An Overview of Solder Bond Evaluation in Electronics Applications Using Acoustic Micro Imaging (AMI)

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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. Acoustic micro imaging (AMI) is one technique that is used for non-destructive evaluation of solder bonds.

Acoustic micro imaging uses high frequency ultrasound (5 to 500 MHz) to image the internal features of samples. Unlike x-ray, which is also a common imaging method, 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 an overview of AMI solder bonding applications and discuss AMI developments to meet the challenges presented by the design and manufacturing of various components and assemblies.

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 distance between the echoes relates to their depth 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 interaction between materials at an 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 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 phase (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.

Resolution using AMI

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.

In acoustic microscopy, 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 resolution (Rayleigh) are discussed below.

According to conventional ultrasonic theory two neighboring objects (flaws) can be distinguished from each other if the separation between them is

$$d_{\text{resolution}} = .707 \times 1.22\ F^{\#}\ \lambda \quad \text{(in pulse echo inspection).}$$

Here $F^{\#} \cong z_0/d$, where d is the diameter of the transducer element, z_0 is the focal length and λ is the wavelength of sound at the center frequency of the transducer. Therefore, a higher frequency transducer emits sound with a smaller wavelength and, hence, affords better resolution. 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 a better resolution.

However, there is a limit to how highly focused the transducers can be and still achieve penetration through the thickness of the silicon chip to the level of interest. If the F# is too small very little of the ultrasound energy incident on the surface from such a transducer penetrates the sample. 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.

It should also be noted that low F# transducers will produce greater edge effects due to the greater refraction of the ultrasound beam. High F# transducers will produce less edge effect however as discussed earlier higher F#s provide poorer resolution for a given frequency.

Another factor that controls resolution in broadband acoustic microscopy systems is frequency downshifting due to attenuation in the water path and material. The ultrasound 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 sample and back, the higher frequencies in the incident pulse suffer more attenuation (reduction) than the lower frequencies. This downshifting can cause a significant reduction in the resolution afforded by a high frequency transducer. Ultimately the performance of a transducer can be monitored using Fourier analysis of the waveform to analyze the frequency content of the ultrasonic pulse, and resolution can be empirically verified using a resolution test target. The challenge is to produce a transducer and necessary support electronics that take into consideration all of the factors mentioned here and still obtain sufficient working distance and optimum resolution for analysis of microelectronic devices.

The following section provides examples of solder bonding applications for a selection of microelectronic components.

Hybrid Die Attach

One application that forced the development of even higher ultrasonic frequency capabilities for Acoustic Micro Imaging is Gallium Arsenide die. The very thin die (typically 75 to 100 microns in thickness) are bonded to substrates using 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 die attach in the very thin GaAs die requires very high axial resolution (high frequency, short pulses) in order to distinguish the subsurface bond interface from the top surface of the thin die. The following examples, Figures 1a and 1b compare the die surface image with the image of the die attach respectively in a GaAs sample.

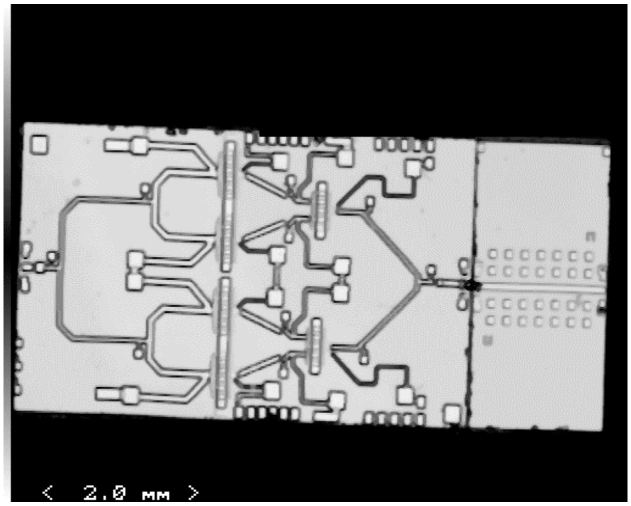

Figure 1a - GaAs die surface

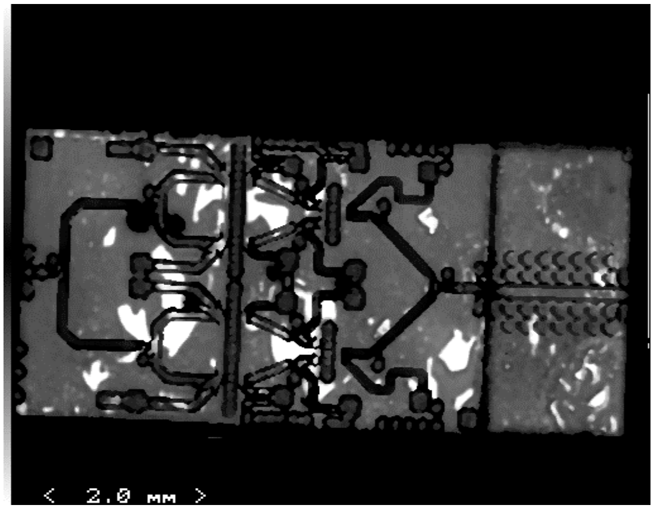

Figure 1b - Die attach

Detail of the surface metallization is apparent in the surface image (Figure 1a). The die attach image (Figure 1b) clearly shows the strong signal reflections corresponding to voids in the solder bond as white features. Lower level reflections from the bonded areas appear dark grey. The influence of the surface metallization can also be seen in the image.

