EVALUATION OF LEAD-FREE SOLDER BONDS AND EFFECTS OF THE LEAD-FREE PROCESS ON DEVICES USING ACOUSTIC MICRO IMAGING

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ABSTRACT

Solder attach has long been established as a method of bonding for various electronic applications. The applications range from the attach of heat sinks in relatively large power devices to the very small flip chip interconnects. The quality of the solder bonds is critical. For example large voids in the bond of a heat sink will prevent proper heat dissipation, and an open solder connection in a flip chip interrupts operation of the device. Clearly a method is needed to assess the quality of the bonds. In addition lead free solder manufacturing process changes must be considered, specifically if higher temperatures are needed for reflow of the different materials. Higher temperatures may have a deleterious effect on the devices or packaging of the devices not directly related to the lead free solder bond integrity. Acoustic micro imaging (AMI) is one technique that is used for non-destructive evaluation of solder bonds and packages.

Acoustic micro imaging uses high frequency ultrasound (5 to 500 MHz) to image the internal features of samples. Unlike x-ray and visual inspection, which are also common methods for evaluating solder bonds, ultrasound is sensitive to variations in the elastic properties of materials and is particularly sensitive to locating air gaps (delaminations and voids). This is unique to ultrasound.

Over the past years much experience has been gained concerning the acoustic detection of various defect types. Also, in working with the manufacturers of the devices, information has been gained concerning the causes of certain failures and phenomena. However, as new products emerge the manufacturing technology changes. Presently there is an effort to convert to lead free soldering methods. There is a need to determine if and how the new materials will influence the quality and lifetime of the devices. Also the new materials may necessitate changes in the acoustic analysis method used to evaluate the devices. With the evolution of flip chip devices to smaller sizes and/or higher IO count the size of the bumps/bonds has become increasingly smaller. This will create the necessity of even higher resolution in AMI in order to visualize and evaluate the small bonds.

This paper will present examples of AMI solder bonding applications in microelectronics with particular attention to lead- free solder bond evaluation, and discuss AMI developments to meet the challenges presented by the design and manufacturing of various components and assemblies.

Key words: Acoustic Micro Imaging, lead-free solder, flip chip, die attach

INTRODUCTION

Basic AMI Principles

Reflection mode 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. In general the higher the frequency the higher the resolution in the acoustic images. Lower frequencies, however, provide more transmission through materials. A focused ultrasonic transducer alternately sends pulses into and receives pulses reflected 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 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.

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 distances between the echoes relates to their depths in the device. The amplitude and phase (polarity) information of the echoes is used to characterize the condition at the interface. The equation that describes the ultrasound reflectivity at an interface between materials 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 material which is encountered by the pulse. The most common imaging method used to evaluate devices for delaminations and voids is the interface scan. This method involves gating the A-Scan signal for the appropriate echo from the interface to be investigated. For accurate data the geometric focus of the acoustic beam must be optimized for the interface as well. The acoustic image of the interface displays both the amplitude and polarity of the gated echoes via the AIPD (Acoustic Impedance Polarity Detector). In this mode an image is made of just the positive echoes or just the negative echoes or both combined within the same image. Different color maps are usually employed to differentiate the echo polarity information and the grey scale/color intensity used to display echo amplitude [1].

Several factors affect the resolution in the acoustic image: The frequency of the transducer, focal length, numerical aperture, fluid path, and signal strength. Current transducers require a minimum working distance for penetration through relatively thick materials or clearance of other components on the substrate. This can compromise the ultimate available resolution in the acoustic images due to frequency dependant attenuation of the acoustic signal in the fluid couplant path. Therefore, detectability of the pertinent details in samples with very small structures would not be optimum. Another issue in imaging flip chips is the edge effect. A drop off of information for the bumps in close proximity to the periphery of the chip can occur with certain transducer designs. However, the design of the transducer can be altered and optimized for the best resolution and to minimize edge effect. This combined with a high acoustic frequency will produce very high definition acoustic images capable of detecting structures such as metallization on the silicon surface, bond pads and of course small bump bonds [2].

