A Catalogue of Failure Mechanisms in Flip Chip Devices Detected Using Acoustic Micro Imaging

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ABSTRACT

Acoustic Micro Imaging (AMI) has been used over the past years to successfully evaluate the quality of flip chip underfill and interconnect bonds. Acoustic micro imaging uses high frequency ultrasound (5 to 500 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, cracks and voids).

Flip chip technology is constantly progressing toward smaller devices and higher IO count which leads to thinner chips, and smaller bumps and bonds which in turn requires higher resolution in the acoustic images. This is driving AMI technology to develop higher frequency transducers to increase the available resolution in both the spatial (x,y) and axial (z) dimensions. Low-k and extra low-k dielectrics are being used in flip chips and these materials present additional challenges for acoustic analysis due to their material properties. However acoustic signal analysis and imaging techniques are available to compensate. As a result of advancements in AMI technology and the refinement of analysis methods more can be determined concerning the nature of the failure mode. For example the failure may be laminar cracking of the passivation or low-k dielectric layers, or failures of the solder bump interconnect. This paper will present a catalogue of flip chip failure modes encountered to date and describe the analysis methods used to detect and define the failure modes.

Key words: Acoustic Micro Imaging (AMI), Acoustic Microscopy, Flip Chip

INTRODUCTION

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. More recently methods such as Frequency Domain Imaging have been used to improve the resolution/detectability of features in acoustic images.

ANALYSIS METHODS

Reflection Mode A-Scan, B-scan, and C-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. 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:

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

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.

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.

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

In addition to separately gating the echoes to scan one level specific x –y area the different depth levels can be displayed in a cross sectional (x –z) view called a B-scan.

More recently many flip chips are back thinned which causes the layers to be 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. However, information from the multiple reflections (resonances) can be used to examine the specific levels and methods such as frequency domain analysis can be used to extract the information from complex echoes.

Frequency Domain (FFT) Imaging

Frequency Domain analysis has been used to enhance the resolution of features in acoustic images. In addition it has been observed that in some instances the detectability of certain internal features or defects is dependant on the frequency content of a specific echo.

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 [1].

The transducers used in AMI range in center 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. These transducers typically have highly damped waveforms in order to achieve better resolution, both spatial and axial, using time domain imaging. Figure 6 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. When using time domain imaging at a center frequency of 50 MHz, one can not manipulate the image data to produce a 30 MHz image or a 75 MHz image, because in the time domain the acoustic pulses themselves do allow frequency separation. However, the data file including the stored A-scans makes this kind of manipulation possible, within limits.

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Figure 1: A-scan displaying typical waveforms (pulses) in the time domain.

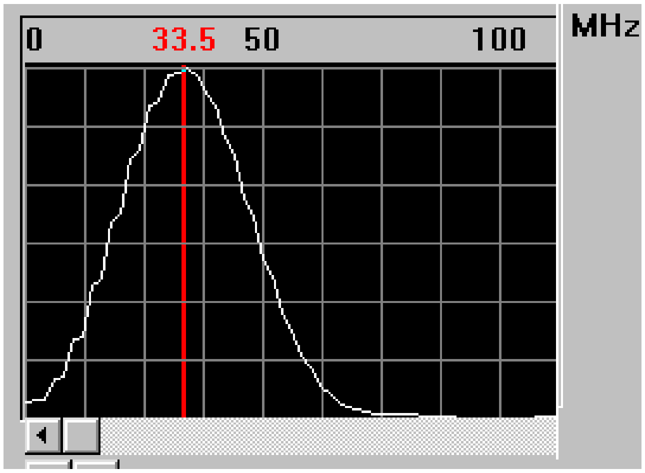

Figure 2: Broadband pulse content in the frequency domain for the echo within the gate on the A-scan in Figure 6.

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. The FFT identifies the different frequency sinusoids and their respective amplitudes. Figure 2 shows the frequency content distribution of the gated echo shown in Figure 6 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.

