposes of process monitoring and quality assurance.

Ultrasonic techniques have been used successfully for thickness measurement and material characterization in several applications primarily because they are nondestructive in nature and can yield reliable results for simple geometries. Acoustic microscopy techniques, in particular, are attractive for IC packaging applications because they afford the potential to perform these measurements over a small, localized area [1].

Ultrasonic thickness measurement is made possible by the reflection of ultrasound at interfaces between dissimilar

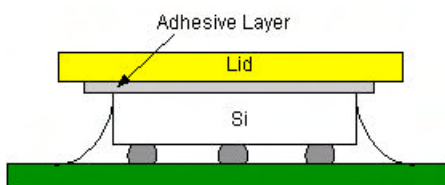


Figure 1. Schematic of thermally enhanced flip chip package showing the thin layer of adhesive between the lid and die. Estimation of the thickness of this layer is the goal of this study.

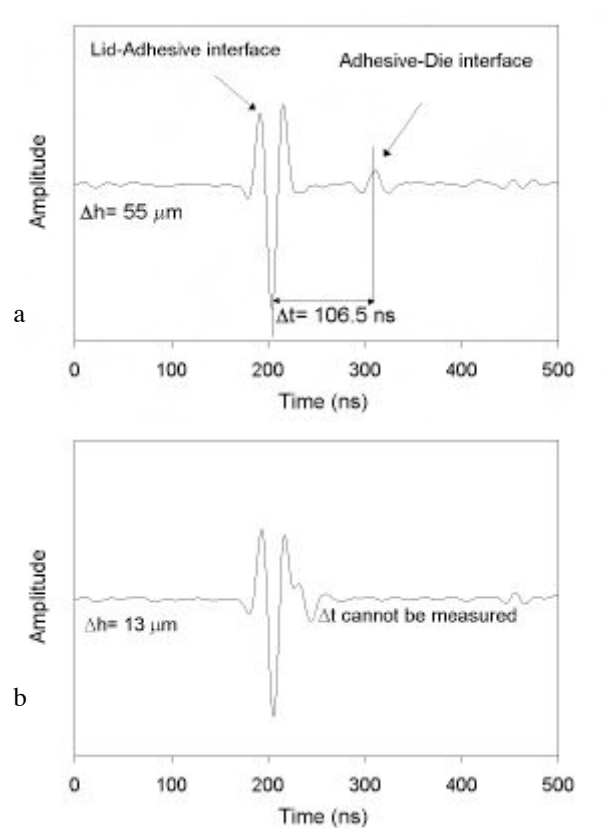


Figure 2. Time trace of the reflections from the front and back surface of a thin layer. a) Conventional techniques can be used to calculate thickness when reflections are separated in time b) the acoustic microprobe technique is needed when the layer thickness is small compared to the wavelength and the reflections are superimposed on each other.

materials. When ultrasound propagating in a material encounters an interface with a dissimilar material (with a different acoustic impedance), a portion of the ultrasonic energy is reflected back. Thus, when ultrasound in the acoustic microscope impinges on an adhesive layer sandwiched between two other materials, it is reflected from both the front and back interfaces. The thickness of the layer can be estimated by measuring the time lag between the two reflections if the velocity of ultrasound in the adhesive is known.

The implementation of the pulse separation technique described above is relatively straightforward when the layer is thicker than a few wavelengths of ultrasound [2]. This is because the reflections from the layer's front and back surface can be clearly separated in the time domain (oscilloscope trace or A-scan). For example, in the plot shown in Figure 2a, the reflection at the lid-adhesive interface is followed by the

reflection from the adhesive-die interface after 106.5 ns. Using a velocity of 1.027 mm/ μ sec for the silicone layer, the thickness is calculated to be 55 μ m using the following equation.

$$\Delta h = V(\Delta t/2) \quad (1)$$

The wavelength of ultrasound in the adhesive for a 50 MHz transducer (nominal center frequency) is 30 μ m.

However, when the layer thickness is less than or comparable to the wavelength of the ultrasound, the reflections from the front and back surface of the layer overlap and the time difference between the two reflections cannot be easily measured. This is illustrated in Figure 2b. The layer thickness at this location was independently measured to be 13 μ m, which is approximately a third of the ultrasonic wavelength. In such cases, thickness can be estimated by solving the inverse problem – comparing experimental measurements of a suitable ultrasonic parameter against the predictions of a theoretical model.