As mentioned previously the contrast in the images is determined by the acoustic impedance mismatch at an interface. In the case of solder bonding tin-lead solder typically shows a close impedance match to materials such as other metals, ceramic and silicon. Therefore there are low reflection levels of the acoustic signal at a bonded interface. By comparison, voids and delaminations (air gap type defects) reflect essentially 100% of the signal. The concern with acoustic analysis of lead-free solder materials is that the change in materials will affect the contrast in the image rendering the defects more difficult to see. As Tin and Lead have very similar impedance values (24.2 and 24.6 respectively) the ratio of tin to lead does not affect the image contrast. One alloy being considered for replacement of lead containing solders is tin-bismuth. Bismuth has an acoustic impedance similar to lead and tin and therefore the contrast at the bond interface should not change. Other likely alloys being considered as replacements for tin-lead contain a high percentage of tin (95% or greater) and small amounts of materials such as copper, gold, silver, antimony and indium [3]. The high percentage of tin in the replacement alloys is expected to keep the contrast of the solder bonds in the acoustic images similar to that of tin-lead. The small percentage of the other materials is not expected to influence the contrast to any great degree.

The following section provides examples comparing lead containing to lead free solder bonding for a selection of microelectronic components.

HYBRIDS AND LASER MODULES

Acoustic evaluation of bonding methods other than tin/lead solder has been done in the past. In many cases gold/tin eutectic has been used for die attach in ceramic packages and hybrids. The higher concentration of gold creates a change in contrast compared to tin/lead. However, the reflection levels in the air gap/voids are still significantly different from the bonded areas and are readily detected.

The first example shows the die attach in a lidded metal package. The intentional air cavity prevents examining the die attach through the lid side of the package and the die surface. It is possible however to introduce the ultrasound through the back (metal package/substrate) side of the hybrid module to evaluate the die bonds. Figure 1 displays the attach of two die to a metal substrate, through the metal substrate. The outline of the two die can be seen in the acoustic image. Voids in the bonds appear as bright areas within the outline of the die. The bonded areas appear dark grey

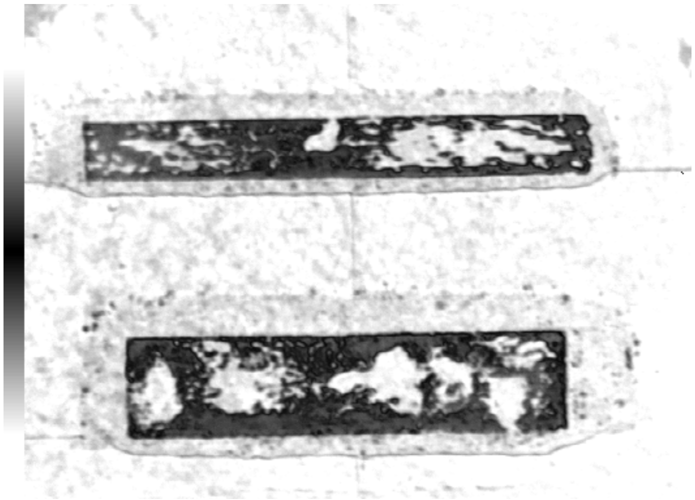

Figure 1 – die attach to a metal substrate.

The next example shows substrate and die attach to a metal substrate using conventional tin-lead solder for comparison of the image contrast. This device also contained more than one bond interface that had to be accessed and evaluated in the package. Figures 2a and 2b show an example where substrates are attached to a metal case and the dies are bonded to the substrates. The first level encountered through the back of the module is the solder bond of the substrates. Voids in the bonds appear as white features. Notice that the intensity levels in the image corresponding to bond vs. voids is similar to what is seen in Figure 1. By changing the electronic gate to the subsequent echo corresponding to the die attach interface, voids in the die bonds are detected. Note that the voids at the interface appear white but voids from the previous level now appear as dark shadows as the ultrasound will not transmit across the air gaps.

