Characterization of Flip Chip Interconnect Failure Modes Using High Frequency Acoustic Micro Imaging With Correlative Analysis

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ABSTRACT

New acoustic micro techniques have been developed for the analysis of flip chip solder interconnects. Previous techniques were only appropriate to generally evaluate the chip to bump interface. The new methods involve using acoustic micro imaging to analyze the solder joint through the entire thickness of the solder ball at the solder/substrate interface and analyzing the interface between the silicon and the bond pad. We have found laminar cracks under the bond pad and in the surrounding glassivation layers on the silicon die in some samples. This paper will include a description of the analysis methods, the acoustic signatures of defects in flip chip interconnects and supporting correlative analyses.

BACKGROUND - ACOUSTIC MICROSCOPY

For the analysis of flip chip devices a reflection mode acoustic micro imaging method is typically used. The method involves pulse-echo ultrasound typically over a range from 5 to 180 MHz to produce images of samples at specific depth levels. A focused ultrasonic transducer alternately sends pulses into and receives echoes from discontinuities within the sample. The echoes are separated in time based on the depths of the reflecting features in the sample. An electronic gate is used to select a specific depth or interface to view. A very high speed mechanical scanner is used to index the transducer across the sample and produce images in tens of seconds.

For flip chip analyses high ultrasonic frequencies ranging from 100 MHz to 180 MHz are needed in order to provide higher resolution of the bumps themselves. Both spatial (x, y) and axial (z dimension) resolution are important considerations in evaluation of flip chip devices. Several imaging techniques were used in the evaluation of the samples in this study. A short discussion of these follows.

A-Scan

In reflection mode acoustic micro imaging the fundamental echo information is contained in what is called the A-Scan. The A-Scan is an oscilloscopic display of 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 distance between the echoes relates to their depth locations. The amplitude and phase polarity information of the echoes are used to characterize the interface. The equation which describes the reflection echo amplitude at a simple interface is as follows:

$$R = I\frac{Z_2 - Z_1}{Z_2 + Z_1}$$

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 at an interface. Since a bond between dissimilar materials gives rise to an echo signal and a disbond also gives rise to an echo signal, the challenge is to interpret the data.

Interface Scan Technique

The most common imaging method used to evaluate devices for delaminations and voids is the interface scan. This method involves electronically gating the A-Scan signal for the appropriate echo from the interface to be investigated. The geometric focus of the acoustic beam is optimized for the interface as well. The acoustic image of an interface displays both the amplitude and phase (polarity) of the gated echoes. In this mode an image is made of just the positive echoes or just the negative echoes or both color coded within the same image.

Loss of Echo at Back Surface

This technique is a variation of the interface scan method. However, in this case the gate is positioned to an interface that is beyond the interface(s) of interest. The amount of ultrasound transmitted to the gate is analyzed. Defects at any level prior to the gate will appear as shadows as the defects block the transmission of the ultrasound to the gated level. The acoustic signal reaching the deeper level is evaluated to gain information on the condition of all the preceding bond interfaces in the sample. This method provides a shadowgraph image of the previous levels. The high sensitivity of the technique is due to the inability of ultrasound to traverse even a small 0.1 micron air gap.

A look at the interface and loss of back surface echo methods applied to a hypothetical flip chip sample is shown in Figure 1.

