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# ACOUSTIC MICRO IMAGING ANALYSIS METHODS FOR 3D PACKAGES

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## ABSTRACT
Earlier studies concerning evaluation of stacked die packages using Acoustic Micro Imaging (AMI) demonstrated the feasibility of using AMI to analyze 3D devices. The construction of the devices evaluated in the studies were typically stacks of silicon chips bonded with an adhesive and using wire bonding for the interconnections. More recently 3D processes include stacked flip chip, silicon interposer, and TSV (Through Silicon Via). The various methods to achieve 3D integration provide challenges to the inspection of the devices using AMI. These challenges include multiple layers, thin silicon layers, different layer thicknesses, varying material properties, small feature sizes and in some cases the devices require analysis post encapsulation.

AMI (Acoustic Micro Imaging) is a non-destructive test method that utilizes high frequency ultrasound in the range of 5 MHz to 500 MHz. Ultrasound is sensitive to variations in the elastic properties of materials and is particularly sensitive to locating air gaps (delaminations, cracks and voids). There is a direct relationship between frequency and resolution in AMI. Higher frequencies have shorter wavelengths and therefore provide higher resolution. Lower frequencies, which have longer wavelengths, provide better penetration of the ultrasound energy through attenuating materials, thicker materials or multiple layer assemblies. Generally a compromise is found between sufficient resolution and maintaining satisfactory penetration and working distance for a given application. In order to accommodate the changing designs in 3D devices AMI technology is evolving. This includes different frequency transducers, and enhanced software tools and imaging techniques to aid in the detectability of features and assist in locating the sequential levels in the devices.

This paper will demonstrate how recent developments in AMI analysis methods can facilitate evaluation of various types of 3D devices.

Key words: Acoustic Micro Imaging (AMI), Flip Chip, Stacked Die, 3D Packaging

## INTRODUCTION
There are a number of methods being proposed and investigated to achieve 3D integration in devices. With varying assemblies and materials and with many device types still in the development phase it can be a challenge to find the optimum evaluation method using acoustic micro imaging. However many 3D package types incorporate technologies used in single layer IC packages and there is much past experience working with these related devices such as flip chips. In addition evaluations of 3D devices that are currently in production such as stacked die parts lend information that can be applied and /or modified to analyze the devices that use different approaches to implement 3D integration or devices that are in development.

This paper will present a review of AMI methods that are applicable to analyses of 3D devices and show example applications.

## REVIEW OF AMI PRINCIPLES
AMI (Acoustic Micro Imaging) is a non-destructive test method that utilizes high frequency ultrasound in the range of 5 MHz to 500 MHz. Ultrasound is sensitive to variations in the elastic properties of materials and is particularly sensitive to locating air gaps (delaminations, cracks and voids). There is a direct relationship between frequency and resolution in AMI. Higher frequencies have shorter wavelengths and, therefore, provide higher resolution. Lower frequencies, which have longer wavelengths, provide better penetration of the ultrasound energy through attenuating materials, thicker materials or multiple layer assemblies.

### A-Scan and - C-Scan (Interface 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 dependent on the acoustic impedance value of the materials involved.

The “interface scan” is the most common imaging method used to evaluate devices for voids and delaminations between layers. 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 equation that describes the pulse reflection at an interface between materials is as follows:

$$R = I \frac{Z2 - Z1}{Z2 + Z1}$$

Where R is the amplitude of the reflected pulse, I is the amplitude of the incident pulse, Z1 is the intrinsic acoustic impedance of the material through which the pulse is traveling and Z2 is that of the next material which is encountered by the pulse.

As the equation indicates the greater the impedance difference between materials the stronger the reflection at the interface. Whereas bonded areas between similar materials or materials with similar impedances (such as solder die attach) show very little signal reflection at a bonded interface die attach using epoxy bonding shows a significant reflected echo even in the bonded areas. Also multiple reflections for the same interface occur periodically at regular intervals based on the thickness to the interface. The magnitude of these echoes maximizes at deeper focus levels in the sample and often is coincident with the time position on the A-scan and focus for actual subsequent interfaces in the sample (Figure 1).