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. Frequency domain (FFT) analysis of the waveforms has been used in the past to measure bond line thickness and has shown the capacity of measuring to thickness well beyond the axial resolution limit of a given frequency [2]. 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.

FLIP CHIP FAILURE MODES

Silicon chip cracks

Cracks can occur in the silicon chip due to some problem with the manufacturing process or handling of the parts. In some instances vertical cracks will extend to the back surface of the chip where they can be seen using optical methods though the crack opening dimension may make it difficult to see. In the acoustic image vertical cracks appear as dark lines in the image. The width of the line however is not restricted to the size of the opening but rather is dependent on the depth of the crack. The larger shadow caused by the crack depth renders the crack more detectable in the acoustic image. In addition there can be laminar cracks in the silicon near or in the active layers of the die that are not detected when viewing the back surface. These cracks are visible in the C-scan acoustic image (similar to a delamination) and further depth information on the crack can be seen using B-scan analysis. Figure 3 shows the B-scan through a laminar crack and vertical cracks in a flip chip device. The cross sectional view shows the laminar crack to extend upward from the chip/bump and underfill interface however this portion of the crack network does not reach the back surface of the device. The vertical segment of the crack does show a small opening at the back surface but this does not give a true indication of the extent of cracking below the surface.

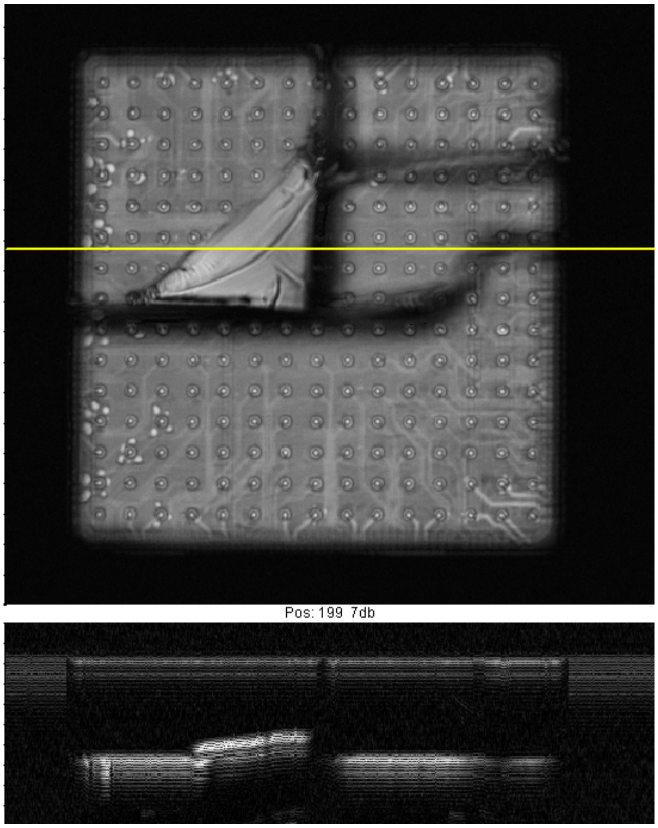

Figure 3: The upper part of the display shows the C-scan image of a flip chip containing large vertical cracks as well as a laminar portion of the crack. A bright line on the image indicates the position of the B-scan cross sectional view shown in the lower portion of the display.

Under bump metallization and passivation delamination

Defects have been detected in flip chips in the region closest to the silicon, just prior to the solder bump [3]. In many cases the features can be identified from their morphology in the acoustic image as they can appear larger than the size of the solder joint as a result of the thin laminar cracks extending into the surrounding passivation or dielectric layers. The position of the signals on the A-Scan indicates that the defects are present in the layers preceding the bond pad to bump level. Using a narrow gate at the leading edge of the chip to bump interface the echoes for the under bump layers can be isolated for the image and the defects clearly detected as seen in Figure 4.