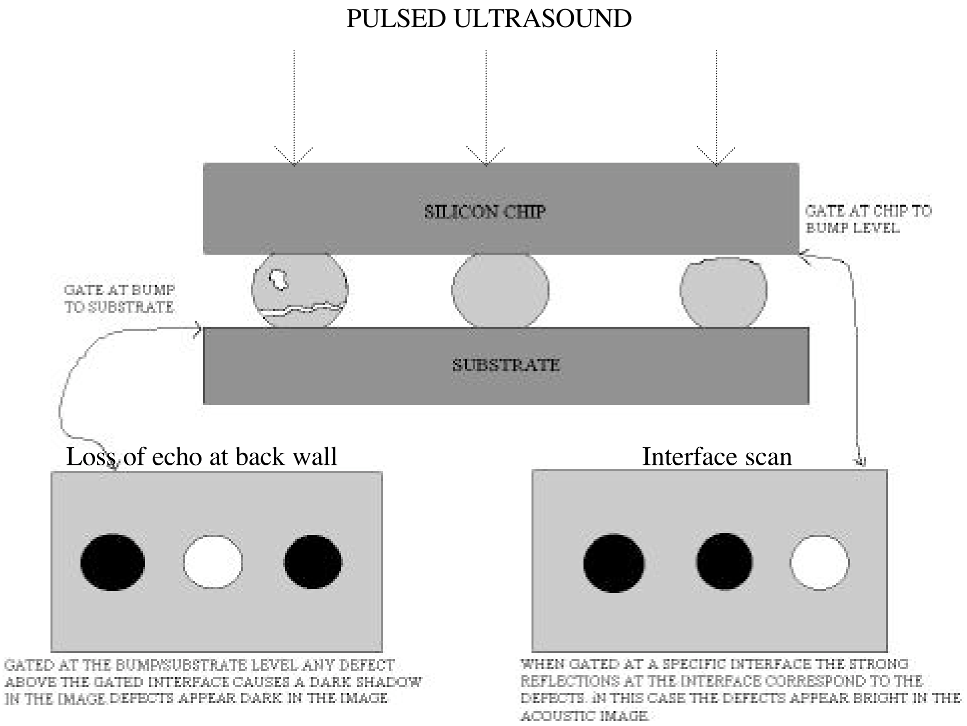


Figure 1 - Loss of echo at back surface versus interface scan. The loss of back surface echo technique will pick up defects at all levels within the interconnect but does not specify the level of the defect. The interface scan is level specific. However, defects occurring at layers below the gated region are not detected.

FLIP CHIP INTERCONNECT EVALUATION

In review, flip chips are mounted circuitry side down (flipped) directly to the substrate connection sites by means of solder bumps (in most cases) or gold bumps. The devices are typically underfilled with an epoxy encapsulant to seal the device and add mechanical strength[1]. A badly bonded bump or voids within the solder can lead to electrical failure. Voids in the underfill material can also cause problems. Flip chip samples are typically evaluated using the reflection mode technique due to the fact that the devices are mounted in many cases to multilayer substrates or composite boards. These types of substrates prohibit access to the bond interfaces of the interconnects in the through transmission mode. The reflection mode allows for single sided access through the back of the silicon die. Flip chip bonds are relatively small in size (typically 50 to 100 microns). This necessitates high resolution in the images in order to view the small features. The higher the ultrasonic frequency the higher the resolution in the acoustic images so flip chip devices are evaluated at frequencies from 100 to 180 MHz. The analyses of various flip chip sample types has been presented in an earlier paper[2] and will not be discussed at length here. Figure 2 shows an example of a 180 MHz image of the chip to solder bump interface on a flip chip sample.

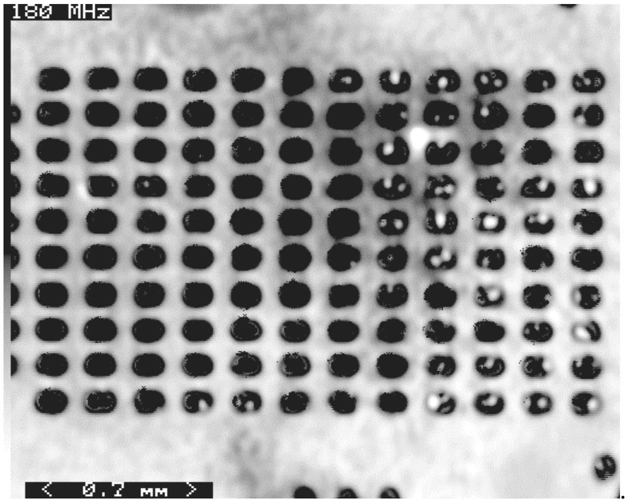


Figure 2 - 180 MHz acoustic image of flip chip bonds. Small voids at the interface appear as white features. Bonded bumps appear dark. A void (white area) is also present in the epoxy underfill