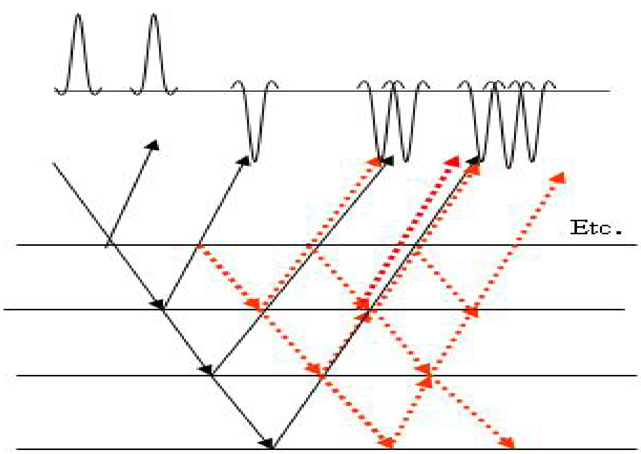


**Figure 1:** At each interface some of the signal transmits across the boundary (if there is no air gap) and some is reflected at the interface for both the incident and returned signal. This causes multiple reflections from the different interfaces that can interfere with the reflections from the actual levels of interest.

There is a time/distance relationship between the echoes based on the acoustic velocities in the materials that can be used to predict the positions of the interface echoes for the various levels.

$$\text{Velocity} = 2 \times \text{depth/time}$$

However, in multilayer silicon devices, typically the layers are very thin relative to the wavelength of the frequency needed for inspection. In some instances the echoes from the various levels may not be completely separated from one another on the A-scan and this causes interference effects that can be difficult to interpret.

In the reflection mode simultaneous sequential gates can be used to image the separate layers. The location of the gates for the different interfaces is based on the acoustic velocity and the thickness of the material(s). But depending on the thickness (or thinness) of the layers and the influence of multiple reflections that can be overlapping information from previous levels can repeat in images of subsequent interfaces.

Information from the multiple reflections (resonances) has proved useful to examine the individual layers. The location of the different interfaces is determined empirically at this time but will be consistent within a part type.

**Resolution: Higher frequency, Lower F#, Shorter Focal Lengths, and Heated Fluid Couplant**

Experience with applications such as flip chip evaluation has shown that there are a number of factors that can be manipulated to increase the resolution capabilities. The frequency of the transducer is the most obvious factor in improving resolution. In general, the higher the ultrasonic frequency the higher the resolution possibilities. At present flip chip devices are routinely evaluated using frequencies of 230 MHz to 300 MHz.

However there are other design factors that affect the resolution at a given frequency. The water path from the transducer to the sample at the point of focus and the interface of interest is one important factor. A shorter fluid path will cause less attenuation of the high frequency portion of the transducer bandwidth and therefore allow for the best resolution in the sample. Shorter focal length transducers can accomplish this but the initial focal length of the transducer has to be sufficient to allow for refraction in the sample and to be able to reach the interface of interest with optimum focus.

The F# of the transducer also affects the resolution. This is the relationship of the transducer element size to the transducer focal length (F# = Focal length/diameter of beam). The F # of a lens is used as a measure of the degree of focusing achieved by the lens. For example, two transducers having the same frequency characteristics but different focal lengths will exhibit the same resolution if their F # s are identical (disregarding the attenuation in the fluid couplant).

A smaller F # results in a more highly focused ultrasonic beam and a better resolution when transducers are focused in a couplant such as water [1].

Another factor that controls resolution in broadband acoustic microscopy systems is frequency downshifting due to attenuation in the water path and material. Most acoustic microscopes employ ultrasound in the frequency range of 15 to 300 MHz. The ultrasound is emitted by a piezoelectric element as a short duration pulse. The finite duration of the pulse results in the ultrasound having a broad range of frequencies whose distribution is similar to a Gaussian function (bell curve). The central peak is usually close to the transducer's rated frequency. As the ultrasonic pulse propagates from the transducer through the water couplant into the device and back, the higher frequencies in the incident pulse suffer more attenuation (reduction) than the lower frequencies. The net effect is that the peak in the spectrum shifts to lower frequencies. In other words, an incident pulse with a center frequency of 50 MHz might resemble, after reflection from the target, a pulse from a 30 MHz transducer. This downshifting can cause a significant reduction in the resolution afforded by a high frequency transducer. It has been shown that a shorter focal length transducer will yield better resolution than a longer focal length transducer because the water path between the transducer and sample surface is smaller.

