Ultrasonic characterisation of interfaces in IC packaging

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Ultrasonic Characterisation of Interfaces in IC Packaging

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**SCHOOL OF
MECHANICAL AND PRODUCTION ENGINEERING
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Abstract

There are many interfaces that exist in IC packaging, such as that between mold compound and silicon chip, and that between silicon die and copper lead-frame. The quality of the interface is becoming a critical issue in the reliability testing of IC packaging and during the manufacturing process as the packages become thinner and denser. Common defects such as delamination and crack can be detected using C-mode scanning acoustic microscope with sufficient confidence as ultrasonic reflection wave changes dramatically in the gross defects area. However, a weak interface due to weak adhesion and poor cohesion has often gone undetected as ultrasonic reflection wave only changes a bit in weak interface area, and weak interface may become potential defective area at a later stage. It is desirable to develop a more sensitive and quantitative method to characterize the weak interface nondestructively, and this has been the motivation and focus of the study, which centres on the quantitative evaluation of interface quality using the oblique incident ultrasonic wave.

An interface spring model for interface between two different media was developed to predict the ultrasonic reflection coefficient relationship with varying interfacial spring constants and incidence angle. The reflection and transmission coefficients can be calculated as a function of incident angle, wave frequency, material property, interface quality and residual stress. The model has been applied to typical interfaces in IC packages, such as MC/silicon and MC/copper interfaces. The incident wave angles at which the reflection coefficient is most sensitive to change in MC/Si interface quality has been identified. It has been shown that the reflection coefficient for the longitudinal wave reflection to longitudinal wave incidence at 35° , $R_{LL}(35^\circ)$, is the most sensitive. It is

about 1.7 times greater than the traditional normal incident reflection coefficient $R_{LL}(0^0)$. This offers significant potential for quantitative evaluation of interface quality.

Numerical model was developed using finite element method to validate the theoretical results, such as the reflection coefficient R_{LL} from the interface with different incident angles and varying interface stiffness. The simulation also allows for the prediction and visualization of time-domain wave propagation signal, thus for selection of testing strategies and comparison with the measurement. It has been shown that the simulated reflection coefficient characteristics have a good agreement with the theoretical results.

Experimental work was also carried out to validate the predicated result for the MC/Si samples with interfaces under varying conditioning process that simulates the degrading of the interface. It has been shown that the measured oblique reflection coefficient in general has good and qualitative agreement with the predicted results in terms of the reflection coefficient amplitude, and its dependence on the interface quality. It is demonstrated that the sensitivity of the reflection coefficient $R_{LL}(35^0)$ was about 1.9 times that of the normal incident $R_{LL}(0^0)$.

The study demonstrates that the quantification evaluation of the interface quality is possible, and oblique reflection coefficient can be used as a criterion for its better sensitivity. The result is also applicable to interfaces in other IC packaging configurations since the interface studied in this work is very generic. However, the actual correlation depends on the configuration, material property, geometry, thickness, etc. Following the approach presented in this work, the most sensitive incident angle for

the oblique wave can be identified, and testing strategy, such as type of ultrasonic wave, incident angle, frequency and pulse type, can be defined.

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Table of Contents

Abstract	i
Acknowledgement	iii
Table of Contents	v
List of Figures	vii
List of Tables	xi

Chapter 1 Introduction

1.1 Background	1
1.2 Objectives	3
1.3 Scopes	3
1.4 Outline of the Report	5

Chapter 2 Literature Review

2.1 IC packaging structure and defects	6
2.2 Causes of defects in IC packages	7
2.3 Failure analysis techniques	12
2.4 Multilayer interface models	16
2.5 Spring interface model	17
2.6 Numerical simulation of interfaces	21
2.7 Weak interfaces samples	23
2.8 Strength tests	24
2.9 Ultrasonic Measurement of Interfaces	26
2.10 Oblique incidence ultrasonic measurement system	27
2.11 Summary	28

Chapter 3 Spring Models of Interfaces

3.1 Introduction	44
3.2 Spring stiffness model of defects	45
3.3 Spring model for normal incidence	51
3.4 Spring model for oblique incidence	53
3.5 Oblique incidence on a surface with residual stress	60
3.6 Software development	63

Chapter 4 Theoretical Results

4.1 Verification of the models and software	70
4.2 MC/Si interfaces	72
4.3 Sensitivity to frequency	77
4.4 Longitudinal stiffness K_{33} and shear stiffness K_{31}, K_{32}	80
4.5 MC/Copper interfaces	82
4.6 Effects of interface stress on reflection coefficients	85
4.7 Reflection coefficient $R_{LL}(0^\circ)$ and $R_{LL}(35^\circ)$ with residual stress	86

4.8	Conclusions	87
 Chapter 5 Finite element simulation of oblique incident wave in IC package interfaces		
5.1	Introduction	110
5.2	Considerations in modelling	113
5.3	Results and discussion	119
 Chapter 6 Conditioning of IC packaging samples with controlled interface and experimental set-up		
6.1	Experimental methodology	139
6.2	Conditioning of interface sample	141
6.3	Experimental setup	143
6.4	Experimental procedure	150
 Chapter 7 Experimental Results and Discussion		
7.1	Characterisation of samples	162
7.2	MC/Si interface reflection coefficient	167
7.3	Measured reflection coefficients	171
7.4	Combined A-scan and lap-shear pull test	175
7.5	Discussions and conclusions	177
 Chapter 8 Conclusions		
8.1	Conclusion	191
8.2	Recommendations for Future work	193
References		196
Appendix		
A	Equations of Oblique Incidence without Stress	204
B	Equations of Oblique Incidence with Stress	206

List of Figures

Fig. 2.1	Schematic drawing of a Plastic-Encapsulated Microcircuit (PEM).	30
Fig. 2.2	Potential defects in plastic-encapsulated microelectronic packages.	31
Fig. 2.3	Principle of X-ray topography	32
Fig. 2.4	Cracks, inclusions, voids detection in IC package using X-ray.	33
Fig. 2.5	Principle of C-mode scanning acoustic microscopy (C-SAM)	34
Fig. 2.6	Delamination, cracks, voids detection in IC package using C-SAM	35
Fig. 2.7	Comparison of exact and the interfacial spring model solutions	36
Fig. 2.8	Predicted reflection coefficients	37
Fig. 2.9	Comparison of exact coefficients R_{β}^L (solid lines) and reflection coefficients for spring layer reflection R_{β}^{-L} (dashed line) versus $\bar{\omega}$, for an incident longitudinal wave.	38
Fig. 2.10	Defects models.	39
Fig. 2.11	Normalized plots of interface stiffness versus fractional contact area of periodic array of slits.	40
Fig. 2.12	Reflection coefficient vs. distributed spring constant for bonds prepared at different times and temperatures.	41
Fig. 2.13	Reflection coefficient vs. frequency.	42
Fig. 2.14	Geometry to measure the oblique coefficient.	43
Fig. 0.1	Leaky lamb wave is used to detect internal defects in composite laminates using pitch-catch setup	43
Fig. 3.1	(a) Displacement across the imperfect interface (b) Reflection and transmission field.	64
Fig. 3.2	Geometry of spring model for the interface	65
Fig. 3.3	Incidence geometry and model coordinate system.	66
Fig. 3.4	Interface samples under mechanical stress loads	67
Fig. 3.5	Flowchart of spring model software.	68
Fig. 4.1	Reflection Coefficient between silica and yttrium aluminium.	90
Fig. 4.2	Spectra of signal from the aluminum plate imperfectly bonded to aluminum substrate.	91
Fig. 4.3	Reflection coefficients for imperfect bonds in IN100 alloy	92
Fig. 4.4	R_{LL} on the MC/Si interface as a function of incident angle.	93
Fig. 4.5	R_{LS} on the MC/Si interface as a function of incident angle.	94
Fig. 4.6	R_{SL} on the MC/Si interface as a function of incident angle.	95
Fig. 4.7	R_{SS} on the MC/Si interface as a function of incident.	96

Fig. 4.8	Sensitivity of R_{LL} to interface stiffness (MC/Si).	97
Fig. 4.9	Sensitivity of R_{SS} to interface stiffness (MC/Si).	98
Fig. 4.10	The reflection coefficient of the MC/Si interface as a function of frequencies	99
Fig. 4.11	$R_{LL}(10^\circ)$ and $R_{LL}(35^\circ)$ with the spring stiffness ratio K_{32}/K_{33} varying from 1 to 0.7.	100
Fig. 4.12	$R_{SS}(10^\circ)$ and $R_{SS}(35^\circ)$ with the spring stiffness ratio K_{32}/K_{33} varying from 1 to 0.7.	101
Fig. 4.13	The R_{LL} from the MC/Copper interface as a function of incident angle.	102
Fig. 4.14	The R_{LS} from the MC/Copper interface as a function of incident angle.	102
Fig. 4.15	The R_{SL} from the MC/Copper interface as a function of incident angle.	103
Fig. 4.16	The R_{SS} from the MC/Copper interface as a function of incident angle.	103
Fig. 4.17	The sensitivity of R_{LL} at 0, 41 and 66° to interface stiffness (MC/Copper).	104
Fig. 4.18	The sensitivity of R_{SS} at 0, 23° , 27° and 32° to interface stiffness (MC/Copper).	105
Fig. 4.19	The effect of compressive stress on $R_{SS}(0^\circ)$ and $R_{SS}(35^\circ)$ from the MC/Si interface.	106
Fig. 4.20	The effect of shear stress on $R_{LL}(0^\circ)$ and $R_{LL}(35^\circ)$ from the MC/Si interface.	107
Fig. 4.21	The effect of compressive stress on $R_{SS}(0^\circ)$ and $R_{SS}(30^\circ)$ from the MC/Si interface.	108
Fig. 4.22	The effect of interfacial stress on the reflection coefficient from MC/Si interface for different interface stiffness.	109
Fig. 5.1	Typical FE Model of Mc/Si with intermediate layer of varying material properties for simulation	128
Fig. 5.2	Element type selected for FE simulation	129
Fig. 5.3	The waveform of the input signal and its spectrum used for finite element simulation.	130
Fig. 5.4	The time-history monitored at nodes along the incident wave path.	131
Fig. 5.5	The time-history monitored at nodes along the reflected longitudinal wave path.	132
Fig. 5.6	The time-history monitored at the nodes along the path of reflected shear wave.	133

Fig. 5.7	Example of calculating the reflection coefficient	134
Fig. 5.8	The reflection coefficient R_{LL} as a function of incident angle for perfect interface	135
Fig. 5.9	The reflection coefficient $R_{LL}(0^\circ)$ for varying interface quality	136
Fig. 5.10	The reflection coefficient $R_{LL}(15^\circ)$ for varying interface quality	137
Fig. 5.11	The reflection coefficient $R_{LL}(30^\circ)$ for varying interface quality	138
Fig. 6.1	The dimensions and mould used to fabricate samples for the experiment	151
Fig. 6.2	Apparatus used in sample preparation and conditioning	152
Fig. 6.3	C-scan images for the samples subjected to moisture conditioning	153
Fig. 6.4	Schematic of the A-Scan set	154
Fig. 6.5	Water tank with aluminum plate for oblique incidence measurement	155
Fig. 6.6	Illustration and transducer setup for oblique incidence measurement	156
Fig. 6.7	Time domain signal from MC/Si sample.	157
Fig. 6.8	Apparatus used for the combined test using universal testing machine and ultrasonic measurement.	158
Fig. 6.9	Testing rig and transducer setup for normal incident pulse echo ultrasound measurement with applied loading on sample (a) photo of setup (b) schematic diagram	159
Fig. 6.10	Load vs extension graph for the MC/Si samples.	160
Fig. 6.11	Testing rig and transducers setup for oblique incident ultrasound measurement with applied loading on sample	161
Fig. 7.1	Moisture content of samples against moisture conditioning time, (a) average weight of samples (b) percentage increase in moisture by weight.	180
Fig. 7.2	C-scan images for the samples A subjected to moisture conditioning	181
Fig. 7.3	C-scan images for the samples B subjected to moisture conditioning	182
Fig. 7.4	Failure stress of samples with different moisture conditioning time	183
Fig. 7.5	Measured time domain ultrasonic reflection from MC/Silicon sample (a) with normal incident wave (b) with oblique incident wave at 35°	184
Fig. 7.6	Typical waveforms and edited LL echoes used in calculation of the oblique incident reflection coefficient $R_{LL}(35^\circ)$	185
Fig. 7.7	The oblique incident reflection coefficient spectrum $R_{LL}(35^\circ)$ obtained with the LL spectra from MC/water and from MC/silicon	186
Fig. 7.8	Theoretical sensitivity of R_{LL} to interface stiffness (MC/Si) in normal incidence and 35° oblique incidence from spring model.	187
Fig. 7.9	Measured reflection coefficient $R_{LL}(0^\circ)$ from the MC/Si interface as a function of good area percentage.	187

Fig.7.10	Measured reflection coefficient $R_{LL}(35^\circ)$ from the MC/Si interface as a function of good area percentage	188
Fig.7.11	Lap-shear pull test combined with normal incidence ultrasonic measurement. Reflection coefficient $R_{LL}(0^\circ)$ against the load of sample (a) sample A (b) sample B	189
Fig.7.12	Lap-shear pull test combined with oblique incidence ultrasonic measurement. Reflection coefficient $R_{LL}(35^\circ)$ against the load of sample (a) sample C (b) sample D	190

List of Tables

Table 4.1	The material properties used in verification.	71
Table 4.2	The material properties used in interface study.	72
Table 4.3	Sensitivity of R_{LL} (0°) over different interface stiffness ranges.	78
Table 4.4	Sensitivity of R_{LL} (10°) over different interface stiffness ranges.	79
Table 4.5	Sensitivity of R_{LL} (35°) over different interface stiffness ranges.	79
Table 4.6	K_{32}/K_{33} theoretical values in different materials and crack structure.	81
Table 4.7	Maximum difference in reflection coefficient with different K_{32}/K_{33} Ratios.	82
Table 5.1	Material properties used in F.E. simulation.	115
Table 5.2	Requirements to satisfy F.E. simulation model.	115
Table 5.3	Comparison of spring model and FEM method.	123
Table 5.4	Sensitivity of simulation results over different interface stiffness ranges.	125
Table 7.1	Reflection coefficient in spring model for bad and good interface.	172
Table 7.2	Reflection coefficient of experiment for bad and good interface.	175

Chapter 1

Introduction

1.1 Background

With the rapid development of IC technology, the size of IC chip has been enlarged, and the package has been made thinner and smaller. The reliability of the package has become an important issue in the IC packaging industry, and the inspection of the quality of packaging is therefore becoming increasingly demanding. There is a strong need to develop quantitative methods to evaluate the interface of package, which motivate the current project.

A plastic-encapsulated microcircuit (PEM) is a plastic package where the IC chip is bonded on a substrate by adhesive resin and then they are encapsulated in mold compound. The encapsulated package is subject to reflow process. The bonding induces internal stress in the chip and substrate due to the solidification of the bonding material and the thermal mismatch between the chip and substrate. Internal stresses are also created due to the difference in thermal expansion coefficients of encapsulated resin and chip.

These stresses cause a weak interface, which may develop into delaminations in the interface at a later stage. Weak interface areas can occur at MC/die, die/attach/die-pad and die-pad/MC, and exact reasons are far from being well understood though it may be due to contamination, inappropriate reflow, voids, weak chemical bonding, etc. The

weak interfaces usually appear in normal bonded condition under visual or x-ray inspection, but may develop into defective areas because of the stresses caused by the mismatch between the coefficients of thermal expansion (CTE) of different materials. When the packages are subjected to environmental testing or during normal loading and service, they may develop into cracks immediately or just deteriorate and grow into delaminations at a later stage.

Currently scanning acoustic microscope (SAM) is one of the commonly used non-destructive inspection techniques in IC packaging industry. The technique can detect the defects inside packaging such as delaminations between the mold compound and silicon, or between mold compound and die-pad, and cracks in the mold compound. However the weak interfaces, which experience degradation but are not characterized by the phase inversion, cannot be detected. Furthermore, electrical testing is unable to detect the weak interface since bonded materials are still in mechanical contact. It is evident that there is no method available to detect the weak interface in the IC packaging. There is strong need and desire to develop nondestructive evaluation techniques which are able to quantify the strength of the adhesion in bonded area, and hence the condition of the weak interface.

It is therefore extremely desirable to be able to monitor the interface quality more quantitatively, preferable at an earlier stage, for example after reflow process, during or even before that. If an early detection of potential defected packaging is possible, a great deal of resources can be saved in terms of time, material and cost. This project is aimed to look into an alternative approach for evaluating interface quality in IC packages.

1.2 Objectives

The aim of this project is to study an alternative nondestructive evaluation techniques to characterize weak interfaces in IC packaging using oblique incident ultrasound wave, and to study the oblique incident ultrasound wave reflection and its relationship with the strength of adhesion. They include,

- To develop an analytical model to describe the imperfect interface between two different media.
- To study the sensitivity of the oblique incident wave as a function of the incident angle, frequency and interface stiffness.
- To simulate the wave propagation through weak interface using numerical methods.
- To develop conditioning techniques that controls the quality of the interfaces which are typically found in IC packaging.
- To validate the theoretical and numerical results with measurement using oblique ultrasound and to develop a measurement methodology to evaluate the weak interface.

1.3 Scope

The scope of this research project can be summarized in the following directions of investigation.

(1) Type of packages and interfaces

Since there are many types of IC packaging, for example, TQFP, BGA, CGA, and there are many interfaces even in the simplest package, such as MC/silicon, silicon/adhesive, and silicon/adhesive/copper, etc. Only generic interfaces are studied in this project. In

particular, focus is placed on the MC/silicon interface, which is the most important and common interface in IC packaging. The techniques developed in this study can be easily extended to other types of interfaces.

(2) Types of defects

It is evident from the literature review in Chapter 2 that there are many types of defects that may exist in IC packaging, such as popcorn cracks, delaminations, disbonds, etc. However, this study focuses on weak interfaces, which are in fact in the pre-defective stage. In general the normal incident C-mode acoustic scanning microscopy is unable to reveal the existence of the weak interfaces.

(3) Analysis of weak interfaces

A spring interface model will be developed to describe the propagation of oblique incident ultrasound through the imperfectly-bonded interface between two elastic media. The oblique ultrasonic reflectivity is studied for its sensitivity as a function of wave frequency, the angle of incidence, the interface spring stiffness. The model is then applied to study the interface in IC packaging. Numerical simulation of wave propagation across the interface is also carried out using finite element method, and predicted results validate the theoretical model. The analyses identify the most sensitive ranges of frequency and incidence angle of ultrasonic wave.

(4) Ultrasonic measurement of interfaces

The MC/Si samples with varying interface quality are fabricated with different conditioning processes that are similar to those used in the industrial manufacturing of plastic package. A measurement system is developed to measure oblique incidence

reflection coefficients and to correlate them with interfacial weakness of samples' interface. The experiment results will be compared with the result of spring model whenever possible.

1.4 Outline of the report

The thesis is organized as follows. Following the introduction in this chapter, a review of relevant research work in the area of IC packaging reliability study and ultrasonic evaluation of interfaces are presented in Chapter 2. An oblique incidence interfacial spring model for interface between two different media is developed in Chapter 3. The application of the model to IC packaging is presented in Chapter 4, where the theoretical results of oblique incident reflection coefficient are described in the case of MC/silicon. Chapter 5 presents the finite element simulation of ultrasonic waves propagating through the interface, where reflection coefficient based on the predicted time response is obtained. In Chapter 6, experiment setups and sample conditioning procedures are described, including sample fabrication, C-scan, normal and oblique incidence ultrasonic reflection measurements. The measurement results of oblique incident reflection coefficient are presented in Chapter 7, with comparison to analytical and numerical results, and discussion on the advantage and disadvantage of the technique using oblique incident methods. Finally conclusions and contributions are summarized in Chapter 8.

Chapter 2

Literature Review

In this chapter, the common defects in IC packages and their causes are first described, followed by the failure analysis techniques currently being used. The ultrasonic evaluation of the interfaces using normal and oblique incident waves are reviewed, together with interface models and simulation, including multilayer model and spring model. Finally, techniques for conditioning the controlled samples of varying quality are discussed.

2.1 IC packaging structure and defects

Electronic packages provide the medium for electrical bridges or interconnections, as well as the mechanical support and protections of the delicate electronics circuitry. With the development of very large scale integration (VLSI) in recent years, industry trend has been to push as much as possible electrical circuits onto the chip while simultaneously reducing the cell area. The increased levels of chip integration have produced a number of higher-level electronic packaging challenges. For example, pinout, the number of input and output (I/O) connections on the chip, has dramatically increased with the advances made in chip integration. Several advanced packaging and interconnection technologies are currently under development to meet the requirement of complex, large and high-speed microelectronics integrated circuits (IC) and systems. As a high density of components is packed onto a limited space, the inspection of quality of IC packaging

is therefore become more and more important and challenging (Pecht, 1995; Michael, 1991).

To allow for connections between the chip and outside world, chip carriers usually contain a metallized pattern which is commonly referred to as a lead frame. Electrical interconnections are then established between conductor pad and formed on chip and lead frame of the chip carrier through either wire bonding, direct solder bonding, or tape-automated bonding processes. The conventional plastic-encapsulated microcircuit (PEM), often called a plastic package can be defined as consisting of a silicon chip, metal leadframe, wires bond interconnect that electrically attach the chip circuits to the leadframe, and plastic epoxy encapsulating material to protect the chip and the interconnecting wires. A schematic representation of a plastic package is shown in Fig. 2.1. It can be seen from the figure that there are many interfaces, for example, MC/Silica, and Si/Die-Pad interface (Michael, 1995).

2.2 Causes of defects in IC packages

Defects may occur at those interfaces, such as interfacial delamination at the weak interface introduced by CTE mismatch at high solder reflow temperatures, cracks at the interface due to the evaporation of absorbed moisture at the reflow temperatures. The main defects that occur in IC package are illustrated in Fig. 2.2. The mechanism of reduction of interface adhesion can be classified into five categories (Lim et al., 1998),

- (1) Moisture - moisture absorbed in to the package can cause delaminations when the moisture vaporises and tries to escape when subjected to higher temperature.

- (2) Temperature - differences in the coefficients of thermal expansion (CTE) of the materials in the PEMs, cause significant stresses to develop at the bonded interfaces during temperature cycling.
- (3) Surface reactions including corrosion and oxidation, etc.
- (4) Surface contamination.
- (5) Material processing.

2.2.1 Moisture effects

It has been observed that delamination at any interface is dependent on the moisture present in the package (Shook, 1993). Tanaka and Nishimura (1995) performed experiments to show the effect of moisture in causing delaminations in PEMs. Moore et. al. (1991) used C-SAM techniques to study the effects of induced moisture. They found that the amount of delamination at the MC/Si interface positively correlates to the amount of moisture ingress. Their work also revealed that MC/Si delaminations start at the silicon die corners and rapidly spread toward the die centre.

The absorption of water in materials causing an increase in mass and volume is termed as hygroscopic swelling. Wong et. al. (2000) studied the effects of hygroscopic swelling in the polymeric materials in electronic packaging and found the polymeric and non-polymeric materials in a typical PEM cause stresses to develop at the interfaces due to hygroscopic swelling effects.

Chowdhury et. al. (1998) studied the effects of moisture ingress under ambient conditions which concluded that delaminations greatly increased the thermal resistances of interfaces, thereby, resulting in reduced thermal performance in PEMs. Bojta (2001)

attempted to model moisture caused failures for PEMs in stress tests. The proposed models provide a simple solution to predict the reliability of the PEMs, however it was difficult to integrate the models in an actual situation.

2.2.2 Temperature effects

It is shown that the delamination due to temperature cycling causes direct failure in plastic packages (van Doorselaer and de Zeeuw, 1990). They used test chips encapsulated in a plastic molding compound and subjected them to temperature cycling in air. The test chips were tested electrically and for delamination by means of Scanning Acoustic Tomography (SCAT) and it was found that delaminations almost always accompany electrical failure of the dies. They concluded that adhesion of the MC/die interface was of utmost importance with respect to electrical failures.

Other studies showed that temperature effect on various package failures. For example, delamination initiated from the edges of the silicon die and then evolved towards the inner area of the die in plastic ball grid array (PBGA) packages due to thermal cycling (Lee et. al., 1997), progressive damage to the silicon die occurred during thermal cycling (Nguyen et al., 1994), bond wire damage and cracks occurred in plastic and die in plastic encapsulated microcircuits (Scalise, 1996).

2.2.3 Combination of moisture and temperature effects

Strifas and Christou (1989) used temperature (25° to 85°) and humidity (50% to 85% RH) to study their effects on delamination in PEMs. They found that the predominant effect was delamination at the MC/Si and die paddle/MC interface. It was concluded that

delamination induced from stresses during temperature cycling and moisture ingress, coupled with the high temperatures during manufacturing processes, was the critical phenomena in failure of PEMs.

Moore and McKenna (1991) used a combination of the two effects and their study found that there was a positive correlation between delamination at the MC/Si interfacial sites and the location of failed wire bonds. Scalise (1996) published his findings on the effects of certain combined temperature and moisture testing on typical PEMs which show the delaminations to be dependent on the types of PEMs, e.g. the size, the internal structures, the materials of the PEMs etc.

2.2.4 Other effects

To build reliable PEMs, it is essential to achieve excellent adhesion at all internal interfaces. Two common inhibitors to good interfacial adhesion within PEMs common effects will influence the quality of adhesion, there are surface contamination and adhesion process.

The contamination is mostly organic in nature and is usually accumulated prior to molding thus causing poor adhesion of the internal parts of the PEMs to molding compound. Ganesan et. al. (1996) studied the effects of contamination on the MC/Si interface. The cleanliness of the Si surface was quantified on the basis of the contact angle (θ) measurement of a drop of De-Ionized water placed on the surface. It was shown that for surfaces with a low θ ($<10^\circ$) produced interfaces that are consistently delamination-free whilst those with a large θ ($>45^\circ$) produced interfaces that consistently contained delaminated areas.