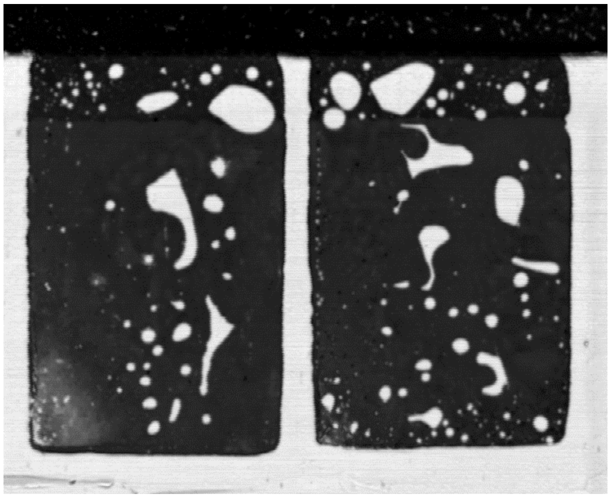

Figure 2a – metal case to substrate attach

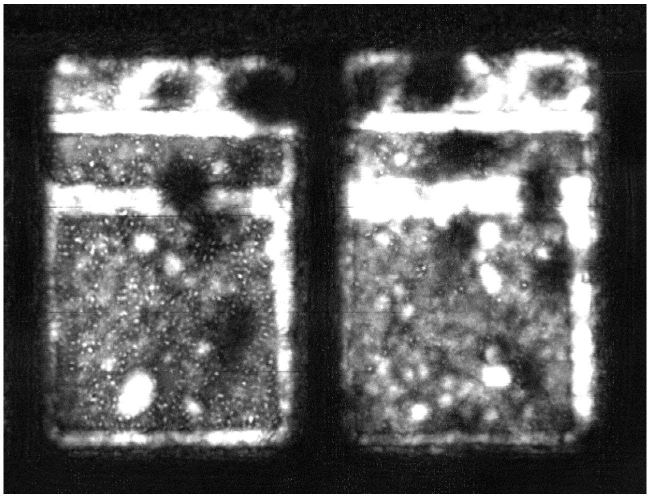

Figure 2b – substrate to die attach

Laser hybrid modules are an application that forced the development of higher ultrasonic frequency capabilities for Acoustic Micro Imaging. Very thin laser diodes (typically 50 to 100 microns in thickness) are bonded to substrates using methods such as Au-Sn eutectic solder or in some cases epoxy. Voids in the die attach can cause insufficient heat dissipation in the circuit which results in improper operation and early failure of the device. Acoustic inspection of the diode attach requires very high axial resolution (high frequency, short pulses) in order to distinguish the subsurface bond interface from the top surface of the thin diode and high spatial (lateral) resolution to detect small voids in the bond.

Wires are apparent in the surface image (Figure 3a). The die attach image (Figure 3b) clearly shows the strong signal reflections corresponding to voids in the diode bond as white features. Lower level reflections from the bonded areas appear grey. The influence of the wires on the surface is also seen in the image. Figure 4 displays the bond interface of a different laser diode. Voids appear as white features as do intentional channels at the bond interface.