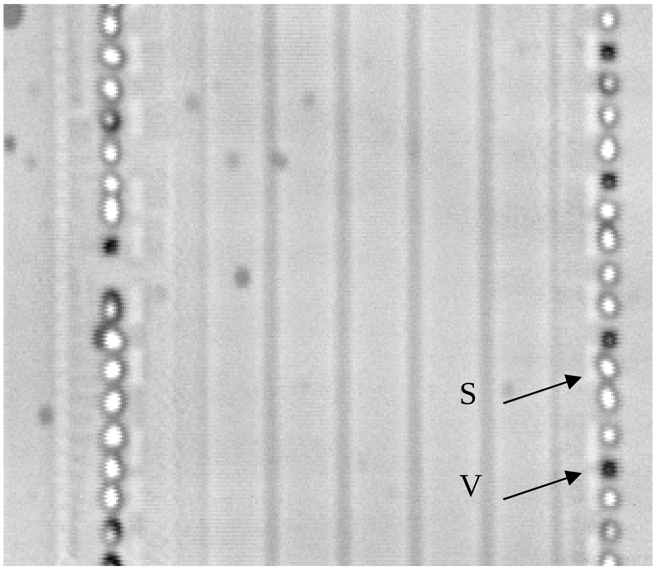

Figure 4: Acoustic image of chip/bond pad level using level specific imaging technique. Variations in the signal intensity are apparent from one bond site to another. the strong signal reflections characteristic of voids and delaminations are shown in white. The white bumps also are the ones which display the larger, irregular shapes. Dark spots (low signal reflections) indicate the bonded pads at this level. Two of the sites are indicated by the arrows for reference in the corresponding A-scan and DPA images.

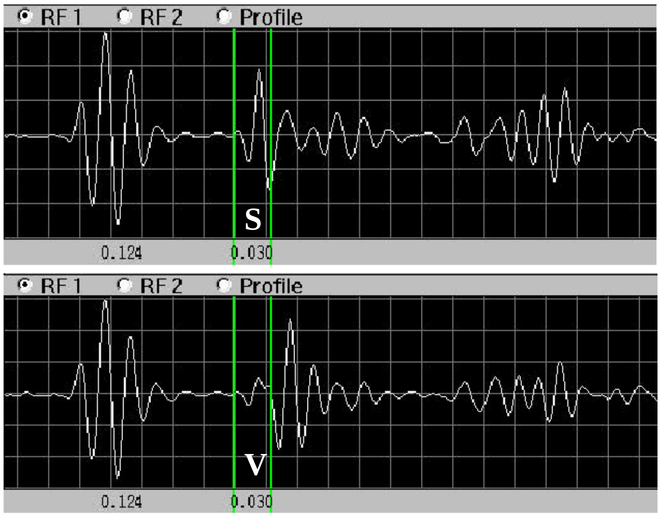

Figure 5: A-Scans showing the location of the gate (designated by the 2 vertical lines over the trace) to obtain the images of the bond pad and passivation separations from the silicon. The echoes corresponding to the defects show significantly higher amplitude than the echoes corresponding to the bonded pads.