Models for this purpose can be broadly categorized by increasing levels of complexity as i) simple pulse superposition schemes [3], ii) reflection coefficient approaches that are still relatively straightforward computationally (for example [4]), and iii) generalized multi-layer approaches [5]. The three approaches attempt to model the physical phenomenon with different degrees of complexity, with the generalized multi-layer approach being the most computationally intensive. In this paper, the focus is on measuring the thickness of a single, thin layer in real time with emphasis on practical, robust and quick measurements. Therefore, the reflection coefficient approach, which affords a balance between ease of implementation and detailed description of the physical phenomena, is adopted here.

Description of Model

The theoretical model uses a closed form solution to the reflection coefficient of a coating-substrate assembly [4]. It was originally suggested for the case of a thin layer on a semi-infinite substrate and used in conjunction with unfocused transducers. The approach has been extended here for the case of a thin layer sandwiched between two thicker layers using a broadband, focused transducer. The materials modeled are shown in Figure 1. The model as implemented in this study is capable of accounting for transducer bandwidth, attenuation in water and attenuation in the materials. Aberrations in high velocity materials and mode conversion due to non-normal incidence are ignored. Since we are primarily interested in performing thickness measurements over a small spot, a focused transducer was used.

Experiment

The C-SAM¹ D-6000 digital acoustic microscope was used in data acquisition. Two transducers with nominal center frequencies of 50 and 100 MHz were used. The model was originally developed for normally incident, unfocused compressional waves. However, an unfocused transducer is not suitable for IC packaging applications because the spot size can be several mm in diameter. Therefore, a mildly focused transducer (ratio of focal length to diameter = 4) was used in

this study. The justification for using mildly focused transducers instead of unfocused transducers has been demonstrated for the case when the layer thickness is smaller than the depth of field of the transducer [6].

A schematic of the flip chip package investigated in this study is shown in Figure 1. The velocity of ultrasound in the Sylgard² 577 primerless silicone adhesive was determined to be 1.027 mm/ μ sec.

Layer Thickness Estimation Procedure

The procedure consists of the following steps:

- 1) *Image Acquisition* - The sample under study is placed in the water tank of the C-SAM. The transducer is focused at the adhesive bond interface and an image of the bond area is acquired.
- 2) *Reference signal* - The transducer is positioned over an area where the bottom surface of the lid is in contact only with the water couplant (outside the perimeter of the die). The ultrasonic pulse reflected from the lid-water interface is electronically gated and windowed using a suitable function (Blackman-Harris). The list of data points is padded with zeros to extend it to 1024 points. A fast Fourier transform operation is performed on the data and the result is stored on the computer.
- 3) *Layer signal* - The transducer is moved to a location where the thickness of the adhesive layer is to be determined. The ultrasonic pulse reflected from the layer (lid-adhesive-die interface) is collected and processed similarly. Data from multiple locations of interest can be collected by moving the transducer over any particular location and repeating the data acquisition.
- 4) *“Experimental” Transfer Function* - An “experimental” transfer function is calculated by deconvolving the layer signal with the reference signal. Deconvolution here entails taking the ratio of the magnitudes of the frequency spectra.
- 5) *“Theoretical” Transfer Function* - A “theoretical” transfer function is calculated using the model, which accepts as input the material, transducer and geometric parameters.
- 6) *Initial guess of thickness by graphical comparison* - An initial guess of the layer thickness is provided by the user based on a visual comparison of the theoretical and experimental transfer functions.
- 7) *Layer Thickness Estimation* - The thickness of the adhesive layer is calculated by the computer using a multi-parametric nonlinear error minimization scheme. The correct estimate is one that minimizes the mean residual error between the “experimental” and “theoretical” transfer function. The fitting routine is capable of calculating attenuation, velocity and acoustic impedance of the adhesive layer simultaneously along with the thickness.

Measurements were performed on 4 samples. Two samples (#1 and #2) had the lid grossly tilted relative to the die. In these samples, the adhesive layer was thick enough over a large portion of the die to permit the use of conventional pulse separation techniques (equation 1).

¹ C-SAM is manufactured by Sonoscan, Inc., USA.

² Manufactured by Dow Corning, USA.

The other two samples (#3 and #4) had a much thinner adhesive layer of uniform thickness across the face of the die. In these samples, thickness could be estimated only by the acoustic microprobe technique.

After performing the measurements by both conventional and acoustic microprobe techniques, samples #1 and #3 were sectioned and polished to obtain correlative destructive data. The thickness of the adhesive layer was measured from the optical micrographs.