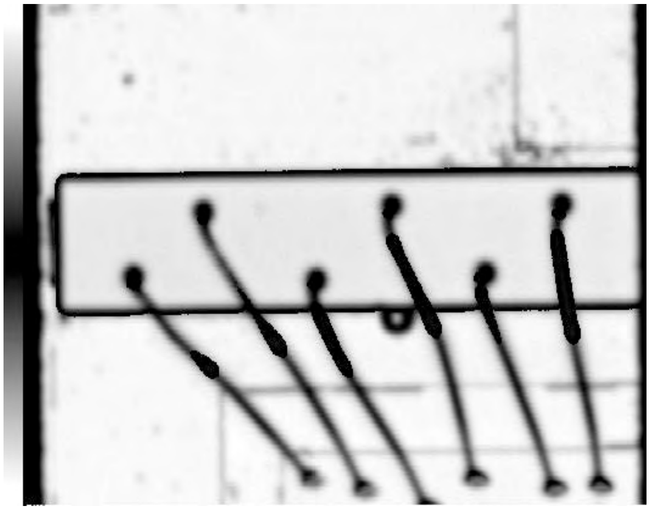

Figure 3a – laser diode surface

Figure 3b – laser diode bond interface

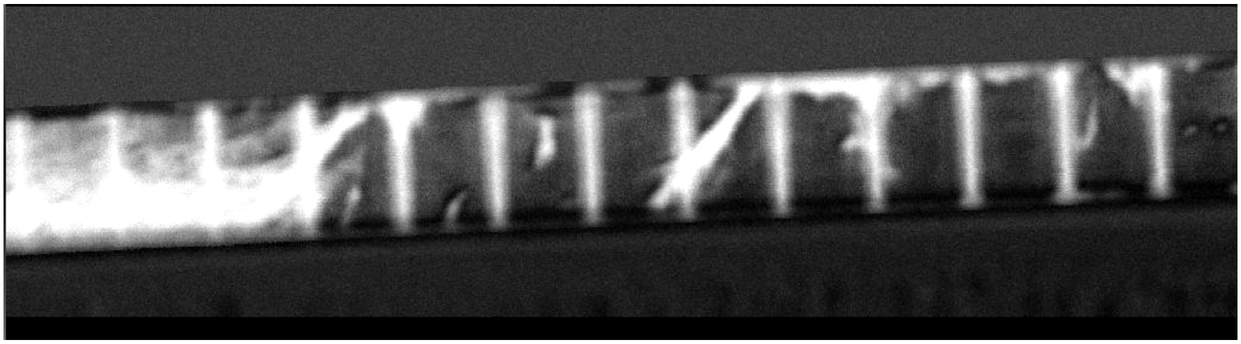

Figure 4 – laser diode bond.

FLIP CHIP

AMI has proven an excellent method for the analyses of flip chip underfill and interconnect bonds. 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. Transducers and imaging techniques provided focused access of the ultrasound beam to the interface of interest (chip/ bump and underfill, or bump and underfill/substrate) through any thickness of silicon commonly encountered. The first application images illustrate some of the early work done to improve the resolution in the acoustic images for flip chips. [4]

The following images compare the same sample at 180 MHz (Figure 5a) and 230 MHz (Figure 5b). There is a significant improvement in the resolution in the image at 230 MHz. The focal length/water path was also modified which contributed to the improvement in the image resolution. However, despite restricting the working distance this transducer can still be used for a wide range of thickness of silicon chips.

More recently flip chip devices are being produced that are much smaller, in some cases the chips are thinner, and the proximity of the smaller bumps can be close to the edge of the parts. These factors have made it necessary to adapt the design of the transducers in general and to create transducers that are part type specific. The example shown in Figure 6a and 6b displays a comparison between images taken with one of the general-purpose transducers and one that has been optimized to correct for edge effects and improve resolution. Notice that there is no drop off in information at the edges of the device and features such as metallization on the silicon can be clearly seen. The white features in the images correspond to underfill voids.