The chemistry behind the adhesion process also contributes to interfacial quality. Leung et. al. (2000) recognised the effects of adding a coupling agent to epoxy based underfill materials in flip-chip assembly enhances interfacial quality by introducing a chemical bonding across the interface. The geometrical properties of the PEMs also contribute to interfacial quality across the different materials present, reported by Saitoh et. al. (2000).

It is evident that many effects can contribute to the deterioration of the interfaces in IC packaging. In typical adhesive bonded interfaces, there are three basic types of defect which may occur, and they are (Adams and Drinkwater, 1997),

- (1) Poor adhesion, which is a weak bond between the adhesive and adherend, is often the result of poor surface preparation and the presence of a contaminant on an adherend. Adhesive strength is very difficult to measure nondestructively since it is an interfacial phenomenon involving a very thin (usually less than 10 μm) layer of material.
- (2) Poor cohesive strength, which is a weak adhesive layer, results from either incomplete mixing, incorrect formulation, or from insufficient cure of the adhesive. Unlike the adhesive strength, the cohesive strength of the adhesive can be estimated with a reasonable degree of confidence by a number of nondestructive methods
- (3) Complete voids, disbonds and porosity: Porosity is caused by entrapped air and volatiles in the adhesive and is present in most bond-lines to some extent cracks in monotonic or cyclic. Voids in the adhesive are caused by air or gases becoming trapped during the application of the adhesive, or because insufficient

adhesive has been applied. Surface unbonds are a form of void which can occur when an uneven coating of adhesive is applied to one adherend such that when the second adherend is introduced some areas have insufficient adhesive present to form a bond between the surfaces.

There are several other methods to characterise interfacial defects, for example, Nagy (1992) described different types of bond imperfections, namely kissing, partial and slip bonds. Kissing bonds occur between compressed but otherwise unbonded surfaces. Other than a weak “sticking” effect, a kissing bond has practically no strength (Kundu et. al., 1998). Partial bond can be characterised as an array of cracks located at the interface (Rehbein et. al., 1982). Slip bonds are rather more complicated to describe. It can be visualised as two adherends “slipping” in opposite transverse directions at the bond interface, resulting in shear stress being developed in the adhesive layer.

2.3 Failure analysis techniques

Non-destructive testing techniques are widely used in failure analysis and reliability testing of IC packaging. Since they have no permanent effect on the part allowing subsequent testing for other failure mechanisms. The suitability of a given method depends, among other considerations, on the size of the defects to be detected, the properties of the bonding materials, the stability of the bond interface, the speed and ease of use. In general, the detection of large voids and delamination is not a difficult problem, unlike the quantitative evaluation of the strength of an adhesion (Plohl and Krauter, 1999).

2.3.1 X-ray diffraction topography

X-ray diffraction topography can detect very small void ($1\ \mu\text{m}$). It uses electromagnetic energy waves to pass through a sample for flaws detection. The energy waves are absorbed differentilly by the samples, depending on its mass density and absorption coefficient. The transmitted energy is captured on film or with an electronic detector and forms “shadow” image of the sample. Principle of X-ray topography is illustrated in Fig. 2.3. Samples of X-ray film where cracks, porosity, inclusions, voids are detected as shown in Fig. 2.4 (Lim et al., 1998).

The capabilities of X-ray are to detect internal defects such as cracks, porosity, inclusions, voids. It is able to determine density and thickness variation. The advantage of X-ray includes its sensitivily to density changes and vertical delamination, with no couplant required, fast and global inspection,etc. Its disadvantage includes radiation hazard and the orientation of planar of linear defects critical to detection. Its sensitivity to defects decreases with increase in scattering radiation and an adequate density difference is required to see defects.

2.3.2 Ultrasonic techniques

Scanning Acoustic Microscopy is the most commonly used non-destructive technique in studying package related failures. The sample under analysis is placed in a water tank, an ultrasonic transducer generates a normal incidet ultrasonic pulse which is focused by a lens to a diffraction-limited spot. After the emission of probing signal, the transducer is switched into detection mode and receives the incoming echoes. The amplitude and the phase of reflecting echo are detected. Through gating, an echo coming from a particular

depth can be selected, and by scanning the transducer relative to the sample an acoustic image of that plane in the sample is gathered. Fig. 2.5 shows the principle of C-SAM testing, and a sample of C-SAM image where delaminations and cracks are detected in IC packaging is shown in Fig. 2.6.

The lateral resolution of the acoustic microscopy depends on the frequency used and the materials under investigation. Ultrasonic transducer can operate at a frequency as high as 1GHz (Jorgensen & Kundu, 2002), however typically it operates in the range between 10 to 100MHz. For a 200MHz transducer, the lateral resolution reportedly lies around 8 μ m, and the vertical resolution was found to be better than 50 μ m. The resolution and non-destructive nature of the technique make it very desirable as a tool for analyzing package-related defects such as die attachment problems, cracking and delamination. It is also possible to use the technique to do analysis of solder bumps and package contacts for flip chip devices which cannot be looked at using normal optical microscopy techniques (Plobl and Krauter, 1999).

The capabilities of the scanning acoustic microscopy include detecting internal gross defects such as: cracks, lack of fusion, inclusions, delaminations and voids. It can produce layer by layer images through the thickness of a sample, can determine material thickness and measure depth of features. The advantages of C-SAM are that it can provide specific interface and depth information and is sensitive to large cracks and delaminations. It needs to access to one side only, and has easy potential for automation. Its disadvantage are that selection of transducer design will limit penetration and resolution and it is not sensitive to vertical delaminations or cracks. Echo gate determines the compositions and interoperation of the images.

For C-SAM, the delamination areas are determined from the ultrasonic images by the phase inversion, that is, ultrasonic signal from delamination experience an 180° phase shift with respect to those from good interface. However, the weak interfaces which experience degradation but not characterised by the phase inversion can not be detected. This disadvantages of C-SAM are the motivation of this project, as the weak interface may develop into delamination after the electrical testing.

C-SAM is widely used in reliability study of electronic packaging. Siettmann et. al. (1992) described the use of C-SAM imaging techniques to evaluate PEMs. He documented the detection of MC/Si interfacial delamination, and the effect that MC thickness and transducer choice have on overall resolution in C-SAM imaging. It was concluded that C-SAM is only able to function as a qualitative tool to track the occurrence of delamination. The technique is unable to quantify interfacial quality.

Ong et. al. (1997) documented that delamination at the MC/Si interfaces can be easily detected using C-scan, as it has phase inversion. Wang (1998) proposed an ultrasonic technique that may possibly be effective in quantifying interfacial quality using reflection amplitude images from C-SAM. Many other methods and setup have been reported. For example, double through-transmission approach (Yang and Goh, 1995), air-coupled ultrasonic transducers (Grandia and Fortunko, 1995), spectral method for adhesive structures (Santos and Perdigao, 1996).

2.4 Multilayer interface models

It is essential to be able to model and to predict the ultrasonic characteristic of the interface, and there are extensive studies available in the open literature. In general two types of models are used, multilayer and spring models.

In multilayer models of interface, the interface layer is assumed to be an isotropic homogeneous thin layer with a particular density, elastic constants, thickness, and have perfect bonding with two adjacent media. The interface layer determines the bonding qualities between the two adjacent media by adjusting the material and geometric parameters associated with the layer.

Multilayer models have been widely used in aerospace application (Thompson and Fiedler, 1984; Cawley et al., 1996), specimens' acoustic microscopical analysis (Kundu, 1992). A typical adhesive-metal interface is formed by a layer of porous metal oxide, and the interlayer between the bulk adhesive and the bulk adherend formed by the oxide or microcomposite; it is a major determinant of strength and durability of the joint. Hydration of oxide layer and plasticisation (moisture softening) of the interfacial adhesive layer often lead to interfacial failure. These physical changes at the interface are accompanied by changes in the elastic properties of the interfacial region, which is called the weak boundary layer (WBL) since interfacial failure occurs in this layer. In reality, a WBL may be formed due to degradation of oxide, insufficient cure of adhesive in the proximity of the interface, adhesive plasticisation, contamination, etc.

Intermediate bond strength can thus be modeled by a thin finite solid layer. When the thin layer has the properties of the adhesive, a rigid bond is formed. When the interface

layer is of properties close to air, disbonding is formed. For varying material property, the reflection coefficient can be calculated using a general multilayer theory (Brekhovskikh, 1980), and related to frequency of the wave and angle of incidence. However, it is very difficult to characterize the exact thickness and material property of the interlayer. It is also difficult to use this model to determine the quality of interface, which has very thin interface layer, such as that between MC/Si.

2.5 Spring interface model

The spring model has been widely used in interface study in many applications, such as adhesive bonded joints in aerospace application. They can be divided into normal incident and oblique incident waves.

2.5.1 Normal incidence model

The spring interface model has been described by many authors, for examples Kendall and Tabor (1971) in study of contact interfaces. Tattersall (1973) had modeled the interface layer between two medium as density of springs with an elastic spring constant K , where K is the ratio of stress on the adjacent surface to the separation between the adjacent surfaces. When an ultrasonic wave is normally incident on the first medium some energy is reflected at the interface and some transmitted to the second medium. The reflection coefficient in terms of spring stiffness can be obtained as,

$$R = \frac{Z_1 - Z_2 + i\omega(Z_1 Z_2 / K)}{Z_1 + Z_2 + i\omega(Z_1 Z_2 / K)} \quad (2.1)$$

If the interface is perfect, the springs are rigid ($K = \infty$) and the amplitude is $R_{12} = (Z_2 - Z_1)/(Z_2 + Z_1)$. In the case of disbond, the springs are slack ($K = 0$) and the reflection coefficient equals to -1 , agreeing with the formula between two media.

The model was later reformulated in terms of the distributed springs, or interfacial stiffness model, as discussed in detail by Baik and Thompson (1984). In that paper, besides the spring stiffness K , another spring parameter “ m ” was introduced. “ m ” was the mass per unit area, and represents the inertial effects of change in density due to inclusions or pores at the interface. The formula of reflection coefficient is more complicated than equation 2.1.

The results of spring models have been compared to the cases for which exact solutions are known. The first case was an interface consisting of a layer containing material with different density and elastic constants (Angel and Achenbach, 1985), the result from both solutions are shown in Fig. 2.7. Each approximate solution by the spring model has a solid and a dashed portion and the solid line indicates the exact solution. It can be seen that the error depends on both Z_1/Z_0 , and v_1/v_0 . In general, when the wavelength is much larger than the interfacial thickness, the interfacial spring model solution provides a good approximation to the exact result.

The normal incidence spring model has been widely used in research communities to predict the reflection coefficient between two media, such as in determining the bond quality of diffusion bonds between two metals (Palmer and Rehbein, 1988; Lavrentyev and Rohklin, 1998).

2.5.2 Oblique incidence spring interface model

There is much less work available in area of oblique incidence spring interface model, as it is complicated for both theory and experiment. However, Margetan et al. (1986) have discussed some cases of the interface between two identical materials.

Margetan and Thompson (1988) applied the spring model to oblique incidence upon metal-jointing bond. Compared to only one spring stiffness constant for normal incidence, there will be nine spring stiffness constants for oblique incidence. Nine constants relate the three possible relative displacements of the two sides of the interface to the three possible applied stress components. However, in many cases, the interface region will have symmetries, which cause several of these components to vanish. Here, it is assumed that the stiffness matrix is diagonal, i.e., the “extra” displacement in the x, y and z directions are proportional to the tractions in those directions only (Palmer et al., 1988).

Margetan et al. (1988) derived the ultrasonic reflectivity of an imperfectly-bonded interface of two identical materials as a function of frequency and angle of incidence. For longitudinal wave incident on imperfect bonds in IN100 alloy, the results are shown in Fig. 2.8.

In 1985, Angel and Achenbach (1985) had presented an exact analysis of the reflection of elastic waves by a periodic array of cracks. Spring model was used to replace the array of cracks by a layer of massless springs. The comparison of spring model and exact reflection coefficient is shown in Fig. 2.9 for different incident angles. It is concluded that the spring approximation agrees with the exact theory at low frequencies.

In this project, the approach by Margetan et al. (1988) will be adapted to develop a spring model for oblique incidence for interfaces between two different media, and will be used for analysis of interfaces in IC packages.

2.5.3 Spring model stiffness K

Research effort has been made to correlate model the spring interface stiffness with the defect properties of interface such as defect pattern and fraction ratio of the defective area.

Since there is no mode conversion in normal incidence, only one stiffness can describe the quality of interface (Palmer et al., 1988). If the disbond distribution is specified, the spring stiffness constants can, in principle, be obtained by calculating the deformation of the bonded structure under static loading. In the most general case, an interface might contain a complex pattern of cracks and contacts randomly distributed porosity, which has no solution available.

As we mentioned before, in general there will be nine spring stiffness constants relating the three possible relative displacements to three stress components. If the disbond distribution is specified, the spring stiffness constants can, in principle, be obtained by calculating the deformation of the bonded structure under static loading. For the simple disbond patterns of interface between two identical materials as shown in Fig. 2.10, stiffness constants have been obtained or estimated by several authors using deformation results tabulated by Tada et al. (1973). Fig. 2.11 shows a plot of spring model stiffness vs A/A_0 , the fractional bonded area, for the case of a periodic array of strip-like disbonds.

It can be seen that spring model stiffness increase monotonically with increasing A/A_0 . This is expected since an increase in the fractional bonded area would tend to increase the interfacial stiffness.

Palmer and Rehbein (1988) reported the verification of spring model. On the inspection of the fractographs, the fractions of bonded area A/A_0 could be obtained experimentally, and then the spring stiffness K was calculated using the theory developed by Baik (1984). Using spring model to predict the reflection coefficient and then compare with the experimental data of failed diffusion bonds of copper to copper shown in Fig. 2.12 and 2.13. In general it proved to be quite successful, particularly for bonds with originally smooth surfaces.

Drinkwater et al. (1997) described that the mass of the interfacial layer can be ignored as the air gaps are very thin in the direction normal to the interface and the density of the interface layer is low due to the presence of the air. So the spring mass parameter m normally can be ignored.

2.6 Numerical simulation of interfaces

A major problem in ultrasonic characterisation of interfaces is the lack of understanding between ultrasonic parameters and interface quality. Different kinds of interfacial imperfections may result in similar interfacial reflectivity. Numerical simulation can assist in the quantitative understanding of this relationship.

The situations in practical ultrasonic nondestructive testing applications are more complicated than that used in analytical models based on plane wave and scattering from

idealised defect shapes. Ludwig and Lord (1988) proposed a finite element formulation in the study of ultrasonic NDT systems that may be able to account for finite transducer apertures and complex defect geometries. The formulation was presented in three dimensional (3-D) form. The results from the 2-D formulation model were compared to experiments, in which the signal of a longitudinal pulse propagates through an aluminium block 1.5 inches thick, with the transducer fixed and the receiver placed at different points along the length of the block. The 2-D plain strain model results only agreed qualitatively with the experiments, however with the increasing power of supercomputers, the potential for a complete solution of the 3-D formulation is great. Sullivan et. al. (1990) later used the same formulation in the simulation of ultrasound NDT of adhesive bond integrity. A comparison of the time-domain analysis of experiments and the simulations were found to be in agreement for the case of total disbond.

You *et. al.* (1991) studied ultrasonic wave propagation in anisotropic and attenuative solid materials. The authors presented an axisymmetric elastodynamic finite element code, which was capable of quantitatively predicting displacement fields for elastic wave propagation in isotropic and transversely isotropic materials. The finite element formulation was later introduced for the acoustic scattering phenomena with an absorbing boundary condition in the frequency domain (Gan H. et. al., 1992). The performance analysis and the numerical simulations showed the efficiency and flexibility of the formulation in simulating acoustic scattering phenomena which can include density as well as sound velocity variations of single and multi-scatterers of any 2-D cross sections. Stucky and Lord (2001) proposed a finite element formulation for the

modelling of ultrasonic waves in linear viscoelastic media, which will allow for the development of a model for wave propagation in absorptive media.

There exists an extensive literature on numerical techniques to model wave propagation using finite difference (FD) methods. For example, Stacey (1991), Stacey and Weight (1992, 1994), Stacey and Lhemery (1994), Caviglia and Morro (1999). However; F-D methods were not able to model interfaces of intermediate quality. Only interfaces with perfect or absolutely imperfect interfaces were able to be modelled using F-D methods. Delsanto and Scalerandi (1998) developed a technique which is in essence an FD method to overcome the above said difficulties. The method aims to directly introduce local interactions in the ultrasound propagation mechanism. This method solves the problem of discontinuities at interfaces by locally matching the relevant physical quantities (i.e. particle displacements and stresses).

2.7 Weak interfaces samples

In order to evaluate the interface quality, samples with controlled bonding quality need to be fabricated. A lot of research has been done on the methods to fabricate the weak interfaces, many in adhesive joints, using methods such as surface treatment (Cawley et al, 1996), curing temperature (Tay, 1998), and moisture effect (Shook, 1993; Chowdhury, 1998).

Surface treatment can be used to vary the sample quality. Cui et.al. (1998, 1999) reported that a treatment of copper might improve its adhesion to epoxy mold compounds IC packaging. The treatment includes initially roughing of the Cu surface by electroless Cu

plating, electrodeposition by chemical etching, and then followed by a treatment by chemical immersion or electrolytic methods in an alkaline solution.

It has been observed that delamination at any interface is dependent on the moisture present in the package (Shook, 1993; Chowdhury, 1998). This concept was applied in their effort to introduce controlled amount of delamination in the die attach region, such as 0%~10%, 20%~35%, 45%~55%, 70%~80% and 90%~100% for each package type. With C-SAM examination, a fairly even distribution of controlled amount of delamination was achieved for both the packages that were within the target delamination range (Shook, 1992).

2.8 Strength tests

Strength tests have been widely used to characterize the quality of adhesively bonded joints.(Chang et. al., 1976; Fahr, 1990; Yata et. al., 1993; Li et. al. 1995). Normally there are three kinds of interfacial adhesion tests, shear test, pull test and peel test (Lim, 1998). Pull and shear adhesion tests are mainly indicative of practical strains in rigid packages (less warpage), and peel test is important when package has serious warpage, especially flexible substrates. For pull test, the test-specimens used tension load to fail the samples in a universal testing machine and the failure load was measured. The shear strength was calculated by dividing the failure load by overlap area. Later, the fracture surfaces were examined with optical microscope to determine failure modes and void or unbonded areas within each specimen were measured.

Other types of structures have also been used. For example, Liu et. al. (1998) used a four point bending sandwich structure to test for adhesion strength between materials in

PEMs. Tanaka and Nishimura (1995) performed three- point bending tests for two-layer end-notched flexure (ENF) specimens and measured the critical bending loads. Yao (1999) subjected double layer specimen with initial cracks to four-point bending tests. This was to measure experimentally the apparent fracture toughness of interface of adhesive and metal substrate. Kawamura et. al. (1998) reported that in order to measure the adhesion strength of the resin and silicon chip, fracture test under shearing load was carried out (Cui et. al., 1999).

Suhir and Sullivan (1992) focused on the adhesive strength of molding compound in shear and measured this strength with a desire to minimise bending stresses and easy fabrication process of test samples. It was found that adhesion strength decreases with an increase in temperature. Kang et. al. (1998) measured the adhesion strength between the copper leadframe and EMC by a button shear test. It was found that the strength was affected by alloy composition, CuO/CU₂O ratios, oxide layer thickness and oxidation conditions.

Rokhlin (1986, 1988) used lap shear specimen to measure the strength of the joint after ultrasonic monitoring of the adhesive curing. Kawamura et al. (1998) reported that in order to measure the adhesion strength of the resin and silicon chip, fracture test under shearing load was carried out. Fahr (1990) reported to use tension load to fail the test-specimens in a universal testing machine and the failure load was measured. From these strength tests, the relationship between the joint strength and other parameters, such as reflection coefficient, stress distribution, crack area fraction, was analyzed.

2.9 Ultrasonic Measurement of Interfaces

There are a few works reported that had related ultrasonic reflection to quality of the interface. Tattersall (1973) studied the reflection coefficient as a function of the quality of the interfaces in three interface cases: the aluminium block and polyethylene, two aluminium plates under compressive loading and two steel plates under compressive loading. The paper shows the change in reflected amplitude of the two materials and the phase between them as the interface was slowly compressed. In the case of $Z_1 > Z_2$, when the load is zero, the interface between the metal and polymer contains air and reflected amplitude is 100%. As the intimacy of contact increases, the reflected amplitude drops to 80%. The phase also behaves as predicted; being zero initially and finally. Tests on bonded interfaces were also carried out.

Canumalla et. al. (1998) examined the degradation of resolution and signal strength in pulsed acoustic microscopy of plastic encapsulated ICs. The reflection of ultrasonic pulses at a layered interface was exploited to obtain the measurement of the thickness and property of the thin interface layer and it is concluded that high frequency C-SAM microscope could be used to measure small variations in layer thickness and material properties nondestructively. Cawley (1992) compared two methods, one is the reflection coefficient measurement from the adhesive/adherend interface, and the other in the measured frequencies of the zeros of reflection coefficient from the adhesive layer. It is shown that measurement of reflection coefficient zeros were much simpler and more reliable than that of reflection coefficient amplitude. However, reflection coefficient zeros are more sensitive to small variations in the adhesive layer properties than to relatively large changes in the interlayer, so reflection coefficient amplitude measurements are more successful in practice.

Surface waves, leaky Rayleigh waves and guided waves were also used to characterise interface (Nakaso et. al., 1991; Richard et. al., 1994). The velocity of such wave is strongly affected by the layer-substrate boundary condition (adhesion). By comparing the absolute position and shape of experimental and calculated dispersion curves for various boundary conditions at the interface (perfect bonding, weak interface and perfect detachment) information on the adhesion of the film on the substrate was extracted.

2.10 Oblique incidence ultrasonic measurement system

The normal incidence reflection coefficient measurements are relatively straightforward since there is no mode conversion between longitudinal and shear wave. A single transducer in pulse echo mode can be used, which reduces alignment problems. Currently effort is being made to correlate the normal incidence reflection coefficient with interface strength in IC packaging (Abdul, 1999). Oblique incidence measurements are sometimes more sensitive to the interfacial properties than normal incidence measurements (Cawley et al, 1996). However, the measurement is not easy as transducer and specimens have to follow specific arrangement and alignment. Due to mode conversion, special hardware and testing rig have to be designed to meet the requirement.

Margetan (1988) reported that a special geometry was carried out to use a single ultrasonic transducer to measure the oblique coefficient of the interface between two plates as shown in Fig. 2.14. This method has the advantage that only a single transducer is used, which makes alignment easier. However, as mode conversion was occurring in two reflections, a large number of pulses were generated and they were very complicated in time domain, where it was very difficult to separate them.

Pialucha and Cawley (1993) used a special rig for measurement of an oblique incidence reflection coefficient. Two ultrasonic transducers, a transmitter and a receiver, are attached to two arms, which are in turn attached to a bearing which is the common axis of rotation for the two arms. Both transducers are positioned so that they point toward the axis of rotation of the arms. The lead screw and follower mechanism are responsible for the rotation of the arms so that the angle of incidence can be adjusted. The setting accuracy of the angle of the arms was estimated to be better than $\pm 0.1^\circ$.

Maslov and Kundu (1997) reported that the oblique incidence and pitch-catch setup as shown in Fig. 2.15 was used in leakage Lamb wave measurement which could generate so called L-scan images. The comparison between images generated by the Lamb wave scanning technique and conventional C-scan images shows that the L-scan technique is more effective for detecting some internal defects such as missing fibers and fiber breakage type defects in a multilayered specimen than the conventional C-scan technique. (Kundu T. et. al., 1996).

2.11 Summary

It is evident that current techniques such as C-SAM inspection is able to detect gross defects such as delamination. However, it is inadequate to detect the weak interface and evaluate the interface quality. There is demand to evaluate the interface quality in IC packaging quantitatively, so the weak interface can be identified and the degree of weakness can be measured. Normal incidence reflection coefficient amplitude and phase measurement may provide the potential to evaluate the interface. Alternative approach may be oblique incidence reflection coefficient in certain range that offers better sensitivity at a lower frequency. However, the theory to predict the oblique incidence

from the interface is not fully developed for the interfaces between two different media, and there is a little study done relating oblique incidence reflection coefficient with the interface strength. These and many other issues have thus formed the motivation and objectives of this project.

Figure 2.1 Schematic drawing of a Plastic-Encapsulated Microcircuit (PEM)

Figure 2.2 Potential defects in plastic-encapsulated microelectronic packages.

Figure 2.3 Principle of X-ray topography

Figure 2.4 Cracks, porosity, inclusions, voids detection in IC package using X-ray.

Figure 2.5 Principle of C-mode scanning acoustic microscopy (C-SAM)

Figure 2.6 Delamination, cracks, voids detection in IC package using C-SAM

(a)

(b)

Figure 2.7 Comparison of exact and the interfacial spring model solutions $Z_I/Z_0=10$, (b) $Z_I/Z_0=10^{1/2}$. Forms are shown for $v_I/v_0=0.5, 1.0, 2.0$, and 4.0 . (Angel and Achenbach, 1985).

Figure 2.8 Predicted reflection coefficients $|R_{LL}|$, for 15MHz wave incident upon imperfect bonds in IN100 alloy. “A” is the crack area fraction. (Margetan et al., 1988)

Figure 2.9 Comparison of exact coefficients R_β^L (solid lines) and reflection coefficients for spring layer reflection R_β^{-L} (dashed line) versus $\bar{\omega}$, for an incident longitudinal wave; (Angel & Achenbach, 1985)

Figure 2.10 Defects models: shaded region indicate cracks at the interface
 (a)horizontal strip crack;
 (b)vertical strip crack;
 (c)distributed circular crack

Figure 2.11 Normalized plots of interface stiffness versus fractional contact area of periodic array of slits. Solid curves are theoretical predictions and dashed curves are asymptotic limits. [Baik and Thompson, 1984].

Figure 2.12 Reflection coefficient vs. distributed spring constant for bonds prepared at different times and temperatures. Solid curve represents theoretical predictions for an interface with mass $m=0$.