The images shown in Figures 2a, b, and c illustrate the effect of F# and focal length in the acoustic image. All three images were made using the same flip chip sample. Figure 2a displays a 230 MHz image using a transducer with F# 2 and a 9.5 mm focal length. White features are present in the image which corresponds to voids at the chip/bump level. Voids in the underfill are also present. Figure 2b is also a 230 MHz image using an F2 transducer but the focal length in this case is 3.8 mm. Notice that the appearance of the voids is more defined in the image. Figure 2c shows a 230 MHz, 3.8 mm focal length image but in this instance an F# 0.8 transducer was used. This image shows the best resolution of the features and additional small voids can be seen when compared to the other images.

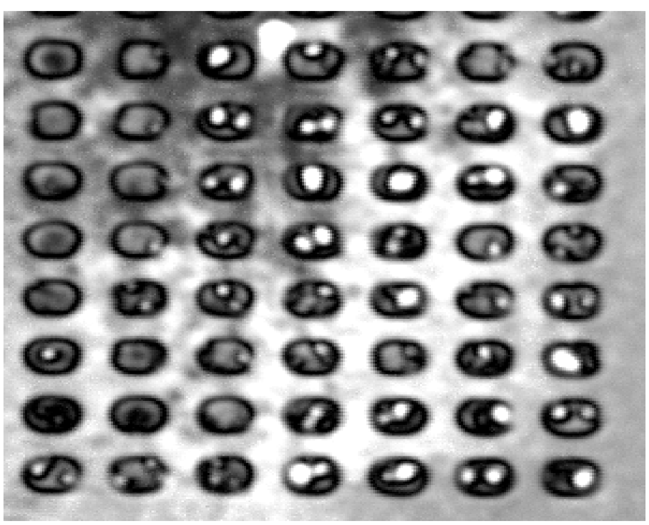

**Figure 2a:** 230 MHz, F# 2, 9.5 mm fl

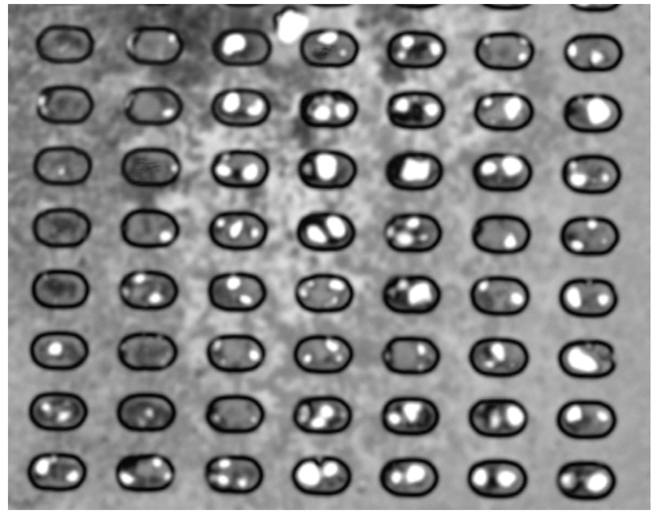

**Figure 2b:** 230 MHz, F# 2, 3.8 mm fl

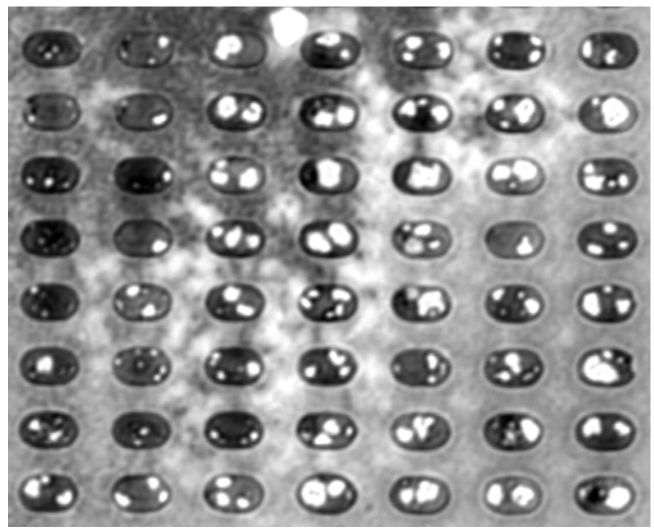

**Figure 2c:** 230 MHz, F# 0.8, 3.8 mm fl

Heating the water couplant to 40-50 degrees Centigrade has also shown improvement in the resolution in acoustic images. There is less attenuation of the high frequency portion of the signal in water at higher temperatures.