ANALYSES OF THERMALLY CYCLED FLIP CHIP DEVICES

The previous image serves as background calibration for the acoustic technique. An interesting set of samples was obtained which had some unusual defects. The devices used in this study demonstrated electrical failures after thermal cycling. The samples were examined

with microfocus x-ray before and after thermal cycling. The samples were examined with microfocus x-ray before and after thermal cycling. Voids in the bumps seen in the x-ray images did not change with thermal cycling and no other defect types were detected. Subsequent destructive physical analysis using standard optical microscopy revealed the presence of large cracks in the solder joints which were thought to be the primary failure mode.

Up to this point acoustic micro imaging had not been employed. Now, flip chip samples which had been thermally cycled were submitted for acoustic analysis to determine if a nondestructive method could be found to locate defects in the solder joints, particularly the expected cracks in the solder joints. The chip was attached to a complex multilayer ceramic substrate which prevented access to the solder joints through the substrate side of the device. All inspection had to be through the chip side of the package. An x-ray view of the multilayer substrate is shown in Figure 3.

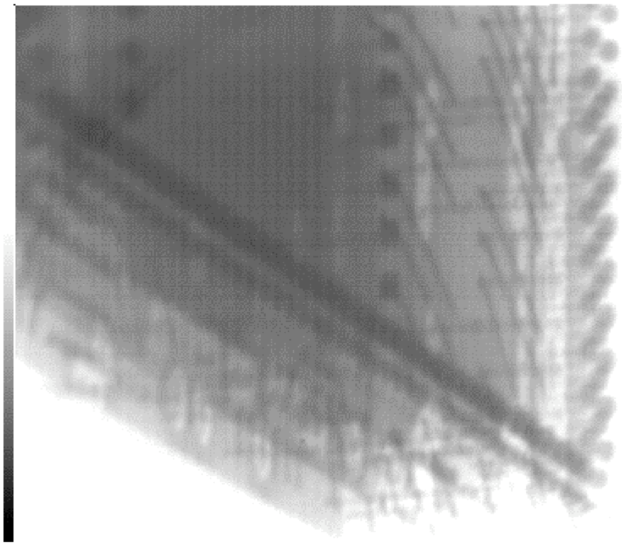


Figure 3 - X-ray image showing the complex multilayer construction of the ceramic substrate.

These samples were evaluated using 100 MHz. At first a technique was employed which looked through the solder joints to the substrate level (Figure 4). In this way any defect within the volume of the solder joint would cause a shadow in the image rendering it detectable. This method had been used in another study involving detection of failures in flip chip devices with promising correlative analyses[3]. In the initial data set a large number of solder bond sites appeared dark in the acoustic images indicating the presence of defects.

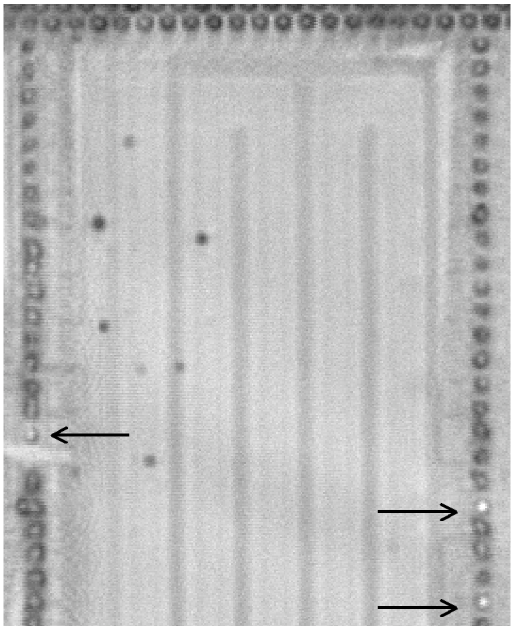
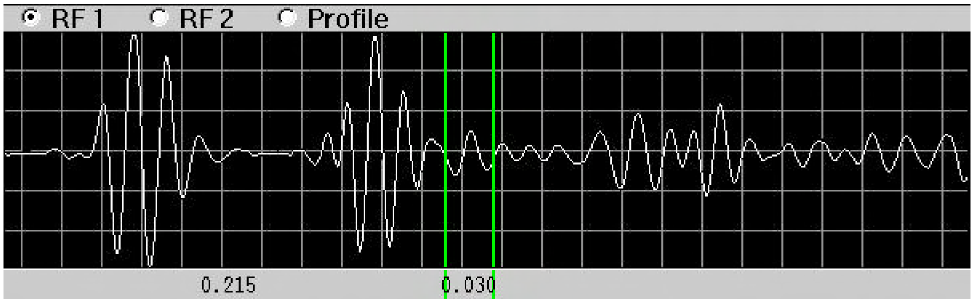