Figure 2.13 Reflection coefficient vs. frequency for a bond prepared at 400⁰C for 0.25h with $K=4.2 \times 10^9$ Mpa/m (randomly distributed contacts).

Figure 2.14 Geometry to measure the oblique coefficient

Figure 2.15 Leaky lamb wave is used to detect internal defects in composite laminates using pitch-catch setup

Chapter 3

Spring Models of Interfaces

In this chapter, the spring models for interfaces between two different media are presented. First of all, plane wave reflection coefficient from the perfect interface between two media is introduced. The interface of intermediate quality is then described using spring stiffness which depends on defects. The spring model for the normal incidence is presented, followed by that for the oblique incidence without and with residual stress.

3.1 Introduction

In an “infinite” bulk medium, there are two modes of wave propagation. First is pressure wave, also called longitudinal wave, because the particles are displaced parallel to the direction of propagation. The other is shear wave, also called transverse wave, because the particles vibrate perpendicular to the direction of propagation. Shear wave can only occur in solids (media with shear elasticity).

It is assumed that the incident plane wave has the sinusoidal acoustic pressure amplitude I_p and reflected and transmitted pressure amplitudes of R_p and T_p respectively. The materials are assumed to be ideal elastic solids. The boundary conditions are that the acoustics pressure and particle velocity must be continuous across the boundary. These dictate that the frequency remains unchanged across the interface.

The reflection and transmission coefficient can be described as functions of the acoustics impedances, Z_i , of the two materials as follows (Auld, 1990),

$$R = \frac{R_p}{I_p} = \frac{Z_2 - Z_1}{Z_2 + Z_1} \quad (3.1)$$

$$T = \frac{T_p}{I_p} = \frac{2Z_2}{Z_2 + Z_1} \quad (3.2)$$

where Z_i is the acoustic impedance of a material, defined as the product of the density ρ_i and the speed of wave v_i in layer I, $Z_i = \rho_i v_i$.

When $Z_2 = Z_1$, the reflectivity is zero because there is no reflection at an ideal interface between two identical materials. However, at a delamination or a crack, i.e. $Z_2 < Z_1$, 100% of the energy is reflected and resulting $R = -1$.

3.2 Spring stiffness model of defects

When a tensile load is applied to an elastic solid containing a planar collection of cracks or voids, the farfield displacement that would occur in the absence of the interface will be increased by localization deformations at the interface. This extra extension can be modeled as the response of two half spaces connected by a distributed spring. The spring stiffness per unit area, K , is a function of topography of the partially contacting surfaces.

If ultrasonic energy with a wavelength, large with respect to the contact separation, illuminates the interfaces, a set of modified boundary conditions involving the interface stiffness K has been found to correctly predict the frequency dependence of reflection and transmission. The distributed spring or equivalent models have proved to be useful

tools in ultrasonic measurement of partially contacting interfaces in studies of friction, fatigue crack closure, adhesive bonding, and shape memory couplers.

Fig. 3.1(a) illustrates the geometry of the interest interface. An interface between two half-spaces is assumed to exist in the vicinity of $x=0$ plane. The inputs of the interfacial spring model for imperfect interfaces are shown in Fig. 3.1(b). When an ultrasonic stress is applied (Fig. 3.1a), the far-field displacement is increased due to local deformation at interface. The total displacement Δ , consists of a standard displacement Δ_p , of the bulk material plus an additive displacement Δ_I , due to local deformation at the interface.

In other words, the total displacement is due to elastic displacement and a (dynamic) crack-opening displacement. For the case of cracks or voids at the interface $\Delta_I > 0$. For the cases of inclusion, Δ_I can be either positive or negative, depending on their shape and their elastic moduli with respect to the half spaces. An interfacial stiffness, K , may be defined as:

$$K = \sigma / \Delta_I \quad (3.3)$$

This can be thought of as the stiffness of the distributed spring which, if used to join two half spaces of material, would reproduce the static displacement. K can be evaluated from solution for Δ_I , which are reported in the literature for a variety of interfacial conditions (Tada et al., 1973; Thompson et al., 1983).

The scattering waves from the same interface are illustrated in Fig. 3.1(b). Here, a time harmonic illuminating plane wave is assumed to be converted into a transmitted and a reflected wave, whose energies must sum to that of the incident wave as long as the

characteristic dimensions of the interfacial geometry are much less than the wavelength. Intuitively, it might be imagined that at these long wavelengths, the scattering properties should be related to the response to a static load.

At the sufficiently long wavelength, the interface is imagined to be represented by the combination of distributed spring and mass as shown in Fig.3.2. In order to correctly reproduce the static deformation. The spring stiffness per unit must be given by equation (3.3). In order to correctly include the inertial effects of change in density due to inclusions or pores at the interface, the mass per unit area, “m” must have the value,

$$m = \int_{-l/2}^{l/2} (\overline{\rho(x)} - \rho_0) dx \quad (3.4)$$

where l is the thickness of a region containing all density charges. ρ_0 is the density of the original material, and $\overline{\rho(x)}$ is the actual density, averaged in the y-z plane. For an interface consisting of an array of cracks, $m=0$. For volumetric imperfections such as pores or inclusions, m can be either positive or negative.

Implicit in the above approach is the assumption that the stresses associated with the ultrasonic wave are sufficiently small that the degree of contact at the interface does not change during the stress cycle. Relaxation of this assumption leads to nonlinear effects.

3.2.1 Spring constants of normal incidence

Since there is no mode conversion in normal incidence, only one stiffness can describe the quality of interface (Palmer et al., 1988). If the disbond distribution is specified, the spring stiffness constants can, in principle, be obtained by calculating the deformation of the bonded structure under static loading. In the most general case, an interface might

contain a complex pattern of cracks and contacts randomly distributed porosity, which has no solution available.

Periodic Strip Disbond and Contacts

An exact solution for stiffness K can be obtained for strip-like disbonds using Westergaard stress function assuming that the disbonds are evenly spaced and are parallel along a planar interface in an identical material, as shown in Fig. 2.10(a). The plane strain solution for K , as suggested previously becomes (Baik and Thompson, 1984).

$$K = \frac{E}{1 - \nu^2} \frac{K^*}{s} \quad (3.5)$$

where

$$K^* = \left\{ \frac{4}{\pi} \ln \left[\sec \frac{\pi(1 - w/s)}{2} \right] \right\}^{-1} \quad (3.6)$$

where E is Young's modulus, ν is Poisson's ratio, w is the width of the bonded ligament, and s is the spacing between the unbonded areas. Note that a plane strain condition has been assumed in order to ensure that the applied stress field corresponds to that in the plane wave ultrasonic case at long wavelengths. The normalized spring stiffness K^* is a dimensionless quantity that depends upon w/s , the fraction of bonded area. It can be seen that K^* increases monotonically with increasing w/s . This is expected since an increase in the fractional bonded area would tend to increase the interfacial stiffness.

Circular Strip disbonds and Contacts

Upon inspection of the fracture surface of an incompletely bonded specimen, one frequently observes a surface with bonded or disbonded areas randomly distributed. Since a solution to this problem is not available, two approximations have been

introduced. First, if the fraction of bonded area, (A/A_0) is low (<0.5), a periodic array of penny-shaped bond may be used for poorly bonded specimen. Second, if the fraction (A/A_0) is high (>0.5), a periodic array of penny-shaped disbond may be used to simulate well-bonded specimen.

For the penny –shaped disbonds, the normalized spring stiffness, K^* is given by (Tada et al., 1973),

$$K^* = \frac{\pi}{8} \left[1.30\alpha - \alpha^2 + 0.667\alpha^3 - 0.42\alpha^4 + 0.14\alpha^5 - 0.030\alpha^6 \right. \\ \left. 0.150\alpha/(1+\alpha) - 1.87\ln(1+\alpha) - 0.420\ln(1-\alpha) \right]^{-1} \quad (3.7)$$

where $\alpha = (s - w)/s$. Here $(s-w)$ and s represent the diameter of the penny-shaped void/disbond and the spacing between disbonds, respectively as shown in Fig. 2.10(c).

A similar analysis may be used to determine K^* for the circumferential disbond (Baik and Thompson, 1984),

$$K^* = \frac{2}{\pi} \left[\frac{1}{\beta} - 1.413 + 0.676\beta^2 - 0.530\beta^3 + 0.195\beta^4 \right. \\ \left. - 0.044\beta^5 + 0.202\beta^6 - 0.152\beta^7 + 0.067\beta^8 \right]^{-1} \quad (3.8)$$

where $\beta = w/s$.

3.2.2 Determination of spring constants for oblique incidence

As we mentioned before, in general there will be nine spring stiffness constants relating the three possible relative displacements to three applied stress components. However, in many cases, the interface region will have symmetries which cause several of those

components vanish. Here, it is assumed that the stiffness matrix is diagonal, these three K describe the “extra” displacement in the x , y and z directions proportional to the tractions in those directions.

$$\begin{Bmatrix} \sigma_x \\ \sigma_y \\ \sigma_z \end{Bmatrix} = \begin{bmatrix} K_{31} & 0 & 0 \\ 0 & K_{32} & 0 \\ 0 & 0 & K_{33} \end{bmatrix} \begin{Bmatrix} u_x \\ u_y \\ u_z \end{Bmatrix} \quad (3.9)$$

If the disbond distribution is specified, the spring stiffness constants can, in principle, be obtained by calculating the deformation of the bonded structure under static loading. For the simple disbond patterns of interface between two identical materials as shown in Fig. 2.10(a), stiffness constants have been obtained or estimated by several authors using deformation results tabulated by Tada et al. (1973) For the array of horizontal strip cracks, the stiffness constants are,

$$K_{33} = \frac{\pi}{4} \frac{E}{(1-\nu^2)} \frac{1}{s} \left\{ \ln \left[\sec \frac{\pi A}{2} \right] \right\}^{-1} \quad (3.10)$$

$$K_{32} = K_{33} \quad (3.11)$$

$$K_{31} = (1-\nu)K_{33} \quad (3.12)$$

where, s is the crack spacing, and $A=(1-w/s)$ is the crack area fraction. If the subscripts 1 and 2 are interchanged in (3.11) and (3.12), the stiffness constants for the array of vertical strip cracks are obtained.

For the periodic distribution of circular cracks, the exact solution is not available. However, when the fractional area of disbonding is low, the cracks are nearly noninteracting and K_{33} can be estimated from the static tensile loading of a cylindrical unit cell containing a single, centered circular crack.

$$K_{33} = \frac{\pi}{8} \frac{E}{(1-\nu^2)} \frac{1}{s} f(A) \quad (3.13)$$

where $f(A)$ is a function dependent on A only. However, no similar solution for K_{31} and K_{32} is known, a constant of proportionality connecting K_{33} with $K_{31}=K_{32}$ has been estimated by Margetan et al. (1986)

$$K_{31} = K_{32} \approx \left(1 - \nu/2\right) K_{33} \quad (3.14)$$

3.3 Spring model for normal incidence

Configuration and assumption

Consider the longitudinal wave normally incident upon the interface between two materials as shown in Fig. 3.2. When longitudinal wave is incident upon the interface (Using stiffness K to describe its quality), one reflected longitudinal wave and one transmitted longitudinal wave are generated. It is assumed that the stresses associated with the ultrasonic wave are sufficiently small that the degree of contact at the interface does not change during the stress cycle.

Wave fields expression

The amplitude of incident wave displacement is assumed to be unity ($I=1$). The longitudinal incident wave, reflected and transmitted wave displacements can be expressed as,

$$U_I = e^{-ik_1 z} \quad (3.15)$$

$$U_R = R e^{ik_1 z} \quad (3.16)$$

$$U_S = T e^{-ik_2 z} \quad (3.17)$$

The wave fields can be obtained in the two media as,

$$U_1 = e^{-ik_1 z} + R e^{ik_1 z} \quad \text{for } z < 0 \quad (3.18)$$

$$U_2 = T e^{-ik_2 z} \quad \text{for } z < 0 \quad (3.19)$$

Constitutive equation

For longitudinal wave incidence, only normal stress exists in this case, and is related to displacement in thickness directions as:

$$\sigma = (\lambda_0 + 2\mu_0) \frac{\partial u}{\partial z} \quad (3.20)$$

where λ_0 and μ_0 are Lamé elastic constants of the medium.

Boundary conditions

From the Newton's Law, the equation relating the net force on a segment of the distributed spring to the acceleration of its center mass is,

$$\sigma_2(0^+) - \sigma_1(0^-) = -\frac{m\omega^2}{2} (U_2(0^+) + U_1(0^-)) \quad (3.21)$$

and equation that expresses the Hooke's Law for an ideal spring is:

$$\frac{1}{2} (\sigma_2(0^+) + \sigma_1(0^-)) = K (U_2(0^+) - U_1(0^-)) \quad (3.22)$$

where U is displacement, σ is the stress, K is the stiffness, m is mass per unit area and ω is the angular frequency of a time harmonic variation of the form $e^{i\omega x}$. These two equations are called interface boundary conditions equations.

Equations (3.18)~ (3.22) may be used to determine the reflection coefficient and the result is:

$$R = \frac{U_R}{U_I} = \frac{\left(\frac{Z_0 - Z_1}{Z_0 + Z_1}\right)\left(1 - \frac{m\omega^2}{4K}\right) + j\omega\left(\frac{Z_0 Z_1}{(Z_0 + Z_1)K} - \frac{m_1}{Z_0 + Z_1}\right)}{\left(1 - \frac{m\omega^2}{4K}\right) + j\omega\left(\frac{Z_0 Z_1}{(Z_0 + Z_1)K} + \frac{m_1}{Z_0 + Z_1}\right)} \quad (3.23)$$

And the transmission coefficient is obtained as,

$$T = \frac{U_R}{U_I} = \frac{\left(\frac{2Z_0}{Z_0 + Z_1}\right)\left(1 + \frac{m\omega^2}{4K}\right)}{\left(1 - \frac{m\omega^2}{4K}\right) + j\omega\left(\frac{Z_0 Z_1}{(Z_0 + Z_1)K} + \frac{m_1}{Z_0 + Z_1}\right)} \quad (3.24)$$

where ω is the angular frequency of the acoustic wave and $Z = \rho v$ is the acoustic impedance. It should be noted that from conservation of energy, $|R|^2 + |T|^2 = 1$.

3.4 Spring model for oblique incidence

The spring model for oblique incidence is more complicated since two reflection waves and two transmission waves are generated in interface due to mode conversion. A complete understanding of such characteristics is one of the main goals of the present work, using the materials and configuration in IC packaging. The type of the wave (longitudinal or transverse, frequency, angle, etc.) that is most sensitive to the weak interface can therefore be identified to evaluate the interface quality.

3.4.1 Longitudinal wave incidence

Configuration and assumption

Consider a longitudinal wave with an incident angle θ to normal incident on the interface as shown in Fig. 3.3, two reflection waves and two transmission waves with angles are generated. In the coordinate system shown in Fig. 3.3, and incident plane

waves polarized in the yz plane. It is convenient to use a single angular coordinate for indicating the propagation direction vector and the positive y-axis. This choice leads to very simple relationship between the propagation angles of the incident and outgoing waves. Notice that the φ , unlike θ , is measured from the surface plane rather than from the normal.

Assume incident angle is φ and from Snell's Law two reflection wave angles and two transmission wave angles are satisfied following relations,

$$\frac{\cos(\varphi)}{V_{L1}} = \frac{\cos(-\varphi)}{V_{L1}} = \frac{\cos(-\varphi_1)}{V_{S1}} = \frac{\cos(-\varphi_2)}{V_{L2}} = \frac{\cos(-\varphi_3)}{V_{S2}} \quad (3.25)$$

where φ is incident angle, $(-\varphi)$ is longitudinal reflection angle, $(-\varphi_1)$ is shear reflection angle, $(-\varphi_2)$ is longitudinal transmission angle and $(-\varphi_3)$ is shear transmission angle. V_{L1} and V_{S1} represent the ultrasonic longitudinal and shear wave velocities respectively in material 1, V_{L2} and V_{S2} are those in material 2.

The two bonded media are assumed to be homogeneous isotropic material. The wavelength, λ , of the incident wave is assumed to be large compared to defects size and space ($\lambda \gg s, w$) so that Bragg diffraction is not a factor. Oscillation amplitudes are assumed to be small enough that of contact does not change during the stress cycle altering the effective crack area fraction. All incident sound energy is assumed to be either reflected from or transmitted through the interface. No energy is lost to frictional effects in the bond zone or to scattering in nonspecular directions.

Wave fields expression

The amplitude of incidence wave displacement is assumed to be unity and can be expressed as:

$$U_I(\varphi) = \begin{pmatrix} U_{Ly}(\varphi) \\ U_{Lz}(\varphi) \end{pmatrix} = \begin{pmatrix} \cos(\varphi) \\ \sin(\varphi) \end{pmatrix} e^{i(\alpha x - k_L y \cos \varphi - k_L z \sin \varphi)} \quad (3.26)$$

where φ is the incident angle measured from the interface, ω is the angular frequency, k_L is the wave number. The reflected longitudinal and shear wave displacements can be expressed as,

$$U_L(-\varphi) = \begin{pmatrix} U_{Ly}(-\varphi) \\ U_{Lz}(-\varphi) \end{pmatrix} = R_{LL} \begin{pmatrix} \cos(\varphi) \\ -\sin(\varphi) \end{pmatrix} e^{i(\alpha x - k_L y \cos \varphi + k_L z \sin \varphi)} \quad (3.27)$$

$$U_S(-\varphi_1) = \begin{pmatrix} U_{Sy}(-\varphi_1) \\ U_{Sz}(-\varphi_1) \end{pmatrix} = R_{LS} \begin{pmatrix} \sin(\varphi_1) \\ \cos(\varphi_1) \end{pmatrix} e^{i(\alpha x - k_S y \cos \varphi_1 + k_S z \sin \varphi_1)} \quad (3.28)$$

The transmitted longitudinal and shear wave are:

$$U_{L2}(\varphi_2) = \begin{pmatrix} U_{L2y}(\varphi_2) \\ U_{L2z}(\varphi_2) \end{pmatrix} = T_{LL} \begin{pmatrix} -\sin(\varphi_2) \\ \cos(\varphi_2) \end{pmatrix} e^{i(\alpha x - k_{L2} y \cos \varphi_2 - k_{L2} z \sin \varphi_2)} \quad (3.29)$$

$$U_{S2}(\varphi_3) = \begin{pmatrix} U_{S2y}(\varphi_3) \\ U_{S2z}(\varphi_3) \end{pmatrix} = T_{LS} \begin{pmatrix} -\sin(\varphi_3) \\ \cos(\varphi_3) \end{pmatrix} e^{i(\alpha x - k_{S2} y \cos \varphi_3 - k_{S2} z \sin \varphi_3)} \quad (3.30)$$

The wave fields in each side of the interface are,

$$U_1 = U_I(\varphi) + R_{LL}U_L(-\varphi) + R_{LS}U_S(-\varphi_1); \quad z < 0 \quad (3.31)$$

$$U_2 = T_{LL}U_{L2}(-\varphi_2) + T_{LS}U_{S2}(-\varphi_3); \quad z > 0 \quad (3.32)$$

where R_{LL} , R_{LS} represent the longitudinal and shear reflection coefficients respectively, T_{LL} and T_{LS} are the corresponding transmission coefficients.

Constitutive equation

As stress fields can be obtained from the constitutive equation:

$$\sigma_{32} = C_{32mn} \frac{\partial U_m}{\partial x_n} = \mu \left(\frac{\partial U_y}{\partial z} + \frac{\partial U_z}{\partial y} \right) \quad (3.33)$$

$$\sigma_{33} = C_{33mn} \frac{\partial U_m}{\partial x_n} = \lambda \frac{\partial U_y}{\partial y} + (\lambda + 2\mu) \frac{\partial U_z}{\partial z} \quad (3.34)$$

where λ_2 and μ_2 denote the two Lamé constants. So the stress in material 1 can be expressed as:

$$\begin{aligned} \sigma_{32} = & \mu \left(-2i \cos(\varphi) k_L e^{i(\omega t - k_L Y \cos \varphi - k_L Z \sin \varphi)} \right. \\ & + 2i R_{LL} \cos(\varphi) k_L e^{i(\omega t - k_L Y \cos \varphi - k_L Z \sin \varphi)} \\ & + i R_{LS} \sin^2(\varphi_1) k_S e^{i(\omega t - k_S Y \cos \varphi_1 + k_S Z \sin \varphi_1)} \\ & \left. - i R_{LS} \cos^2(\varphi_1) k_S e^{i(\omega t - k_S Y \cos \varphi_1 + k_S Z \sin \varphi_1)} \right) \\ \sigma_{33} = & \lambda \left(-i \cos^2(\varphi) k_L e^{i(\omega t - k_L Y \cos \varphi - k_L Z \sin \varphi)} \right. \\ & - i R_{LL} \cos^2(\varphi) k_L e^{i(\omega t - k_L Y \cos \varphi - k_L Z \sin \varphi)} \\ & - i R_{LS} \sin(\varphi_1) \cos(\varphi_1) k_S e^{i(\omega t - k_S Y \cos \varphi_1 + k_S Z \sin \varphi_1)} \\ & + (\lambda + 2\mu) \left(-i \sin^2(\varphi) k_L e^{i(\omega t - k_L Y \cos \varphi - k_L Z \sin \varphi)} \right. \\ & - i R_{LL} \sin^2(\varphi) k_L e^{i(\omega t - k_L Y \cos \varphi - k_L Z \sin \varphi)} \\ & \left. \left. + i R_{LS} \sin(\varphi_1) \cos(\varphi_1) k_S e^{i(\omega t - k_S Y \cos \varphi_1 + k_S Z \sin \varphi_1)} \right) \right) \end{aligned} \quad (3.35)$$

and the stress in material 2 is:

$$\begin{aligned} \sigma_{32} = & \mu_2 \left(-2i T_{LL} k_{L2} \sin(\varphi_2) \cos(\varphi_2) e^{i(\omega t - k_{L2} Y \cos \varphi_2 - k_{L2} Z \sin \varphi_2)} \right. \\ & \left. + i T_{LS} k_{S2} \sin^2(\varphi_3) e^{i(\omega t - k_{S2} Y \cos \varphi_3 - k_{S2} Z \sin \varphi_3)} \right) \end{aligned}$$

$$\begin{aligned}
& -iT_{LS}k_{S2} \cos^2(\varphi_3) e^{i(\omega t - k_{S2}Y \cos \varphi_3 - k_{S2}Z \sin \varphi_3)} \\
& \sigma_{33} = \lambda_2 \left(-iT_{LL}k_{L2} \cos^2(\varphi_2) e^{i(\omega t - k_{L2}Y \cos \varphi_2 - k_{L2}Z \sin \varphi_2)} \right. \\
& \left. + iT_{LS}k_{S2} \sin(\varphi_3) \cos(\varphi_3) e^{i(\omega t - k_{S2}Y \cos \varphi_3 - k_{S2}Z \sin \varphi_3)} \right) + \\
& (\lambda_2 + 2\mu_2) \left(-iT_{LL}k_{L2} \sin^2(\varphi_2) e^{i(\omega t - k_{L2}Y \cos \varphi_2 - k_{L2}Z \sin \varphi_2)} \right. \\
& \left. - iT_{LS}k_{S2} \sin(\varphi_3) \cos(\varphi_3) e^{i(\omega t - k_{S2}Y \cos \varphi_3 - k_{S2}Z \sin \varphi_3)} \right) \quad (3.36)
\end{aligned}$$

where λ_2 and μ_2 denote the two Lamé constants in material 2.

Boundary conditions

From the Newton's Law which relates force on a segment of the distributed spring to the acceleration of its center mass, the equation in the interface $z=0$ is:

$$\sigma_{32}(0^+) - \sigma_{32}(0^-) = -\frac{m\omega^2}{2} (U_2(0^+) + U_2(0^-)) \quad (3.37)$$

$$\sigma_{33}(0^+) - \sigma_{33}(0^-) = -\frac{m\omega^2}{2} (U_3(0^+) + U_3(0^-)) \quad (3.38)$$

and equation expressing the Hooke's Law for an ideal spring is:

$$\frac{1}{2} (\sigma_{32}(0^+) + \sigma_{32}(0^-)) = K_S (U_2(0^+) - U_2(0^-)) \quad (3.39)$$

$$\frac{1}{2} (\sigma_{33}(0^+) + \sigma_{33}(0^-)) = K_L (U_3(0^+) - U_3(0^-)) \quad (3.40)$$

where, $0^+ \equiv (x, y, z = 0^+)$ refers to that in material 1, and $0^- \equiv (x, y, z = 0^-)$ refers to that in material 2. U_j denotes the j th component of a particle's displacement from its equilibrium position, and σ_{3j} is the j th component of the force per unit area exerted on

the bond boundary by the adjoining solid. ‘ m ’ is mass per unit area and ω is the angular frequency of a time harmonic variation of the form $e^{i\omega t}$.

The spring stiffness constant K_L , is associated with longitudinal stresses in the z -direction which would tend to “open” the interface. K_S and K_{31} , are associated with shear stresses (acting in the plane of Fig. 3.3, and perpendicular to that plane respectively) which would tend to “slide” or “tear” the interface. When $K_L = \infty$, it ensures continuity of displacement; thus, a perfectly bonded interface is one limit of the present model. Other familiar limiting cases include the stress free surface, $K=0$, and the perfect slip interface, $K_L = \infty$, $K_S=0$.

Substituting Eqns. (3.26) to (3.36) into the (3.37) to (3.40), four equations can be obtained and re-written in a matrix form as below,

$$\begin{bmatrix} A_{11} & A_{12} & A_{13} & A_{14} \\ A_{21} & A_{22} & A_{23} & A_{24} \\ A_{31} & A_{32} & A_{33} & A_{34} \\ A_{41} & A_{42} & A_{43} & A_{44} \end{bmatrix} \begin{bmatrix} R_{LL} \\ R_{TL} \\ T_{LL} \\ T_{LT} \end{bmatrix} = \begin{bmatrix} -A_{11}^* \\ A_{21}^* \\ -A_{31}^* \\ A_{41}^* \end{bmatrix} \quad (3.41)$$

where * denotes the complex conjugate. The coefficients of the above matrix are given in Appendix A. By solving the above matrix equation, the two reflection coefficients (R_{LL} and R_{LS}) and two transmission coefficients (T_{LL} and T_{LS}) can be found.

