PROCESS CONTROL INSPECTION OF SURFACE MOUNTED COMPONENTS USING ACOUSTIC MICRO IMAGING – A REVIEW

Janet E. Semmens
Sonoscan, Inc.
2149 E. Pratt Boulevard
Elk Grove Village, IL 60007 USA
jsemmens@sonoscan.com

ABSTRACT
Acoustic micro imaging has been used in the microelectronics industry for years to evaluate the quality of devices and in some instances to evaluate the quality of their attachments to substrates. As this method is non-destructive components can be evaluated at various stages of the manufacturing process, screened for possible internal defects before mounting to the substrates, and/or tested before and after various stages of life cycle testing.

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.

INTRODUCTION
Basic AMI Principles
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A-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 equation that describes the pulse reflection at an interface between materials is as follows:

\[ R = \frac{I}{Z_2 + Z_1} \]

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.

This paper will present an overview of AMI applications pertaining to surface mount processes and discuss AMI developments to meet the challenges presented by new device designs and manufacturing processes.

Key words: Acoustic Micro Imaging, surface mount, flip chip, molded underfill (MUF)
C-Scan (Interface Scan)
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 conventional C-scan output is only two-dimensional consisting of an x-y plot of one specific plane in the z dimension. Features existing in the device but not included in the electronic gate or features with lesser signal strength at a given position will not be displayed for analysis in the image. The A-scans for each point on the sample are not typically saved with the images due to file size considerations when documenting a significant number of samples. Since the A-scans are not saved, the data cannot be re-gated, nor can the echoes be reprocessed to create different image information. But the conventional C-Scan is very useful and has been the standard since acoustic micro imaging was developed.

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.

In acoustic microscopy of IC packages, as in optical microscopy, focused beams are used to obtain good transverse definition and high beam intensity at a point of interest. A spherical lens focuses the beam from the piezoelectric element to a spot (much smaller than the element diameter) the size of which is limited by diffraction. Some factors affecting transverse definition or resolution are discussed below. According to conventional ultrasonic theory two neighboring objects (flaws) can be distinguished from each other if the separation between them is

Resolution = \( 0.707 \times 1.22 \times F# \times \lambda \)

\[ F# = \frac{\text{diameter of the transducer element}}{\text{focal length}} \]

\[ \lambda = \text{wavelength of ultrasound at a given frequency} \]

Therefore, a higher frequency transducer emits sound with a smaller wavelength and, hence, affords better resolution.

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 will exhibit the same resolution if their F#s are identical. In general, when transducers are focused in a couplant, such as water, a smaller F# results in a more highly focused ultrasonic beam and better resolution [1]. However, highly focused transducers are not suitable for all inspection cases. For example, flaws deep inside IC packages may not be detectable using highly focused transducers because very little of the ultrasound energy incident on the surface from such a transducer penetrates the package. This behavior follows Snell’s law of refraction and rays incident at large angles suffer total internal reflection. Thus, there is a limit to which resolution can be improved by reducing the F# when inspecting for flaws inside solids; the limit is controlled by the ratio of the velocities of the sound waves in the solid and couplant. 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 ultrasonic 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 IC package 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. In such cases a broadband resolution model can be used to predict actual resolution accurately [2]. 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 1a, 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 1a 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 correspond to voids at the chip/bump level. Voids in the underfill are also present. Figure 1b is also a 230 MHz image using a 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 1c shows a 230 MHz, 3.8 mm focal length image but in this instance a 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 1a: 230 MHz, F# 2, 9.5 mm FL

Figure 1b: 230 MHz, F# 2, 3.8 mm FL

Figure 1c: 230 MHz, F# 0.8, 3.8 mm FL

Figure 2 shows an image of 3 micron resolution test target features through 425 microns of a glass wafer using a 230 MHz, F# 0.8, 3.8 mm focal length transducer [2]. The fact that these small features can be detected in a test wafer lends confidence that these size flaws may in some cases be detected in actual devices using the same transducer.

Figure 2: 230 MHz, F# 0.8, 3.8 mm FL, showing 3µ resolution target features.

