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Scanning Acoustic Microscopy Study of Flip-Chip Underfill Cure Degree

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1 Introduction

The motivation for this work has been to gain a fast and reliable Compression UnderFill (CUF) based flip-chip interconnection process for MEMS components. In this process electrical contact between bumps and pads is established mechanically by the high curing shrinkage of the underfill, figure 1.

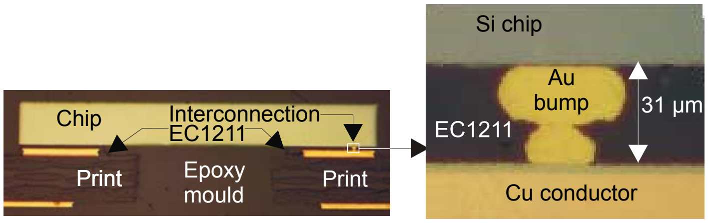

Figure 1: Cross section through bump – pad electrical interconnection between flip-chipped MEMS pressure sensor chip and print.

Although the studied CUF material EC1211 has been cure characterised by Differential Scanning Calorimetry (DSC), the actual temperature environments experienced by the underfill in the flip-chip process might be much different from expected. When trying to run the process as fast as possible it might therefore be that the CUF is not uniformly cured. Using DSC for evaluation is tedious and destructive because samples of the CUF will have to be taken out for the analysis. A better alternative is Scanning Acoustic Microscopy (SAM). Here detection of cure degree relies on the big mechanical (stiffness E) differences between cured and uncured material and the great advantages are that the inspection is 2D and non-destructive.

Acoustic microscopy has many applications, SAM especially in the microelectronics industry to detect failures e.g. cracks, bubbles, delaminations in chip encapsulations, solderings, gluings etc. Generally SAM is a Non Destructive Testing (NDT) method for microinspection which functions like a sonar, though using much higher frequencies, MHz – GHz. Ultrasound is transmitted through a liquid medium, typically water, to the component and its interior where it is reflected and transmitted at an interface between two materials 1 and 2 with amplitudes $A(R)_{12}$, $A(T)_{12}$ because of the changes in acoustic impedance according to [1]:

$$A(R)_{12} = A_0 R_{12} = A_0 \frac{Z_2 - Z_1}{Z_1 + Z_2} \tag{1}$$

$$A(T)_{12} = A_0 T_{12} = A_0 \frac{2Z_2}{Z_1 + Z_2} \qquad (2)$$

where A_0 is the incoming wave amplitude, R_{12} and T_{12} are the reflection and transmission coefficients respectively, Z_1 and Z_2 are the acoustic impedances of materials 1 and 2 respectively, figures 2, 3.

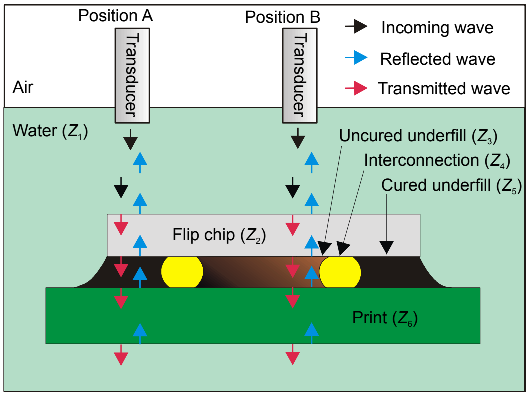

Figure 2: Illustration of SAM study on flip-chip with cured / uncured underfill.

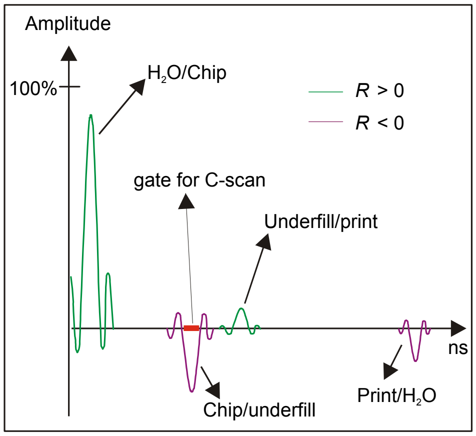

Figure 3: A-scan on flip-chip in figure 1. Reflected sound at chip / underfill varies according to cure degree.