Plastic materials are more attenuating to high frequency ultrasound than water. However even though heating water improves the acoustic transmission through the couplant it has the opposite effect on polymer encapsulant materials. Therefore it is not always advisable to use a heated fluid couplant on encapsulated devices.

Shorter focal length transducers still provide an advantage as there is less attenuation from the water path before reaching the part but the smaller working distance from the parts can be a clearance issue for production screening of an entire strip or batch of parts at a time.

**Frequency Domain (FFT) Imaging**

Currently 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 is one method that can extract further information by using the frequency content of the signal. In this technique each A-scan of the image relates to the localized frequency response of the corresponding pixel in the sample. For reference, the conventional image is a time domain image in which each pixel relates to the magnitude of a return echo [2].

Transducers typically used in AMI have highly damped waveforms in order to achieve better resolution, both spatial and axial, using time domain imaging. Figure 3 displays an A-scan with typical echoes (pulses) as seen in the time domain. However these highly damped waveforms contain broad-spectrum frequency information that can be displayed in the Fourier (frequency) domain.

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. 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 FFT identifies the different frequencies present in the bandwidth and their respective amplitudes. Figure 4 shows the frequency content distribution of the gated echo shown in Figure 3 in the time domain. Images can then be reconstructed from components of the frequency information.


**Figure 3:** A-scan displaying typical waveforms (pulses) in the time domain.

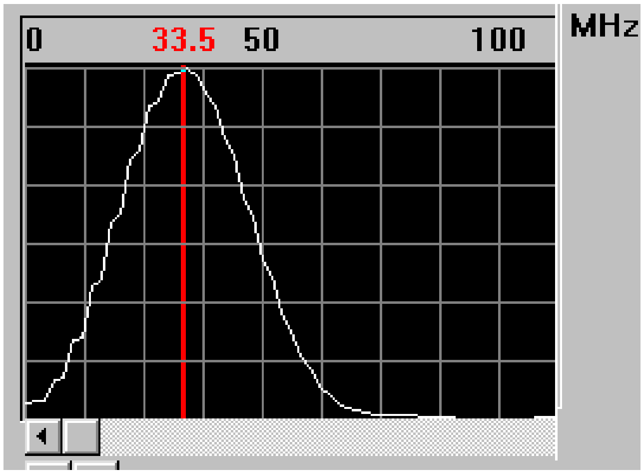


**Figure 4:** Broadband pulse content in the frequency domain for the echo within the gate on the A-scan in Figure 3.

Frequency domain imaging can be used to improve detection/resolution in the lateral dimensions by removing the low frequency component from the image. Conversely by selecting a lower frequency component of the bandwidth features that were masked by the high frequency portion of the signal have been detected.

## APPLICATIONS

### Stacked Die Packages

In this example an un-encapsulated six die stack is shown using reflection mode C-Scans [3]. As this sample was un-encapsulated it could be evaluated at a frequency of 230 MHz. In Figure 5 the die attach interface of the first to second die is shown. A large delamination at the lower left corner of the die attach is present in the image as well as a band of smaller voids. The corner delamination corresponds to the position of one of the dark areas in the through scan image but a more central dark area in the through scan is not accounted for at this level. At a subsequent level in the stack a large void area is detected that corresponds to the more circular area toward the center of the part in the through scan (Figure 6). Please note that the orientation of alternating dies was rotated 90º creating an area of intentional disbond at the edges of the stack which also shows up in the images.