Results

An acoustic micrograph of the lid-adhesive interface is shown in Figure 3a. While making this image, the electronic gate was set wide enough to include reflections from both the lid-adhesive interface and the adhesive-die interface. The aluminum lid in this sample was tilted relative to the die at an angle, with the right end being closer to the die. Constructive interference between the lid-adhesive and the adhesive-die reflections increases the brightness of the image near the right edge of the die. The thickness data in sample #1 were collected along the dashed line in Figure 3b using a 50 MHz transducer.

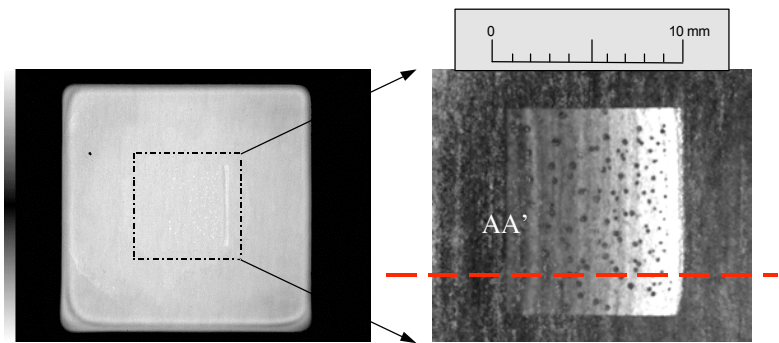


Figure 3. Acoustic images of sample #1 a) lid-adhesive interface b) adhesive-die interface.

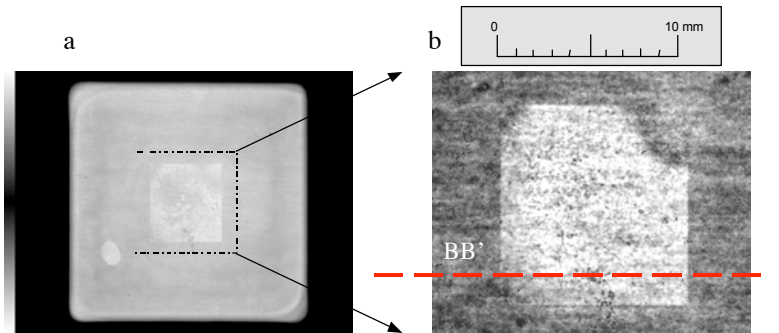


Figure 4. Acoustic images of sample #3 a) lid-adhesive interface b) adhesive-die interface.

Representative examples of the time domain data from sample #1 are shown in Figure 5. The reference signal is shown in Figure 5a, while the layer signal is shown in Figure 5b. The layer signal illustrates the case where the reflection from the lid-adhesive and adhesive-die interfaces overlap such that it is not possible to estimate the layer thickness using equation 1.

The measured transfer function for this case is shown by the data points in Figure 6. The solid line in Figure 6 represents the best fit of the model to the experimental data, from which layer thickness was estimated to be 35 μm .

The lid-adhesive interface image of sample #3 is shown in Figure 4a. The thickness of the adhesive layer in this sample was not only uniform, but was also much smaller. The

thickness of the adhesive layer along the dashed line in Figure 4b was estimated by the acoustic microprobe technique using a 100 MHz transducer. A 100 MHz transducer had to be used instead of the 50 MHz transducer because the useful bandwidth of the 50 MHz transducer lay in the flat region of the transfer function for layer in sample #3 and #4. This made fitting the data difficult and adversely affected the convergence of the solution procedure. Using the 100 MHz transducer ensured that the useful frequency range of the transducer spanned the minima in the theoretical transfer function. Extending the argument, a higher frequency transducer would be necessary for metrology of even thinner adhesive layers. It should be noted that transducer requirements would be different for different material systems depending on the