The acoustic impedance is expressed by [2]:

$$Z = \rho V_L = \rho \sqrt{\frac{B(1-\nu)}{\rho(1+\nu)\cdot(1-2\nu)}} = \sqrt{\frac{\rho B(1-\nu)}{(1+\nu)\cdot(1-2\nu)}} \approx \sqrt{\frac{\rho E(1-\nu)}{(1+\nu)\cdot(1-2\nu)}} \approx \sqrt{\rho E} \qquad (3)$$

where V_L is the longitudinal wave velocity, B is the bulk modulus, E is Young's modulus, ρ is the density, and ν is Poisson's ratio. Both E and ρ will increase by curing and therefore $Z_{\text{cured}} > Z_{\text{uncured}}$.

SAM can be considered as a supplement to other NDT methods like X-ray inspection. The contrast in X-ray inspection relies on absorption due to differences in the atomic mass. Bubbles, cracks etc. in polymers are for instance not easy to see with X-rays, though they are easy to see with sound.

Results are most often presented as C-scans, which are 2D pictures of the sound reflected from a certain depth range corresponding to a certain echo time delay where a gate is placed in a sample, figure 3. Pulses and echoes are transmitted and received by the same transducer, which is scanned over the surface of the sample.

In SAM resolution and penetration depth depends on frequency (focal spot size), focus position, stiffness and stiffness changes in the materials. High frequency gives high resolution but low penetration depth and vice versa. Lateral and depth resolution is expressed by equations 4 and 5 below respectively.

$$\Delta_{lateral} = 1.22\lambda_{material} \frac{F}{D} \qquad (4)$$

$$\Delta_{depth} = 2.44\lambda_{material}\left(\frac{F}{D}\right)^2 \tag{5}$$

where $\lambda_{material}$ is the wavelength in the study material, F is the focal length and Δ is the transducer aperture diameter.

The detection limit of delaminations or other gaps (air or vacuum) is below 0.1 µm since even such narrow defects have been demonstrated to reflect all the sound [3]. For best results plane and smooth surfaces are required. Using 200 MHz and the KSI WINSAM 200 instrument of this study a lateral resolution of 8 µm in the interface between bonded silicon and glass has been achieved.

2 Results

Two approaches for determining the degree of CUF curing degree have been studied. First it was attempted to determine the cure degree from differences in sound speed. This requires knowledge about the CUF thickness and reflection time delay between the top and bottom interfaces. The method turns out not to be feasible for typical CUF thicknesses (30 µm – 70 µm) because of too low depth resolution. Even with thick bond lines and therefore well separated reflections from top and bottom interfaces it is difficult to determine the speed with sufficient accuracy because the waves do not have the same form and the places on the waves to measure from / to are not well defined. Though, using C-scan grey tone values good results can be achieved.

2.1 Acoustic impedance calculations from C-scan grey tone values

The advantage of this approach compared to the speed of sound method is that only the degree of reflection at the same depth between different materials e.g. cured / uncured CUF is measured. Depending on the situation, with reference to figure 4, two different calculations can be used to find the acoustic impedance of a material under another:

- The acoustic impedance Z_1 of the top material is unknown.

Calculation of Z_x is based on the approximation that R_{12} has a linear dependence on Z_2. Then Z_x is given by:

$$Z_x = Z_b + (g_x - g_b)\frac{Z_b - Z_a}{g_b - g_a} \tag{6}$$

I.e. to determine Z_x two reference acoustic impedances Z_a, Z_b for materials under the top material are needed. Their grey tone values and that for the studied material x are measured in the C-scan picture.

- The acoustic impedance Z_1 of the top material is known

Calculation of Z_x is based on the linear dependence of g_x on R. Then Z_x is given by:

$$Z_x = Z_1 \frac{g_a(Z_a + Z_1) + g_x(Z_a - Z_1)}{g_a(Z_a + Z_1) - g_x(Z_a - Z_1)} \tag{7}$$

I.e. to determine Z_x in this case only one reference acoustic impedance Z_a for a material underneath the top material is needed. Again the corresponding grey tone value g_a and that for the studied material g_x is found in the C-scan picture.

Normally underfill materials contain a silica filler to lower the Coefficient of Thermal Expansion (CTE). In an attempt to evaluate the uniformity of the filler in cured underfill the above equation 7 has previously been derived in a slightly different form [4].