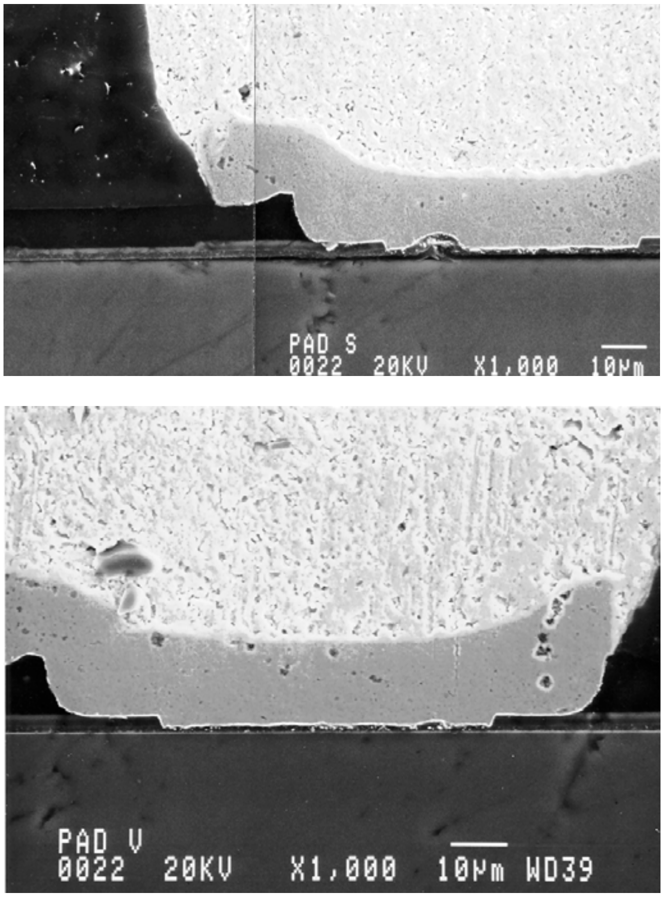

Figure 6: DPA sections corresponding to bumps S and V are shown. Bump S shows a delamination under the bond pad and extending under the adjacent passivation layers. Bump V shows a bonded bump and bond pad with no delamination of the passivation.

Air gap defects (voids and cracks) within the volume of the solder bump

In some cases the defect is at a deeper level within the solder joint such as a void within the solder bump or an open between the chip and the substrate rather than at either interface. Placing the electronic gate between the echoes from the chip and the substrate levels will display air gap defects as white features in the acoustic image (Figure 7).

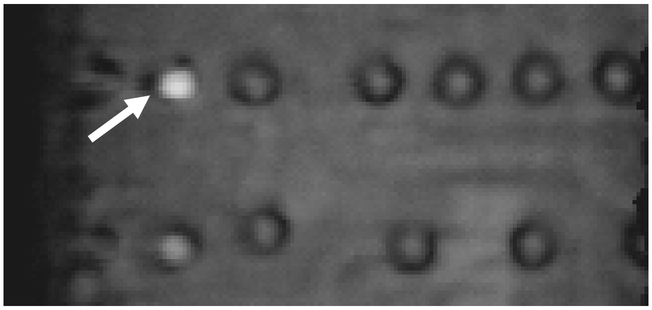

Figure 7: This 230 MHz acoustic image shows a section of a flip chip sample gated between the chip and the substrate. The mid-bump flaw appears as the bright white bump in the image.

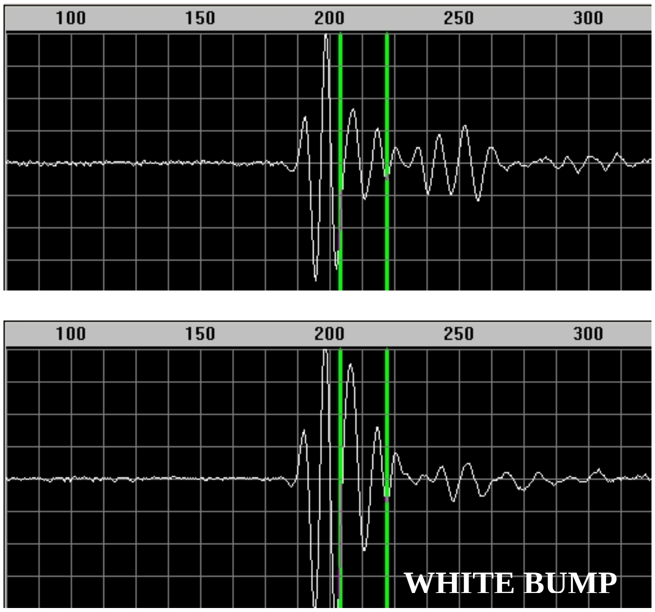

Figure 8: A-Scans showing the location of the gate (designated by the 2 vertical lines over the trace) to obtain the images of the defects between the chip and the substrate. The white bump shows significantly higher amplitude than the echo from the darker adjacent bump.