3.4.2 Shear wave incidence

For the case of shear wave incidence, similar procedure can be used to solve for the reflection and transmission coefficients at the interface. As the incidence angle is

$\varphi = 90^\circ - \theta$, from the Snell's Law two reflection wave angles and two transmission wave angles can be carried out,

$$\frac{\cos(\varphi)}{V_{S1}} = \frac{\cos(-\varphi_1)}{V_{L1}} = \frac{\cos(-\varphi)}{V_{S1}} = \frac{\cos(-\varphi_2)}{V_{L2}} = \frac{\cos(-\varphi_3)}{V_{S2}} \quad (3.42)$$

where φ is incident angle, $(-\varphi_1)$ is longitudinal reflection angle, $(-\varphi)$ is shear reflection angle, $(-\varphi_2)$ is longitudinal transmission angle and $(-\varphi_3)$ is shear transmission angle.

The total displacement field on each half-plane is now written

$$\bar{U}_1 = \hat{u}_s(\varphi) + R_{SL}\hat{u}_L(-\varphi_1) + R_{SS}\hat{u}_s(\varphi); \quad z < 0 \quad (3.43)$$

and

$$\bar{U}_2 = T_{SL}\hat{u}_L(\varphi_2) + T_{SS}\hat{u}_s(\varphi_3); \quad z > 0 \quad (3.44)$$

Again, the boundary conditions are imposed and the resulting matrix equation for the reflection and transmission coefficients can be written

$$\begin{bmatrix} A_{11} & A_{12} & A_{13} & A_{14} \\ A_{21} & A_{22} & A_{23} & A_{24} \\ A_{31} & A_{32} & A_{33} & A_{34} \\ A_{41} & A_{42} & A_{43} & A_{44} \end{bmatrix} \begin{bmatrix} R_{TL} \\ R_{TT} \\ T_{TL} \\ T_{TT} \end{bmatrix} = \begin{bmatrix} A_{12}^* \\ -A_{22}^* \\ A_{32}^* \\ -A_{42}^* \end{bmatrix} \quad (3.45)$$

where * denotes the complex conjugate. By solving the above matrix equation, the two reflection coefficient (R_{SL} and R_{SS}) and two transmission coefficients (T_{SL} and T_{SS}) can be found.

3.5 Oblique incidence on a surface with residual stress

It is an important issue for treatment of wave propagation in the pre-stressed medium. Most papers use the conventional acoustoelastic theory which assumes that the medium is hyperelastic and the stresses result from elastic deformations. This makes the results inapplicable to the important case of residual stresses which usually arise from nonelastic processes. Man and Lu (1987) developed a theory which does not make a hyperelasticity assumption and thus is applicable to both applied and residual stresses. In this paper we follow their derivation of governing equations for wave propagation through interfaces in the pre-stressed medium. This makes all the results obtained applicable to the case of residual stress, which is of greater practical interest.

In this section we briefly review the derivation of equations which describe wave propagation in pre-stressed medium. We follow the approach proposed by Man and Lu (1987) who derived the generalized Christoffel equation for a stressed medium which is valid for both applied and residual stresses.

The pre-stressed configuration is the only reference configuration in this approach and the initial stress is included in the constitutive equation (Man and Lu, 1987):

$$\sigma_{ij} = \sigma_{ij}^0 + C_{ijmn} \frac{\partial U_m}{\partial x_n} + \frac{\partial U_i}{\partial x_k} \sigma_{kj}^0 \quad (3.46)$$

where σ_{ij} is the first Piola-Kirchhoff stress tensor, σ_{ij}^0 is the initial static stress, U_i is the displacement vector due to wave propagation.

3.5.1 Longitudinal wave incidence with stress

Configuration and assumption

Consider a longitudinal wave with an incident angle ϕ incident on the interface (using stiffness K to describe its quality), as shown in Fig. 3.4, two reflection waves and two transmission waves with angles are generated. Similar approach to Section 3.4.1 can be taken.

When we have the initial stress as in Fig. 3.4, stress fields can be obtained from the constitutive equation:

$$\sigma_{32} = \sigma_{32}^0 + C_{32mn} \frac{\partial U_m}{\partial x_n} + \frac{\partial U_3}{\partial x_k} \sigma_{k2}^0 = \sigma_{32}^0 + \mu \left(\frac{\partial U_y}{\partial z} + \frac{\partial U_z}{\partial y} \right) + \frac{\partial U_z}{\partial z} \sigma_{32}^0 \quad (3.47)$$

$$\begin{aligned} \sigma_{33} &= \sigma_{33}^0 + C_{33mn} \frac{\partial U_m}{\partial x_n} + \frac{\partial U_3}{\partial x_k} \sigma_{k3}^0 \\ &= \sigma_{33}^0 + \lambda \frac{\partial U_y}{\partial y} + (\lambda + 2\mu) \frac{\partial U_z}{\partial z} + \frac{\partial U_z}{\partial z} \sigma_{33}^0 \end{aligned} \quad (3.48)$$

where λ and μ denote the two Lamé constants. So the stress in material 1 and in material 2 can be obtained. In the above equation, the σ_{32}^0 is the residual or applied shear stress on the interface, and σ_{33}^0 is residual or applied longitudinal stress on the interface which is shown in Fig. 3.4. Fig. 3.4 (a) and (b) show longitudinal stress and shear stress applied on the interface respectively.

Similar approach to Section 3.4.1 can be taken and four equations of the theory can be obtained and re-written into a matrix form as below,

$$\begin{bmatrix} B_{11} & B_{12} & B_{13} & B_{14} \\ B_{21} & B_{22} & B_{23} & B_{24} \\ B_{31} & B_{32} & B_{33} & B_{34} \\ B_{41} & B_{42} & B_{43} & B_{44} \end{bmatrix} \begin{bmatrix} R_{LL} \\ R_{TL} \\ T_{LL} \\ T_{LT} \end{bmatrix} = \begin{bmatrix} -B_{11}^* \\ B_{21}^* \\ -B_{31}^* \\ B_{41}^* \end{bmatrix} \quad (3.49)$$

The coefficients in above matrix are included in Appendix (B). By solving above matrix equation, the two reflection coefficients (R_{LL} and R_{LS}) and two transmission coefficients (T_{LL} and T_{LS}) for longitudinal incidence can be found. The result can show the influence of the shear or longitudinal stress to the reflection coefficients and transmission coefficients.

3.5.2 Shear wave incidence with residual stress

For the case of shear wave incidence, similar procedure can be used to solve the reflection and transmission from the interface.

$$\frac{\cos(\varphi)}{V_{S1}} = \frac{\cos(-\varphi_1)}{V_{L1}} = \frac{\cos(-\varphi)}{V_{S1}} = \frac{\cos(-\varphi_2)}{V_{L2}} = \frac{\cos(-\varphi_3)}{V_{S2}} \quad (3.50)$$

where φ is incident angle, $(-\varphi_1)$ is longitudinal reflection angle, $(-\varphi)$ is shear reflection angle, $(-\varphi_2)$ is longitudinal transmission angle and $(-\varphi_3)$ is shear transmission angle.

The total displacement field on each half-plane is now written

$$\bar{U}_1 = \hat{u}_S(\varphi) + R_{SL}\hat{u}_L(-\varphi_1) + R_{SS}\hat{u}_S(\varphi); \quad z < 0 \quad (3.51)$$

and

$$\bar{U}_2 = T_{TL}\hat{u}_L(\varphi_2) + T_{TT}\hat{u}_T(\varphi_3); \quad z > 0 \quad (3.52)$$

Again, the boundary conditions are imposed and the resulting matrix equation for the reflection and transmission coefficients can be written

$$\begin{bmatrix} B_{11} & B_{12} & B_{13} & B_{14} \\ B_{21} & B_{22} & B_{23} & B_{24} \\ B_{31} & B_{32} & B_{33} & B_{34} \\ B_{41} & B_{42} & B_{43} & B_{44} \end{bmatrix} \begin{bmatrix} R_{TL} \\ R_{TT} \\ T_{TL} \\ T_{TT} \end{bmatrix} = \begin{bmatrix} B_{12}^* \\ -B_{22}^* \\ B_{32}^* \\ -B_{42}^* \end{bmatrix} \quad (3.53)$$

where * denotes the complex conjugate. By solving above matrix equation, the two reflection coefficient (R_{SL} and R_{SS}) and two transmission coefficients (T_{SL} and T_{SS}) can be found.

3.6 Software development

The model has been implemented in a program such that the reflection and transmission coefficients in terms of different properties of material, geometry of layers, incidence wave frequency and angle, interface stiffness constant can be obtained. Since a lot of matrix computation is involved in the program, MATLAB language is used with friendly interface. The flow chart of the programs is shown in Fig. 3.5 to illustrate the main functions.

Figure 3.1 (a) Displacement across the imperfect interface;
(b) Reflection and transmission field.

Figure 3.2 Geometry of spring model for the interface

Figure 3.3 Incident geometry and model coordinate system.

Figure 3.4 Interface samples under mechanical stress loads
 (a) for compressive stress load (b) for shear stress load

Figure 3.5 Flowchart of spring model software.

Chapter 4

Theoretical Results

Theoretical results using oblique incident wave spring interface model are presented in this chapter. First of all three testing cases are calculated to verify the theory and robustness of the software. Two interface configurations are then considered with typical interfaces found in IC packaging. The first case is that between mold compound and silicon, which is the most important and the second interface case is the interface between mold compound and copper leadframe. The above materials and configuration were chosen so that experiment can be conducted in the lab with simulated samples.

4.1 Verification of the models and software

Case 1 is an oblique incidence on a perfect interface between two materials, case 2 is a normal incidence on a weak interface between two aluminum layers; and case 3 is oblique incidence case on the weak interface between two identical materials (steel). The results are compared with that reported in the literature when possible.

Oblique incidence upon a perfect interface

The first case is longitudinal wave incident on the perfect interface between fused silica and yttrium aluminum. This case is used as the results which is available in a textbook (Auld B.A., 1990, pp. 34). The material properties used are listed in Table 4.1.

	Fused Silica	Yttrium aluminum	Aluminum	Alloy IN100
Density ρ (kg/m ³)	2200	4550	2710	7840
Longitudinal wave velocity c_L (m/s)	5973.4	8557	6350	6080
Transverse wave velocity c_T (m/s)	3765.9	5027.4	3100	3280
Acoustic impedance (longitudinal) Z_L ($\times 10^6$ kg/m ² s)	13.1	38.9	17.2	47.7

Table 4.1 The material properties used in verification

The stiffness constants K_L and K_S were set to ∞ to simulate the perfect interface, and reflection coefficient as a function of incident angle was calculated and for a plane wave of 20MHz frequency and shown in Fig. 4.1. It has an excellent agreement with that in the reference.

Normal incidence on an imperfect interface

Lavrentyev and Rohklin (1998) studied the ultrasonic spectroscopy of imperfect contact interface between two solids using a normal incidence spring model, and the spectra of the signal reflected from the 0.47-mm-thick aluminum plate enclosed between aluminum substrates was calculated. Material properties for aluminum are shown in Table 4.1, and the reflection coefficient is plotted in Fig. 4.2. It has an excellent agreement with that in the reference.

Oblique incidence on interface of two identical media ($Z_1=Z_2$)

The third case is to calculate ultrasonic reflectivity of an imperfectly-bonded interface of two identical materials as a function of frequency and angle of incidence, which is reported in literature (Margetan *et al.*, 1988). The reflection coefficient R_{LL} is calculated

for a longitudinal wave of 15MHz frequency and shown in Fig. 4.3. Excellent agreement is obtained in comparison with that in Fig. 2.8. The material is Alloy IN100 and properties are listed in Table 4.1.

4.2 MC/Si interfaces

In this section the model is used to calculate the reflectivity of the interface between two different materials. The materials are silicon and mold compound (MC), which are widely used in IC packaging industry and this is the common interface that can be found in all PEMs. The material properties are shown in Table 4.2. The above materials are chosen so that future experiment can be conducted. In this case, ultrasonic waves first travel in the mold compound (MC) material and then strike on the interface between MC and silicon. Only waves with frequency 10MHz are studied here, and we assume that $K_{32}=K_{31}=K_{33}$, which will be explained and discussed later. The results are presented in terms of plots of 4 different reflection coefficients, R_{LL} , R_{LS} , R_{SL} , R_{SS} as a function of incident angle and interface stiffness. Materials properties are shown in the Table 4.2.

	Silicon	Mold Compound	Copper
Density ρ (kg/m ³)	2330	1880	8920
Longitudinal wave velocity c_L (m/s)	9232.3	3314	4520
Transverse wave velocity c_T (m/s)	5330.3	1669.6	2142
Acoustic impedance (longitudinal) Z_L ($\times 10^6$ kg/m ² s)	21.5	6.23	40.31
Acoustic impedance (transverse) Z_T ($\times 10^6$ kg/m ² s)	12.55	3.14	19.11

Table 4.2 The material properties used in interface study

4.2.1 Reflection coefficient R_{LL}

Reflection coefficient R_{LL} is defined as the ratio of reflected longitudinal wave to the incident longitudinal wave. Its relationship with the angle of incidence is shown in Fig. 4.4 for four different interface stiffness K values ranging from 1×10^{12} to 1×10^{16} .

From the figure, it is noted that the amplitude approaches 1 when the incident angle is 0 (normal incident) for stiffness equal to 1×10^{12} , which means bad bonding quality. For high stiffness of 1×10^{16} , which means good bonding condition, the reflection is 0.5512 at 0° . This agrees with the value found using basic perfect interface reflection equation as,

$$R_{LL}(0^\circ) = \frac{Z_2 - Z_1}{Z_2 + Z_1} = 0.5507 \quad (4.1)$$

It can be seen that reflection coefficient R_{LL} approaches unity as incident angle $\theta \rightarrow 90^\circ$ for each value of the stiffness appearing in the figure. It changes sharply near the angle 21° and 38° . From the theory when one wave is incident on the interface, two refraction waves are generated. One is longitudinal wave (L-wave) and the second one is the shear wave (S-wave). From the Snell's Law in Eq. 3.25, the first critical angle, at which the refracted L-wave disappears (90°) is given by,

$$\theta_{cr1} = \sin^{-1} \frac{C_{LMC}}{C_{LSi}} \quad (4.2)$$

where C_{LMC} and C_{LSi} are the L-wave velocities in MC and silicon respectively. If the incident angle, $\theta_i > \theta_{cr1}$, the L-wave refraction angle will be a pure imaginary angle and the refraction L-wave is an evanescent wave. From the calculation using Eq. 3.25, the first critical angle, $\theta_i^* = 21.04^\circ$.

The second critical angle (where the refracted S-wave disappears) can be calculated using Eq. (4.3) as follows,

$$\theta_{cr2} = \sin^{-1} \frac{C_{LMC}}{C_{SSi}} \quad (4.3)$$

where C_{SSi} is the S-wave velocity in silicon. The second critical angle obtained is 38.45° .

When the incident angle is larger than 21° , the refraction L-wave will vanish, and if the incident angle is larger than 38° , no energy will be transmitted to the silicon layer. This explains why the characteristics of R_{LL} experience sharp change near these two angles. It can be seen from Fig. 4.4 that the amplitude difference between different K , in incident angle of 35° , is more than that for normal incidence and at any other angle of incidence.

4.2.2 Reflection coefficient R_{LS}

Reflection coefficient R_{LS} is defined as the ratio of the reflected shear wave to the incident longitudinal wave. Similarly, its relationship with the angle of incidence is shown in Fig. 4.5 for 4 different interface stiffness constants K values ranging from 1×10^{13} to 1×10^{16} . Fig. 4.5 shows R_{LS} changing in terms of incident angle. In normal incidence, only L-wave is generated, so the amplitude is zero for each value of stiffness. Each curve also changes sharply in the region near 21° and 38° , reason being same as what is discussed for R_{LL} .

4.2.3 Reflection coefficient R_{SL}

Fig. 4.6 shows R_{SL} , the reflection coefficient in terms of the reflected longitudinal wave due to shear incident wave. In normal incidence, only S-wave is generated, so the amplitude for R_{SL} is zero. If the incident angle is greater than 29° , each curve equal to

zero. The reason is also because Snell's law, the reflection angle is $\theta'_L = \arcsin(\sin \theta_i V_{LMC} / V_{TMC})$. And if the incident angle is larger than $\arcsin(V_{TMC} / V_{LMC}) = 26^\circ$, L-wave reflection angle θ'_L will be a pure imaginary angle and the reflection L-wave is an evanescent wave.

The reflection coefficient R_{LS} and R_{SL} are less important due to their transmit time within the interface. The waveform echoes corresponding to R_{LS} and R_{SL} are almost overlapped in time domain, and it is difficult to separate one from the other in experiments.

4.2.4 Reflection coefficient R_{SS}

This is the shear wave reflection coefficient upon shear wave incidence as function of incidence angle, and the result is plotted in Fig. 4.7. From the figure, it is noted that the amplitude approaches 1 for the normal incidence when stiffness is 1×10^{12} , which means bad bonding quality. When K is 1×10^{16} , which means good bonding condition, the reflection coefficient is 0.59 when angle is 0° , and is same as that given by the equation (3.1).

Because of the Snell's Law, the longitudinal refraction wave vanishes after 10° , and shear refraction wave vanishes after 17.4° . If the incident angle is larger than 31° , no reflected longitudinal wave will be generated. This explains why the characteristics of R_{SS} experience a sharp change near these two angles. So each curve changes sharply at 10° and 18° , and reflection amplitude is equal to unity after 31° .

It is observed from Fig. 4.7 that the amplitude difference between the curves for different K , at angle 10° , is larger than that at angle 0° , indicating that it is more sensitive to change in interface stiffness for 10° incidence.

4.2.5 Sensitivity to interface stiffness

The reflection coefficient could be plotted in Fig. 4.8 as a function of K in the stiffness constant for different incident angles (angles are 0° , 10° , 35° , 70°), which are identified with sharp changes. It can be seen that when the stiffness is smaller than 10^{13} , the reflection coefficient is same as that for the delamination. Beyond 10^{15} , the reflection coefficient is almost the same as that for perfect interface. As for the reflection coefficient R_{LL} in between 10^{13} and 10^{15} , the interface is considered to be of intermediate quality.

For incidence at angle 0° and 10° , the difference in the reflection amplitude is about 0.4 between good and bad. However, the difference is close to 0.7 for the incident angle of 35° . It is therefore evident that the reflection coefficient for the incident angle of 35° , R_{LL} (35°), is most sensitive to the interface stiffness change. This may offer potential alternative for quantitative evaluation of interface quality and will be verified using experiment. The reflection coefficient R_{LS} is less important due to its arriving time. R_{LS} and R_{SL} are almost overlapped in time domain, and it is difficult to separate them in experiment. The reflection coefficient R_{SS} is also shown to be very sensitive for the incident angle of 10° . However, the difficulty in measuring shear waves off the interface would make it less attractive.

4.3 Sensitivity to frequency

Fig. 4.10(a) shows the normal incidence reflection coefficient amplitude, $R_{LL}(0^\circ)$, as a function of interfacial stiffness K for four different frequencies, 1, 5, 10 and 20MHz. It is noted that the horizontal axis is in a logarithmic scale.

It can be seen from Fig. 4.10(a) that all four curves converge to a value of $R_{LL}(0^\circ) = 0.5508$ at large values of K , i.e. perfect interface. It can also be seen that when K is of small value, all curves converge to $R_{LL}(0^\circ) = 1$, indicating the two materials are separated (delamination) resulting in total reflection. It is evident that the reflection coefficient is not very sensitive to changes in the interface quality that is either close to perfect or delaminated.

However, it can be seen that there exists an approximate negative linear relationship between the reflection coefficient R and the interface stiffness K on the logarithmic scale, over a range, for all four frequencies. This linear portion of the curves signifies an interface of intermediate quality, and the reflection coefficient is very sensitive to K within this range. For example, for the 20 MHz wave, $R_{LL}(0^\circ)$ is particularly sensitive to the change in K within the range $3.66 \times 10^{14} < K < 2.03 \times 10^{15}$.

It can be seen that the reflection coefficient is dependent on the ultrasonic frequency of the wave. For a fixed interface quality of K , the spring model predicts a higher reflection coefficient with higher frequency wave. For example, at $K = 2 \times 10^{15}$, the reflection coefficient amplitude $R_{LL}(0^\circ) = 0.5509$ for 1 MHz, while $R_{LL}(0^\circ) = 0.6020$ for 20 MHz.

It can also be seen from Fig 4.10(a) that the curved region are shifted towards higher value of K with increasing frequency, suggesting that higher frequency waves are more sensitive to the changes in interface quality in the region of good interface quality ($\Delta R/\Delta K$). For example, in a good quality region where $K = 7 \times 10^{15}$, the reflection coefficients for 1 and 20 MHz are 0.551 and 0.555 respectively. Assume the interface quality deteriorates and decreases to $K = 7 \times 10^{14}$, the reflection coefficients are now 0.552 and 0.777 for 1 and 20 MHz respectively. Hence, a larger change in reflection coefficient value is observed for 20 MHz than that for 1 MHz, for the same deterioration in good interface quality. The increase in R as indicated by the 1 MHz suggests that the interface is still in the “good” range while the 20 MHz suggests that the interface is now in the intermediate range.

The table below shows the changes of $R_{LL}(0^\circ)$ over different interface stiffness ranges. It is evident that the reflection coefficients at different frequencies have different sensitive range to the change in interface quality K . The 1MHz one is more sensitive in the range from 1×10^{13} to 1×10^{14} , 5MHz is more sensitive in the range from 1×10^{14} to 1×10^{15} , 10MHz is more sensitive in the range from 1×10^{15} to 1×10^{16} , and 20MHz is more sensitive in the range from 1×10^{14} to 1×10^{16} . This should be noted when testing different quality of interface samples.

	$R_{LL}(0^\circ)$ 1MHz	$R_{LL}(0^\circ)$ 5MHz	$R_{LL}(0^\circ)$ 10MHz	$R_{LL}(0^\circ)$ 20MHz
Change in K from 1×10^{12} to 1×10^{13}	0.0355	0.0015	0.0004	0.0001
Change in K from 1×10^{13} to 1×10^{14}	0.3632	0.1116	0.0349	0.0093
Change in K from 1×10^{14} to 1×10^{15}	0.0496	0.3220	0.3630	0.2899
Change in K from 1×10^{15} to 1×10^{16}	0.0006	0.0140	0.0505	0.1477

Table 4.3 Sensitivity of $R_{LL}(0^\circ)$ over different interface stiffness ranges

Fig. 4.10(b) and Fig. 4.10(c) show two oblique incident wave reflection coefficient amplitudes, $R_{LL}(10^\circ)$ and $R_{LL}(35^\circ)$, as a function of interfacial stiffness K for four different frequencies 1, 5, 10 and 20MHz where the horizontal axis is in a logarithmic scale. The result is similar to that of the normal incidence.

Tables 4.4 and 4.5 show the changes of $R_{LL}(10^\circ)$ and $R_{LL}(35^\circ)$ over different interface stiffness ranges, it is clear that the varies of different frequency have different levels of sensitivity to the variation of K in different ranges for both curves.

	$R_{LL}(10^\circ)$ 1MHz	$R_{LL}(10^\circ)$ 5MHz	$R_{LL}(10^\circ)$ 10MHz	$R_{LL}(10^\circ)$ 20MHz
Change in K from 1×10^{12} to 1×10^{13}	0.0331	0.0014	0.0004	0.0001
Change in K from 1×10^{13} to 1×10^{14}	0.3603	0.1069	0.0325	0.0085
Change in K from 1×10^{14} to 1×10^{15}	0.0502	0.3219	0.3600	0.2848
Change in K from 1×10^{15} to 1×10^{16}	0.0006	0.0141	0.0511	0.1489

Table 4.4 Sensitivity of $R_{LL}(10^\circ)$ over different interface stiffness ranges

	$R_{LL}(35^\circ)$ 1MHz	$R_{LL}(35^\circ)$ 5MHz	$R_{LL}(35^\circ)$ 10MHz	$R_{LL}(35^\circ)$ 20MHz
Change in K from 1×10^{12} to 1×10^{13}	0.0382	0.0016	0.0004	0.0001
Change in K from 1×10^{13} to 1×10^{14}	0.4442	0.1218	0.0375	0.0099
Change in K from 1×10^{14} to 1×10^{15}	0.1592	0.4448	0.4434	0.3268
Change in K from 1×10^{15} to 1×10^{16}	0.0165	0.0832	0.1611	0.2873

Table 4.5 Sensitivity of $R_{LL}(35^\circ)$ over different interface stiffness ranges

4.4 Longitudinal stiffness K_{33} and shear stiffness K_{31} , K_{32}

As we mentioned in Chapter 3 Section 3.2.2, in general there will be nine spring stiffness constants. However, in many cases, the interface region will have symmetries which cause several of those components vanish. Here, it is assumed that the stiffness matrix is diagonal, these three K describe the “extra” displacement in the x, y and z directions proportional to the tractions in those directions. In the most general case, an interface might contain a complex pattern of cracks and contacts randomly distributed porosity, which means two shear stiffnesses K_{32} and K_{31} should be same, so actually there are two spring stiffness values in real application. Now we want to find out the relationship between longitudinal stiffness K_{33} and shear stiffness K_{32} and K_{31} .

In Chapter 3 Section 3.2.2, equations for the array of horizontal strip cracks, the stiffness constants are,

$$K_{32} = K_{33} \quad (3.11)$$

$$K_{31} = (1 - \nu)K_{33} \quad (3.12)$$

where ν is the Poisson's Ratio of the material.

For the periodic distribution of circular cracks,

$$K_{31} = K_{32} \approx \left(1 - \frac{\nu}{2}\right) K_{33} \quad (3.14)$$

For the typical materials used in semiconductor, the Poisson's Ratio is between 0.25 and 0.33, and for the materials used in this analysis, theoretical value of K_{32}/K_{33} are shown below in Table 4.6.