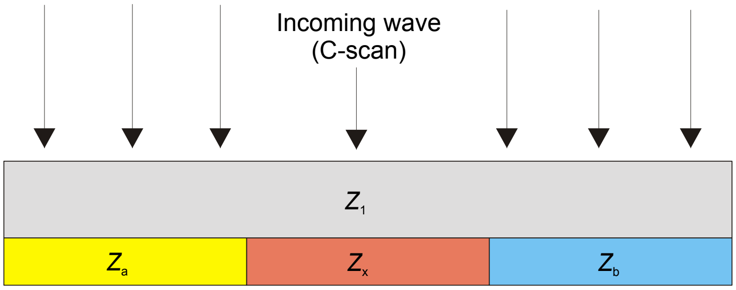

Figure 4: Illustration of the variables in equations 6 and 7.

2.2 Test 1: Determination of acoustic impedance of isopropanole

To test the methods of determining acoustic impedances isopropanole, air, water, and adhesive were placed between two microscope slides (glass) with the purpose of determining the acoustic impedance of isopropanole, fig 5. Isopropanole and air were entrapped in small aluminum pans meant for DSC measurements.

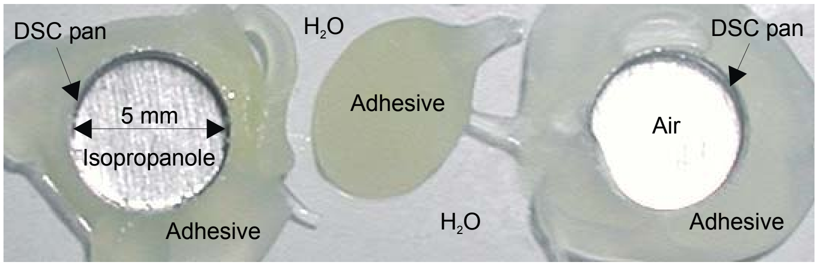

Figure 5: Isopropanole, air, water, and adhesive between two microscope slides.

The sample was placed in the water filled SAM inspection vessel and a gate for the C-scan covering the whole reflected wave from the bottom interface of the microscope slide was placed, figure 6. The C-scan was performed and grey tone values determined with KSI WINSAM 200 software, figure 7.

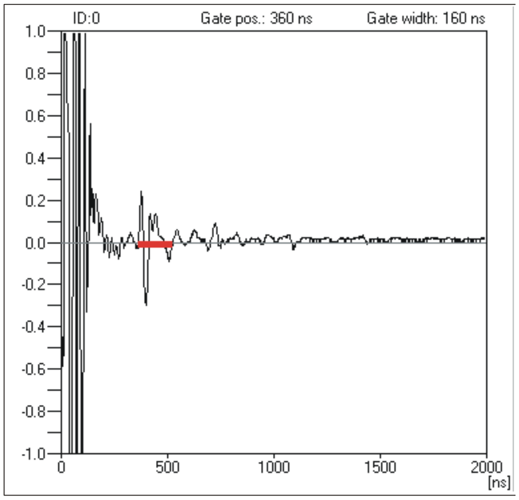

Figure 6: 110 MHz A-scan in centre of figure 5 sample (adhesive under microscope slide).

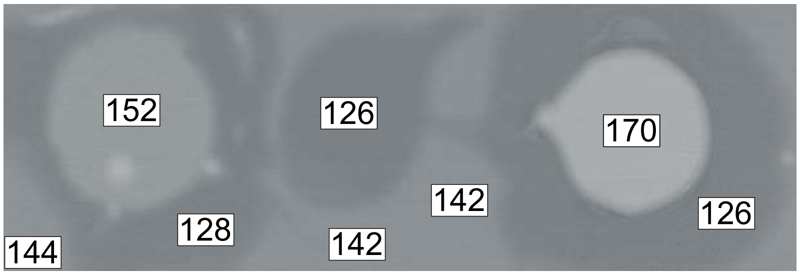

Figure 7: 110 MHz C-scan. Grey tone values for isopropanole, air, water, and adhesive.

The grey tone and the reference acoustic impedance values used for the calculations are shown in table 1. The results derived by use of equation 6 and 7 show satisfactory agreement with the tabulated *Z* value for isopropanole, table 2.

Table 1: Determined grey tone values and reference acoustic impedances.