Open solder bump connection at the substrate

Disbonds of the solder bump connections can also occur at the bump/substrate interface. Similar to the previous examples by placing the electronic gate at the proper position the substrate level of the device can be imaged. In this example a device was showing an open site using electrical tests. Examination of the chip/bump level showed no anomalies of the bump bunds at the chip level. The image of the substrate level however showed a bright, white bump site indicative of an air-gap type defect (delamination) at the substrate (Figure 10). The position of the white bump correlated with the open bond site detected by electrical test.

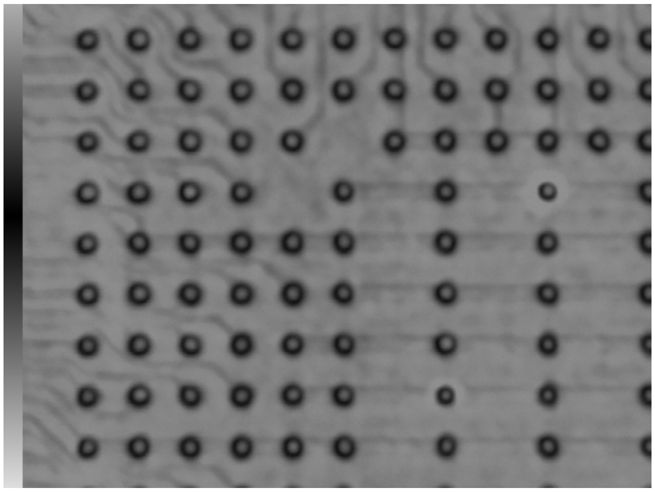

Figure 9: 230 MHz acoustic image showing no bump bond defects at the chip/bump interface.

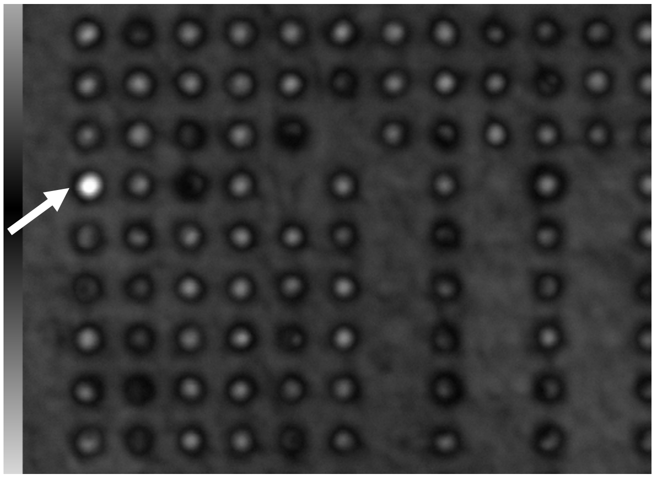

Figure 10: 230 MHz acoustic image of the same device shown in figure 9 at the substrate level. An open connection (white bump) is present at the substrate level.

