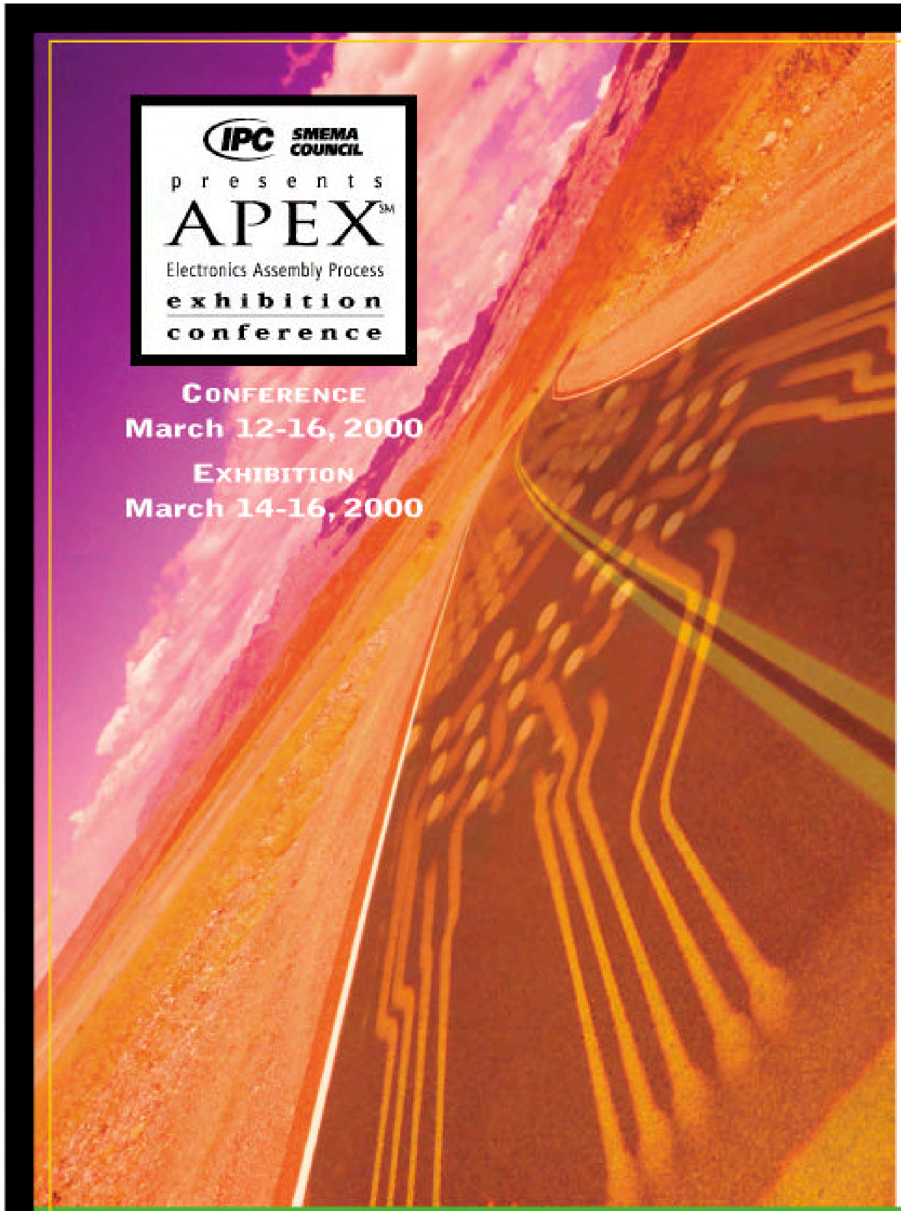

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High Frequency Acoustic Micro Imaging For Process Monitoring and Quality Control In Flip Chip Underfill Assembly

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Abstract

Solder bump technology is being used increasingly as a method of interconnection of chips or packages to the substrate. Underfill is used to encapsulate the solder joints commonly in flip chips and is starting to be used between BGA packages and the boards. The condition of the underfill layer is critical to the operation of the device as this layer serves to redistribute the mechanical stresses in the sample and thereby reduce the stresses on the solder interconnections[1]. Voids and delaminations in the underfill can compromise the reliability of the device and seriously reduce its lifetime. For reliability assessment of the underfill a nondestructive method is needed. X-ray imaging has been used to examine the condition of the solder bumps in flip chip and BGA packages; however, the contrast provided in the x-ray images is insufficient for analysis of the underfill. Acoustic Micro Imaging (AMI) is a method that has been used over the past several years for evaluation of underfill in flip chips with successful results. More recently the application of AMI to study underfill has been extended to underfill evaluation of BGA packages mounted on PC boards.