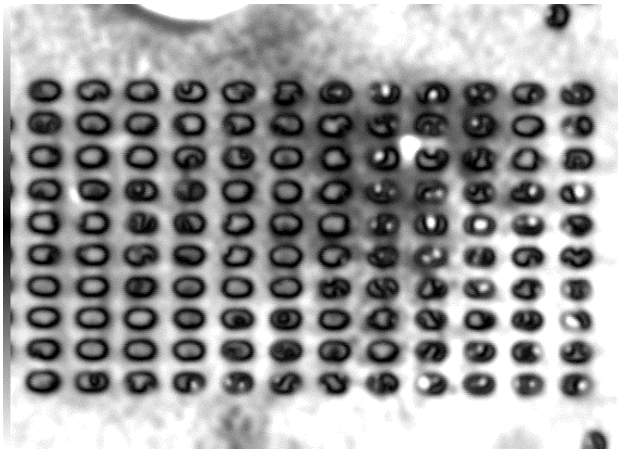

Figure 5a- 180 MHz

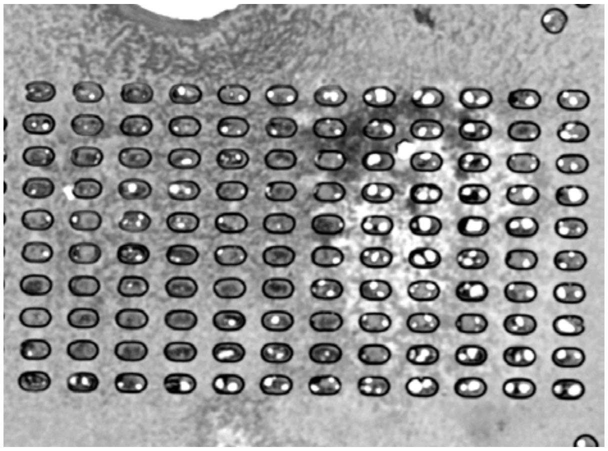

Figure 5b – 230 MHz

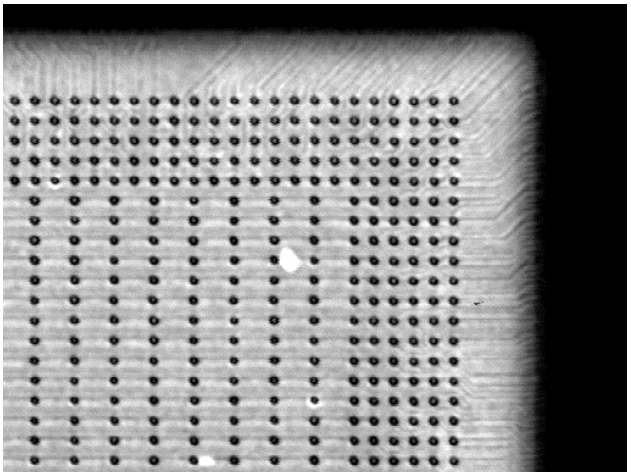

Figure 6a – Image taken with a general purpose 230 MHz transducer.

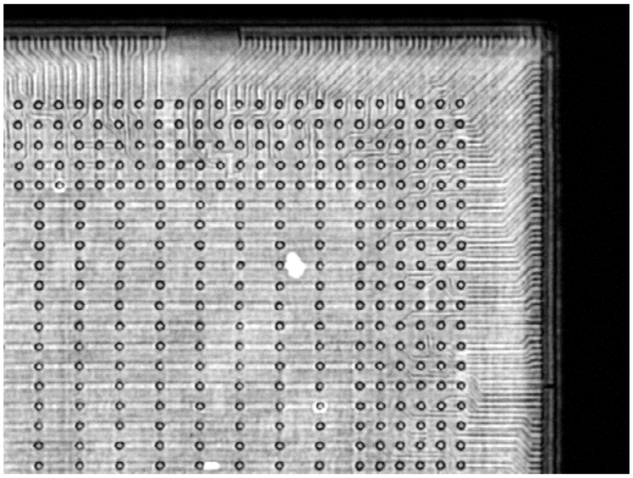

Figure 6b – Image taken with a 230 MHz transducer designed to improve resolution and minimize edge effect.

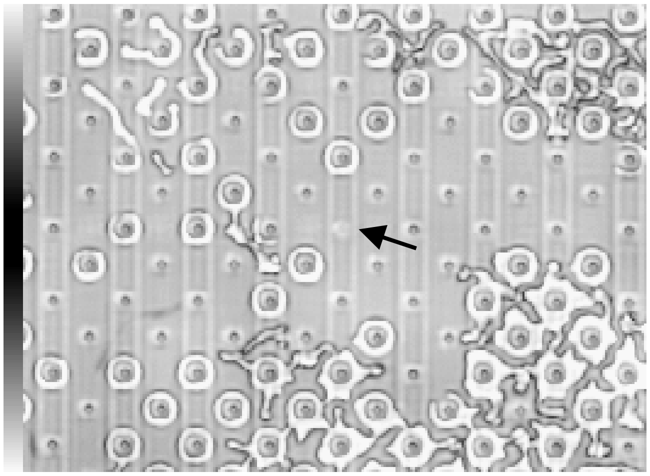

Figure 7a – chip to bump and underfill.