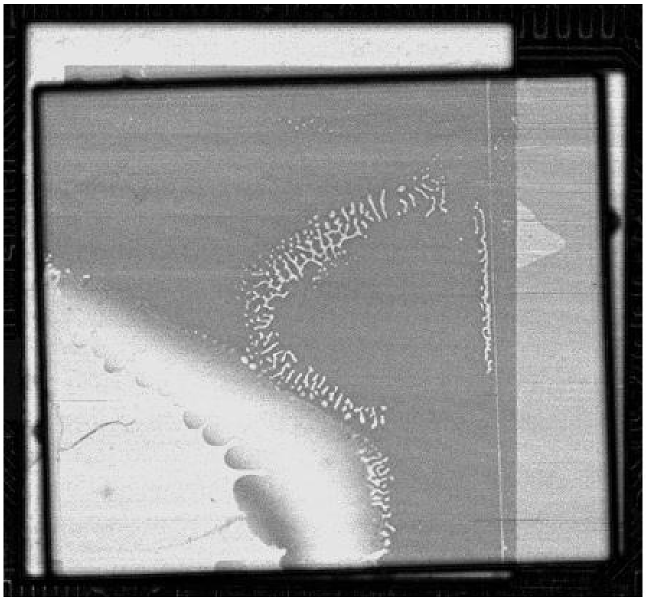

**Figure 5:** Reflection mode C-Scan image of the first die attach level in a stacked die part. A large corner void and additional smaller voids (white areas) are present in the bond.

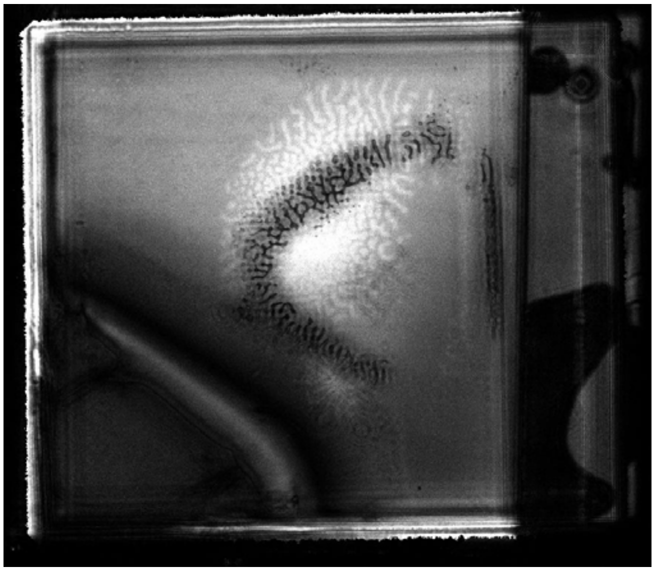

**Figure 6:** Reflection mode C-Scan of a die attach level deeper in the stack revealing another large void (white area). The shadows from the voids at die attach level one are also present in the image.

In Figures 7, 8, and 9 voids were detected in an encapsulated four stack die package with 80µ nominal die thickness using through transmission imaging. However, initial reflection mode scans using 75 MHz did not reveal the presence of several of the defects. Subsequent scans at 100 MHz did show the presence of the defects at the deepest die attach level (die 4 to substrate). Using Frequency Domain imaging the appearance of the voids in the image was much improved when the image was reconstructed using a single frequency of 51 MHz.

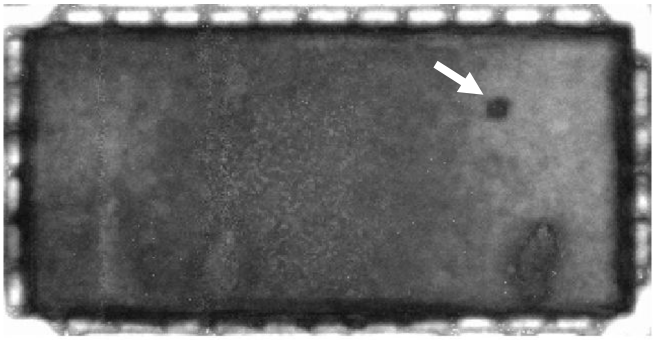

**Figure 7:** 75 MHz acoustic image of deepest die (die 4) attach to substrate. The shadow of one void from a previous level is seen (white arrow).