Acoustic microscopes utilize high frequency ultrasound to examine the internal features in materials and components. The instrument used for the data presented in this study was a C-SAM (C-Mode Scanning Acoustic Microscope) operating in the reflection mode at frequencies ranging from 15 to 230 MHz. Analysis methods include interface specific imaging presenting one x-y plane, nondestructive cross-sectional analysis and three-dimensional reconstruction of acoustic information. Recently methods have been developed to determine the mechanical properties of underfill compounds[2] and monitor the thickness of thin layers such as the underfill using acoustic information[3]. The combination of the analysis techniques allows for accurate detection and detailed characterization of the underfill material and any flaws that are present. The information is then used to help determine optimum process parameters for underfill dispensing. AMI is used as well for inspection to monitor the process after set-up and for quality control applications.

This paper will discuss methods of inspection for flip chip devices using acoustic microscopy. The results presented will provide an overview of the types of flaws and properties of the underfill that can be detected using acoustic methods.

Background

For the analysis of the underfill in flip chip and BGA devices a reflection-mode Acoustic Micro Imaging method is typically used. The method involves pulse-echo ultrasound typically over a range from 15 to 230 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.

Several imaging techniques were used in the evaluation of the samples in this study. Basically, defects can be imaged at the level they occur or the influence of the defects can be detected at a subsequent interface(s). This factor is important to realize when using AMI for evaluation of the packages because all defects and structures at previous interfaces affect the information available at subsequent interfaces. A brief summary of several methods for evaluating devices using Acoustic Micro Imaging follows.

Through-Transmission

Through-transmission Acoustic Micro Imaging relies on sending the pulse of sound through the entire thickness of a sample and detecting the transmitted signal using a separate receiver. The C-SAM through-transmission mode uses a second transducer as the detector. Defects, if present, may block the ultrasound from reaching the detector and will appear as dark shadows in the acoustic image. 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.

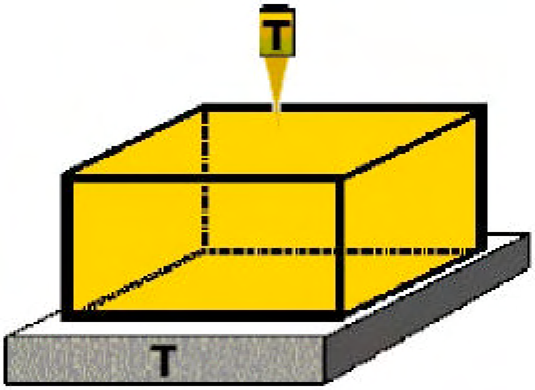

Figure 1 - C-SAM THRU-Scan. Lighter Shaded Areas Indicate Zone of Inspection

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 is used to characterize the interface. The equation that 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.

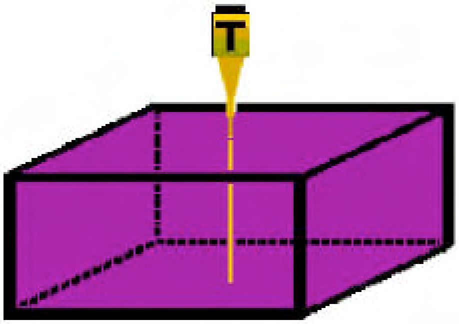

Figure 2 - A-Scan. Lighter Shaded Areas Indicate Zone of Inspection.

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.

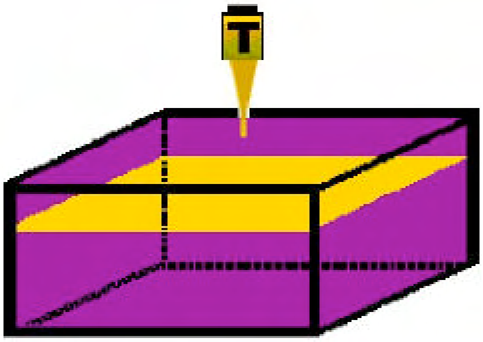

Figure 3 – Interface Scan (C-Scan). Lighter Shaded Areas Indicate Zone of Inspection.

3D Reconstruction and Analysis

A sequential series of interface scans can be automatically acquired through a specified thickness of a device or through an entire sample. These individual scans can then be electronically assembled to create a reconstruction of the sample. This "virtual sample" can then be sectioned using the software to reveal internal features and defects within the device at the exact level at which they occur.

Examples of underfill analyses are given in the following section.