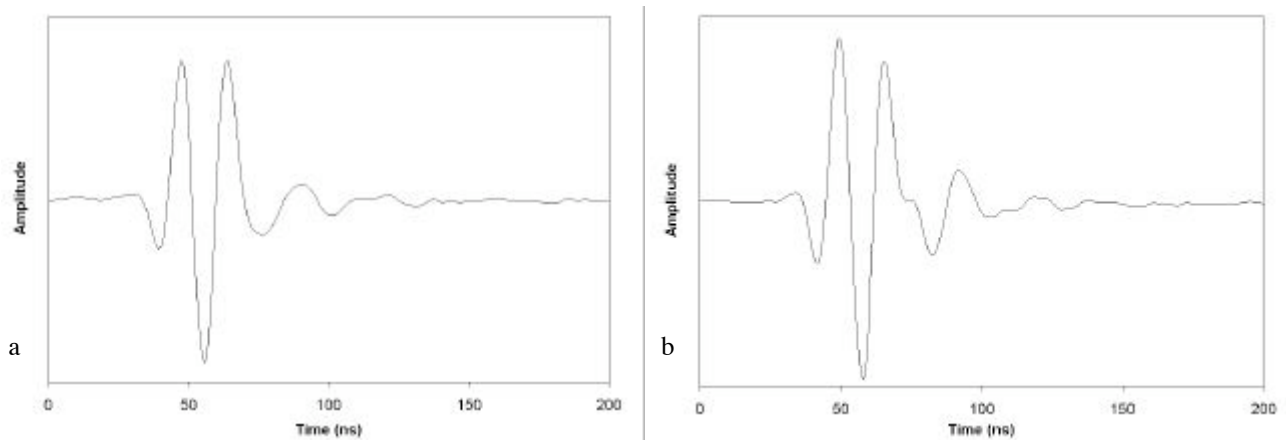


Figure 5. Representative time domain data of a) reference signal, and b) layer signal in sample #1 for an estimated layer thickness of 35 μm .

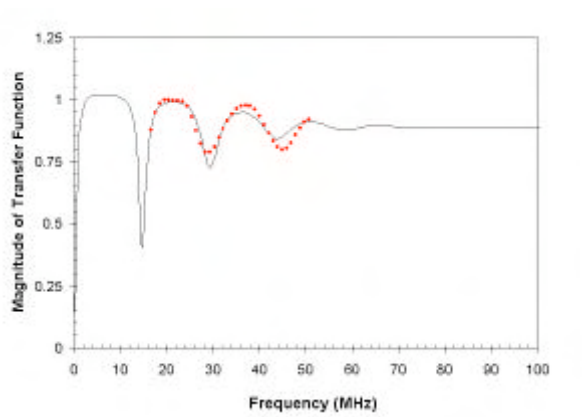


Figure 6. Comparison of theoretical (solid line) and experimental transfer function (points) for an estimated layer thickness of 35 μm in sample #1.

velocity of ultrasound and other material properties.

Data for sample #3 are shown in Figure 7, where the experimentally measured transfer function is shown by the points and the best fit of the model is represented by the solid line. In this case, the thickness was estimated to be 9 μm . For all samples, the theoretical model described the experimentally measured data very well.

The thickness distribution of the adhesive layer over the face of the die for samples #1 and #3 is discussed below. Data collected along the dashed line AA in Figure 3b are shown in Figure 8, while the data collected along the dashed line BB are shown in Figure 9.

For sample #1, the adhesive layer thickness is approximately 100 μm at the left edge of the die while it is approximately 10 μm at the right edge of the die. The relatively greater layer thickness allowed measurement by conventional echo separation methods over most of the die. These measurements are plotted alongside the model estimates and DPA (destructive physical analysis) measurements in Figure 8. It is seen that there is very good correlation between the different measurement techniques.

The lower limit of thickness that can be estimated by the acoustic microprobe technique is inversely proportional to the frequency of the ultrasound. Thus, in general, higher frequency transducers are needed to measure thinner layers. In this respect, both the pulse separation technique and the acoustic microprobe technique have similar limitations placed on their applicability. The conventional echo separation technique is capable of measuring thickness only down to about 30 μm , while the acoustic microprobe technique proposed in this study is capable of measuring much thinner layers.

The correlation between the destructive cross sectioning and the acoustic microprobe measurements of the layer thickness are shown in Figure 9 for sample #3. The *average*, *maximum* and *minimum* disagreement between the DPA data and the acoustic data were, respectively, 0.5 μm , 2 μm and 0.15 μm . The surface roughness of the lid in contact with the adhesive was also of the same magnitude as the adhesive layer thickness and the absolute error of the technique is being investigated. The preliminary destructive sectioning data

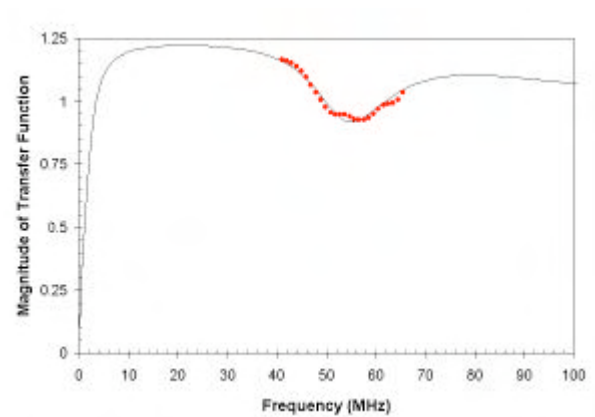


Figure 7. Comparison of theoretical (solid line) and experimental transfer function (points) for an estimated layer thickness of 9 μm in sample #3.

presented in this paper indicate that the average accuracy of thickness estimate is 0.5 μm with the 100 MHz transducer.