	Silicon	Mold Compound	Copper
K_{32}/K_{33} (horizontal strip cracks)	1	1	1
K_{31}/K_{33} (horizontal strip cracks)	0.75	0.67	0.68
$K_{31}/K_{33} = K_{32}/K_{33}$ (periodic distribution of circular cracks)	0.875	0.835	0.84

Table 4.6 K_{32}/K_{33} theoretical values for different materials and crack structure

Table 4.6 shows that K_{32}/K_{33} is from 0.7~1.0 theoretical. Those are the results only for the above three materials, calculation shows other materials give similar results. So we can come to a conclusion that in for semiconductor materials, K_{32}/K_{33} varies from 0.7~1.0.

The normal incidence reflection coefficient depends only on one interface stiffness. For example, R_{LL} only depends on K_{33} and R_{SS} only on shear stiffness K_{32} . For the oblique incidence the reflection coefficient may depend on both longitudinal stiffness and shear stiffness.

Reflection coefficient on the MC/Si interface as a function of interface spring stiffness K_{33} for different K_{32}/K_{33} ratios varying from 0.7 to 1.0 are shown in Fig 4.11 for $R_{LL}(10^\circ)$ and $R_{LL}(35^\circ)$, and in Fig 4.12 for $R_{SS}(10^\circ)$ and $R_{SS}(30^\circ)$. It can be seen from these four diagrams that the difference between lines is very small and some even overlap. Table 4.7 shows the maximum difference between reflection coefficients for the different K_{32}/K_{33} ratios.

	$R_{LL}(10^\circ)$	$R_{LL}(35^\circ)$	$R_{SS}(10^\circ)$	$R_{SS}(30^\circ)$
K_{32}/K_{33} from 0.7 to 1.0	0.0027	0.053	0.109	0.072

Table 4.7 Maximum difference in reflection coefficient with different K_{32}/K_{33} ratios

Table 4.7 shows when the ratio K_{32}/K_{33} changes from 0.7 to 1.0, the reflection coefficient does not change significantly, in particular even for the most sensitive incidence angle, $R_{LL}(35^\circ)$ the change is very little, only 0.053. Since the accurate relationship between K_{32} and K_{33} is unknown we assume $K_{32}=K_{33}$ to simplify the calculation. This is justified from above error analysis.

4.5 MC/Copper interfaces

In this section the model is used to calculate the reflectivity of the interface between mold compound (MC) and copper, that are widely used in IC packaging industries and it is a common interface that can be found in PEMs, where the leadframe is embedded in the mold compound package. The material properties are included in Table 4.2. The results are presented in terms of plots of 4 different reflection coefficients, R_{LL} , R_{LS} , R_{SL} , R_{SS} as a function of incident angle and interface stiffness.

4.5.1 Reflection coefficient R_{LL}

Reflection coefficient R_{LL} as a function incident angle is shown in Fig. 4.13 for four different interface stiffness K values ranging from 1×10^{13} to 1×10^{16} . It can be seen from the figure that the amplitude approaches 1 when the incident angle is 0 (normal incident) for stiffness is 1×10^{13} , which means a bad bonding quality. For high stiffness of 1×10^{16} ,

which means a good bonding condition, the reflection is 0.73 at 0° which agrees with the value found using the perfect interface reflection equation.

It can be seen that the reflection coefficient R_{LL} approaches unity as the incident angle $\theta \rightarrow 90^\circ$ for each value of the stiffness appearing in the figure. It changes sharply near 47° angle. This is the first critical angle θ_{cr1} , at which the refracted L-wave disappears (90°), can be calculated by Snell's Law.

If the incident angle, $\theta_i > \theta_{cr1}$, the L-wave refraction angle will be a pure imaginary angle and the refraction L-wave is an evanescent wave. From the calculation using Eq. 3.25, the first critical angle, $\theta_i^* = 47.15^\circ$. This explains why the characteristics of R_{LL} experiences a sharp change near 47° .

4.5.2 Reflection coefficient R_{LS}

The relationship of the reflection coefficient R_{LS} with the angle of incidence is shown in Fig. 4.14 for 4 different interface stiffness constant K values ranging from 1×10^{13} to 1×10^{16} . In normal incidence, only L-wave is generated, so the amplitude is zero for each value of stiffness. Each curve also changes sharply in the region near 47° , reason being same as what is discussed for R_{LL} .

4.5.3 Reflection coefficient R_{SL}

Fig. 4.15 shows R_{SL} , the reflection coefficient in terms of reflected longitudinal wave due to shear incident wave. In normal incidence, only S-wave is generated, so the amplitude

for R_{SL} is zero. If the incident angle is larger than 30° , each curve equals to zero. The reason is also because Snell's law, the reflection angle is $\theta'_L = \arcsin(\sin \theta_i V_{LMC} / V_{SMC})$. And if the incident angle is larger than $\arcsin(V_{TMC} / V_{LMC}) = 30.3^\circ$, L-wave reflection angle θ'_L will be a pure imaginary angle and the reflection L-wave is an evanescent wave.

The reflection coefficient R_{LS} and R_{SL} are less important due to their arriving time. R_{LS} and R_{SL} are almost overlapped in time domain, and it is difficult to separate them one from other in experiment.

4.5.4 Reflection coefficient R_{SS}

This is the shear wave reflection coefficient for shear wave incidence as a function of the incident angle, and result is plotted in Fig. 4.16. From the figure, it is noted that the amplitude approaches 1 for the normal incidence when stiffness is 1×10^{13} , which means bad bonding quality. For $K = 1 \times 10^{16}$, which means good bonding condition, when angle is 0° , the reflection coefficient is 0.718, and is same as that given by the equation (3.25).

Because of the Snell's Law, the longitudinal refraction wave vanishes after 21.7° , and shear refraction wave vanishes after 51.2° . If the incident angle is larger than 30.3° , no reflected longitudinal wave will be generated. So each curve changes sharply near the range 20° to 30° , and the reflection amplitude is equal to unity after 51.2° .

4.5.5 Sensitivity to interface stiffness

The sensitivity of the oblique incident reflection coefficient to varying interface quality in terms of the interface stiffness is discussed in this section. The reflection coefficient R_{LL} is plotted in Fig. 4.17 in terms of change in the stiffness constant for three incident angles of interest 0° , 41° , and 66° , and R_{SS} is plotted in Fig. 4.18 for four different angles of interest 0° , 23° , 27° and 32° . The angles are chosen since sharp changes are observed and show potential for application.

It can be seen that when the stiffness is smaller than 10^{13} , the reflection coefficient is same as that for the delamination. Beyond 10^{15} , the reflection coefficient is almost same as that for perfect interface. As for the reflection coefficient R_{LL} between 10^{13} and 10^{15} , the interface is considered to be of intermediate quality. For incidence angles 0° and 10° , the difference in amplitude is about 0.25 between good and bad interfaces. However, the difference is close to 0.45 for the incident angle of 32° . R_{SS} (32°) is therefore more sensitive to the interface stiffness change than any other incident angles. This may offer potential alternatives for quantitative evaluation of interface quality.

4.6 Effects of interface stress on reflection coefficients

It is an important issue for treatment of wave propagation in the pre-stressed medium and interface that is under mechanical stress load. In the previous chapter the equation of the acoustical wave reflection at the interface under stress loading has been derived, it is shown that the reflection coefficient depends on the incident angle, wave frequency, material properties, interface stiffness and interface stress. The effect of the interface

stress on the oblique reflection coefficients from the interface of varying quality are discussed here.

The 3-D diagrams in Fig. 4.19 - Fig. 4.21 show the calculated reflection coefficient at certain angle as a function of stress load and interface quality (K). In general those results show that the reflection coefficient is only significantly influenced by the residual stress when the stress load is above several GPa. When stress load is small, the effect is less significant. For example, for R_{SS} at an incident angle of 30° , and wave frequency of 10 MHz, the amplitude change R_{SS} can be more than 50% when stress load reaches 30 GPa. However, when the stress load is about 10 MPa, the change accounts less than 1%.

In practice, the IC package may experience some thermal stress load due to mismatch in thermal expansion coefficient of the media that are bonded. However, the value of the thermal stress load is likely in the range of several MPa since large stress above that range will cause the damage to the silicon chips itself, so the influence of the normal residual stress to reflection coefficient is expected small, and this can be verified by the experiments carried out in Chapter 7.

4.7 Reflection coefficient $R_{LL}(0^\circ)$ and $R_{LL}(35^\circ)$ with residual stress

Fig 4.22 shows the effect of stress on the normal incident reflection coefficient $R_{LL}(0^\circ)$ for different interface quality with K ranging from 1×10^{13} to 1×10^{16} . It can be seen that for good quality interface with high stiffness above 1×10^{16} , the amplitude decrease with the stress. However, for the poor quality interface with stiffness constant below 1×10^{14} , the reflection coefficient almost remains unchanged with the stress. It means for poor

interface with the stiffness below 1×10^{14} , the $R_{LL}(0^\circ)$ is not sensitive to the stress load at all. It sounds reasonable since the interface is likely disbonded.

However, the effect of stress on the oblique incident reflection coefficient $R_{LL}(35^\circ)$ for interface with varying quality is very different as shown in Fig 4.22. It can be seen from the figure that for good quality interface with high stiffness of 1×10^{15} to 1×10^{16} , the reflection coefficient amplitude increases with the shear stress, and it may reach to 0.2 when the stress increases to 15 GPa. Similar trend is observed for interface of intermediate quality (3×10^{14} to 3×10^{15}). However, for bad quality interface with low stiffness below 1×10^{14} , the reflection coefficient reduces with the shear stress, and may experience a reduction of less than 0.1 when the stress increases from 0 to 15 GPa.

Above discussion is only the theoretical analysis, as in the normal environment and experiment, the stress is less than 10MPa, and that only influence the reflection coefficient less than 1%, that can be ignored in the experiment.

4.8 Conclusions

Theoretical study and analysis on oblique incident ultrasound in the IC package interface have been presented in this chapter. The oblique incident reflection coefficients, R_{LL} , R_{LS} , R_{SL} and R_{SS} are derived. It is shown that they depend on following parameters, property of interface materials, interface quality, wave frequency, and angle of incidence.

The spring model is first verified against the classical cases and then applied to the typical interface configuration that is found in IC packaging, the interface between mold

compound and silicon substrate, and that between mold compound and copper leadframe. However, the focus has been more on the former configuration since the experiment is carried out using that configuration.

The results include the reflection coefficient spectrum as a function of angle of incidence, the sensitivity to interface quality in terms of varying interface stiffness, and the dependence on wave frequency. However, the discussion on results focus on the characteristics of the longitudinal wave reflection to longitudinal wave incidence R_{LL} , and shear wave reflection to shear wave incidence R_{SS} . Other reflection coefficients, R_{LS} and R_{SL} , are briefly discussed since their corresponding ultrasonic echoes are likely to arrive at the same time and pose difficulty in obtaining the reflection coefficients in measurement. In addition, comparison with the property of the normal incident longitudinal wave reflection coefficient is made whenever possible. The analysis aims to identify the most sensitive reflection coefficient that may have potential to offer alternative to evaluate to quality of interface, so further numerical and experimental studies can be carried out.

Among all the incident angles of interest it is found that the reflection coefficient $R_{LL}(35^\circ)$, which is defined as the longitudinal reflection to the longitudinal incident at 35° , is the most sensitive angle to the interface quality. It is shown that its sensitivity is double in comparison to that of $R_{LL}(0^\circ)$. The shear wave reflection coefficient is most sensitive at 30° , however, the difficulty in measurement may render it less attractive than using longitudinal wave reflection coefficient.

The influence of frequency on the sensitivity of the reflection coefficient has also been discussed. In general it is shown that the sensitivity range moves upward with higher frequency. This indicates that higher frequency wave is able to see or sense the change in better quality interface, and its detectability is increased. It should be noted however that this advantage is at the expense of signal to noise ratio since high frequency wave usually attenuates more in mold compound polymer.

Finally, the effects of interface stress on the reflection coefficients are discussed. It is found that the effect is only significant when the stress load reaches GPa range and effect on the reflection coefficient may depend on the interface quality, while in the stress load in the MPa range, which is typically experienced by IC package, the effect of stress is less significant.

Figure 4.1 Reflection Coefficient R_{LL} between fused silica and yttrium aluminum.

Figure 4.2 Spectra of signal from the aluminum plate imperfectly bonded to aluminum substrate. Calculations are done for different interfacial stiffness.

Figure 4.3 Reflection coefficients $|R_{LL}|$, for longitudinal 15MHz wave incident upon imperfect bonds in IN100 alloy. “A” denotes the cracks area fraction.

Figure 4.4 R_{LL} on the MC/Si interface as a function of incident angle.

Figure 4.5 R_{LS} on the MC/Si interface as a function of incident angle.

Figure 4.6 R_{SL} on the MC/Si interface as a function of incident angle.

Figure 4.7 R_{ss} on the MC/Si interface as a function of incident.

Figure 4.8 Sensitivity of R_{LL} to interface stiffness (MC/Si).

Figure 4.9 Sensitivity of R_{ss} to interface stiffness (MC/Si).

Figure 4.10 The reflection coefficient of the MC/Si interface as a function of frequency
 (a) $R_{LL}(0^\circ)$ (b) $R_{LL}(10^\circ)$ (c) $R_{LL}(35^\circ)$

Figure 4.11 $R_{LL}(10^\circ)$ and $R_{LL}(35^\circ)$ with the spring stiffness ratio K_{32}/K_{33} varying from 1 to 0.7. (a) $R_{LL}(10^\circ)$ (b) $R_{LL}(35^\circ)$

Figure 4.12 $R_{ss}(10^\circ)$ and $R_{ss}(35^\circ)$ with the spring stiffness ratio K_{32}/K_{33} varying from 1 to 0.7. (a) $R_{ss}(10^\circ)$ (b) $R_{ss}(35^\circ)$.

Figure 4.13 The R_{LL} from the MC/Copper interface as a function of incident angle.

Figure 4.14 The R_{LS} from the MC/Copper interface as a function of incident angle.

Figure 4.15 The R_{SL} from the MC/Copper interface as a function of incident angle.

Figure 4.16 The R_{SS} from the MC/Copper interface as a function of incident angle.

Figure 4.17 The sensitivity of R_{LL} at 0, 41 and 66⁰ to interface stiffness (MC/Copper).

Figure 4.18 The sensitivity of R_{ss} at 0, 23°, 27° and 32° to interface stiffness (MC/Copper).

Figure 4.19 The effect of compressive stress on $R_{LL}(0^\circ)$ and $R_{LL}(35^\circ)$ from the MC/Si interface

Figure 4.20 The effect of shear stress on $R_{LL}(0^\circ)$ and $R_{LL}(35^\circ)$ from the MC/Si interface

Figure 4.21 The effect of compressive stress on $R_{ss}(0^\circ)$ and $R_{ss}(30^\circ)$ from the MC/Si interface

Figure 4.22 The effect of interfacial stress on the reflection coefficient from MC/Si interface for different interface stiffness (a) $R_{LL}(0^\circ)$ (b) $R_{LL}(35^\circ)$

Chapter 5

Finite element simulation of oblique incident wave in IC package interfaces

In this chapter, ultrasonic wave propagation across the interface is simulated using finite element models, and results are compared with the theoretical prediction presented in previous chapter. The numerical simulation is very useful as it can assist in providing better physical insight to the nature of ultrasound and its interaction with defects, in designing testing samples for planned ultrasonic tests, for saving time and effort prior to experimentation and finally in benchmarking studies for the validation of defect characterization.

First, the backgrounds of finite element method are presented, followed by the discussion of finite element formulation. The procedures and considerations involved in modeling are also discussed. The results of simulation with different incident angle and interface quality are then presented. Finally, the simulated results are compared against the theoretical results.

5.1 Introduction

The finite element method of engineering analysis is relatively new and can trace its roots back to the mid-1950s. The paper that signalled the beginning of finite element analysis was written in 1956 by Turner et al.. The finite element method requires the use of modern digital computing equipment with floating-point capability and considerable

memory and disk capacity. For this reason, the development and popularity of the method has closely followed the evolution of the computing hardware over the past 40 years.

The finite element method is a numerical technique, which gives approximate solutions to differential equations that model problems arising in different fields of science and engineering. The fundamental concept of the finite element method is to subdivide a complex problem, which might be any real physical entity, into smaller more manageable 'finite elements'. These finite elements have certain shape functions which can be relatively easily calculated and are commonly available in the library of the software package. The behaviour of each individual finite element under loading thus can be obtained and resultant of adding the response of each of the finite elements would allow one to obtain the overall approximate response of the structure under consideration.

The finite element (F.E.) formulation for modeling ultrasonic NDT systems have been presented elsewhere (Ludwig and Lord, 1988). Most of the study is concerned with bulk wave propagation with two-dimensional plane strain assumption, and the numerical results only agree qualitatively with measurement. Unlike the analytical results obtained from the spring interface model and the multi-layer model, numerical simulation presents the response of the system in the time domain to an input of ultrasonic pulse. It is possible to observe the displacement and stress responses at the points of interest.

The computer program implementation of the finite element formulation can be carried out by appropriate spatial and temporal discretizations in conjunction with a suitable choice of element type. Typically, a two dimensional plain-strain model is used where

the z -direction displacement is neglected and variables are functions of the x and y coordinates only.

In the application to the study of weak interfaces between two semi-infinite media, it is proposed that a three-layer model be used with an intermediate layer sandwiched between mold compound and silicon. The thicknesses of the first (MC) and third (silicon) layers are carefully selected so that the reflections from the boundary would not interfere with the interface echo of interest. The approach is essentially similar to that taken in the multi-layer model, in that the weak interface is modeled by varying the material properties of the intermediate layer.

The simulation in this project is done using the commercially available finite element software package, ANSYS (version 5.6). It is written in Fortran and is widely used in industries, laboratories and tertiary education centres for analysis and design. It can solve wide range of practical engineering problems, namely structural, mechanical, electrical, electromagnetic, electronic, thermal, fluid and biomedical. ANSYS can also perform static and transient dynamic analysis with linear or non-linear characteristics. The ANSYS software is available on many types of computers such as PCs (Personal Computers), workstations, minicomputers, supercomputer, mainframe, etc.

Ultrasonic waves are basically mechanical vibrations. The propagation of these waves in a material is therefore a time-dependent process. In order to be able to model the wave propagation, transient dynamic analysis is used in the simulation. It is a technique used to determine the dynamic response of a structure under the action of any general time-dependant loads. Normally, the time-varying displacements, strain, or forces in a

structure can be calculated as it responds to any combination of static, transient, and harmonic loads. The time scale of loading is such that the inertia or damping effects are considered to be important.

The time increment between successive time points is called the integration time step. The selection of the integration time step is critical as the accuracy of the transient dynamic solution is dependent of this time step. As the time step decreases, the accuracy of the result increases. A time step that is too large will introduce errors that affect the response of the higher modes (and hence the overall response). However, an integration time step that is too small will use a great quantity of computer resources. Therefore, there exists an optimum integration time step that would yield sufficiently accurate results without consuming excess computing resources.

5.2 Considerations in modeling

There are some important considerations for the following aspects in the modelling process, as to ensure the accuracy of the simulated result and to reduce the required computational time.

5.2.1 Geometry of the model and element

A typical model generated is shown in Fig. 5.1. The problem is modelled in two-dimensional by assuming the plain strain situation (thickness in z-direction is large, so that $\varepsilon_z = 0$). The model consists of 3 layers with first layer being MC, second and third layers are Si. The second layer (Si) represents the interface layer, which is used to alter the interface quality by varying its material properties. The MC/intermediate layer and

intermediate layer/Si interfaces are assumed to be perfect in the model. The lower left corner of the first layer is tapered at certain angle depending on the incident angle of the wave, as for the ease of inputting the wave. For intermediate layer Si, it is required that the thickness to be smaller than $\lambda/10$ as to meet the requirement of spring model. The thickness of the third layer (Si) is chosen such that the signal of reflected waves from the intermediate and free surface of the third layer can be easily separated. As to minimise the computational time of simulation, the thickness is kept as small as possible. For the height of the model, it varies with the incident angle. For example, as the incident angle increases, the angles of reflected waves also increase. The height of model is then adjusted accordingly in order to provide sufficient space for the reflected wave to travel before it reaches the free surface.

For this simulation, a 6-node plane strain triangular element is used to mesh the model. This type of element has quadratic displacement behaviour and can be used to model irregular meshes. The element is defined by six nodes having two degrees of freedom at each node: translations in x and y directions (refer to Fig.5.2). The element also has plasticity, creep, swelling, stress stiffening, large deflection, and large strain capabilities. It is one of the elements recommended for the simulation of 2-D solid model in dynamic transient analysis.

5.2.2 Sizing of element and model meshing

For optimal results, the FEM formulation requires the condition that there are at least 6 nodes per ultrasonic wavelength. By dividing the thickness of first layer by the wavelength of the input wave and then multiplying by the number of nodes per wavelength, the number of nodes or the number of divisions required along x -direction

can be determined. Table 5.1 shows the materials property used in the analysis, from these the number of elements in x-direction and the size of element of first layer can then be found and are shown in the Table 5.2. The element sizes of intermediate and third layers are kept the same as that in the first layer. In the simulation, 12 nodes per wavelength are used in MC to further improve the accuracy of the result.

	Mold Compound	Intermediate Layer	Silicon
Young's modulus, (GPa)	13.94	Varies	165.5
Density (kg/m ³)	1880	Varies	2330
Poisson ratio	0.33	0.25	0.25

Table 5.1 Material properties used in F.E. simulation

	Mold Compound	Silicon
Longitudinal Velocity (m/s)	3315	9232
Frequency (MHz)	10	10
Wavelength (m)	3.315×10^{-4}	9.232×10^{-4}
Min. no. of nodes per wavelength	6	6
Length of division for min. condition (m)	6.630×10^{-5}	1.846×10^{-4}
Intermediate layer Max. thickness (m)	-	9.232×10^{-5}
Thickness chosen in x-direction (m)	3.5×10^{-3}	3×10^{-5}
No. of divisions required in x-direction	52.8	0.45
No. of divisions actually chosen	118	2
Actual no. of nodes per wavelength	12.17	61.54

Table 5.2 Requirements to satisfy F.E. simulation model

In order to ensure the perfect bonding between different layers in the model, the meshing density of two different layers must be the same. If the mesh of one side is denser than the other side, extra reflection known as spurious reflection may occur. (Chandrupatla and Belegundu, 1997), Therefore to get same meshing densities in two layers, the same number of nodes is specified in the line joining both layers. In addition, three different layers in the model are meshed using the same element type. In finite element analysis, the more numbers of elements or the finer the meshing, the more accurate the result would be. However, this is limited by the memory of the computer system and the run-time will also be longer if the number of elements increases. Therefore, the meshing density and element size should be properly selected.

5.2.3 Application of Loading and Boundary Conditions

The goal of a finite element analysis is to examine how a structure or component responds to certain loading and boundary conditions. Thus, specifying the proper loading and boundary condition is one of the key steps in the analysis. In the simulation, the incident ultrasonic wave is modelled as a small displacement of the nodes. The input wave used is given as:

$$y = \cos(\omega t) \sin\left(\frac{\omega x}{4}\right) \quad (5.1)$$

where t = time

$\omega = 2\pi f$, angular frequency

The waveform can be described as a half-cycle sine weighted two-cycle cosine waveform with a frequency of 10MHz as shown in Fig. 5.3. The small displacement is input in the direction of the wave propagation to simulate the longitudinal wave. To model the input from a typical transducer which is not a point source, the small

displacements are input at a number of nodes along the middle of tapered free surface of the MC (see Fig. 5.1). The maximum number of input nodes can be determined from diameter of transducer which can be calculated from the formula:

$$N = \frac{D^2}{4\lambda} = \frac{D^2 f}{4V} \quad (5.2)$$

where D is diameter of transducer, V is the velocity of wave in material and N is the range of near field.

This is to ensure the wave incident on the first interface is plane wave and free from the influences of near field. If the number of input nodes chosen is too low, this will lead to the high beam spreading problem. Therefore, the actual number of input is optimised such that the problems of beam spreading and interferences in near field can be eliminated. The time step for inputting the displacement was chosen to be 2×10^{-9} sec, which is smaller than the time required for the ultrasonic wave to travel across one element in order to obtain a reasonable response. The model is then fixed in place by applying the constraints along the upper and lower surfaces of the model.

Suppose the applied loading is at angle θ_l , as in the ANSYS software only X or Y direction load is acceptable. Below calculation can be done,

$$\begin{aligned} Load_{X-direction} &= Load \bullet \cos \theta_l \\ Load_{Y-direction} &= Load \bullet \sin \theta_l \end{aligned} \quad (5.3)$$

With above equation, the load in any angle can be applied in the simulation area.

5.2.4 Variation of interface quality

As to describe the properties of the intermediate layer between MC and silicon, the two main parameters specified are the young's modulus and density. These two parameters can be related to the parameters, K and m in spring model as follow:

$$K_{33} = \frac{E}{d}, \quad m = \frac{\rho}{d} \quad (5.4)$$

where K_{33} is stiffness of interface, m is mass per unit area spring model parameter, refer to Chapter 3 Equation 3.4), E is young's modulus of intermediate layer, ρ is density of intermediate layer, d is thickness of intermediate layer.

As to simulate different bonding quality between the MC and silicon, the young's modulus of intermediate silicon layer is varied from 100% to 0.1% of the original value with the density being fixed.

5.2.5 Monitoring of response

As to monitor the behaviour of waves along the propagation path, the displacement of nodes is monitored along incident wave, reflected shear and reflected longitudinal waves. Similarly, the direction of reflected waves can be found using the Snell's law as in Eq. 3.25. At least six nodes are selected along the propagation path of incident wave for monitoring, and the same number of nodes is also selected for the reflected shear and longitudinal waves. The monitored nodes are separated by fixed interval as shown in Fig. 5.1. Normally, the response of the second or third monitored node from the interface of MC/Si is selected for calculation of reflection coefficient. If the monitored node selected is too close to the interface, the signal separation would be a problem especially for the

reflected wave. This is due to the mode conversion of reflected wave which complicates the signal obtained in this region.