Underfill Analysis On PBGA Devices Bonded to Composite PC Boards

In the following example plastic BGA devices were mounted on a multi-layer PCB and the space between the package and the PCB was underfill encapsulated. Air spaces within the underfill are undesirable and a method to detect these voids is necessary. The relatively complex structure of the BGA device and the multi-layer PCB make the access to the layer of interest difficult for acoustic analysis particularly at high frequencies. Typically, applications involving evaluation of composite PC boards or bonding to PCBs are not considered ideal for acoustic methods because of the poor transmission of ultrasound through the board. However, evaluation of composite boards for delaminations using relatively low frequency through-transmission imaging has been successful. Similarly, individual PBGA packages are routinely inspected for internal anomalies using through-transmission AMI. Once the packages are mounted on the boards there is an intentional air space between the device and the board that inhibits transmission of the ultrasound and prevents acoustic inspection. However, with underfill in place there is now conduction of the ultrasound through the entire thickness of the PCB/PBGA assembly (assuming there are no defects in the PBGA or the PCB or the underfill between them). In contrast, any air gap between the layers is detectable as a dark shadow. The acoustic images in Figures 4a, 4b and 5 were taken at a frequency of 30 MHz. Figure 4b shows the through-transmission image of a PBGA on a board. The influence of the structures in the BGA and the board affect the image; however, the incomplete underfill at one corner of the package is clearly visible as a dark shadow. The through-transmission mode has the advantage of displaying the entire volume of the underfill in one scan/image. The underfill can be evaluated through the package in the reflection-mode as well but as this mode is level specific, it requires several scans to insure that the entire underfill area and thickness is analyzed. The location of this defect was identified in the reflection-mode as starting at the BGA to underfill level. The reflection-mode image of this defect is shown in Figure 5.

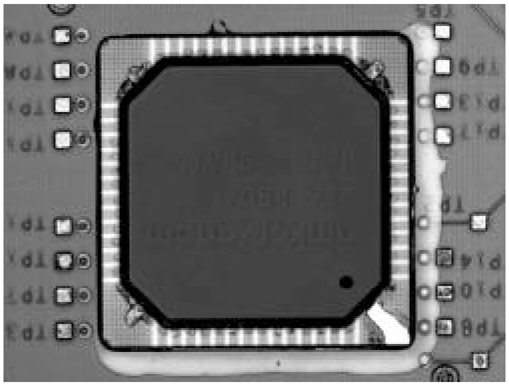

Figure 4a – Shows an Acoustic Surface Scan of the PBGA

The excess flow from the underfill can be seen at the right side and bottom edge of the part.

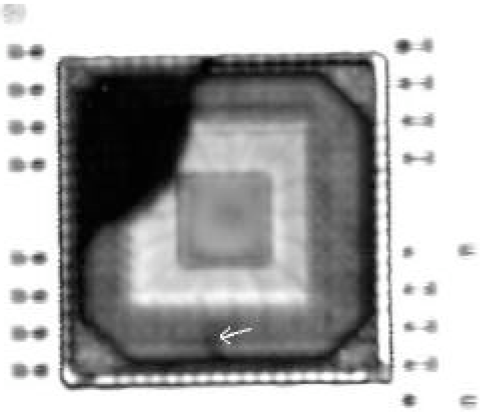

Figure 4b – The Through-Transmission Image of the Board

Underfill and PBGA shows a large dark corner that corresponds to a void in the underfill. A smaller void is also present (arrow). The influence of the structures in the BGA and the board are also seen in the image.

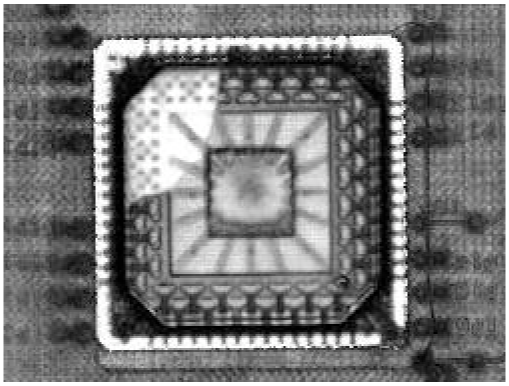

Figure 5 – Reflection-Mode Image at the BGA Package to Underfill Level

The bright white corner corresponds to the large void in the underfill between the package and the board. The smaller void (seen in the through-transmission picture) is not present in the image of this level. The smaller void was found to be at the underfill/board interface.