Figure 4 - 100 MHz Acoustic image of the bump to substrate level through the chip side of the sample. In this image the entire volume of the bump is interrogated. There is a contrast reversal using this imaging method which causes the bonded bumps to appear bright. Bright areas indicate where the sound transmits through the entire thickness of the bump unobstructed. Defects at the chip/bump level or within the solder bumps above the substrate interface block the signal from the interface so the defective bumps appear dark.

A-Scan in area of bonded solder bump.



A-Scan in area of defective solder bump.

Figure 5 - Example of 100 MHz A-Scans using the loss of back wall echo method. At this level the bond sites which do not contain defects show a signal within the gate and the bonds containing delaminations, voids and cracks show no signal in the gate.

The samples were then subjected to destructive physical analysis (DPA) and conventional optical microscopy for correlative analysis. At this time the defects were assumed to be cracks and voids in the solder based on previous samples which had not undergone acoustic analysis. Bumps which were cracked as seen in the DPA showed defects acoustically. However, many of the solder bumps indicated to be defective acoustically did not appear to be cracked in the DPA results.

Additional samples of the same type were evaluated acoustically. Samples which had been thermally cycled showed many defects. The technique used to acoustically image the bumps up to this point will pick up defects at any level above the imaged interface, not just within the solder bump, so a further effort was made to determine the level at which the acoustically revealed defects were occurring by scanning the chip/bump interface. Using the interface scan technique, the bond sites all appeared to show low reflection levels in the acoustic images which suggests the bumps are bonded. However, an initial hint of the problem came from the observation that some of the bond sites appeared larger than others and somewhat irregular in shape (Figure 6). This did not correlate with any part of the construction process. In reality the “chip/bump interface” consists of several very thin layers - silicon, glassivation, bond pad, polyimide and solder bump. Shadows or destructive interference of the signal caused by a defect in the surface layers on the silicon could cause the bonded and defective bond sites to appear similar in the acoustic image. By using a microslicing acoustic imaging technique the complex interface could be examined more closely. In the region closest to the silicon, just prior to the bump, the scans now exhibited strong signal reflections in some of the bond sites characteristic of the presence of disbonds. Some features were observed which appeared larger than the size of the solder joint. The position of the signals on the A-Scan suggested that defects were present in the layers preceding the bond pad to bump level. It was also likely that the cracks were very thin. Acoustic microscopy is capable of detecting laminar flaws below 0.1 micron in the depth dimension. This could account for the flaws being missed during the initial correlative studies. Figure 7 displays an acoustic image of a thermally cycled sample containing the white, irregular defects.

