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In situ Elastic Property Characterization of Flip-Chip Underfills

Sridhar Canumalla and Michael G. Oravecz
Sonoscan, Inc., 530 E. Green Street
Bensenville, Illinois 60106, USA.
(630) 766-7088/4603 (fax)
canumallas@worldnet.att.net

ABSTRACT

The elastic properties of processing related inhomogeneities, such as filler settling and voids, are characterized using the acoustic microscope. A procedure to calculate the acoustic impedance of materials, and hence the elastic properties, at internal interfaces is proposed. The acoustic impedance of the silica filled polymer material under the die is measured at different locations corresponding to areas of different brightness in the acoustic image. Correlating the acoustic impedance measurements with the HS- model indicated that a) darker areas are regions where the underfill has a homogeneous distribution of filler b) lighter areas are regions characterized by filler settling. Destructive cross sectioning and microscopy confirmed the above predictions. Further, the elastic properties of the different areas adjacent to the die are estimated using the model. The relatively quick, nondestructive technique presented in this paper could be useful in advanced process control, rapid yield management and in providing input into package reliability studies (such as finite element analysis).

INTRODUCTION

Plastics used in electronic packaging are engineered to achieve specified mechanical properties by the addition of various additives such as fillers. Due to processing variations, these properties may vary sufficiently to affect the package reliability (Suryanarayana et al., 1991). Knowledge of the relative variation in these properties, as well as the absolute values, could help in advanced process control, rapid yield management, and package reliability studies (such as finite element analysis). The properties of interest, such as stiffness and strength, should preferably be measured on production packages, nondestructively and over a microscopic area. Ultrasound, and specifically acoustic microscopy, is investigated for making these measurements in this study.

Results of an earlier investigation (Canumalla and Kessler, 1997) found ultrasonic velocity and attenuation varied significantly between molding compounds. This indicated that ultrasound could be sensitive to variations in composition in these molding compounds, and that ultrasonic parameters could be used to monitor changes in material properties of underfills. While much work has been done in measuring material properties using the acoustic microscope (for example, Canumalla et al. 1997), these techniques are not applicable for measuring properties at internal interfaces away from the surface.

Processing related inhomogeneities in flip chip packages, such as filler segregation and voids, have been found to degrade fatigue life (Suryanarayana et al., 1991). Nondestructive inspections of flip-chip underfills, routinely achieved through acoustic microscopy, can reveal inhomogeneities in the underfill, as illustrated in Figure 1 and 2, but the elastic properties of these inhomogeneities are not readily revealed. Information about the elastic properties, such as actual stiffness and CTE in these regions, could help in a more precise determination of their effect on reliability.

The goal of this study is to quantitatively characterize variations observed in the underfill of flip-chip packages. The first step is to measure the acoustic impedance of the material below the die. The measured acoustic impedance is compared to predictions from a micromechanical model to estimate the filler content. Finally, the model is used to estimate different elastic properties corresponding to that filler content.

In this study, the Hashin-Shtrikman lower bound (HS-) is used as the micromechanical model to predict the elastic properties. The impedance of the material below the die is measured using the acoustic microscope over a small area. Destructive cross sectioning followed by microscopy indicates that the estimates of filler content via the model correlates with the filler settling observed.

THEORY

Engineering Moduli of Materials via Ultrasound

In order to determine the engineering moduli via ultrasonic techniques, density (ρ), shear velocity (V_S), and compressional velocity (V_C) need to be measured. The engineering moduli are calculated using Equations 1a to d:

$$\left.\begin{aligned}&\text{Shear Modulus } \mu = \rho V_s^2\\&\text{Bulk Modulus } \kappa = \rho\left(V_c^2 - 4\frac{V_s^2}{3}\right)\\&\text{Young's Modulus } E = \frac{\rho V_s^2\left(3V_c^2 - 4V_s^2\right)}{V_c^2 - V_s^2}\\&\text{Poisson's Ratio } \upsilon = \frac{E}{2\mu} - 1\end{aligned}\right\}\qquad (1\text{a - d})$$

The velocities are calculated using:

$$V_S = 2d / \Delta t_S \text{ and } V_C = 2d / \Delta t_C \qquad (2)$$

The procedure for measuring the compressional (Δt_C) and shear wave (Δt_S) time of flights is discussed in an earlier publication (Canumalla and Oravecz, 1997).

Another ultrasonic parameter used to describe the reflection and transmission of ultrasound at interfaces between two materials is the acoustic impedance, which is defined as:

$$Z_C = \rho V_C \qquad (3)$$

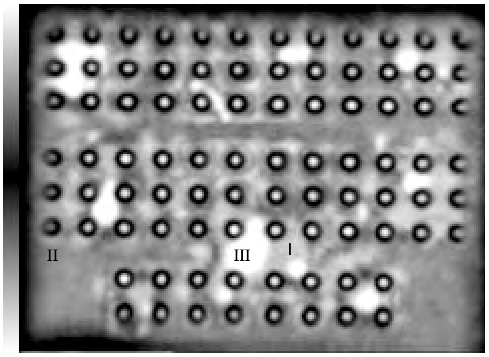

Figure 1. Acoustic image of the die/underfill interface showing areas of different brightness I) normal background II) light gray areas III) bright white areas.