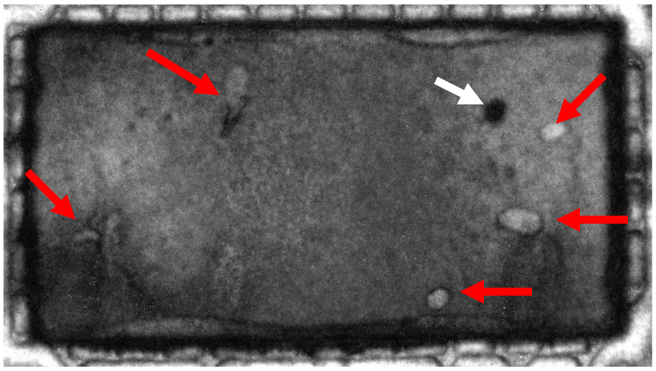

**Figure 8:** 100 MHz acoustic image of die 4 to substrate. In addition to the void at a level above the interface (white arrow) additional voids are revealed at the interface (red arrows).

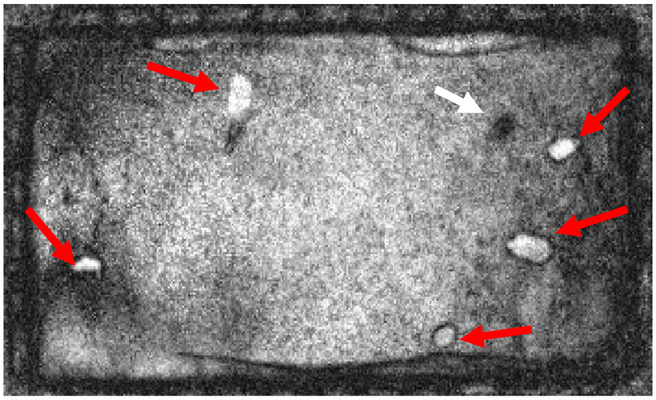

**Figure 9:** 51 MHz Frequency Domain image of the same die attach level as shown in Figures 8 and 9. The voids in the die 4 attach (red arrows) are much more evident in this image. The shadow of the void from an earlier interface is still present (white arrow).

In this case the interface and defects of interest required sufficient frequency content in the bandwidth of the transducer around 50 MHz to be detected. However it is not as easy as simply using a 50 MHz transducer to begin with. Due to downshifting of the transducer center frequency in the fluid path and in the molding compound 50 MHz and 75 MHz transducers no longer contained sufficient frequency response at 50 MHz to detect the defects.

**Micro Bump Flip Chip and Silicon Interposer**

This example of a stacked flip chip application involves the top silicon die bonded using "micro bumps" to a silicon interposer and the interposer is bonded to the substrate using larger size bumps. Analysis of micro bump attach is similar to typical flip chip evaluation. It necessitates high frequency transducers and minimizing the fluid path to achieve the best resolution in the images of the bumps. However the optimum transducer for evaluating the top die usually is not suitable for accessing the bump bond interface of the lower interposer and a slightly lower frequency and greater focal length/working distance is required. Figure 10 shows a 300 MHz image of 20µ micro bump bonds of the top die in a silicon interposer sample. Figure 11 shows a 230 MHz image of the larger interposer bump bonds.

Similar to analysis of standard flip chip devices, other factors that affect the analysis of stacked flip chips are the thickness of both silicon layers and the type of die coating or dielectric materials being used.