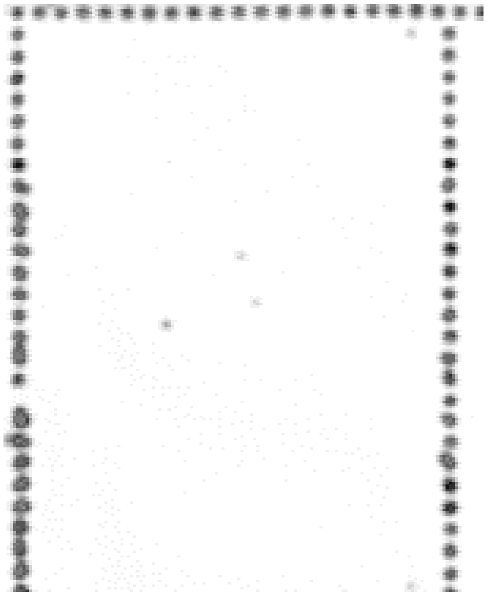


Figure 6 - Acoustic image including all levels between the silicon and the solder bump. The bond sites show low reflection levels which would typically indicate bonding at the interface. However, some of the sites appear larger than the nominal size of the bonds and irregular in shape

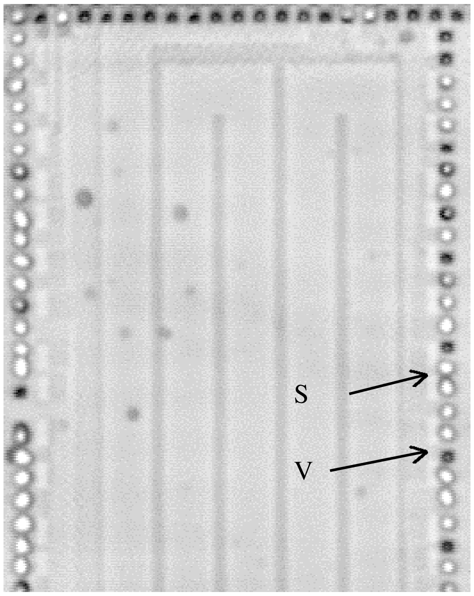
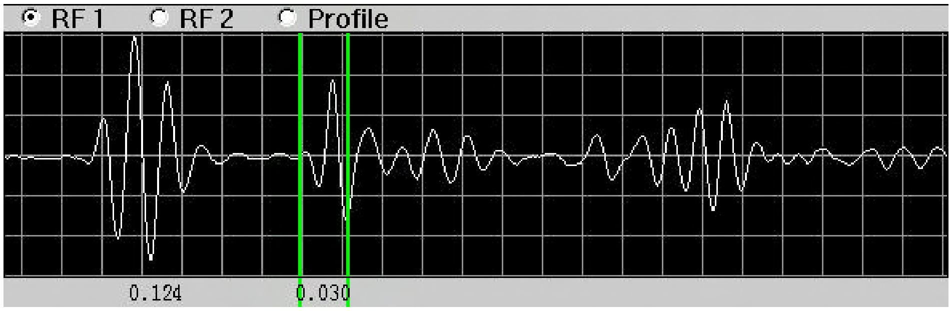


Figure 7 - Acoustic image of chip/bond pad level using level specific imaging technique. Now variations in the signal intensity are apparent from one bond site to another. In contrast to Figure 6 the parameters for this image cause the strong signal reflections characteristic of voids and delaminations to be 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. Several of the sites are indicated by the arrows for reference in the corresponding DPA images.

A-Scan corresponding to laminar crack under bond pad.



A-Scan corresponding to bonded pad.