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. The graphs shown in Figures 3a and b illustrate the influence of fluid temperature and focal distance on the frequency downshift.
APPLICATIONS

Flip Chip

The following flip chip applications images were originally presented at the Pan Pacific 2011 conference [3].

Due to the good acoustic transmission properties in materials such as silicon increasingly higher frequencies can be used to achieve higher resolution as long as the ultrasound can penetrate a sufficient thickness of the material to reach the interface of interest. Currently the thickness of the silicon die is typically much thinner (25µ - 100µ) than what was seen in past applications (500µ - 800µ). This allows for shorter focal lengths and lower F#s of the transducers to obtain the best possible resolution at the high frequencies.

In previous studies high frequency transducers were developed with various focal lengths to best suit different thicknesses of silicon. The resolution was demonstrated using test wafers with embedded features of known sizes. The following images show examples of images on actual devices using two types of high frequency transducers.

Figures 4 and 5 show 300 MHz images of flip chip devices. Both these examples had 600µ to 650µ thick die. Figure 4 shows an area of a flip chip showing variations in the conditions of the bump bonds. A number of white bumps are present indicating delaminated sites [3]. Some bump bonds appear partially delaminated. Bonded bumps are shown in dark grey. Metallization lines and pads can be seen as well in the image.

Figure 5 is also of a flip chip but with a redistribution layer. Again features such as the metal traces and bump sites are clearly visible as well as a large void (irregularly shaped white area) in the underfill.

The construction of the flip chip with redistribution layer is similar to another type of surface mount device WLCSP (Wafer level Chip Scale Package) that has been inspected using similar frequencies and methods as flip chips.
Molded Underfill (MUF) Devices
With flip chip devices we see a trend toward using a molded underfill (MUF) process. As the name implies the underfill and over-mold are accomplished in one step so the evaluation can only be done post encapsulation.

Once the silicon device is encapsulated the molding compound introduces another challenge to gaining access to the solder bump bonds with high enough image resolution to evaluate their condition. Plastic materials are more absorbing of high frequency ultrasound and the filler particles in the material cause scattering. The over mold/underfill (MUF) compounds use a high filler particle density with a small particle size necessary to flow under the thin space below the die and fill narrow spaces between devices [4]. Uneven distribution of the filler particles and/or voids in the over mold will affect the ultrasound transmission to the interface of interest.

Additionally it is not always advisable to use a heated fluid couplant. Although heating water improves the acoustic transmission through the couplant it has the opposite effect on polymer encapsulant materials. It may seem counterintuitive but once the devices are encapsulated it may be necessary to use a lower frequency to get the clearest detail of the features of interest.

Figures 6a and 6b compare images of the same molded underfill (MUF) device with a 150µ thick die using two different 120 MHz transducers. Upon critical examination of the images the shorter focal length transducer produces the best resolution in the image however it also produces a greater scattering effect in the image that can make the features of interest (the bump bonds) less easily distinguished from the background texture in the image. The transducer with a longer focal length allows for slightly more downshift of the frequency and is therefore somewhat less sensitive to the scattering from the filler particles in the encapsulation. The bump bonds may not appear as crisply defined as in the previous image however there is less background structure due to scattering.

Surface Mount Multi Chip Module
This application shows an example of a MCM (Multi Chip Module) solder bonded to a printed circuit board. Due to the construction of the assembly both the device and the bond to the PCB could be inspected. Figures 7a and 7b show defects located at both interfaces in this device. Notice also in figure 7b that the delaminations present at the previous interface now appear as dark shadows in the image of the deeper interface. Once an air gap is detected the ultrasound is blocked from transmission to any deeper level therefore no further information is available beyond that level.
Ceramic Ball Grid Array

In ceramic BGA packages the components on the ceramic package substrate as well as the bond to the PCB can be evaluated. In the example shown in Figure 8 the 50 MHz ultrasound is focused at the solder ball bonds on the underside of the ceramic BGA. The un-bonded solder ball is seen missing from the pattern.

Manufacturing Process Effects on Packages

Reliability issues related to the manufacturing process such as changing to lead free solders are not isolated to the solder bonds alone. 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 9a and 9b [6]. Figure 9a 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 9b 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 9a: 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 9b: 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 9b 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
Surface mount 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. Additionally AMI can be used for evaluation of the components. 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