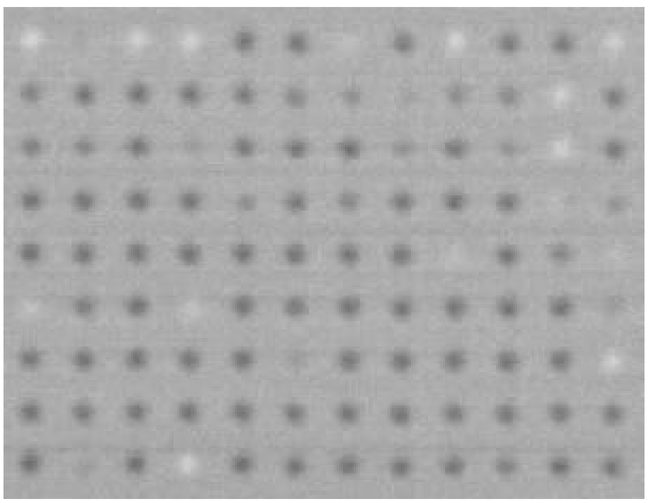

**Figure 10:** 300 MHz image of 20µ flip chip micro bumps. Disbonded bumps appear white or absent in the image.

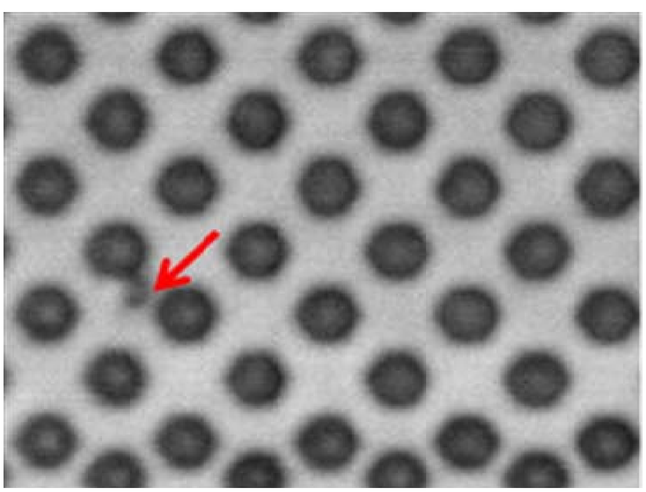

**Figure 11:** Bump bonds of silicon interposer. A small defect in the underfill is seen adjacent to one of the bumps.

**Cu-Cu Wafer Bonding**

Another method of stacking silicon die is to bond silicon wafers using Cu-Cu thermo compression bonding. The Cu metallization features provide the interconnections between the two wafers. Usually one of the wafers is back thinned and can be as thin as 25µ. Again here, similar to flip chips, the challenge is to find a transducer that can provide adequate resolution and still penetrate through the thickness of the silicon. Figure 12 displays an area of a Cu-Cu bonded wafer with resolution test features at the interface. The smaller copper bumps are approaching the resolution limits for this transducer however a missing bump is still detected.

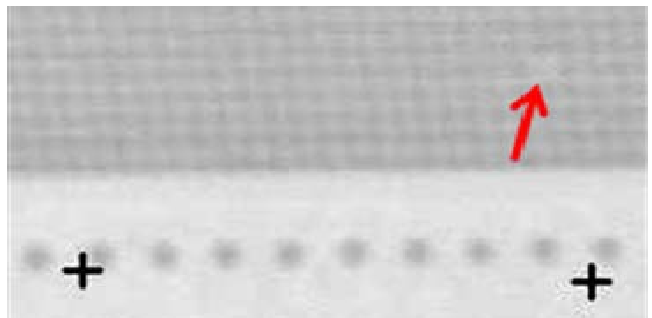

**Figure 12:** 230 MHz image of Cu-Cu thermo compression bonded test features in a bonded wafer. The distance between the cursors is 200µ.

**CONCLUSION**

During the development of a 3D device construction and materials are changed or modified. Design and construction varies significantly between types of 3D devices and can vary between manufacturers for the same type of device. Fortunately many of the methods that are currently in use to evaluate standard device types can be used or modified to analyze 3D packages. The diversity of 3D device types also necessitates continuing experimentation and development of acoustic methods and transducers to accommodate evolving device technology.

**REFERENCES**

[1] Shriram Ramanathan, Gerald Leatherman, Janet E. Semmens, and Lawrence W. Kessler, "High-Frequency Acoustic Microscopy Studies of Buried Interfaces in Silicon", ECTC 2006, San Diego, CA

[2] Janet Semmens and Lawrence Kessler, "Acoustic Micro Imaging in the Fourier Domain for Evaluation of Advanced Packaging", Proceedings of Pan Pacific Conference, Maui, Hawaii, 2002.

[3] Janet Semmens, "Update on the Evaluation of Stacked Die Packages using Acoustic Micro Imaging", Proceedings of Pan Pacific Conference, Kauai, Hawaii, 2008.