The compressional wave acoustic impedance, defined here, will be used later in characterizing the processing variations in underfills.

Measuring the Acoustic Impedance of the Underfill

Acoustic images (Figures 1 and 2) of the die/underfill interface show regions with distinctly different amplitudes of reflection. These changes in reflected amplitude are a result of changes in the acoustic impedance mismatch. This principle is used to calculate the impedance of the flaw (Z_{Flaw}) relative to the impedance of the normal background ($Z_{Underfill}$).

Ultrasonic pulses are reflected at any interface when there is a change in the acoustic impedance from one medium to the next. For a pulse incident from Silicon onto a void (known impedance of 0), the reflection coefficient is given by

$$R_{Si-Void} = \frac{Z_{Void} - Z_{Si}}{Z_{Void} + Z_{Si}} \tag{4}$$

To determine $R_{Si-Void}$, the impedance of silicon and the void are needed. Silicon is anisotropic and the ultrasonic velocity varies with direction of propagation and polarization. Lacking information about the precise crystallographic orientation of the Si die, the wafers are assumed to possess a {100} orientation, with compressional waves propagating in the [100] direction

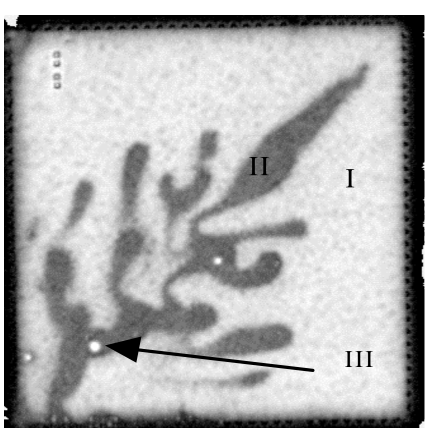

Figure 2. Acoustic image of a flip chip sample revealing processing variations as areas of different brightness I) normal background II) gray fingers III) voids.

(polarization also in <100> direction). From velocity and density values reported in literature (Dieulesaint and Royer, 1980), the impedance of silicon in the <100> direction is calculated to be 19.7 MRayl. Alternatively, a value of 21.9 MRayl could have been used (assuming a wafer orientation of {111}). However, the error in the predicted absolute values of impedance is expected to be only 5% (approximately) even if the correct

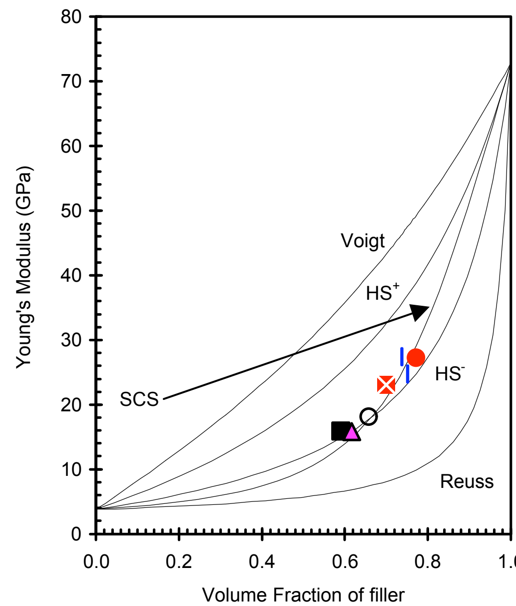

Figure 3. Comparison of ultrasonically measured Young's modulus with predictions of different models..

orientation were {111} instead of {100}. The impedance of the void is taken to be zero.

The impedance at any point is determined from the equation:

$$Z_{Point} = Z_{Si}\left(\frac{\beta + R_{Si-Void}}{\beta - R_{Si-Void}}\right) \tag{5}$$

where the pulse amplitudes from any point other than the void (A_{Point}) and from the void regions (A_{Void}), are used to compute the ratio:

$$\beta_{Point} = \frac{A_{Void}}{A_{Point}} \tag{5}$$

Once the impedance is determined, a suitable micromechanical model is required to translate this into a corresponding elastic property such as Young's modulus.

Modeling the Elastic Properties of Underfill

Modern plastic encapsulants used in IC packaging are largely composed of fused silica filler (>50% by weight), epoxy resin and hardener. The filler typically consists of a combination of *spherical* and *ground* fused silica in a broad size distribution (Pecht et al., 1995). Although other additives are present for stress reduction, fire retardation, etc., it is assumed that the elastic properties are dominated by the polymer matrix and the volume fraction of the filler. In other words, the encapsulant is treated as a two-phase composite: a polymer matrix reinforced with silica particles.

The validity of the Hashin-Shtrikman lower bound (HS-) model for predicting the elastic properties of IC encapsulants has been described in detail in a previous publication (Canumalla and Oravecz, 1997). A comparison of the Young's moduli measured for several commercial molding compounds with the predictions of various models is shown in Figure 3 for illustration.