Underfill Analysis in Flip Chips Using Interface Scans and Three-Dimensional Reconstruction

Flip chip underfill analysis is typically done at high frequencies (greater than 200 MHz) in order to obtain the best resolution possible. At these frequencies through-transmission is limited in its ability to penetrate through thicker and/or more elastic materials. Although silicon is very transmissive to ultrasound, the substrates the chips are bonded to (composite PCBs or multi-layer ceramic packages) often are not. For this reason through-transmission is not commonly used in flip chip evaluation. Single sided reflection-mode access through the silicon chip has allowed for analysis of flip chips at high frequencies.

AMI has proven an excellent method for the analysis of flip chip underfill. Defects such as delaminations and voids are readily detected and the morphology and depth location of the defects can give important information as to the cause of the flaws.

Features that can be determined from the acoustic images include the dispense pattern of the underfill, filler particle distribution and/or settling[2],[4] and knit lines in the underfill from merging mold fronts. Voids or a lack of fill that occur due to any of the above phenomenon are acoustically visible even though they cannot be seen using optical methods. "Halo" voids surrounding the solder bumps have been detected that are the result of flux residue on the chip surface. Delaminations of the underfill that result from thermal stress have also been detected[5]. Acoustic imaging is sensitive to any feature that is the result of a significant change in the material properties or an air gap in the device. In some instances the features or voids may not be deleterious to the device based on their location. For example, a small, isolated void in the underfill away from any interconnect sites may cause no problems with the operation of the device; however, any voids near the solder interconnects lead to poor mechanical support to the solder joint and possibly solder creep into the void. Therefore, it is important to obtain as much information as possible as to the exact location and nature of the flaw. Figures 6 and 7 show examples of underfill in flip chips with variations in the filler particle distribution and voids in the underfill. Notice that the pattern of the filler particle variations is different for each sample. This is because the dispense pattern of the underfill process is different between the two samples. In Figure 6 the voids are within the areas of higher filler particle density (resin starved areas) but away from the perimeter bump bonds. The voids shown in the underfill of the sample in Figure 7 immediately next to the bumps showing the "halo effect".

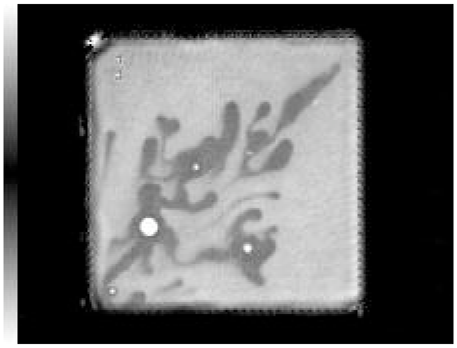

Figure 6 - The Darker Areas Indicate Regions of Higher Filler Particle Density

Based on the pattern the dispense of the underfill was along the top and right sides. The voids are the white features within the areas of higher particle density.

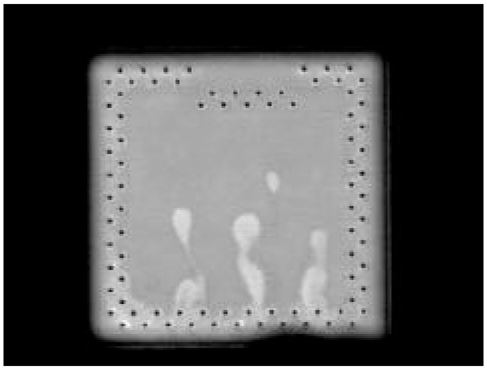

Figure 7 - The Filler Particle Pattern in This Sample Appears as Lighter Grey Regions

In these regions the particles have settled closer to the substrate. The dispense pattern was along the top edge of the device in the image. Small "halo" voids (white features) are seen in the proximity of several solder bumps.

In the interface scans shown in Figures 6 and 7 the features of interest were specifically at the chip to underfill level. Information within the volume of the underfill or at the substrate level is not available in these images. As previously discussed, interface scans are level specific and several images are required to cover the entire volume of the underfill. By using 3V reconstruction a number of images or "slices" can automatically be taken covering the entire underfill thickness and reconstructed into an electronic model of the sample. The sample can then be repeatedly sectioned and reconstructed in order to fully analyze features and defects at any depth within the volume of the part.

In the first 3V example (shown in Figure 8) voids are present in the underfill but most of the voiding occurs just below the chip/underfill interface rather than at the interface. Destructive interference results from the chip/underfill and underfill void signals causing the voids to appear as less signal in the chip/underfill image. The strong reflections characteristic of voids are not seen until subsequent levels in the underfill are imaged. The voids could be mistakenly interpreted at the chip/underfill level as variations in filler particle concentration if the subsequent images were not available. The cutout in the 3D reconstruction shown in Figure 8 illustrates the offset in the depth of the voids relative to the chip/underfill interface. Some flip chips contain a polyimide layer on the die and the coating causes the offset in the position of the silicon/bump versus the die coat/underfill level. However, in this device some voids were observed at the inner surface of the chip suggesting that this chip did not contain a polymer die coat. It is interesting to note that there are a large number of voids and that the location of the voids is concentrated in the proximity of the bump interconnect sites at the perimeter of the chip. There is no voiding detected in the central area of this sample.