5.2.6 Procedure in modelling

In this project, the simulation done is limited to the cases using longitudinal wave as incident wave. This is due to the long computational time of simulation and time constraints in the project. For perfect interface (100% E) cases, the simulation was carried out for the incident angles ranging from 0° to 80° with 10° increments. For incident angles of 0°, 15° and 30°, the E is varied from 100% to 0.1%, such as 100%, 50%, 20%, 10%, 5%, 1% and 0.1%. As a result, there are approximately 30 sets of simulation done in the project.

5.3 Results and discussion

5.3.1 Time history monitored

Suppose the wave is incident on the interface at angle θ_i , the angle of reflected longitudinal wave θ_L and the angle of reflected shear wave θ_s , can be obtained using the Snell's law as in Eq. 3.25. The displacement value of each nod in X or Y direction can be found from the software. So the displacement along different paths can be calculated as shown below.

$$D_i = X \bullet \cos \theta_i + Y \bullet \sin \theta_i$$

$$D_s = -X \bullet \cos \theta_s + Y \bullet \sin \theta_s$$

$$D_L = -X \bullet \cos \theta_L + Y \bullet \sin \theta_L \quad (5.5)$$

D_I , D_L and D_S are the displacements along the incidence wave path, longitudinal reflected wave path and shear reflected wave path respectively. With above equation, the time response of each monitored nodes in different directions can be obtained.

Fig. 5.4 to 5.6 show examples of the waveforms monitored at the nodes along the incident wave path, reflected longitudinal wave path, and reflected shear wave path respectively for a case where the incident wave is at 30° measured from the normal to the interface.

A time of flight (TOF) analysis can be performed to check on the accuracy of the FEM results. The arrival time of the respective waveforms can be found using the material data. Generally, the time history monitored at the nodes along the path of incident wave path, only incident waveform can be found. For example, TOF of second monitor point in the incident wave path is $0.180\mu\text{s}$, and $0.282\mu\text{s}$ for third point shown in Fig. 5.4. It can be seen that the calculated TOF values are very close to the arrival of the respective waveforms predicted by FEM. Same analysis can be performed to check the arrival time of the waveform at the nodes along the path of reflected wave. However, there are two waveform in those nodes, one is direct arrival of incident wave and another one is reflected wave. The calculation shows the calculated TOF values is close to the FEM results.

Fig 5.4 shows the waveform obtained at 6 nodes along the incident wave path, from the starting node to the node near the interface as indicated in Fig. 5.1. It can be seen that the incident wave is propagating forward toward the interface, and some scattering reflection from the interface can be observed.

Fig 5.5 shows the time history monitored at the nodes along the path of reflected longitudinal wave as illustrated in Fig 5.1, in addition, time history at the two nodes along the incident path near the interface is also included for comparison. It can be seen from L-(1) where the node is near the interface, the signal marked by LL is overlapped with other signal. However, at the nodes away from the interface, the echo LL is clearly separated and propagating away along the path. The echo is identified as the longitudinal reflection from their propagating speed in the mold compound. The well-separated LL echo can be used to calculate the reflection coefficient R_{LL} for this angle of incidence.

Similarly Fig 5.6 shows the time history monitored at the nodes along the path of reflected shear wave as illustrated in Fig 5.1, in addition, time history at the two nodes along the incident path near the interface is also included for comparison. It can be seen from S-(1) where the node is near the interface, the echo marked by LS represents the reflected shear wave. With the nodes away from the interface, the echo LS is propagating away along the path. The shear wave echo is identified by their propagating speed in the mold compound from the successive echoes. The well-separated LS echo can be used to calculate the reflection coefficient R_{LS} for this angle of incidence.

5.3.2 Reflection coefficients

The marked echo in the time history monitored along the respective wave path is used to calculate the reflection coefficient, and usually the echoes from the nodes at the middle of the incident and reflected paths are used since they are well separated. The reflection coefficient can be obtained as follows:

$$R = \frac{A}{I} \quad (5.6)$$

where A is the amplitude of the reflected echo, and I being the amplitude of the incident wave. A and I can be found directly from the amplitude of the echoes in time domain.

Alternatively a Fast Fourier transform can be performed on the specified echo to obtain the spectral amplitude in the frequency domain as what we use in this project. This can be done by first editing out the desired signal echo and incident echo (Fig. 5.7(a)) and padding zero to a defined length (Fig. 5.7(b)). The data which is padded zero was done FFT and frequency spectrum can be obtained as in Fig. 5.7(c). The corresponding reflection spectrum is then divided by that of the incident wave to obtain the reflection coefficient spectrum which shows in Fig. 5.7(d). The value at the nominal frequency (10MHz) of the incident wave is used as the result.

R_{LL} vs incident angle for perfect interface

Since only the reflection coefficient for the longitudinal wave reflection to the longitudinal incidence is our focus, only the results for R_{LL} are presented. Fig 5.8 shows the simulated reflection coefficients R_{LL} for different incident angles from a perfect mold compound / silicon interface. Also included is the theoretical result calculated using the spring model.

It can be seen that the simulated reflection coefficient in general follows the theoretical curve. When the incident angle is less than 20°, the reflection coefficient R_{LL} is at around 0.5, the spring model and simulation all give out the same results. On the other hand, R_{LL} of spring model and simulation all drop to less than 0.1 when incident angle is near 30°.

When the incident angle reaches to spring model and simulation, both spring model and simulation results sharply increase to 0.8, and then drop when incident angle increases until 70°. It is clear that spring model result and simulation result have the same trend.

Table 5.3 is the result comparison between two models.

	R_{LL} (spring model)	R_{LL} (simulation)	Difference	Difference percentage
0°	0.551	0.539	0.012	2.2%
10°	0.524	0.584	0.060	11.5%
15°	0.501	0.555	0.054	10.8%
20°	0.555	0.482	0.073	13.2%
30°	0.074	0.125	0.051	68.9%
40°	0.683	0.813	0.130	19.0%
50°	0.821	0.663	0.158	19.2%
60°	0.510	0.380	0.130	25.5%
70°	0.377	0.325	0.052	13.8%
80°	0.558	0.616	0.058	10.4%

Table 5.3 Comparison of spring model and FEM method

In the chart ‘difference’ means the value of $|R_{LL(\text{spring model})} - R_{LL(\text{Simulation})}|$, and

difference percentage is calculated by: $\frac{|R_{LL(\text{spring model})} - R_{LL(\text{Simulation})}|}{R_{LL(\text{spring model})}} \times 100\%$.

From the chart, it can be observed that the R_{LL} difference between two models is from 2% to 68.9%, and most value differences are less than 20%. In the case of normal

incidence, which mean incident angle is zero, the difference is minimum, much less than that of other angles. This should be because of the simplicity of normal incidence as no mode conversion occurs in this case. For the incident angle of 30° , the R_{LL} difference reaches its maximum value which is 68.9%. As the angle of 30° which is near critical angle, mode conversion become complicated and that influences the accuracy of the value. It is also because R_{LL} value is very small near 30° , so even a small difference between two model results can have big difference in percentage. The details of the error analysis is discussed in the following section.

Sensitivity of simulation results over stiffness

It can be concluded from the previous theoretical analysis that the reflection coefficient for 30° to 35° degree is most sensitive to the change in the interface quality. The reflection coefficient for the angle of incidence of 0° , 15° and 30° are simulated with varying interface stiffness and presented in Fig. 5.9 to Fig. 5.11 respectively.

In Fig. 5.9 it can be seen that the results obtained are in good agreement with the result from the spring model. When the spring stiffness is less than 5×10^{13} , which means a bad interface quality, the reflection coefficient $R_{LL}(0^\circ)$ is at 1, the spring model and simulation give the same results. As the spring stiffness increases from 5×10^{13} , $R_{LL}(0^\circ)$ for both spring model and simulation drop sharply until 0.5. When the spring stiffness reaches 1×10^{15} , which means a good interface quality, the reflection coefficient R_{LL} of spring model and simulation becomes stable when the stiffness increases. From calculation, the difference of $R_{LL}(0^\circ)$ between the two models is from 0.02 to 0.1 and most value difference is less than 10% and it can be said that the two results match well.

It can be observed from Fig. 5.10 and Fig. 5.11 that the results are similar to that of Fig. 5.9. However the difference between the two model predictions for $R_{LL}(15^\circ)$ and $R_{LL}(30^\circ)$ is larger than that for $R_{LL}(0^\circ)$, and this is because of mode conversion that occurs for the oblique incidence and simulation becomes more complicated for oblique incidence. From the calculation, we see that the difference between the two models is from 0.01 to 0.1 for $R_{LL}(15^\circ)$ and most differences are less than 10%, however, this difference for $R_{LL}(30^\circ)$ is higher, from 0.03 to 0.2.

	$R_{LL}(0^\circ)$	$R_{LL}(15^\circ)$	$R_{LL}(30^\circ)$
Change in K from 5.5×10^{12} to 5.5×10^{13}	0.172	0.000	0.077
Change in K from 5.5×10^{13} to 5.5×10^{15}	0.261	0.452	0.724
Change in K from 5.5×10^{15} to 5.5×10^{17}	0.018	0.022	0.000

Table 5.4 Sensitivity of simulation results over different interface stiffness ranges

Table 5.4 shows the sensitivity of simulation results over different interface stiffness ranges, it can be seen in the bad interface quality range when the spring model stiffness changes from 5.5×10^{12} to 5.5×10^{13} , $R_{LL}(0^\circ)$, $R_{LL}(15^\circ)$ and $R_{LL}(30^\circ)$ all change little. At large values of K , from 5.5×10^{15} to 5.5×10^{17} , means good quality interface, it can also be seen that $R_{LL}(0^\circ)$, $R_{LL}(15^\circ)$ and $R_{LL}(30^\circ)$ are of small changes. It is evident that the reflection coefficient is not very sensitive to changes in the interface quality that is either close to perfect or delaminated.

However, for the interface of intermediate quality, the reflection coefficient is very sensitive to K within this range (5.5×10^{13} to 5.5×10^{15}). It is clear that $R_{LL}(35^\circ)$ is most sensitive to the change of stiffness, as it changes by 0.724 when for $R_{LL}(0^\circ)$ this change is only 0.261 for the same variation of K . So the simulation results verify the theoretical

conclusion that oblique incidence reflection coefficient near 30° is most sensitive to the change of interface quality.

5.3.3 Error Analysis

It can be observed that there are some differences between the simulation and theoretical results and these errors could be due to many factors. First the theoretical model assumes the case of semi-infinite media, this is not possible to achieve in simulation due to the limitation of the computer resources available. Hence, the reflections from the upper and lower surfaces may complicate the signal at monitor points. The monitored nodes chosen in the simulation are at certain distances away from the interface for the ease of signal separation. This may also affect the signals obtained due to the beam spreading. Besides, some monitored nodes selected are at a short distance off the centreline of the propagation path as the nodes generated from meshing process may not be located exactly on the desired position. As a result, the accuracy of the angles of incidence and reflection waves may be affected.

The input wave is longitudinal i.e. only along the direction of the propagation path the displacements existed theoretically, however, it is observed that there exists other direction displacement for the analyzed node, for all FEM simulations. This may be attributed to the fact that part of the longitudinal input wave is converted into SAW (Szilard, J., 1992; Doyle, J.F., 1997) which propagates from the respective input nodes to the top and bottom boundaries. As such, the wave that propagates through the mold compound, incurs component losses due to the SAW. In the spring model, plane longitudinal wave is assumed, thus accounting for the discrepancy between the modeling results.

Other possible sources of error include beam scattering, dispersion due to mesh geometry, and finite lateral dimensions in the FE model. In fact, the finite element method only provides an approximate solution due to the discretization of the model for the ease of solving problem. The accuracy of the results depends directly on the type and size of element. Therefore, the results with greater accuracy could be expected if the higher order or smaller elements are used but again the computer resources and computational time are the limiting factors.

Figure 5.1 Typical FE Model of Mc/Si with intermediate layer of varying material properties for simulation

Figure 5.2 Element type selected for FE simulation

Figure 5.3 The waveform of the input signal and its spectrum used for finite element simulation. (a) waveform (b) frequency spectrum

Figure 5.4 The time-history monitored at nodes along the incident wave path.
(*I*: Incidence wave, *R*: Reflected wave from boundary)

Figure 5.5 The time-history monitored at nodes along the reflected longitudinal wave path (D : Direct arrival of incident wave, DS : Direct arrival of shear wave, LL : reflected longitudinal wave)

Figure 5.6 The time-history monitored at the nodes along the path of reflected shear wave (D : Direct arrival of incident wave, LS : reflected shear wave)

Figure 5.7 Example of calculating the reflection coefficient

Figure 5.8 The reflection coefficient R_{LL} as a function of incident angle for perfect interface (line: spring model, symbols: simulation result).

Figure 5.9 The reflection coefficient $R_{LL}(0^\circ)$ for varying interface quality (line: spring model, symbols: simulation result).

Figure 5.10 The reflection coefficient $R_{LL}(15^\circ)$ for varying interface quality (line: spring model, symbols: simulation result).

Figure 5.11 The reflection coefficient $R_{LL}(30^\circ)$ for varying interface quality (Oline: spring model, symbols: simulation result).

Chapter 6

Conditioning of IC packaging samples with controlled interface and experimental set-up

To evaluate the interface samples quantitatively, it is essential to fabricate IC packaging of controlled interface quality. In this chapter, the methods to fabricate controlled interface samples are described. The set-up of the experiment and measurement are presented, together with the experimental procedure.

6.1 Experimental methodology

The main result of the spring model is that it predicts that for some special angle the oblique incidence ultrasonic wave is much more sensitive to the weak interface than that of normal incidence. The experiment is used to verify this result. To fulfil this purpose, samples of controlled, differing, weak interface quality, which will be subjected to a form of ultrasonic inspection, with the results compared to those obtained from the analytical and numerical methods is needed to be fabricated. Some method also must be found to quantitatively determine the weakness of the samples interface. After that the normal and oblique ultrasonic measurement system must be setup to verify the theoretical results.

The most important part of experiment is control the MC/Si interface quality. In the literature review, it was obvious that temperature cycling and moisture absorption effects were the most prevalent causes for delamination at the MC/Si interface in PEMs. To

simulate this in the experiments is most relevant to the study of ultrasonic inspection of PEMs.

The intention is to fabricate samples of controlled, differing, weak interface quality, which will be subjected to a form of ultrasonic inspection, with the results compared to those obtained from the analytical and numerical methods.

Temperature cycling depends on the inherent defects found in the PEMs. Initial cracks will quickly propagate in an uncontrolled manner when subject to temperature cycling. Thus, the use of temperature cycling to control the MC/Si interfacial quality would prove to be difficult. To achieve any sort of consistency in controlling interfacial quality with temperature cycling, it is suggested that the initial MC/Si interface is to be of good quality (no inherent defects) before the temperature cycling be performed.

To control the interfacial quality, moisture conditioning of the samples can be an effective method. For equal sample size and equal conditions, the moisture absorption rate by the samples would be theoretically the same. The samples were to be conditioned by placing them in an 85°C and 85 % relative humidity (85°C/85RH) environment for moisture conditioning.

To validate the differences in the interfacial quality imposed on the samples by the various conditioning techniques, a lap-shear pull test was used. A shear load was to be applied along the MC/Si interface in the samples to separate the MC and the Si (failure of the samples). A better quality interface, should theoretically, be able to withstand a higher shear load, before failure. The load is applied in steps of 50N, with the sample

dimensions, the shear stress at the MC/Si interface can be easily calculated. With every applied load, the MC/Si interface quality should theoretically decrease. An ultrasonic inspection at every applied load step should validate this.

6.2 Conditioning of interface sample

In this section, the details of the steps taken to prepare the samples are discussed. This includes the sample description, the steps taken for sample moisture conditioning, temperature cycling, and variation of PMC processes. The equipment used will also be documented in this section.

6.2.1 Sample description

A detailed drawing of the samples, including dimensions is shown Fig. 6.1(a). The mold, manufactured by OPTIK TOOLING Pte Ltd, is shown, together with some samples, in Fig. 6.1(b). A detailed drawing for the mold is unfortunately unavailable because the sample removing pin system is proprietary to the manufacturer. The mold compound used, was a commercially available type, the SMT-B-1 manufactured by PLASKON.

The silicon chips were encapsulated only on one side, causing high thermal stresses when cooled to room temperature, thus causing them to warp, inducing cracks in the chips. A low CTE MC (the SMT-B1) coupled with thicker silicon chips were used to alleviate this problem. The details for the Si wafers are; 6" diameter, Silicon, 1.5 mm thick, flatness as per Semiconductor Equipment and Materials International (SEMI) standard flat, single side polished. As the Si wafers are thicker than those normally found in typical PEMs (ranging from 0.4 to 0.7 mm), typical methods such as scribing and using a diamond wheel cutter for cutting the wafers into dies or chips, were not

useful. The wafers had to be cut using a Neodymium Doped, Yttrium Aluminum Garnet (Nd:YAG) laser, produced by a laser system manufactured by MAHO (model no. 77523). To isolate interfacial defects due to surface contamination, the Si chips were chemically cleaned using acetone and placed in an oven at 125°C to dry for an hour before the molding process. The MC was preheated for 30 seconds in the preheater, the SD323, manufactured by SHIN JHOUN as shown in Fig. 6.2(a), prior to the transfer molding process. This preheating process is also a recommended (by PLASKON) practice.

The transfer molding machine used for the molding process, is the FSTM125-7TANM24, manufactured by FUSEI as shown in Fig. 6.2(b). Transfer molding process used in the fabrication of the samples, simulated, as close as possible, the industrial practices for the manufacture of PEMs.

6.2.2 Moisture conditioning

Moisture conditioning was carried out by placing the samples in a moisture chamber, the SH-220/240 manufactured by ESPEC (Fig. 6.2(c)), with the environment held constant at 85°C/85RH. In total six sets of samples were fabricated, with a sample size of 6 for each set. Among them, five sets of samples were conditioned in the moisture chamber for 1, 2, 3, 4, and 5 hours respectively. A reference set of samples was not subject to any moisture conditioning.

At every one hour interval, the samples were removed from the moisture chamber for C-Scan. The sample C-Scan images are shown in Fig. 6.3. Typical A-scan (time response) measurement was also collected for that particular interval. This is done in order to monitor the gradual change of the reflection echo from the interface of the sample. The

samples were then placed back into the moisture chamber for another hour of moisture conditioning. The cycle was repeated until the prescribed time lapse is reached.

The samples were also weighed before being placed in the moisture chamber and after they were removed from it. This was done to compare the moisture absorbed by each sample. The weighing scale used for the weight measurement is the Analytical Plus, manufactured by OHAUS, it is capable of measurement up to 0.1 mg with a claimed maximum error of ± 0.1 mg.

6.3 Experimental Setup

Three types of measurements will be carried out in this project. They are ultrasonic measurement to obtain the oblique incident wave reflection coefficient, lap-shear pull test to obtain the interface quality of the samples, and the combined test that measures ultrasonic reflection coefficient of the interface that is under stress load.

6.3.1 Normal and oblique incidence measurement using water tank

Water tank with rotary stages

From previous report, it is shown that the 35° longitudinal wave incidence angle is the most sensitive to change in the MC/Si interfacial quality. However, both models are constructed based on the transducer being ‘embedded’ into the material. This is impossible to be achieved experimentally and thus, water is being used as the traveling medium. From Snell’s Law, if longitudinal wave with 35° incidence angle need to be generated in the MC, 13° degree wave must be incident in the water. Also from the Snell’s Law, the wave reflected in the MC/Si interface will travel back into water with 13 degrees angle. So two transducers, one is transmitter and one is receiver, are need to

be mounted with 13° degree angle with respect to the normal direction of the sample surface.

For this reason water tank (Fig. 6.5(a)) with Newport 481 Series high accuracy manually Rotation Stages is designed. The versatile Model 481 rotary stage is ideal for fine-tuning the angular orientation of any component after rotating it to an approximate angle. An inner stage rotates 360° in a precision bored bushing, which locks with a side mounted thumbscrew. The outer stage is a high resolution, tangentially driven design. Scale markings indicating every degree and a vernier with 5 arc min markings are engraved on the side of the stage. The whole design is to fulfill the following requirements,

1. To control the accurate incidence angle,
2. Easily adjust the distance of two transducers, as the distance of transmitter and receiver is different for different reflected wave,
3. The height of transducer can be adjusted to achieve the best result,
4. The position of sample.

An aluminum plate with two slot tank is installed on the water tank. The rotation stage is mounted on slot of this aluminum plate with screw, so the two rotation stage can be move along the slot. (See Fig. 6.5(b))

Ultrasonic equipment

Two unfocused immersion transducers were used in pitch –catch mode, one for transmitting (20MHz V317-SU) and the other for receiving (5MHz V309-SU) as shown in Fig. 6.6(b). The reason to use a different transducer is that the attenuation of wave in MC material is very high, especially for high frequency wave. When 20MHz centre

frequency transducer is used in experiment, the wave which reflects from MC/Si interface and then transmits back to water have only 3 MHz centre frequency. So the 5 MHz transducer is chosen for receiver.

Both the transmitter and receiver are connected to a pulser/receiver (PANAMETRICS 5052 PRX). The received signal is displayed on a digital oscilloscope (Dual 300MHz LECROY 9310M). All data displayed in this digital oscilloscope is digitized and transferred to a personal computer through IEEE 488 interface. Finally the waveform is stored for further analysis.

Both transducers were first aligned to be normal to the tank side surface, and were aligned in the same yz plane (same plane normal to the sample surface). Finally, they were adjusted to be normal to the sample top surface. The alignment is done with the help of the A-Scan setup. The signal is zoomed in and amplified to obtain the maximum possible signal. Rotation stage can be used to rotate the transducer from normal to the desired degree such as 13° and the Rotary stage is slid along the slot to obtain the best signal. The schematic diagram of the reflection wave from the interface is shown in Fig. 6.6(a).

Identification of ultrasonic echoes

The sample is immersed in a water bath and a transmitting transducer launches a longitudinal wave through the water at an angle θ_i to the normal. When the wave meets the water-MC interface, some of its energy is reflected (FF) and some is transmitted as longitudinal and shear wave in the silicon at the angles of θ_L and θ_s respectively. These transmitted waves then interact with the MC-Si interface. Some of the energy of the

longitudinal and shear waves produced by reflection at the interface is then converted into longitudinal waves in the water which is detected by the receiving transducer.

As discussed before, four reflection coefficients from the MC/Si interface can be considered according to the types of waves in incident and reflection. They are longitudinal wave incident-longitudinal wave reflected (*LL*), longitudinal –shear (*LS*), shear-longitudinal (*SL*) and shear-shear (*SS*). However, the signals produced by the *LS* and *SL* reflections from the interface arrive at the receiver at the same time and cannot be separated. Only *LL* reflections are of interest to us and are considered in this thesis.

In the measurement, we first confirm which echo is the directly reflected wave from the water/MC interface (*FF*) and which is the reflected longitudinal wave from MC/silicon interface (*LL*). During the experiment, the transmitter needs to be fixed first at the desired angle. The sample is positioned below the water. The receiver is then moved along the slot until the echoes of interest are maximized. From theory, echoes representing *FF*, *LL*, *LS*, *SS* wave position are different, and their travel path and time are also different as shown in Fig. 6.6(a). For example, at an incidence angle of 13° in water, distance difference between *LL* and *FF* is calculated to be 5.05mm and their corresponding travel time differs by $2.77\mu\text{s}$.

Fig 6.7 shows an example of the measured signal from the MC/silicon sample immersed in water. It was obtained by moving the receiver along the expected *LL* wave path until the amplitude of the echo reaches a maximum. This echo can be identified as *LL* wave. Another echo (*FF*) which is also present in the signal can be identified as the directly reflected wave from water/MC interface. They are confirmed by the distance between the

two echoes being 5.4 mm and the time delay being 2.05 μ s. It can be seen that the echo train of the signal *FF* is much longer and frequency is much higher than that for the *LL* echo. This is because of the mold compound being highly attenuative.

6.3.2 Lap-shear testing

The equipment used for this test is the Universal Testing Machine (INSTRON 5565) as shown in Fig. 6.8. This equipment allowed a controlled loading to be applied to the samples. The loading applied to the samples is schematically illustrated in Fig. 6.9(b). The blocker in Fig. 6.9(b) is applied by means of loading the sample in the rig (Fig. 6.9 (a)). The applied force is along the plane of the interface and thus can be converted to interfacial stress by taking,

$$\text{Interfacial stress} = \frac{\text{Applied load (N)}}{\text{Contact Area between Si chip and MC (m}^2\text{)}}$$

The applied loading is at a rate of 150N/minute until the interface is separated. The failure criterion at the onset of failure is taken when the change in the rate of extension exceeds 25%. The rig was so designed to reduce bending moments that may arise during the lap shear tests. An example of the load against extension for an arbitrarily chosen sample is shown in Fig. 6.10.

The range (a) shown in Fig. 6.10 depicts the initial portion where the Universal machine crossheads pick up the “slack” from the rig loaded with the sample. The range (b) shows the actual load against extension for the MC/Si interface. The curve is observed to be non linear. After the failure point at 680 N, the crosshead travels a small distance before

coming to a halt. The quality of the interface is then characterised by the failure stress of the sample.

The sample MC thickness of 4 mm was chosen despite the fact that the material is highly attenuative. Typically the thickness of PEMs ranges from 2 to 6 mm (Pecht et. al., 1995), including the die, the die pads, the leads, copper traces etc. Thus, the common thickness of MC on one side of the die is about 1 to 3 mm at the most. The typical thickness was not used here because the stiffness of the MC at 1 to 3 mm was insufficient, resulting in undesirably large extension of the polymeric MC material. It was experienced that at a thickness of 2 mm, the MC failed prior to the interface during the lap-shear pull tests.