Reference acoustic impedances / MRayl			Grey tone values (0 => 256)		
Z_1(glass)	Z_a(H_2O)	Z_b(air)	g_a(H_2O)	g_b(air)	g_x(isopropanole)
15	1.48	0.0004	142	170	152

Table 2: Acoustic impedance of isopropanole.

Z_x(isopropanole) / MRayl		
Equation 6	Equation 7	Table
0.95	0.97	0.92

2.3 Test 2: Test on flip-chip with CUF

Cured / uncured epoxy EC1211 CUF material between a 2 cm x 2 cm x 0.35 mm test flip-chip with approximately 30 µm bumps and a Printed Circuit Board (PCB) were studied, figure 8. The narrow gate around the middle of CUF material in the figure 9 A-scan results in a clear picture of the bump positions, figure 10. To get the grey tone values a gate is placed which covers the whole reflected wave at the chip / CUF / PCB interfaces, figure 9. The resulting C-scan picture with grey tone values is shown in figure 11.

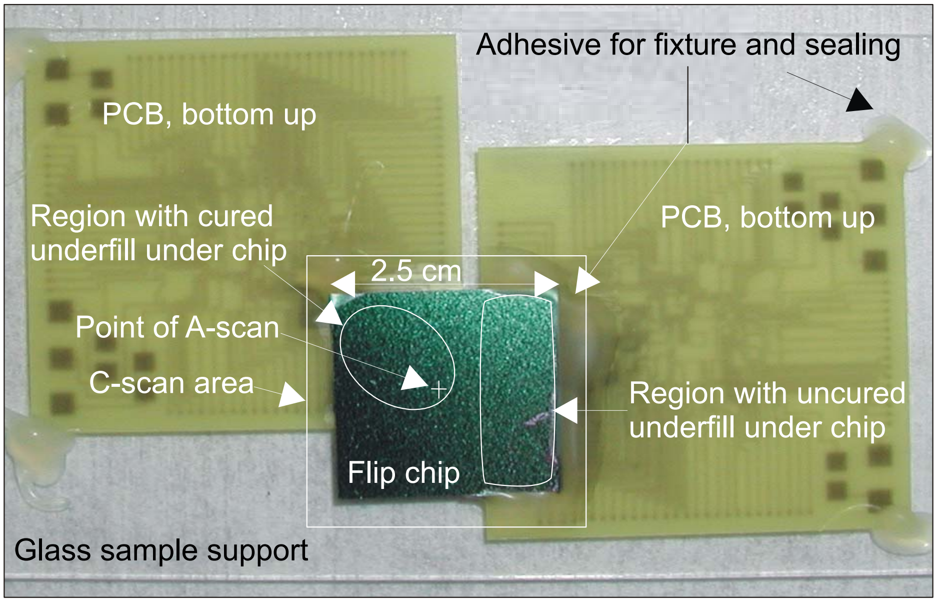

Figure 8: Test flip-chip with 30 µm bump height on PCB's with cured / uncured EC1211 CUF material. During investigation water is under the chip in the bottom left corner.

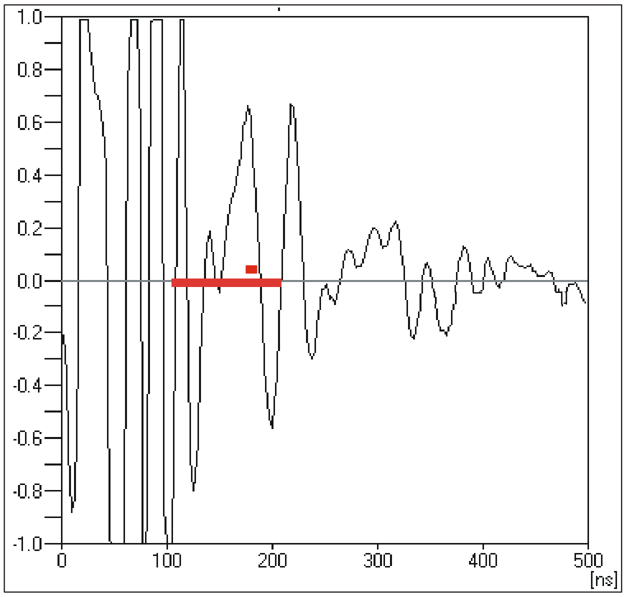

Figure 9: 50 MHz A-scan on flip-chip in figure 8 (white cross)..