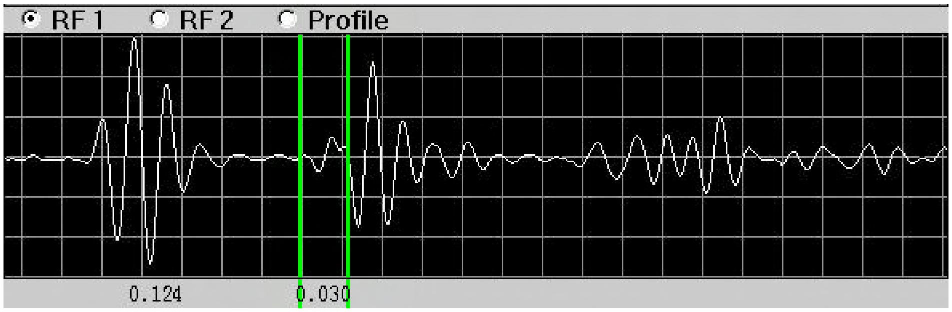
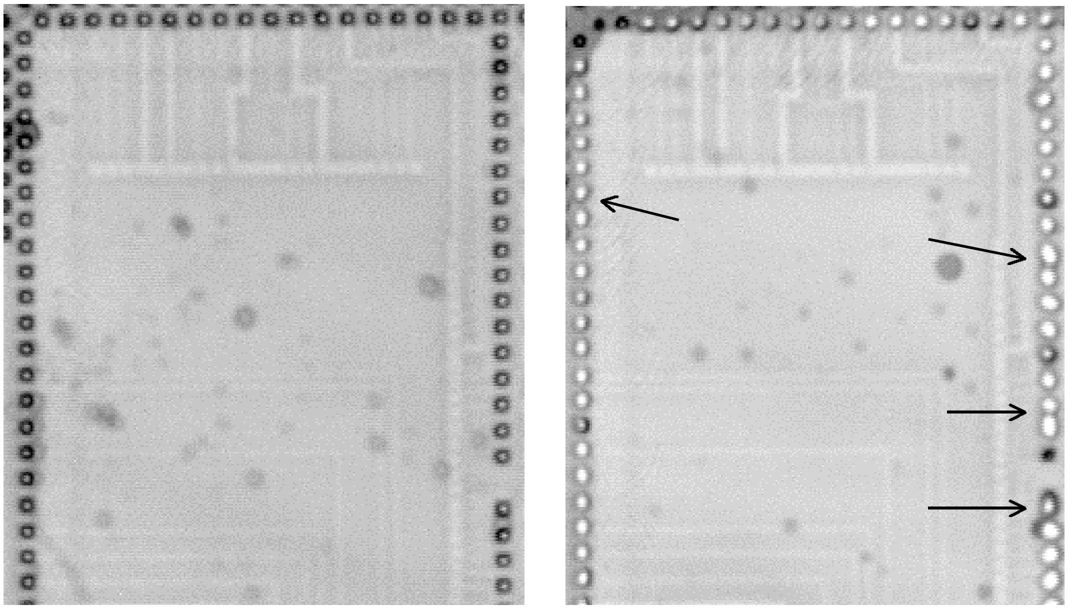


Figure 8 - A-Scans showing the location of the gate (designated by the 2 vertical lines over the trace) to obtain the images of the bond pad and glassivation separations from the silicon. The echoes corresponding to the defects show a significantly higher amplitude than the echoes corresponding to the bonded pads.

Another device of the same type which had not been thermally cycled was also evaluated acoustically using the same technique. The defects were not present in this sample at this time. The bond sites appeared uniform. This sample was subsequently thermally cycled and evaluated again acoustically after cycling. Now the device showed defects similar to the type seen in the previous sample. Figure 9 compares the acoustic image of the same device before and after cycling. Clearly the thermal cycling was inducing other defects in addition to the cracks in the solder balls.

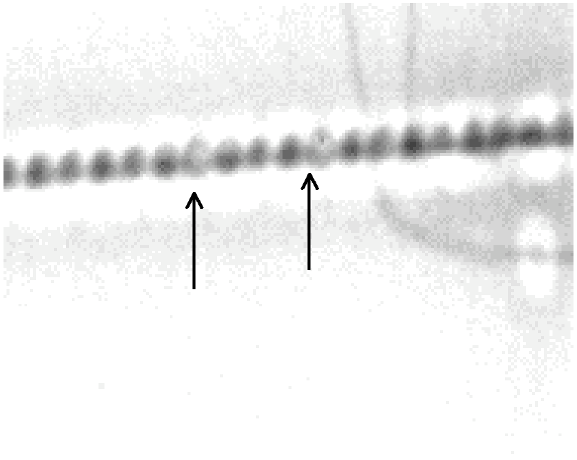


Before Thermal Stress

After Thermal Stress

Figure 9 - Acoustic images of the same device before and after thermal stress. The bond sites appear as dark circles, uniform in size before stress. After stress most of the bond sites now appear bright white and some are considerably larger in size and irregularly shaped. Examples are indicated by arrows.

