Acoustic Micro Imaging in the Fourier Domain for Evaluation of Advanced Packaging

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ABSTRACT
Acoustic Micro Imaging (AMI) has long been established as a method of evaluating materials and bonding for various micro electronic applications. Acoustic micro imaging uses high frequency ultrasound (5 to 300 MHz) to image the internal features of samples. Ultrasound is sensitive to variations in the elastic properties of materials and is particularly sensitive to locating air gaps (delaminations and voids). The method of imaging most commonly used at present involves time gating of a selected echo or echoes on an A-scan, which is a single point depth profile through the sample, to select a specific depth in the sample for display/analysis. This is known as time domain imaging. There is a direct relationship between frequency and resolution in AMI. The higher the frequency the shorter the wavelength and the higher the resolution potential. With the evolution of microelectronic devices to smaller sizes and/or higher I/O counts the sizes of the features have become increasingly smaller and layer thicknesses increasingly thinner. This has pushed the development of higher frequency imaging in AMI to increase the available resolution in both the spatial (x-y) and axial (z) dimensions. However, there is a point at which further methods are needed to extract additional information beyond what can be done by standard time domain (C-Scan) acoustic imaging.

Recently, studies have been done in AMI using Fourier analysis of echo waveform distortions to measure minute thickness variations in materials. More recently imaging in the frequency domain has been used to enhance features and bring out information previously unavailable when using time domain AMI. In the work done for this study the method involves mathematically converting the captured waveforms within a time gate to the frequency domain. Specific frequencies are selected from the FFT spectra and an image is then reconstructed from the frequency information.

This paper will present case studies where FFT frequency domain imaging has been used to reveal features down to only Angstroms in thickness, which is substantially below the accepted wavelength limit of the resolution, in applications such as wafer bonding and flip chips.

Keywords: AMI, Frequency Domain Imaging

BACKGROUND
Acoustic Micro Imaging
Acoustic microscopes operate in the pulse-echo mode, typically over a range from 5 to 300 MHz, to produce images of samples at specific depth levels. With time domain C-mode acoustic microscopy (C-Scan) a focused ultrasonic transducer alternately sends pulses into and receives reflected pulses (echoes) from discontinuities within the sample. Since the echoes are separated in time based on the depths of the reflecting features in the sample, an electronic gate can be used to select a specific depth or interface to view. A very high speed mechanical scanner scans the transducer over the sample and by collecting data point-by-point produces images in tens of seconds. Acoustic Micro Imaging can be optimized for analytical studies where layer-by-layer analysis is needed. The higher resolution capabilities require higher acoustic frequencies. Lower frequencies, however, provide more penetration through materials. A frequency that provides the best compromise of resolution and penetration can be found to suit most applications.

There are several important Acoustic Micro Imaging techniques used to analyze samples. A short discussion of these follows:

A-Scan
In reflection mode Acoustic Micro Imaging the fundamental information is contained in what is called the A-Scan. The A-Scan displays the echo depth information in the sample at each x, y coordinate. Echoes displayed in the A-Scan correspond to different interfaces in the device being examined. There is a time - distance relationship between the echoes related to their depth in the device and the ultrasonic velocity in the materials. The amplitude and phase (polarity) information of the echoes is used to characterize the condition at the interface and is dependant on the acoustic impedance value of the materials involved. The equation that describes the pulse reflection at an interface between materials is as follows:

\[ R = \frac{Z_2 - Z_1}{Z_2 + Z_1} \]

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Where $R$ is the amplitude of the reflected pulse, $I$ is the amplitude of the incident pulse, $Z_1$ is the intrinsic acoustic impedance of the material through which the pulse is traveling and $Z_2$ is that of the next material which is encountered by the pulse.

**Interface Scan - C-Scan**
The most common imaging method used to evaluate devices for delaminations between layers and voids is the “interface scan”. This method involves gating the A-Scan signal for the appropriate echo from the interface to be investigated. The gate corresponds to a time window that is selected and applied to each x-y position for the scan. The geometric focus of the acoustic beam is optimized for the interface as well. At each x-y position only the peak intensity value and the polarity of the echo within the gate are displayed.

The conventional C-scan output is only two dimensional consisting of an x-y plot of one specific plane in the z dimension. Features existing in the device but not included in the electronic gate or features with lesser signal strength at a given position will not be displayed for analysis in the image. The A-scans for each point on the sample are not typically saved with the images due to file size considerations when documenting a significant number of samples. Since the A-scans are not saved, the data cannot be re-gated, nor can the echoes be reprocessed to create different image information. But the conventional C-Scan is very useful and has been the standard since acoustic micro imaging was developed.

**A-scan Storage**
More recently a method is used that stores the A-scan information for each x-y point in a scan. From the stored information images of depths within the device not included in the original gate for the image can be recreated and/or waveforms (echoes) can be viewed for analysis without rescanning the sample. In addition to this the echoes can be digitally processed, frequency filtered, etc., to extract further information about the condition of the sample, or extract information at or slightly beyond the limits of conventional AMI.

**Frequency Domain imaging**
Frequency Domain imaging is one method that can extract further information by using the frequency content of the signal.