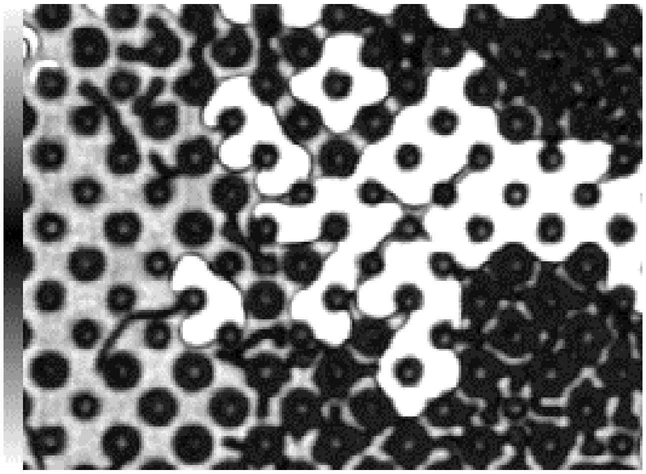

Figure 7b – bump and underfill to substrate.

The example shown in figures 7a and 7b displays flip chip bonding using lead free solder. The image of the chip/bump and underfill level was made using a 300 MHz transducer designed to maximize resolution and reduce edge effect. The size of the bumps is smaller than in previously pictured samples and the bonding material is lead-free however contrast of the bonded bumps is still clear. The voids in the underfill are clearly distinguished as white features and a disbonded bump appears missing at one position in the pattern. The bump and underfill to substrate is also pictured (Figure 7b). Additional voids in the underfill (white areas) are present at the substrate level. Voids in the bumps and in the underfill at the previous interface now appear as black shadows.

LEAD FREE PROCESS EFFECTS ON PACKAGES

Reliability issues related to changing to lead free solders are not isolated to the solder bonds only. The condition of the components themselves can also be affected. Particularly by the higher reflow temperatures required for lead free alloys. As mentioned previously AMI is routinely employed to evaluate a variety of microelectronic components for internal defects. So naturally the technique has utility to examine the same types of components for changes or damage possibly induced by the lead free process. For example a recent lead free study by NEMI [5] assessed the reliability of lead free solder joints. In addition changes in the components were also monitored using acoustic microscopy. The study showed an increase in the occurrence of internal defects in encapsulated devices using the lead free process however in most instances the defects created were not sufficient to cause rejection according to the IPC/JEDEC J-STD-020. The recommendations call for use of less moisture sensitive encapsulation materials rated to the higher reflow temperatures, and longer bake out times.

Example images from the NEMI study are shown in figures 8a and 8b [6]. Figure 8a shows an example of a device prior to exposure to the lead free process. No defects were observed in the packages at this time. Figure 8b shows an example package after using the lead free reflow profile. The process has caused delamination which would be cause for rejection of the device according to the IPC/JEDEC standard.

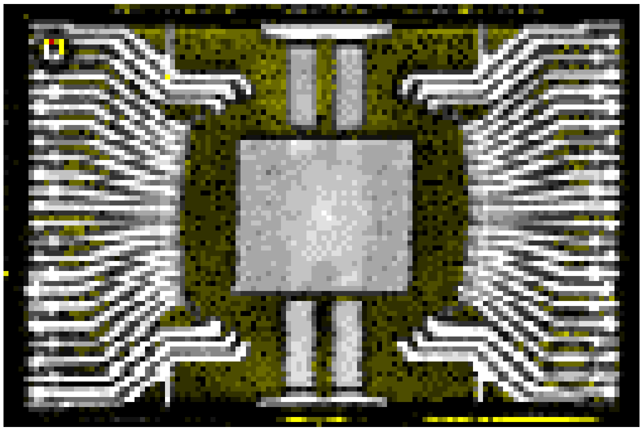

Figure 8a – Electronically magnified (zoomed) acoustic image of one part from an image of a tray of TSOPs showing no delaminations prior to lead free reflow.