For the purposes of correlative analysis one of the thermally cycled parts was evaluated using micro focus x-ray (Figure 10). The x-ray results did not detect any cracks or delaminations but did show voids in some of the solder bumps. The voids could also be detected in the acoustic images of the device prior to thermal cycling (Figure 11). After thermal stress the defects induced by the cycling obscured this level from ultrasonic inspection.



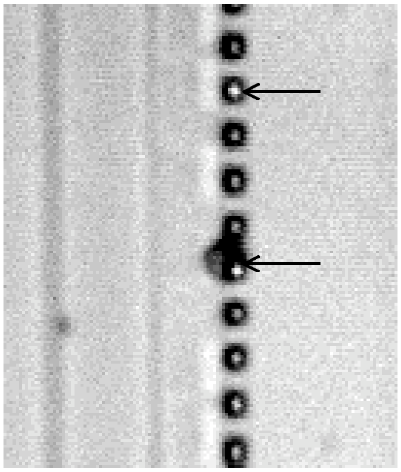


Figure 10 - X-ray image of solder bumps. Two of the bumps appear brighter indicating the presence of voids.

These two bumps correspond with the bumps shown in the acoustic image.

Figure 11 - Acoustic image of a row of solder bumps. Two of the bumps appear brighter in the center indicating the presence of voids in the solder bumps.

A thermally cycled part was cross sectioned and this time Scanning Electron Microscopy (SEM) was used to examine the section. The SEM evaluation did reveal the defects which caused the anomalies seen in the acoustic images. The defects were thin laminar cracks under the bond pads on the chip. In some cases the cracks extended out beyond the bump location under the glassivation layers (Figure 12). This is why some of the defects acoustically appeared larger than the expected size of the bond pads. A good correlation was now seen between acoustic data and DPA results. In retrospect, the original cross sectioning had produced over rounding of the sample in the areas of interest and optical microscopy did not provide high enough resolution to image the thin cracks. The original sectioning did show some bumps with large cracks and attention was focused on these flaws. This is why the more subtle defects were not detected in the DPA initially and why the results of the DPA and acoustic analysis did not appear to show correlation at first.