The transducers used in AMI range in frequency from 5 MHz to 300 MHz and above. In conventional acoustic imaging, the choice of transducer determines the spatial resolution, penetration, and other parameters. If a sample is scanned with a 50 MHz transducer, one can not manipulate the image data to produce a 10 MHz image or a 100 MHz image, because the acoustic pulses themselves do not have sufficiently wide frequency content. However, the data file including the stored A-scans makes this kind of manipulation possible, within limits. Data collected at 50 MHz can be used to create images showing the sample at frequencies from 30 MHz to 70 MHz, and data collected at 300 MHz can be used to create images showing the sample at frequencies from 225 MHz to 375 MHz. But much larger excursions in frequency – for example, using a data file collected at 10 MHz to create 300 MHz C-Mode images – are not possible. The sample can of course be physically scanned with a variety of transducers.

Because the A-scans for each point in the image are collected with the image changes in frequency that may occur during reflection can be analyzed. For example, a pulse of 15 MHz ultrasound launched toward a material interface (such as molding compound to die) may be reflected with a different frequency content than originally pulsed, and this change – not otherwise detectable – may be indicative of the interface condition. The gated echo(es) from the stored A-scans can be filtered by means of a Fast Fourier Transform (FFT), also called a Frequency Domain algorithm, to isolate a given frequency. The Fourier transform decomposes the selected waveform(s) into sinusoids of different frequencies. An illustration of a pulse and its component sinusoids is shown in Figure 1.

![Figure 1 - sinusoids of single frequencies combine constructively/destructively to form a single broadband waveform.](image)

The FFT identifies the different frequency sinusoids and their respective amplitudes. Figures 2 and 3 compare the appearance of a pulse in the time domain to the frequency content distribution in the frequency domain. Images can then be reconstructed from components of the frequency information. Specific features may yield more information at one frequency than another; therefore, FFT filtering of the echo can bring out image detail that may not be visible with conventional time domain imaging.
The following examples demonstrate instances where the frequency domain imaging has been able to bring out features that were either not clear or not detectable in the time domain images.

APPLICATIONS

**Plastic Encapsulated Packages**

In the following example a TQFP plastic encapsulated package is shown using time domain imaging and frequency domain imaging. Using time domain imaging the most significant echo over the duration of the gate is displayed for any given point. The various levels in the package can be seen such as the die surface, die pad surrounding the die and the lead frame. A delamination at the die pad can be seen as a red region (dark grey in the black and white print of the color image), the red color indicating the area of inverted polarity. Information below the die (die attach) is not evident in this image as the die surface and die attach echo compete within the gate at the same x-y position for display to the image. The die surface echo in this case shows the stronger signal and is the one displayed. The frequency domain image (Figure 4b) of the same gated area however brings out the detail not present in the time domain image. A delamination at the die attach interface now can be seen which is continuous with the die pad delamination and the dimple pattern of the die pad becomes visible.

**Silicon Wafers**

Figures 5a and 5b reveals an issue of detecting poly-silicon dioxide layers on a silicon wafer. The wafer shown here was the remaining part of a silicon/silicon bonded wafer where the other wafer had been removed. The purpose was to detect the presence/absence of the poly-silicon dioxide layers remaining at the bond interface and to determine if
this had any relationship to the presence of voids in the bond. The appearance of the wafer in the time domain image (5a) shows very faint evidence of the presence of the poly-SiO₂ layers in the lower left quadrant of the image. The frequency domain (FFT) image enhances the appearance of the poly-SiO₂ layers. The reported thickness of these layers is only 2 to 150 Angstroms.

Frequency domain (FFT) analysis of the waveforms has been used in the past to measure bondline thickness and has shown the capacity of measuring to thickness well beyond the axial resolution limit of a given frequency. Frequency domain imaging can be used to improve detection/resolution in the lateral dimensions by removing the low frequency component from the image. Figure 6a shows the time domain image of a flip chip at the chip/bump interface. The bump bonds can be seen as well as an associated laminar crack next to one of the bumps. The evidence of the metallization on the chip is very faintly visible in some areas. The frequency domain image using the higher frequency portion of the signal (Figure 6b) shows the metallization clearly.

**Figure 5a – Time domain image of silicon wafer**

**Figure 5b – FFT single frequency image of silicon wafer**

**Figure 6a - time domain image of flip chip**

**Figure 6b - frequency domain image of flip chip**

**Flip Chip**
Advancements have been made in recent years with respect to higher resolution in the acoustic images by increasing the frequency/design of the transducers. However there is a point where the thickness and type of material in the packaging will limit the use of even higher frequency ultrasound even though package features are becoming increasingly smaller and internal layers increasingly thinner.

**Small Void Detection**
Voids in underfill can reduce the field life of the device particularly when the voids are in close association to the interconnect bumps. Halo voids that surround the bump totally or partially at the chip/bump level typically result from flux residue or other contamination on the chip surface. Figure 7a displays a time domain image of a flip
chip that shows halo voids associated with two of the bump bond sites. Figure 7b shows the corresponding frequency domain image. The image was made again using the higher frequency content of the pulse. In the FFT enhanced image many other halo voids become apparent.

Figure 7a - time domain image of flip chip with halo voids in the underfill

Figure 7b - frequency domain image of flip chip. Now many more bumps show associated halo voids.

SUMMARY
The examples presented here demonstrate only some of the instances where imaging in the frequency domain has been useful. The drive to manufacture smaller and thinner microelectronic devices and features in the devices is pushing the limits of the inspection technologies to resolve/detect these features. Frequency domain imaging is one tool that can be used with AMI to evaluate advanced microelectronic packages.

REFERENCES