6.3.3 Combined lap-shear pull test with A-scan

The combined lap-shear pull test and A-scan measurements were performed by loading the rig into the Universal testing machine, with the transducer attached to the pulser/receiver and taking ultrasonic A-scan measurements at each loading step. The premise is that an interfacial stress, when applied at the interface, lowers interface quality, thus a succession of increasing stress will produce an interface with a decreasing quality. The samples were loaded in step of 50 N, at every load step, an A-scan measurement was taken and the reflection coefficient, R , was obtained. The loading rate is kept constant at 150N/min throughout the experiments. The load steps are applied until the samples fail, i.e. when the interface is separated. The resulting values of R are plotted as a function of the applied interfacial stress.

A factor to note in the lap-shear tests is the resultant frictional force due to the action of the transducer on the sample. The force exerted by the transducer is normal to the

direction of the applied load and is the result of the spring loading in the rig. The tip of the transducer delay, a Perspex material, contacts the sample with the ultrasonic gel in between. The movement of the MC when the force is applied is very small, with most of the extension accounted for by the stretching of the polymeric MC material. The smooth surface of the transducer tip, the coupling gel, coupled with the small movements in the direction of the applied loading, results in the frictional force being small and is thus neglected. Furthermore, the force exerted by the spring loading is small compared to the applied forces at the interface.

6.3.4 Combined lap-shear pull test with A-scan using oblique incident ultrasound

The experiment in this section is similar to the experiment mentioned above but with a different test rig used as shown in Fig. 6.11. This rig is so designed to allow the measurement of oblique incidence reflection coefficient while the lap-shear loading can be varied. Angle blocks with pre-cut slots which enable various desired incident angles are used in the test to mount the transducers, however only the results with incident angle of 35° are presented.

The interface sample is first loaded on to the pull test rig. The transducers are inserted into the slot on the angle block, and secured by tightening the screw on top to a fixed pressure. The angle block with mounted transducers is then fitted into position. It should be noted that coupling gel had to be applied to all contact surfaces to ensure good contact and wave transmission.

6.4 Experimental procedure

Once the samples are fabricated and conditioned using moisture conditioning, ultrasound measurement using A-scan are carried out to obtain the normal incident and oblique incident reflection coefficient. Meanwhile, the lap-shear pull test is conducted to obtain the failure strength of the sample. Finally, the combined lap-shear pull test is conducted to study the loading effect. To facilitate all the tests, six samples were fabricated for each condition. All results, data analysis and discussion are presented in Chapter 7.

(b)

Figure 6.1 The dimensions and mould used to fabricate samples for the experiment
 (a) Drawing for samples, with dimensions.
 (b) Image of samples and mould

Figure 6.2 Apparatus used in sample preparation and conditioning
(a) Pre-heater (b) Transfer moulding machine (c) Moisture chamber

Figure 6.3 C-scan images for the samples subjected to moisture conditioning

Figure 6.4 Schematic of the A-Scan set

(a)

(b)

Figure 6.5 Water tank with aluminum plate for oblique incidence measurement
(a) photo of water tank (b) schematic drawing for water tank

Figure 6.6 Illustration and transducer setup for oblique incidence measurement
(a) Schematic diagram (b) photo of instrument

Figure 6.7 Time domain signal from MC/Si sample.

Figure 6.8 Apparatus used for the combined test using universal testing machine and ultrasonic measurement.

Figure 6.9 Testing rig and transducer setup for normal incident pulse echo ultrasound measurement with applied loading on sample (a) photo of setup (b) schematic diagram

Figure 6.10 Load vs extension graph for the MC/Si samples.

Figure 6.11 Testing rig and transducers setup for oblique incident ultrasound measurement with applied loading on sample
(a) schematic diagram (b) photo of setup

Chapter 7

Experimental Results and Discussion

The results of the experiments will be presented in this chapter together with discussions on the significance of the results. A comparative discussion on the relationships between the experimental data and the theoretical data will also be included.

7.1 Characterisation of samples

7.1.1 Weight of samples

Weight of the samples against the time of stay in the moisture chamber is shown graphically in Fig. 7.1. For each duration of moisture conditioning, 6 samples are fabricated. The points on the graph signify the average weight of the 6 samples at that particular conditioning (0, 1, 2 hours etc.). It can be observed from Fig. 7.1(a) that starting from no moisture conditioning (0 hours) the weight of the samples increases linearly with the time spent in moisture chamber. The figure does not show the logarithmic curve because of the time stay in moisture room is still short.

Taking the 0 hours samples as reference, since the samples have not undergone the moisture conditioning, they are assumed to have 0 percent moisture absorbed, Fig. 7.1(b) shows the average percentage moisture gain by weight for each sample conditioning type. As observed in the previous figure, the percentage increase linearly with the time spent in moisture chamber.

7.1.2 C-scan image

Many samples were fabricated using the method described in Chapter 6.2.1. Then the samples were placed in the moisture chamber, with the environment held constant at 85°C/85RH. Sample from each condition were performed a C-Scan of the MC/Si interface, the images can be observed in Fig. 7.2. In picture of 0 hour, the centre square grey part is the MC/Silicon interface, and the yellow areas represent the MC/water interface. The red colour represents the interface area where the C-mode interface echoes exceed a pre-defined threshold amplitude (such as certain % of the amplitude from a good interface). The threshold is so defined that it corresponds to poor adhesion, poor cohesion, or weak interface in general, the size of the area thus may depend on the threshold defined. In the experiment, the moisture exposure is so applied to vary the degree of weak interface that is represented by the red colour. The red areas (dark in B/W copies) in the hour 1,2,3 and 4 hours pictures' centre square depict areas where the reflected wave is of higher amplitudes, thus of poorer interfacial quality.

The C-scan images in Fig. 7.2 show the propagation of defects due to the moisture. The 0 hour sample (no moisture conditioning), contains almost no red colour. As the samples spend more time in the moisture chamber, more red areas are noted in the C-Scan images. It is obvious that the 4 hours sample contains the largest area of red colour. The C-scan images also show a trend where the brighter areas proliferate from the edges towards the centre of the Silicon chip in line with what was observed in experiments conducted by Tanaka and Nishimura (1995).

Generally as the samples spend more time in the moisture chamber, more poor quality areas are noted in the C-Scan images. However, the speed of propagation of defects in

samples varies greatly among the samples even in the same batch, Fig. 7.3 shows a sample which has only small part of interface with poor quality after four hours in moisture chamber. The reason of it is unknown to author.

7.1.3 Conditioning time and failure stress

As the sample Silicon die/chips were encapsulated on a single side, the rate of moisture ingress at the MC/Si interface would be much higher than for typical PEMs where the dies are encapsulated all around. Lap-shear test was conducted for six samples for each condition, and the interfacial failure stresses were averaged and used as a method to characterise the interface quality. Fig. 7.4 shows the average failure stresses of the samples as a function of the increasing moisture conditioning time. The error bar indicates the spread from the average value.

It can be seen that the average failure stress of the interface is initially at 7.19 MPa for the 0 hour samples, and first increase to 10.57 MPa for 1 hours then gradually decreased when the samples spent a longer time in the moisture chamber. In the specification of mold compound, after the sample is formed in the transfer moulding machine, a post-cure process (150° for 20 min) is usually introduced to make the material and interface bonded well. However, in our conditioning process, this step is not employed, so the sample can be easily conditioned and deteriorated. When the sample is subject to 1 hour moisture absorption, the moisture process is carried out in moisture chamber at temperature of 85°C . This environment condition is similar in certain way to the post-cure process and therefore makes the interface quality increase after the first hour of moisture exposure. However, when the sample is exposed longer time in moisture chamber, more moisture is absorbed by the samples, the interfacial quality decreases. If

the sample for zero-hour is excluded from the data set, an approximate linear relationship can be observed.

It is noted from Fig. 7.4, for each condition the failure stress of the interface varies significantly, with values scattering in a range from 2 to 5 MP depending on the condition. It means that sample failure value varies greatly even among the same batch. The exact reason is not clear why the spread is so large. It could be due to various reasons, such as less consistent alignment of the sample holder and sampling making approach.

An extensive effort has been made over a large amount of experiments, however similar result is obtained. It shows the moisture chamber procedure can make samples of different quality; however, it is very hard to control the interface quality consistently.

It must be emphasised that the most difficult part of the experimental work in this study is to fabricate the interface samples with controlled interface quality. Many methods have been tried to fabricate the controllable and consistent MC/Si interface, such as

- Thermal cycling, starting from an initial temperature of 25°C the samples are heated up to 200°C at a rate of 40°C per minute, the samples are allowed to dwell at 200° for 20 minutes. The temperature is then lowered to 25°C at a ramp down rate of 40°C per minute followed by letting the samples dwell at 20°C for 20 minutes before another cycle starts.

- Thermal shock, put the sample in high temperature chamber, like 350C° for 10 minutes and then immediately move to low temperature chamber for another 10 minutes. Repeat the above procedure.
- Change the transfer moulding machine process parameter, like moulding pressure value, press process duration time, and pressure increase speed.
- The silicon chip was first subjected to certain surface conditioning e.g. applying a thin layer of powder on the chip surface before fabrication procedure.

Most of the methods can change the MC/Si interface quality; however, it is less satisfied all these methods cannot make the controllable and consistent quality interface. In the end the moisture conditioning approach is selected to make the samples with different quality interface.

7.1.4 Percentage of the good area in interface

A non-destructive approach is introduced to characterise the quality of the interface. This method uses the C-Scan image to characterise the interface quality. In the C-Scan image as shown in Fig 7.2, the grey colour in the centre square part represents the low amplitude reflection wave and no phase reversal, and thus of good interfacial quality. However, the red or colour areas (dark in B/W copies) in the centre square depict areas where the reflected wave is of higher amplitudes and has phase reversal, thus of poor interfacial quality. For the above reason, we treat the grey colour area as good contact interface and red or colour area as poor quality interface. When we measure the value of

grey square area and divide it by the total area, the percentage of good area can be obtained.

For example, in 0 hour picture of Fig. 7.2, the centre square is the MC/Si interface, as the whole square is grey colour and we conclude that this sample has 100% good area. In the 1 hour sample image, however, only part of the area is of grey colour and the value of the grey area can be obtained using imaging software so that the percentage of good area is calculated, 57.78%. This value is used to characterise the interface quality in this project.

7.2 MC/Si interface reflection coefficient

In the ultrasonic measurement of MC/Si samples described in chapter 6, the waveform of normal incidence and oblique incidence can be obtained as show in Fig. 7.5. In Fig. 7.5(a), it is normal incidence where *FF* wave is the direct reflection from the water/MC interface and *LL* is the reflected wave from MC/Si interface.

Fig. 7.5(b) shows the waveform obtained in oblique incidence of 13^0 at water/MC interface. This is to generate a longitudinal wave at 35^0 at MC/silicon interface and also certain shear wave as illustrated in Fig. 6.6(a). The waveform in Fig. 7.5(b) includes following echoes: *FF* echo is the direct reflection from the water/MC interface, the *LL* echo is the longitudinal incidence and longitudinal reflected wave from MC/Si interface, the *LS* echo is the longitudinal incidence and shear reflected wave from MC/Si interface, and finally the *SS* echo that is the reflected shear wave due to the shear wave being generated in mold compound. Below the method to obtain the reflection coefficient from the waveform is introduced.

7.2.1 Oblique reflection coefficient calculation method

To obtain the oblique incidence reflection coefficient, a technique based on frequency domain responses of signals is used (Guo *et. al.* 1995). In the experiment, the reflection coefficient is obtained by comparing the reflection from the MC/Si interface with a known reference, for example that from the MC/water interface. Reflection coefficient (MC/water) can be obtained theoretically from the multilayer model (Auld, 1990) for perfect interface. The procedure of obtaining the $R_{LL}(35^\circ)$ of MC/Silicon from the measured time response signal is described as follows:

From Fig. 6.6(a), the LL_0 echo can be obtained from MC/water sample,

$$LL_0 = I * T_{water/MC}(13^\circ) * R_{MC/water(LL)}(35^\circ) * T_{MC/water}(35^\circ) \quad (7.1)$$

where LL_0 is the reflected wave to the receiving transducer when the mold compound without the silicon immersed in the water, the $T_{water/MC}(13^\circ)$ is the transmission coefficient of water to mold compound interface. $T_{MC/water}(35^\circ)$ is the transmission coefficient of mold compound to water interface. $R_{MC/water(LL)}(35^\circ)$ is the reflection coefficient of mold compound to water interface.

Similarly, the LL_1 echo can be obtained,

$$LL_1 = I * T_{water/MC}(13^\circ) * R_{MC/Si(LL)}(35^\circ) * T_{MC/water}(35^\circ) \quad (7.2)$$

where LL_1 is the reflected wave to the receiving transducer when the mold compound/silicon sample is put in the water. $R_{MC/Si(LL)}(35^\circ)$ is the reflection coefficient of mold compound to silicon interface.

From equations (7.1) and (7.2) we can get,

$$R_{MC/Si(LL)}(35^\circ) = \frac{LL_1}{LL_0} * R_{MC/water(LL)}(35^\circ) \quad (7.3)$$

where $R_{MC/water(LL)}(35^\circ) = 0.351$, this value is obtained using the multilayer theoretical model (Auld, 1990), and the materials property used are listed in Table 4.2. With measurement of the LL_1 echo from the MC/silicon interface sample and the LL_0 reference echo, the reflection coefficient $R_{MC/Si(LL)}(35^\circ)$ can be obtained.

7.2.2 Reflection coefficient using spectral method

In actual experiment, the measured reflection coefficient is obtained with the spectral method. This method requires an extraction of the relevant echo from the measured signal, a Fast Fourier Transform (FFT) is then performed on the echo of interest. The calculation procedure is illustrated in Fig. 7.6 and 7.7, and is similar to that procedure used for simulation study in Chapter 5.

This can be done by first editing out the LL_1 echo and LL_0 echo as shown in Fig. 7.6(c) and (d), and padding zero to a defined length which is shown in Fig. 7.6(b). The data with padded zero is transformed using FFT and relevant frequency spectrum can be obtained as shown in Fig. 7.7(a) and (b). Finally, the LL_1 spectrum is divided by the reference LL_0 spectrum together with a multiplier value of $R_{MC/water(LL)}(35^\circ)$ to obtain the reflection coefficient spectrum as shown in Fig. 7.7(c) and (d). The magnitude at the nominal frequency (at 3.6 MHz) of the spectrum is used as the final result for the reflection coefficient $R_{LL}(35^\circ)$ of MC/silicon.

It should be noted that although a 20 MHz transducer is used as transmitter, the FFT results at 3.6 MHz is used as the results since peak spectral amplitude occurring at a this

frequency for both longitudinal reflected wave (LL_0) in MC/water interface and that (LL_1) in MC/Si interface. This is attributed to the highly attenuative nature of the MC material. For all the oblique incidence experiments in water, the amplitude at 3.6 MHz is used throughout when the reflection coefficient is calculated.

7.2.3 Normal incidence reflection coefficients calculation method

The normal incidence reflection coefficient is also measured and the result is compared with the oblique incident value. The normal incident reflection coefficient can be obtained as,

$$\frac{R_{MC/Si}(0^\circ)}{R_{MC/water}(0^\circ)} = \frac{LL_1}{LL_0} \quad (7.4)$$

where LL_0 is the reflected echo from the mold compound/water interface, and LL_1 is the reflected signal from the interface between mold compound and silicon as shown in Fig.7.5. $R_{MC/Water}$ is the reflection coefficient of mold compound and water interface, and can be found as 0.616 from the plane wave theory using the material property listed in Table 4.2.

By measuring LL_0 and LL_1 , the reflection coefficient of mold compound and silicon interface, $R_{MC/Si}(0^\circ)$, can thus be found,

$$R_{MC/Si}(0^\circ) = R_{MC/water}(0^\circ) * LL_1 / LL_0 \quad (7.5)$$

$R_{LL}(0^\circ)$ can be taken as the reflection coefficient from the MC/silicon interface (dropping the MC/Si subscript). The procedure to obtain the reflection coefficient $R_{LL}(0^\circ)$ is similar to the process of obtaining $R_{LL}(35^\circ)$ that is described in the above section.

7.3 Measured reflection coefficients

With the method described in Section 6.3.1, measurement of normal and oblique incident reflection coefficients were carried out. From previous theoretical and simulation work, $R_{LL}(35^\circ)$, the reflection coefficient of longitudinal reflection wave to the longitudinal incident wave at 35° , is most sensitive to change in interface quality of MC/silicon interface. Our experimental work is therefore focused on the verification of this finding and the comparison between the oblique reflection coefficient $R_{LL}(35^\circ)$ and the conventional normal reflection coefficient $R_{LL}(0^\circ)$. Fig. 7.8 and Fig. 7.9 show the measured reflection coefficients $R_{LL}(0^\circ)$ and $R_{LL}(35^\circ)$ against its good area percentage of the interface.

However, before detail discussion of the measurement results, theoretical results of $R_{LL}(0^\circ)$ and $R_{LL}(35^\circ)$ against the interface stiffness K , as described in Chapter 4, is reviewed as shown in Fig. 7.10. It can be seen that $R_{LL}(0^\circ)$ decrease when K become large which means the interface quality increases. When K is below 5×10^{13} , which means the interface is delaminated, $R_{LL}(0^\circ)$ almost remained unchanged with value of 1, when K is larger than 2×10^{15} , $R_{LL}(0^\circ)$ remains unchanged at a value of 0.55, and over the intermediate range when K changes from 5×10^{13} to 2×10^{15} , the $R_{LL}(0^\circ)$ change sharply from 1 to 0.55.

	$R_{LL}(0^\circ)$ of spring model	$R_{LL}(35^\circ)$ of spring model
$K \leq 5 \times 10^{13}$	1.00	0.68
$K \geq 1 \times 10^{16}$	0.55	0.01
Difference between poor and good	0.45	0.67
Ratio of poor to good	1.82	68

Table 7.1 Reflection coefficient in spring model for poor and good interface.

Similarly Fig. 7.10 shows the characteristics of oblique incident reflection coefficient at 35° . When the spring model stiffness K is below 5×10^{13} , $R_{LL}(35^\circ)$ shows almost no change at 0.68, when K is larger than 5×10^{15} , $R_{LL}(35^\circ)$ is relatively constant at 0.01, and over the intermediate range K from 5×10^{13} to 5×10^{15} , value of $R_{LL}(35^\circ)$ changes sharply from 0.68 to 0.01.

Table 7.1 shows the comparison between $R_{LL}(0^\circ)$ and $R_{LL}(35^\circ)$. The most important result from the theory is that when the quality of interface changes from total delamination to perfect, which means the stiffness change from small to large, the reflection coefficient $R_{LL}(0^\circ)$ changes 0.45 and $R_{LL}(35^\circ)$ changes 0.67, the change of $R_{LL}(35^\circ)$ is around 1.5 times larger than that of $R_{LL}(0^\circ)$. The theory predicts the oblique incidence reflection coefficient $R_{LL}(35^\circ)$ is more sensitive to the interface quality change than the normal incidence reflection coefficient $R_{LL}(0^\circ)$. It is therefore important that this is verified by the measurement.

Fig 7.8 shows the experimental results of $R_{LL}(0^\circ)$ against the percentage of good area of the interface. It can be seen that, when the good area percentage is less than 30%, which

means poor quality of the interface, the $R_{LL}(0^\circ)$ varies within a range from 0.55 to 0.80, with an average value of 0.661 and standard deviation of 0.081. The curve remains relatively constant, insensitive to the change in the interface quality. The measured value is substantially less than the theoretical value range of 0.95 to 1.00 for poor quality interface. This may be due to the averaging effect of uneven interface quality. Since the transducer has a finite diameter, and signals received are the summation of reflected waves from the interface of uneven interface quality. Also because that the experimental results are for bounded ultrasonic beams while the analytical results are for plane waves of infinite width.

When the good area percentage is greater than 70%, which means the interface is in good quality band, the $R_{LL}(0^\circ)$ varies from 0.27 to 0.39, with an average value of 0.339 and standard deviation of 0.029. The curve remains relatively constant. The measured value is also substantially less than the theoretical value range of 0.50 to 0.55 for good quality interface. However, the change of the reflection coefficient is about 0.32 when the interface is changed from poor to good quality, and this is very close to the change of 0.45 from the theory.

Over the intermediate quality range of the interface, where the good area percentage is between 30% and 70%, it can be seen that the reflection coefficient $R_{LL}(0^\circ)$ experience a sharp change, varying from 0.661 to 0.339, a change of 0.32 in reflection coefficient value. This indicates that when the interface quality changes from poor to good; the amplitude of wave reflected from the poor quality interface is 1.95 times that from the good quality interface.

Fig 7.9 shows the experiment result of $R_{LL}(35^\circ)$ against the good interface area percentage, and similar analysis can be carried out. It can be seen that when the good area percentage is less than 30%, which means the interface is in poor quality, the value of $R_{LL}(35^\circ)$ fluctuates from 0.613 to 0.910, with an average value of 0.723 and standard deviation 0.085. The averaged value of the reflection coefficient shows a good agreement with the theoretical value of 0.68.

When good area percentage is larger than 70%, which means the interface is in good quality band, the value of $R_{LL}(35^\circ)$ scatters from 0.1 to 0.28, with an average value of 0.173 and standard deviation of 0.055. It can be seen that at this range, the reflected signal is very small that noise has a significant effect. Taking this into consideration the measured averaged value of the reflection coefficient shows a reasonable agreement with the theoretical value of 0.01.

Over the intermediate quality range of the interface, where the good area percentage is between 30% and 70%, it can be seen that the reflection coefficient $R_{LL}(35^\circ)$ experience a sharp change, varying from 0.723 to 0.173, a change of 0.55 in reflection coefficient value. This indicates when the interface quality changes from poor to good; the amplitude of wave reflected from the poor quality interface is 4.3 times that from the good quality interface. The measured range the reflection coefficient of 0.55 shows a good agreement with the theoretical range of 0.67 when the interface quality change from poor to good range.

	$R_{LL}(0^\circ)$ of experiment	$R_{LL}(35^\circ)$ of experiment
Contact area $\leq 30\%$	0.661 ± 0.081	0.723 ± 0.085
Contact area $\geq 70\%$	0.339 ± 0.029	0.173 ± 0.055
Difference between poor and good	0.322	0.550
Ratio of poor and good	1.95	4.17

Table 7.2 Reflection coefficient of experiment for poor and good interface.

It can be seen from Fig. 7.8 and Fig. 7.9 that the measured reflection coefficient curves in general shows an excellent agreement in characteristics with the predicted one in Fig. 7.10 by the spring theory and simulation.

Table 7.2 shows the comparison of the measured results of $R_{LL}(0^\circ)$ and $R_{LL}(35^\circ)$ in different quality ranges. It can be seen that over the intermediate quality range, the change in reflection coefficient is 0.55 for $R_{LL}(35^\circ)$, and 0.32 for $R_{LL}(0^\circ)$, this is 1.74 times in difference over the range. This shows a good agreement to the predicted difference of 1.5 times between $R_{LL}(35^\circ)$ and $R_{LL}(0^\circ)$. It is evident that the oblique incident reflection coefficient $R_{LL}(35^\circ)$ is more sensitive than the traditional normal incident reflection coefficient $R_{LL}(0^\circ)$ to the change in the interface quality.

7.4 Combined A-scan and lap-shear pull test

The combined lap-shear pull test and ultrasound measurement are conducted by the procedure described in Section 6.3.2 to Section 6.3.4. A shear stress load is applied along the MC/Si interface, and ultrasonic signal reflection (A-Scan) is taken while holding the

stress constant. It is followed by increasing the stress to the next load step and the procedure is repeated until the sample fails.

Fig. 7.11 shows the examples of the measured normal reflection coefficient $R_{LL}(0^\circ)$ as a function of the stress load for two interface samples of good quality. It can be seen that the normal reflection coefficient curve is relatively insensitive to the change of stress load, varying from 0.50 to 0.62.

Fig. 7.12 shows the measured oblique incident reflection coefficient $R_{LL}(35^\circ)$ as a function of the stress load for two samples, one being good quality with good area percentage 95% and the other being poor quality with good area percentage less than 30%. It can be seen from Fig 7.12(a) that the reflection coefficient curve for poor sample is gradually increased with the shear stress load, varying from 0.62 to 0.82 when the stress load is increased from 0 to 5 MPa. However, for good sample as shown in Fig 7.12(b), the oblique incident reflection coefficient remains relatively unchanged, varying slightly from 0.12 to 0.20.

Similar combined lap shear and ultrasonic measurements have been carried out with about one hundred samples for the normal incidence reflection and with around twenty samples for oblique incidence reflection. However, the results seem showing no significant change of reflection coefficients $R_{LL}(0^\circ)$ and $R_{LL}(35^\circ)$ when the shear stress load was applied.

This may be due to the stress load applied is too small to have any significant effect on the ultrasonic wave propagation. It is shown previously from the predicted results

presented in Section 4.7 that the reflection coefficient is only influenced by the applied stress when the stress load is in the GPa range. At small stress load level, such as in MPa range, its effect on the reflection coefficient is negligible. This seems to be in agreement with the current experimental results.

7.5 Discussions and conclusions

In general it is shown that there is a good qualitative agreement between the theoretical and experimental results in terms of the reflection coefficients from the interfaces of varying quality. The discrepancy observed could be due to various reasons, for example,

- (1) In theory, the interface is an uniform interface, and the ultrasonic wave is a plane wave. But in the actual experiment, the interface is not uniform and the poor quality interface is randomly distributed in the interface and it influences the result.
- (2) The MC is a highly attenuative material, when the ultrasonic wave travels through the MC, most energy is lost, especially for the high frequency wave and that influences the accuracy of the measurement.
- (3) The complexity of high frequency ultrasonic measurement, and difficulty in angle alignment.

In general, the oblique incident wave measurement is more difficult to set up and complicated to interpret than the normal incident wave measurement, such as the particular angle to be used, the angle alignment of transducers, and the set up. This is the reason why the normal incident wave is still widely used in conventional testing of defects. However, as it is shown in this study, once the incident angle of measurement can be determined from theoretical and numerical study, the oblique incident

measurement can be achieved, and it offers many advantages over the normal incident wave measurement.