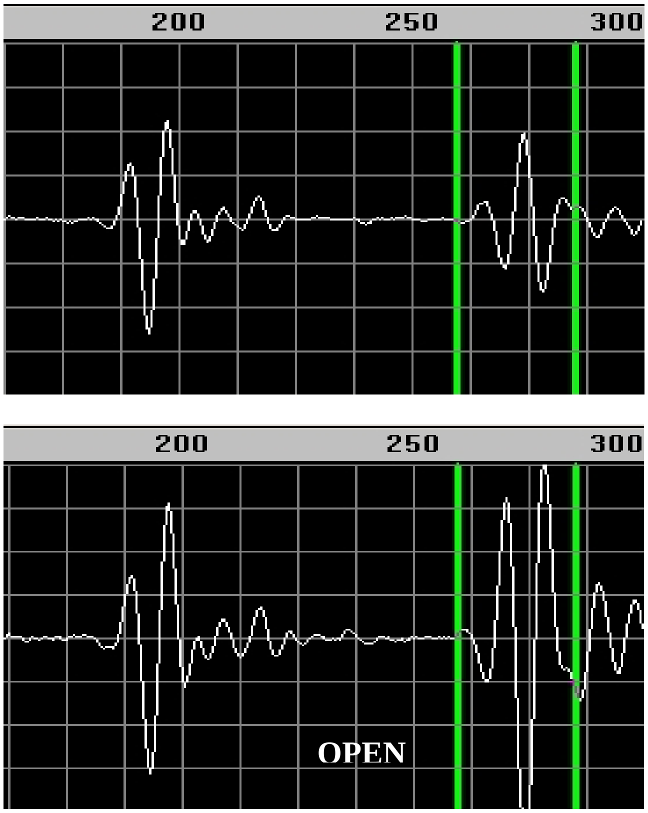

Figure 11: A-Scans showing the location of the gate (designated by the 2 vertical lines over the trace) to obtain the image of the open connection at the substrate. The white (open) bump at the substrate shows significantly higher amplitude and an inverted polarity compared to the echo from a darker (bonded) bump.

Underfill voids

Underfill voids can also be detected using AMI at the die or substrate level or within the bulk of the underfill using similar methods to the detection of solder bump bond issues. This example illustrates an instance of where Fourier Domain Imaging was used to enhance the detection of underfill voids [1]. 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 12a displays a time domain image of a flip chip that shows halo voids associated with two of the bump bond sites. Figure 12bb 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.

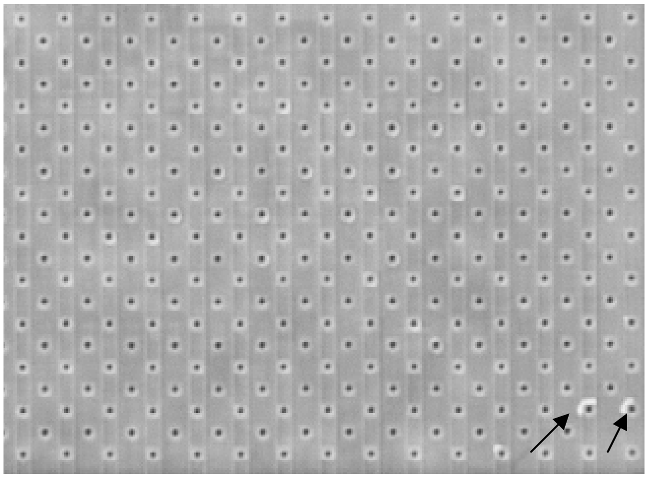

Figure 12a -Time domain image of flip chip with halo voids in the underfill

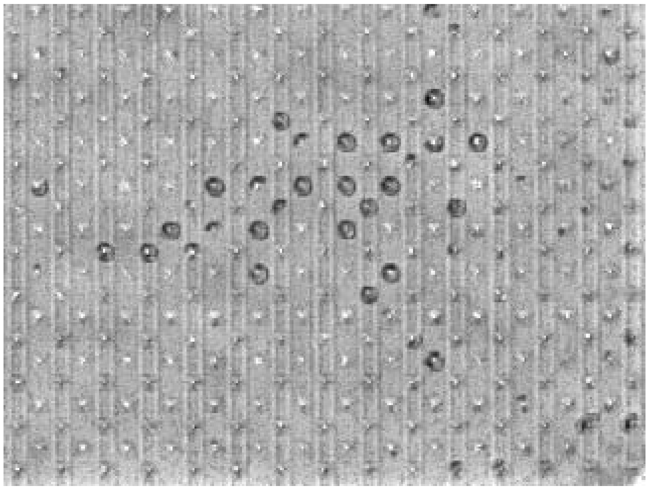

Figure 12b - frequency domain image of flip chip. Now many more bumps show associated halo voids.

CONCLUSION

The examples presented here include the main categories of flip chip failure modes encountered over years of experience using AMI. In addition to developing the acoustic methods to analyze the different kinds of defects that can be present in flip chip devices correlative analysis has been performed in many instances (including DPA, X-Ray or electrical testing) to verify the presence of the defects. This information base is valuable when evaluating future samples however flip chip technology is continually evolving in complexity. In the future AMI developments will continue to meet the challenges presented by changes in the design and manufacturing of flip chips and the catalogue will be updated to reflect the changes.

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