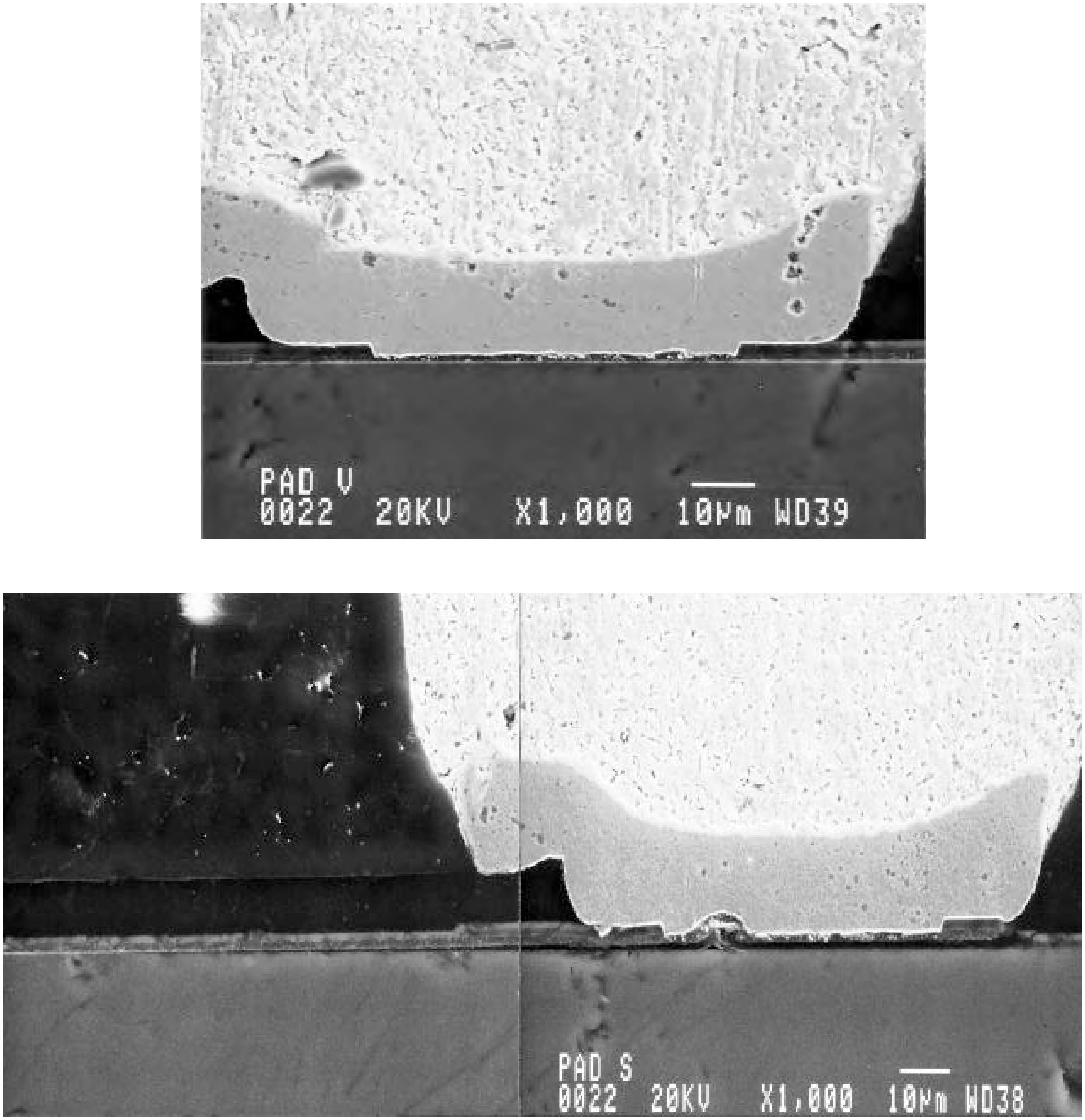


Figure 12 - SEM micrographs of DPA cross sections of bumps V and S shown in Figure 8. Site V appeared dark in the acoustic image indicating bond at this level. The DPA section shows no defects in the bond of the bond pad to the silicon or

glassivation layers. Site S displays a laminar crack under the bond pad. The crack extends under the surrounding glassivation layers. This bump appeared bright indicating a defect in the acoustic image.

CONCLUSION

Proper investigation of bumps in flip chip devices requires the appropriate acoustic micro imaging technique. In some cases the flaws may be subtle and further refinement to existing acoustic micro imaging techniques are required in order to reveal the flaws. The DPA methods employed must also be suitable to reveal the same type of defect in order to provide meaningful correlative analysis and establish confidence in the nondestructive method.

Thin laminar cracks were detected using acoustic micro imaging at the silicon/bond pad level. These defects were not detected by any other nondestructive imaging method and were not easily detected in the DPA except by the SEM after using the acoustic images for guidance.

ACKNOWLEDGMENTS

The authors would like to thank Mr. Bruce Smith and Mr. David Drake of Northrop/Grumman for their valuable assistance in providing the x-ray, DPA and SEM analysis

REFERENCES

[1] John H. Lau, “Flip Chip Technologies”, McGraw Hill, 1996, pp. 25-30.

[2] J.E. Semmens, S.R. Martell, L.W. Kessler, “Evaluation of Interconnects Using Acoustic Microscopy for FailureAnalysis and Process Control Applications”, 4th International Conference & Exhibition on Multichip Modules, April 19-21, 1995, Denver, CO, pp. 279-285.

[3] O. Diaz d’Leon, M. Nassirian, R. Chowdry, “Flip Chip and BGA Failure Analysis Through Acoustic Microscopy’, the 22nd International Symposium for Testing and Failure Analysis, November 18-22, 1996, Los Angeles, CA, pp. 277-283.