For example, in IC package, the mold compound used is a highly attenuative material for ultrasound. When a 20 MHz incident wave is incident to the material, the reflection from the interface is largely around 3 to 5 MHz since high frequency is lost. And when a 10 MHz incident wave is incident to the material, the reflection is largely around 1.7 MHz. This makes pulse echo normal incident set up less efficient since same transducer must be used for both transmitting and receiving wave. However, a pitch-catch set up is used in oblique incident wave measurement, where two separate transducers are used as transmitter and receiver. The frequency of the transducers can therefore be tailored to the frequency desired. For example, 20 MHz probe can be used as the transmitter and a 5 MHz probe as receiver. This will increase the efficiency and signal to noise ratio of the measurement. Therefore, the oblique incident wave measurement is more suitable in high attenuative material.

Another advantage of the oblique incident measurement is the better signal separation for quantitative evaluation of materials and interfaces. IC packaging is a multilayer structure and each layer is very thin ranging from 0.1 to 0.5 mm in thickness. The reflected signals from different layers may be overlapped in time domain. In oblique incidence, the refracted longitudinal waves in general travel longer distance than that by the normal incidence wave, so the separation in transit time is much larger than that of the normal incidence, more accurate measurement is possible.

Finally and most importantly, the experiment shows that the oblique incident wave is more sensitive than the normal incident wave to the change in interface quality, which is our concern in current study. In particular, it is shown that the sensitivity of oblique incident reflection coefficient $R_{LL}(35^0)$ can be as high as 1.7 times the normal incident reflection coefficient, $R_{LL}(0^0)$. This is significant since it has potential to be used for quantitative evaluation of interface quality in IC packaging.

(a)

(b)

Figure 7.1 Moisture content of samples against moisture conditioning time,
(a) average weight of samples;
(b) percentage increase in moisture by weight.

0hr, 100%

1hr, 57.78%

2hrs, 44.87%

3hrs, 42.58%

4hrs, 20.78%

Figure 7.2 C-scan images for the samples A subjected to moisture conditioning

Figure 7.3 C-scan images for the samples B subjected to moisture conditioning

Figure 7.4 Failure stress of samples with different moisture conditioning time
(The symbol is the average, and range from 6 samples for each set)

Figure 7.5 Measured time domain ultrasonic reflection from MC/Silicon sample
(a) with normal incident wave (b) with oblique incident wave at 35°

Figure 7.6 Typical waveforms and edited LL echoes used in calculation of the oblique incident reflection coefficient $R_{LL}(35^\circ)$ (left: reference signal from MC/water; right: signal from MC/silicon)

Figure 7.7 The oblique incident reflection coefficient spectrum $R_{LL}(35^\circ)$ obtained with the LL spectra from MC/water and from MC/silicon

Figure 7.8 Measured reflection coefficient $R_{LL}(0^\circ)$ from the MC/Si interface as a function of good area percentage.

Figure 7.9 Measured reflection coefficient $R_{LL}(35^\circ)$ from the MC/Si interface as a function of good area percentage

Figure 7.10 Theoretical sensitivity of R_{LL} to interface stiffness (MC/Si) in normal incidence and 35° oblique incidence from the spring model.

Figure 7.11 Lap-shear pull test combined with normal incidence ultrasonic measurement. Reflection coefficient $R_{LL}(0^\circ)$ against the load of sample (a) sample A (b) sample B

Figure 7.12 Lap-shear pull test combined with oblique incidence ultrasonic measurement. Reflection coefficient $R_{LL}(35^\circ)$ against the load of sample (a) sample C (b) sample D

Chapter 8

Conclusions

This final chapter summarises the results and knowledge gained from the modelling and the experiment work conducted in the study. Recommendations for future work will also be included.

8.1 Conclusions

Interfacial quality is critical to the functionality and survival life of plastic encapsulated microcircuits (PEMs). Due to the bonding of materials with mismatched coefficient of thermal expansion (CTEs), stresses are developed in packages and it may cause imperfect or weak interfaces. It is evident from the review that the current technology, such as C-SAM, is sufficient to detect gross defects such as delamination in IC packages as ultrasonic reflection wave changes dramatically in the gross defects area. However, weak interfaces, which may lead to delamination, is difficult to be detected as ultrasonic reflection wave only changes a bit in those area. It is desirable to develop a more sensitive and quantitative method to characterize the weak interface, and this has been the motivation and focus of the study, which centres on the quantitative evaluation of interface quality using the oblique incident ultrasonic wave with theoretical, numerical and experimental approaches

Ultrasonic wave propagation through the interfaces has been studied. A spring interface model for oblique incident wave upon the interface between two different materials has

been developed. The model has been implemented in software and verified so that the reflection and transmission coefficients can be calculated as a function of incident wave angle, wave frequency, material property, interface stiffness and residual stress.

In this project, the oblique incidence technique has been investigated due to its superior sensitivity to the interface quality for some special angles of incidence and the influence of interface residual stress to the reflection coefficient is calculated. This model has the advantages over other models especially in the case whereby the actual properties and thickness of interface is difficult to obtain, thus its validity is to be verified and reinforced through the numerical method as well as the experiment.

The spring interface model has been applied to typical interfaces in IC packages, such as MC/silicon and MC/copper interfaces. The sensitive study of oblique incident wave reflection coefficient is carried out in terms of interface quality, incident wave angle and wave frequency. In particular, the incident wave angles at which the reflection coefficient is most sensitive to changes in interface quality have been identified. It has been shown that the reflection coefficient for the longitudinal wave reflection to longitudinal wave incidence at 35° , $R_{LL}(35^\circ)$, is the most sensitive. It is about 1.7 times greater than the traditional normal incident reflection coefficient $R_{LL}(0^\circ)$. This offers significant potential for quantitative evaluation of interface quality.

Numerical model has been developed using finite element method to validate the theoretical results obtained using the spring interface model, such as the reflection coefficient R_{LL} from the interface with different incident angles and varying interface stiffness. The simulation method also allows for the prediction and visualization of time-

domain wave propagation signal, thus for better understanding and comparison with the measurement. The simulation of oblique wave propagation and reflection from the interface has been carried out with longitudinal incident wave at 0° , 30° and 70° . It is shown that for incident longitudinal wave at 30° , wave packets representing *LL*, *LS* can be observed and identified in the reflected wave field. It has been shown that the simulated reflection coefficient characteristics have a good agreement with the theoretical results.

Experimental work is also carried out to validate the predicated result. To study interfacial quality, it is important to first create controlled interfaces of varying qualities. For example, samples with perfect interface, samples with intermediate quality, and samples with poor interface such as near delamination. Many conditioning techniques have been investigated and moisture conditioning method was chosen as it is most relevant to the environment that weak MC/Si interfaces are typically found in PEMs.

Three types of experiment work were carried out. The first was the sample characterisation, including weight measurement, static test to find out failure strength of the sample interfaces and C-scan to define good area percentage for each type of sample. The second test was the ultrasonic measurement of reflection coefficients using A-scan wave signal. Finally the effect of stress load was investigated by using the combined test which measures the reflection coefficient when the sample interface was subject to varying lap-shear load. To facilitate those tests, various jigs and transducer holders had been developed.

It has been shown that the measured oblique reflection coefficient in general has good and qualitative agreement with the predicted result from the spring interface model in

terms of the amplitude of the reflection coefficient, and its dependence on the interface quality. It is demonstrated that the sensitivity of the reflection coefficient $R_{LL}(35^\circ)$ is about 1.9 times that of the normal incident wave reflection coefficient $R_{LL}(0^\circ)$. However, the combined test result shows that no significant influence of shear stress on the measured reflection coefficients and this in general agrees with the theory since the applied load is relatively small.

8.2 Recommendations for future work

The principle of quantitative evaluation of interface in IC packaging using oblique incident wave technique has been proven in this study. However for practical application, further study and development are needed, for example,

A scanning system can be developed to capture the ultrasonic image of the interface using oblique incident waves. A pitch-catch setup with two transducers, one as transmitter and the other as receiver, will be used in the system. An automated rotary system can be used to mount the transducer and to adjust the incident wave angle according to the desired angle predicted from the spring interface model. With reference echo defined from the MC/water interface, a scan image based on the oblique incident wave reflection coefficient value can be obtained. Since the oblique incident reflection is more sensitive than the normal incidence to the change in interface quality, a more quantitative ultrasound image can be obtained and used to interpret change in interface quality. Obvious disadvantage is the system being more complicated than the conventional C-SAM system currently in use.

Further work need to develop a methodology that defines the interface failure of a sample, or the criterion to reject a sample of intermediate quality. Extensive experiment work may need to develop the correlation between the sample quality and reflection coefficient for a particular interface configuration. A methodology can be proposed, where once the reflection coefficient exceeds certain value, the interface can be regarded as marginal quality, and should be rejected from the batch. This should be useful not only for reliability testing in IC packaging as well as for potential on-line evaluation during the production.

The interface studied in this work is very generic, and the results should be applicable to interfaces in other IC packaging configuration, such as BGA, Flip Chip etc. However, the actual correlation depends on the configuration, material property, geometry, thickness, etc. Following the approach presented in this work, the most sensitive incident angle for the oblique wave reflection coefficient can be identified, and testing strategy, such as type of ultrasonic wave, incident angle, frequency and pulse type, can be defined.

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Appendix A

Details of Equations of Oblique Incidence without Stress

Details of equations and expressions in Chapter 3 are described here. We submit Eqs.3.26 to 3.36 into the Eqs.3.37 to 3.40 and then four equations of the spring model for oblique longitudinal wave incidence are obtained,

Equation 1:

$$\begin{aligned} & \lambda_2 \left(-iT_{LL} \cos^2(\varphi_2)k_{L2} + iT_{LS} \sin(\varphi_3)k_{s2} \cos(\varphi_3) \right) \\ & + (\lambda_2 + 2\mu_2) \left(-iT_{LL} \sin^2(\varphi_2)k_{L2} - iT_{LS} \sin(\varphi_3)k_{s2} \cos(\varphi_3) \right) \\ & - \lambda \left(-i \cos^2(\varphi)k_L - iR_{LL} \cos^2(\varphi)k_L - iR_{LS} \sin(\varphi_1)k_s \cos(\varphi_1) \right) \\ & - (\lambda + 2\mu) \left(-i \sin^2(\varphi)k_L - iR_{LL} \sin^2(\varphi)k_L + iR_{LS} \sin(\varphi_1)k_s \cos(\varphi_1) \right) = \\ & - \frac{1}{2} m \omega^2 \left(T_{LL} \sin(\varphi_2) + T_{LS} \cos(\varphi_3) + \sin(\varphi) - R_{LL} \sin(\varphi) + R_{LS} \cos(\varphi_1) \right) \end{aligned}$$

Equation 2:

$$\begin{aligned} & \mu_2 \left(-2iT_{LL} \cos(\varphi_2)k_{L2} \sin(\varphi_2) + iT_{LS} \sin^2(\varphi_3)k_{s2} - iT_{LS} \cos^2(\varphi_3)k_{s2} \right) \\ & - \mu \left(-2i \cos(\varphi) \sin(\varphi)k_L + 2iR_{LL} \cos(\varphi)k_L \sin(\varphi) \right. \\ & \left. + iR_{LS} \sin^2(\varphi_1)k_s - iR_{LS} \cos^2(\varphi_1)k_s \right) = \\ & - \frac{1}{2} m \omega^2 \left(T_{LL} \cos(\varphi_2) - T_{LS} \sin(\varphi_3) + \cos(\varphi) + R_{LL} \cos(\varphi) + R_{LS} \sin(\varphi_1) \right) \end{aligned}$$

Equation 3:

$$\begin{aligned} & \lambda_2 \left(-iT_{LL} \cos^2(\varphi_2)k_{L2} + iT_{LT} \sin(\varphi_3)k_{s2} \cos(\varphi_3) \right) \\ & + (\lambda_2 + 2\mu_2) \left(-iT_{LL} \sin^2(\varphi_2)k_{L2} - iT_{LS} \sin(\varphi_3)k_{s2} \cos(\varphi_3) \right) \\ & + \lambda \left(-i \cos^2(\varphi)k_L - iR_{LL} \cos^2(\varphi)k_L - iR_{LS} \sin(\varphi_1)k_s \cos(\varphi_1) \right) \\ & - (\lambda + 2\mu) \left(-i \sin^2(\varphi)k_L - iR_{LL} \sin^2(\varphi)k_L + iR_{LS} \sin(\varphi_1)k_s \cos(\varphi_1) \right) = \\ & 2K_L \left(T_{LL} \sin(\varphi_2) + T_{LS} \cos(\varphi_3) - \sin(\varphi) + R_{LL} \sin(\varphi) - R_{LS} \cos(\varphi_1) \right) \end{aligned}$$

Equation 4:

$$\begin{aligned}
& \mu_2 \left(-2iT_{LL} \cos(\varphi_2) k_{L2} \sin(\varphi_2) + iT_{LS} \sin^2(\varphi_3) k_{s2} - iT_{LS} \cos^2(\varphi_3) k_{s2} \right) \\
& + \mu \left(-2i \cos(\varphi) \sin(\varphi) k_L + 2iR_{LL} \cos(\varphi) k_L \sin(\varphi) \right. \\
& \left. + iR_{LS} \sin^2(\varphi_1) k_s - iR_{LS} \cos^2(\varphi_1) k_s \right) \\
& = K_s \left(T_{LL} \cos(\varphi_2) - T_{LS} \sin(\varphi_3) - \cos(\varphi) - R_{LL} \cos(\varphi) - R_{LS} \sin(\varphi_1) \right)
\end{aligned}$$

The above four equations can be rewrite into matrix form as below,

$$\begin{bmatrix} A_{11} & A_{12} & A_{13} & A_{14} \\ A_{21} & A_{22} & A_{23} & A_{24} \\ A_{31} & A_{32} & A_{33} & A_{34} \\ A_{41} & A_{42} & A_{43} & A_{44} \end{bmatrix} \begin{bmatrix} R_{LL} \\ R_{TL} \\ T_{LL} \\ T_{LT} \end{bmatrix} = \begin{bmatrix} -A_{11}^* \\ A_{21}^* \\ -A_{31}^* \\ A_{41}^* \end{bmatrix}$$

where * denotes complex conjugation and the coefficient of matrix are,

$$A_{11} = 2\lambda K_L i + 4\mu K_L i - 4\mu K_L \cos^2(\varphi) i - m\omega^2 \sin(\varphi)$$

$$A_{12} = -\cos(\varphi_1) (4\mu \sin(\varphi_1) i K_s - m\omega^2)$$

$$A_{13} = -2\lambda_2 \lambda K_{L2} i - 4\mu_2 K_{L2} i + 4\mu_2 K_{L2} i \cos^2(\varphi_2) + m\omega^2 \sin(\varphi_2)$$

$$A_{14} = -\cos(\varphi_3) (4\mu_2 \sin(\varphi_3) K_{s2} i - m\omega^2)$$

$$A_{21} = -\cos(\varphi) (4\mu \sin(\varphi) K_L i - m\omega^2)$$

$$A_{22} = -2\mu K_s i + 4\mu \cos^2(\varphi_1) K_s i + m\omega^2 \sin(\varphi_1)$$

$$A_{23} = -\cos(\varphi_2) (4\mu_2 \sin(\varphi_2) K_{L2} i - m\omega^2)$$

$$A_{24} = 2\mu_2 K_{s2} i - 4\mu_2 \cos^2(\varphi_3) K_{s2} i - m\omega^2 \sin(\varphi_3)$$

$$A_{31} = \lambda K_L i + 2\mu K_L i - 2\mu i K_L \cos^2(\varphi) + 2K_{33} \sin(\varphi)$$

$$A_{32} = -2\cos(\varphi_1) (\mu \sin(\varphi_1) i K_s + K_{33})$$

$$A_{33} = \lambda_2 K_{L2} i + 2\mu_2 K_{L2} i - 2\mu_2 i K_{L2} \cos^2(\varphi_2) + 2K_{33} \sin(\varphi_2)$$

$$A_{34} = 2\cos(\varphi_3) (\mu_2 \sin(\varphi_3) i K_{s2} + K_{33})$$

$$A_{41} = -\cos(\varphi) (\mu \sin(\varphi) i K_L + K_{32})$$

$$A_{42} = (-\mu K_s i + 2\mu \cos^2(\varphi_1) K_s i - 2K_{32} \sin(\varphi_1)) / 2$$

$$A_{43} = \cos(\varphi_2) (\mu_2 \sin(\varphi_2) i K_{L2} + K_{32})$$

$$A_{44} = (-\mu_2 K_{s2} i + 2\mu_2 \cos^2(\varphi_3) K_{s2} i - 2K_{32} \sin(\varphi_3)) / 2$$

Appendix B

Details of Equations of Oblique Incidence with Stress

Details of equations and expressions in Chapter 3.5.1 are described here. Four equations of the spring model for oblique longitudinal wave incidence with residual stress are,

Equation 1:

$$\begin{aligned}
 & \lambda_2 \left(-iT_{LL} \cos^2(\varphi_2)k_{L2} + iT_{LT} \sin(\varphi_3)k_{S2} \cos(\varphi_3) \right) \\
 & + (\lambda_2 + 2\mu_2 + \sigma_{33}) \left(-iT_{LL} \sin^2(\varphi_2)k_{L2} - iT_{LS} \sin(\varphi_3)k_{S2} \cos(\varphi_3) \right) \\
 & - \lambda \left(-i \cos^2(\varphi)k_L - iR_{LL} \cos^2(\varphi)k_L - iR_{LS} \sin(\varphi_1)k_S \cos(\varphi_1) \right) \\
 & - (\lambda + 2\mu + \sigma_{33}) \left(-i \sin^2(\varphi)k_L - iR_{LL} \sin^2(\varphi)k_L + iR_{LS} \sin(\varphi_1)k_S \cos(\varphi_1) \right) = \\
 & - \frac{1}{2} m \omega^2 \left(T_{LL} \sin(\varphi_2) + T_{LS} \cos(\varphi_3) + \sin(\varphi) - R_{LL} \sin(\varphi) + R_{LS} \cos(\varphi_1) \right)
 \end{aligned}$$

Equation 2:

$$\begin{aligned}
 & \mu_2 \left(-2iT_{LL} \cos(\varphi_2)k_{L2} \sin(\varphi_2) + iT_{LS} \sin^2(\varphi_3)k_{S2} - iT_{LS} \cos^2(\varphi_3)k_{S2} \right) \\
 & + \sigma_{32} \left(-iT_{LL} \sin^2(\varphi_2)k_{L2} - iT_{LS} \sin(\varphi_3)k_{S2} \cos(\varphi_3) + i \sin^2(\varphi)k_L \right. \\
 & \left. + iR_{LL} \sin^2(\varphi)k_L - iR_{LT} \sin(\varphi_1)k_S \cos(\varphi_1) \right) - \mu \left(-2i \cos(\varphi) \sin(\varphi)k_L \right. \\
 & \left. + 2iR_{LL} \cos(\varphi)k_L \sin(\varphi) + iR_{LS} \sin^2(\varphi_1)k_T - iR_{LS} \cos^2(\varphi_1)k_S \right) \\
 & = - \frac{1}{2} m \omega^2 \left(T_{LL} \cos(\varphi_2) - T_{LS} \sin(\varphi_3) + \cos(\varphi) + R_{LL} \cos(\varphi) + R_{LS} \sin(\varphi_1) \right)
 \end{aligned}$$

Equation 3:

$$\begin{aligned}
& \lambda_2 \left(-iT_{LL} \cos^2(\varphi_2)k_{L2} + iT_{LS} \sin(\varphi_3)k_{s2} \cos(\varphi_3) \right) \\
& + (\lambda_2 + 2\mu_2 + \sigma_{33}) \left(-iT_{LL} \sin^2(\varphi_2)k_{L2} - iT_{LT} \sin(\varphi_3)k_{s2} \cos(\varphi_3) \right) \\
& + \lambda \left(-i \cos^2(\varphi)k_L - iR_{LL} \cos^2(\varphi)k_L - iR_{LS} \sin(\varphi_1)k_s \cos(\varphi_1) \right) \\
& - (\lambda + 2\mu + \sigma_{33}) \left(-i \sin^2(\varphi)k_L - iR_{LL} \sin^2(\varphi)k_L + iR_{LT} \sin(\varphi_1)k_s \cos(\varphi_1) \right) = \\
& K_L \left(T_{LL} \sin(\varphi_2) + T_{LS} \cos(\varphi_3) - \sin(\varphi) + R_{LL} \sin(\varphi) - R_{LS} \cos(\varphi_1) \right)
\end{aligned}$$

Equation 4:

$$\begin{aligned}
& \mu_2 \left(-2iT_{LL} \cos(\varphi_2)k_{L2} \sin(\varphi_2) + iT_{LS} \sin^2(\varphi_3)k_{s2} - iT_{LS} \cos^2(\varphi_3)k_{s2} \right) \\
& + \sigma_{32} \left(-iT_{LL} \sin^2(\varphi_2)k_{L2} + iT_{LS} \cos(\varphi_3)k_{s2} \sin(\varphi_3) - i \sin^2(\varphi)k_L \right. \\
& \left. - iR_{LL} \sin^2(\varphi)k_L + iR_{LS} \sin(\varphi_1)k_s \cos(\varphi_1) \right) + \mu \left(-2i \cos(\varphi) \sin(\varphi)k_L \right. \\
& \left. + 2iR_{LL} \cos(\varphi)k_L \sin(\varphi) + iR_{LS} \sin^2(\varphi_1)k_s - iR_{LS} \cos^2(\varphi_1)k_s \right) \\
& = K_S \left(T_{LL} \cos(\varphi_2) - T_{LS} \sin(\varphi_3) - \cos(\varphi) - R_{LL} \cos(\varphi) - R_{LS} \sin(\varphi_1) \right)
\end{aligned}$$

The above four equations can be rewrite into matrix form as below,

$$\begin{bmatrix} B_{11} & B_{12} & B_{13} & B_{14} \\ B_{21} & B_{22} & B_{23} & B_{24} \\ B_{31} & B_{32} & B_{33} & B_{34} \\ B_{41} & B_{42} & B_{43} & B_{44} \end{bmatrix} \begin{bmatrix} R_{LL} \\ R_{TL} \\ T_{LL} \\ T_{LT} \end{bmatrix} = \begin{bmatrix} -B_{11}^* \\ B_{21}^* \\ -B_{31}^* \\ B_{41}^* \end{bmatrix}$$

Where * denotes complex conjugation and the coefficient of matrix are,

$$B_{11} = 2\lambda K_L i + 2\sigma_{33} K_L i - 2\sigma_{33} K_L \cos^2(\varphi) i + 4\mu K_L i - 4\mu K_L \cos^2(\varphi) i - m\omega^2 \sin(\varphi)$$

$$B_{12} = -\cos(\varphi_1)(4\mu \sin(\varphi_1) i K_S - m\omega^2 + 2\sigma_{33} \sin(\varphi_1) i K_S)$$

$$B_{13} = -2\lambda_2 \lambda K_{L2} i - 4\mu_2 K_{L2} i + 4\mu_2 K_{L2} i \cos^2(\varphi_2) - 2\sigma_{33} K_{L2} i - 2\sigma_{33} K_{L2} i \cos^2(\varphi_2) + m\omega^2 \sin(\varphi_2)$$

$$B_{14} = -\cos(\varphi_3)(4\mu_2 \sin(\varphi_3) K_{S2} i - m\omega^2 + 2\sigma_{33} \sin(\varphi_3) K_{S2} i)$$

$$B_{21} = -\cos(\varphi)(4\mu \sin(\varphi) K_L i - m\omega^2) + 2\sigma_{32} K_L i (1 + \cos^2(\varphi))$$

$$B_{22} = -2\mu K_S i + 4\mu \cos^2(\varphi_1) K_S i + m\omega^2 \sin(\varphi_1) - 2\sigma_{32} \cos(\varphi_1) K_S \sin(\varphi_1) i$$

$$B_{23} = -\cos(\varphi_2)(4\mu_2 \sin(\varphi_2) K_{L2} i - m\omega^2) - 2\sigma_{32} K_{L2} \sin^2(\varphi_2) i$$

$$B_{24} = 2\mu_2 K_{S2} i - 4\mu_2 \cos^2(\varphi_3) K_{S2} i - 2\sigma_{32} \cos(\varphi_3) K_{S2} \sin(\varphi_3) i - m\omega^2 \sin(\varphi_3)$$

$$B_{31} = \lambda K_L i + (2\mu + \sigma_{33}) K_L i - (2\mu + \sigma_{33}) i K_L \cos^2(\varphi) + 2K_{33} \sin(\varphi)$$

$$B_{32} = -\cos(\varphi_1)((2\mu + \sigma_{33}) \sin(\varphi_1) i K_S + 2K_{33})$$

$$B_{33} = \lambda_2 K_{L2} i + (2\mu_2 + \sigma_{33}) K_{L2} i - (2\mu_2 + \sigma_{33}) i K_{L2} \cos^2(\varphi_2) + 2K_{33} \sin(\varphi_2)$$

$$B_{34} = \cos(\varphi_3)((2\mu_2 + \sigma_{33}) \sin(\varphi_3) i K_{S2} + K_{33})$$

$$B_{41} = -\cos(\varphi)(\mu \sin(\varphi) i K_L + K_{32}) + \sigma_{32} K_L \sin^2(\varphi) i$$

$$B_{42} = (-\mu K_S i + 2\mu \cos^2(\varphi_1) K_S i - 2K_{32} \sin(\varphi_1) - \sigma_{32} \cos(\varphi_1) K_S \sin(\varphi_1) i) / 2$$

$$B_{43} = \cos(\varphi_2)(\mu_2 \sin(\varphi_2) i K_{L2} + K_{32}) + \sigma_{32} K_{L2} \sin^2(\varphi_2) i$$

$$B_{44} = (-\mu_2 K_{S2} i + 2\mu_2 \cos^2(\varphi_3) K_{S2} i - 2K_{32} \sin(\varphi_3) + \sigma_{32} \cos(\varphi_3) K_{S2} \sin(\varphi_3) i) / 2$$