In this study, acoustic impedance is used to gauge the elastic properties of the underfill. Results of the modeling showed that the acoustic impedance was sensitive to the volume fraction of the filler suggesting its appropriateness as an indicator of the elastic properties. Table 2 presents the engineering properties predicted by the HS^- bound for volume fraction of filler ranging from 0 to 1.

EXPERIMENT

The samples used to characterize underfill variations consisted of six different flip chip packages from two manufacturers.

The equipment used to measure the echo amplitude included an acoustic microscope (C-SAM) and focused, delay-line, immersion transducers of center frequency 80 and 100 MHz. Water was used as the coupling medium. The procedure consisted of:

a) Immersing the sample in the water bath
b) Centering the scanner over the die and leveling the stage
c) Focusing on the die/underfill interface by changing the distance between the transducer and the sample until the compressional wave echo from this interface was maximized
d) Acquiring a full gray-scale image of the entire die area
e) Measuring the amplitude of the die/underfill interface echo, via the A-scan display, at multiple locations.

RESULTS AND DISCUSSION

The images of two different kinds of flip chip packages are shown in Figure 1 and 2. In both cases, the image of the die-underfill interface shows variations due to non-optimal flow of the underfill in addition to voids.

Areas having three different reflectivities can be seen:: I) lighter background area II) darker gray areas and III) bright white areas. The amplitudes of the reflected echoes at this interface were measured over different areas in two chips and the averages for each chip are shown in Table 1. Acoustic impedance values estimated for areas I and II are tabulated in the last two columns. These results indicate that area I is composed of material with an effective impedance of about 3.3, which is close to that of the unfilled epoxy (from Table 2). Thus, area I appears to have very little filler adjacent to the die.

Destructive cross sectioning of the flip chip package supports the above conclusion. The package shown in Figure 2 was sectioned to verify that the bright white areas were indeed voids. Examining the polished cross section also indicated that in the dark areas (II), the underfill (epoxy + filler) was uniformly distributed throughout the thickness. On the other hand, in the bright areas (I), it was found that there was a layer of epoxy just below the die varying from 5 to 10 microns. Thus, in the brighter areas (I), filler settling was manifest, while the darker areas (II) were characterized by a uniform filler distribution in the underfill.

In addition, quantitative estimates of the filler content may also be drawn from the measured acoustic impedance. For instance, in the package shown in Figure 1, a measured acoustic impedance of 5.5 corresponds to a filler loading of approximately 0.55 weight fraction, which corresponds to a Young's modulus of about 14 GPa and a CTE of 28. For the package in Figure 2, a measured acoustic impedance of about 7.7 corresponds to a filler weight fraction of approximately 0.77-0.8. The model predicts that this material possesses a Young's modulus of about 29 GPa and a CTE of about 13. Thus, it appears that the underfill in the latter package is more highly loaded with silica particles and has higher elastic properties and a lower CTE.

A recent analytical study (Michaeledes and Sitaraman, 1997) found that a 20% reduction in the stiffness of the underfill could degrade the fatigue of a flip chip device life by about 11%. It was, therefore, deemed to be a relatively less severe flaw compared to voiding. However, if filler settling caused a 50% degradation in the stiffness, with a 50% increase in CTE, as found in the present study, these flaws could prove more detrimental than previously believed. Further work involving acoustic microscopy in conjunction with thermal cycling will be needed to better assess the reliability impact of such flaws.

CONCLUSIONS

Table 1. Measured amplitudes at the die/underfill interface at the different regions

	Sample name	III	II	I	$R_{Si\text{-}Void}$	β_{II}	β_I	Z_{II}	Z_I
Figure 2	A	57.7	32.5	42.2	-1	1.78	1.37	5.5	3.1
	B	57.2	33.0	43.4	-1	1.73	1.32	5.3	2.7
Figure 3	A	447	194	325	-1	2.30	1.38	7.7	3.1
	B	448	200	320	-1	2.24	1.40	7.5	3.3
	C	352	150	239	-1	2.35	1.47	7.9	3.8
	D	348	152	240	-1	2.29	1.45	7.7	3.6
	E	353	157	252	-1	2.25	1.40	7.5	3.3
	F	350	158	249	-1	2.22	1.41	7.4	3.3

The acoustic microscope is used for quantitative, *in situ* material property measurement in electronic packages over a microscopic area.

Processing related material property variations in the underfill were characterized by acoustic microscopy. The Hashin-Shtrikman lower bound (HS^-) was employed in modeling the elastic properties of the underfill material. The bright areas in the acoustic image were identified to be voids. Impedance measurements indicate that the dark areas have uniform filler distribution and the lighter gray areas were areas characterized by filler settling. Destructive cross sectioning confirmed these predictions.

Further, the elastic properties of the two areas (I & II) were estimated by correlating the measured impedance with the HS-model assuming that filler content dominated the elastic properties. For example, resin rich areas are predicted to have a filler volume fraction of 0.15 as compared to 0.40 for the base material. This filler content would result in a Young's modulus and CTE of 7 GPa and 41 x 10^{-6}/°C, as compared to a base value of 14 GPa and 26 x 10^{-6} /°C, respectively. Techniques presented in this paper are believed to be attractive for advanced process control, rapid yield management and for providing input into package reliability studies (such as finite element analysis).

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