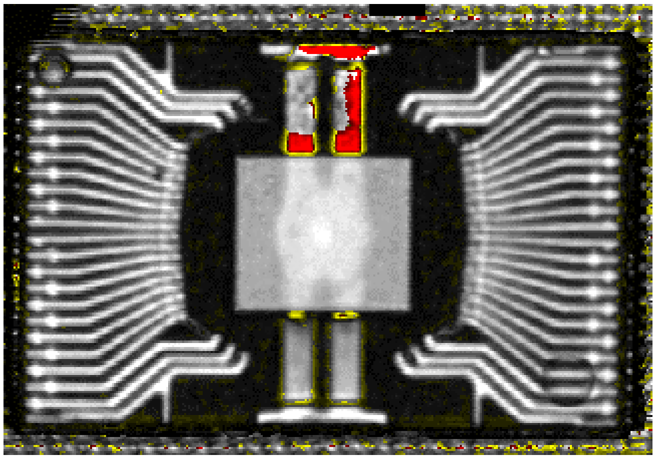

Figure 8b – Component with delamination between the molding compound and the tie bars with a path along the entire length of the top right tie bar (after lead-free profile used).

While Figure 8b does show an extreme case of internal damage, it gives an example of unacceptable damage according to J-STD-020 standard. This component has a direct path between the outside environment and the die, since there is delamination along the entire length of the tie bar. Further reliability studies would be required, if there was a desire to utilize this component using the current lead-free reflow process.

SUMMARY

Solder bond evaluation using AMI has the advantage of being particularly sensitive to air gaps characteristic of voids and delaminations. AMI also is a level specific imaging method so the exact depth/interface of a flaw or feature can be determined. Although the lead-free solders present some concerns for manufacturing/processing the lead-free solder methods do not present difficulties for inspection using AMI. In fact, there is little if any difference in imaging these materials when compared to the lead containing solders. Additionally AMI can be used for evaluation of the components to determine if the lead-free soldering process has had any deleterious effect on the components themselves. The trend in microelectronic packaging is leading to increasingly smaller devices which will force the development of higher resolution transducers to keep pace with the device developments. However the thickness of the devices may still be relatively large in comparison to the size of the features that need to be detected, and/or contain many internal levels. This necessitates transducers that are more sample specific in as far as focal length/working distance in order to derive the optimum frequency performance from the transducer and still be able to access all interfaces in the package.

REFERENCES

[1] L.W. Kessler, “Acoustic Microscopy” in Metals Handbook, Ninth Edition, Vol. 17 - Nondestructive Evaluation and Quality Control - ASM International, Materials Park, OH, 1989, pp. 465-482.

[2] S. Canumalla, “Resolution of Broadband Transducers in Acoustic Microscopy of Encapsulated ICs – Transducer Selection.,” IEEE Transactions on Components and Packaging Technology, Vol.22, No. 4, December 1999.

[3] R. Shane Fazzio, “Effects of Lead –Free Solders on Imaging Characteristics of the HP 5DX Laminographic X-ray Inspection System”, HP 5DX User’s Group Conference, May 13-14, 1998.

[4] J.E. Semmens, “Flip Chips and Acoustic Micro Imaging: An Overview of Past Applications, Present Status, And Roadmap for the Future”, Proceedings of ESREF conference, Dresden, Germany, Oct. 2000.

[5] J. Bath, “NEMI Executive Summary Lead-free Process Group Report”, October 2002.

[6] S. Martell, “Interim Acoustic Microscopy (AM) Analysis Report for NEMI Lead Free Solder Study:
Pre & Post Reflow Evaluations”, April 2002.