The second example, Figures 9a and 9b, show another flip chip with underfill. Figure 9a shows a corner of the reconstructed sample prior to "sectioning". Only the chip/underfill and bump level is visible. A void is present at this level as a white feature. Figure 9b shows a cutout section that reveals additional features at deeper levels in the sample. Again there is an offset to the depth position of some of the voids compared to the silicon/underfill interface and the depth of the voids is not due to a die coating. There are only a few voids in this sample but the proximity of the voids to the bumps would be cause for concern. In this sample one of the bump bond sites appears brighter than the surrounding bumps indicating a strong signal reflection. This bump corresponds to an open site that was also detected by electrical testing. Note that the bump is bonded at the chip/bump level shown in Figure 9a.

Although the 3D viewing can show the internal depth profile of delaminations and/or voids in the underfill it is important to remember one limitation of ultrasound when interpreting the images - ultrasound cannot transmit across an air gap. For this reason 3D views or resulting cross-sections of the reconstructed sample cannot see additional voids or delaminations directly below a gap at a previous level and the cross-sections cannot be used to determine the thickness of a gap.

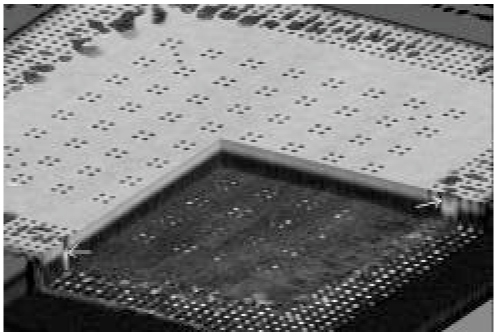

Figure 8 - A Reconstruction of A Flip Chip Sample Beginning with the Chip/Underfill And Bump Level Down to the Underfill and Bump to Substrate Interface is Shown in this Image.

The reconstructed sample has been cut out at one corner to show the variation in depth of two voids in the underfill (arrows).

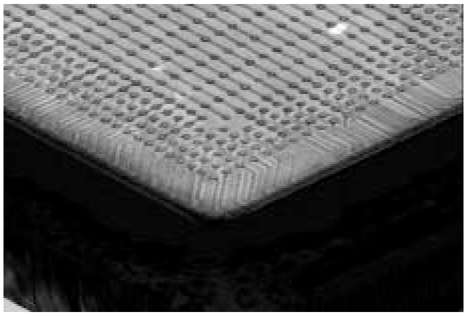

Figure 9a - The Image Displays the Reconstruction Before Sectioning

The chip to underfill and bump level is displayed showing the metallization on the chip and bond sites. White features indicate voids at the interface.

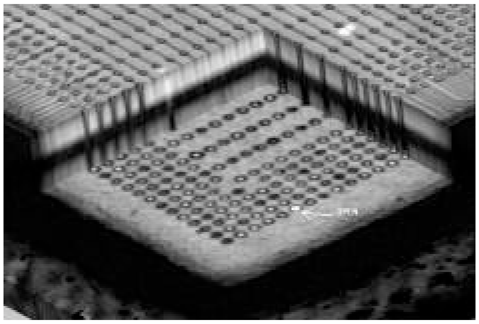

Figure 9b - Shows a Cutout of the "Virtual" Flip Chip Now Reveals a Void Below the Chip/Underfill Interface and an Open Connection at the Bump/Substrate Level

Conclusion

A number of AMI techniques are available for the analysis of underfill in flip chips or other types of packages. Although the analysis of BGAs on composite boards is a difficult application due to the nature of the materials and the complex structure of the devices, through-transmission imaging has proven effective for the evaluation of defects in the underfill. Reflection-mode imaging is preferred for the analysis of flip chip devices as it allows for evaluation at high frequencies to obtain maximum available resolution in the images. Interface scans are typically used to evaluate one depth specific layer in the sample at a time. Additionally, three-dimensional reconstruction of the parts from any number of sequential image slices allows for evaluation of the entire volume of the underfill and adds depth perspective to the acoustic information. The virtual sample can also be sectioned and reconstructed numerous times for analysis of internal features without having to re-scan the device.

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