The nonlinear fitting procedure used in this paper converges to the correct result only if the initial guess lies within a certain window bracketing the actual thickness. For example, for the case of a 35 μm layer, initial guesses between 44 μm and 21 μm converged to the correct value. For initial guesses outside this range, the solution procedure converged to an incorrect solution. However, an incorrect solution can be identified by two independent methods. One measure of the quality of the solution is by a visual, graphical comparison of the fit and the experimental data, such as shown in Figure 6 and 7. The user can make a qualitative decision about the appropriateness of the solution based on how closely the fit matches the experimental transfer function. An alternative method involves the comparison of the residual error of the fit for a range of initial guesses bracketing the anticipated thickness. In this case, the solution that yields the lowest residual error of fit is the best estimate of the thickness. The algorithm used in this paper is being improved to make it more robust and amenable for automation. Details of the improved algorithm and ultrasonic model theory will be presented in a subsequent publication.

Conclusions

A nondestructive procedure to measure the thickness of adhesive bond layers in IC packages (thickness $\geq 5 \mu\text{m}$) is demonstrated in this paper. The acoustic microprobe technique is capable of measuring over a relatively small area (diameter $\leq 50 \mu\text{m}$) the thickness and elastic properties of thin layers even when they are not exposed to the surface. A thermally enhanced flip chip package is discussed as a representative case study. The thickness is estimated via an algorithm that minimizes the averaged residual error between the experimental response and theoretical prediction of a transfer function. The thickness of the Sylgard 577 adhesive was measured down to about 5 μm using transducers with nominal center frequencies of 50 and 100 MHz. The average error of the acoustic microprobe technique has been verified by destructive sectioning to about 0.5 μm .

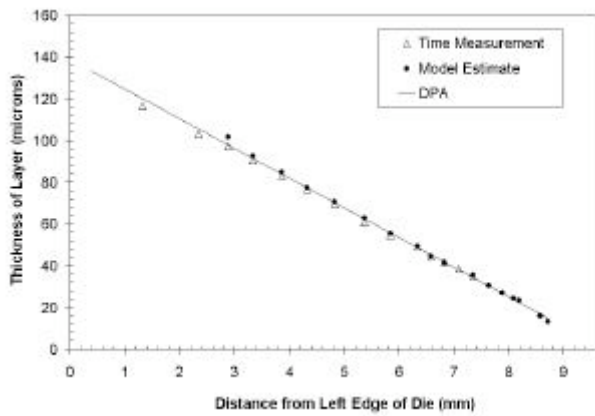


Figure 8. Estimate of layer thickness by the acoustic microprobe technique (model estimate) along dashed line AA for sample #1.

The acoustic microprobe technique is relatively straightforward and robust. Implemented on an acoustic microscope, it can offer a quick, nondestructive alternative to DPA. The minimum thickness measurable thickness limit of the acoustic microprobe techniques is several times better (smaller) than that of conventional time based techniques using the same transducer. The acoustic microprobe technique is to be an attractive candidate for process monitoring, reliability evaluation and failure analysis applications.

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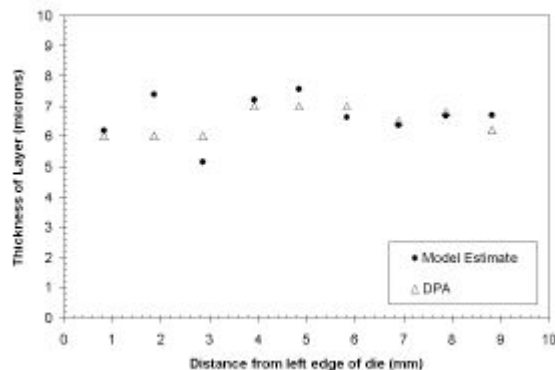


Figure 9. Estimate of layer thickness by the acoustic microprobe technique (model estimate) along dashed line BB for sample #3.