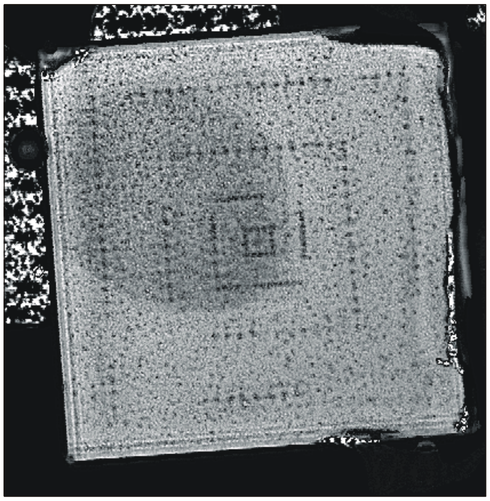

Figure 10: 50 MHz C-scan corresponding to narrow gate in A-scan shown in figure 9.

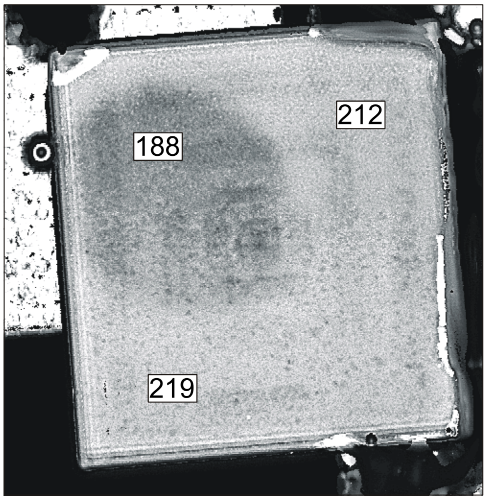

Figure 11: 50 MHz C-scan corresponding to broad gate in A-scan. Numbers indicate grey tone values.

The grey tone and reference acoustic impedance values used for the calculations are shown in table 3. The results derived by use of equation 7 show satisfactory agreements with the tabulated *Z* value for typical cured epoxy, table 4.

Table 3: Determined grey tone values and reference acoustic impedances.

Reference acoustic impedances / MRayl		Grey tone values (0 => 256)		
Z_1(silicon)	Z_a(H_2O)	g_a(H_2O)	g_x(EC1211 cured)	g_x(EC1211 uncured)
20	1.48	219	188	212

Table 4: EC1211 and typical epoxy acoustic impedances.

EC1211 acoustic impedances / MRayl		
Equation 7		Table (typical epoxy)
Z_x(cured)	Z_x(uncured)	Z(cured)
3.0	1.8	3 - 4

4 Discussion

The speed sound in the [111] direction of single crystalline silicon is 8.4 μm/ns. I.e. sound travels forth and back in the 350 μm flip-chip within 83 ns. The broad gate for grey tone determination starts about 20 ns later. The surface which is detected automatically at some level which might be quite low can be the explanation for this. Further the explanation might be the roughness of the unpolished top side of the chip. The speed of sound in cured epoxy is around 3 μm/ns. The wave length at 50 MHz is 60 μm. With a bump height of 30 μm the reflections from the chip / EC1211 and EC1211 / print interfaces with a time delay of around 20 ns cannot be resolved according to (5). Though, this interference from the EC1211 / print interface reflection is not critical since the two materials are acoustically well matched, which means that most of the sound is transmitted (see figure 3). This is also evidenced by the fact that A-scan wave forms in the flip-chip test case, figure

9 resembles the A-scan wave form in the isopropanole test case where the thickness of the adhesive is 2 mm.

On curing EC1211 the acoustic impedance changes about 1 MRayl unit / 20 grey tone values. By measuring at different places the uncertainty was estimated to be approximately 2 grey tone values corresponding to 0.1 MRayl.

5 Conclusion

It has been demonstrated that SAM can be used to determine acoustic impedances of materials in layered structures. Two equations have been verified. The usability of one equation depending on knowledge about the top layer acoustic impedance and only one other acoustic impedance of a material in the same depth as the analysed one has been demonstrated on a CUF flip chip with 30 μm bump height. A clear difference between cured / uncured CUF can be observed.

6 Acknowledgement

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