In many instances complete hybrid devices are in a lidded metal or ceramic package. The intentional air cavity prevents examining the die attach through the lid side of the package and the die surface. It is possible to however to introduce the ultrasound through the back (substrate or heat sink) side of the hybrid module to evaluate the die attach. The example shown in Figure 2 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.

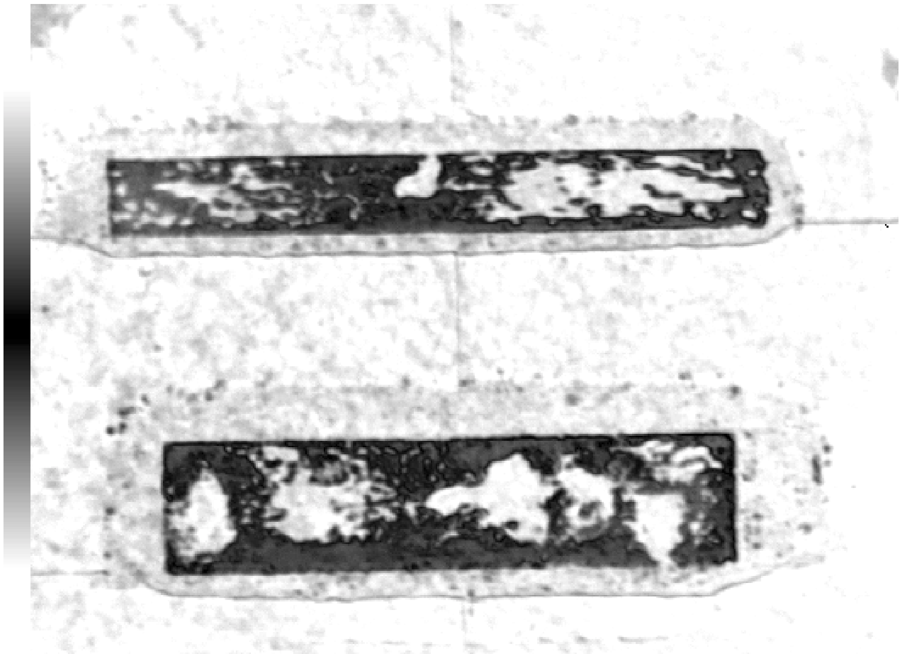

Figure 2 – Die attach to a metal substrate.

Another factor in the evaluation of hybrid modules, such as laser modules is that there is often more than one bond interface that must be accessed and evaluated in a single package. Figures 3a and 3b 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. 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.

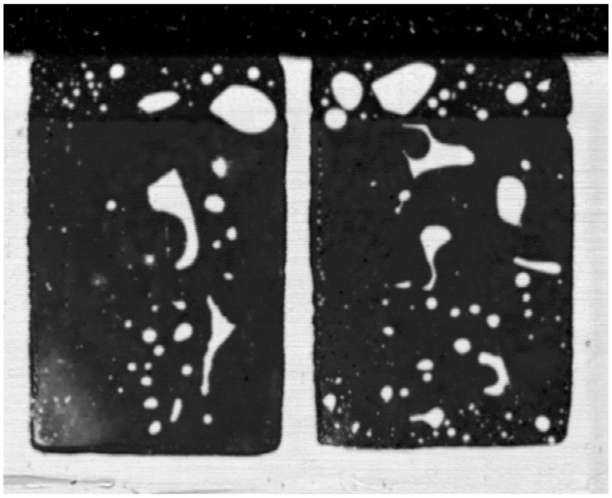

Figure 3a – Metal case to substrate attach

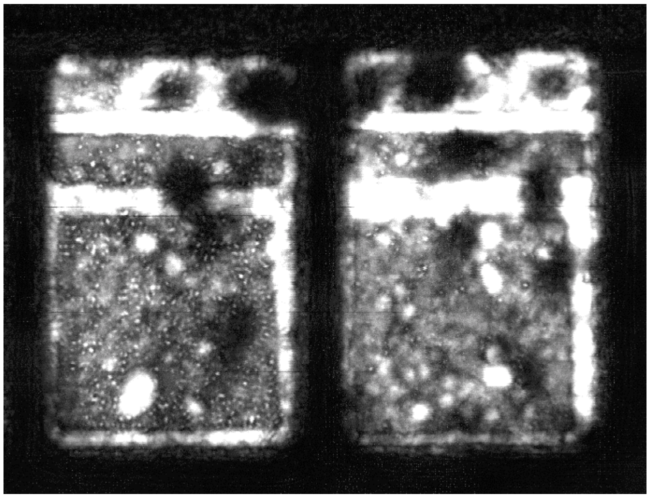

Figure 3b – substrate to die attach

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.

The Images compare the same sample at 180 MHz (Figure 4a) and 230 MHz (Figure 4b). 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.

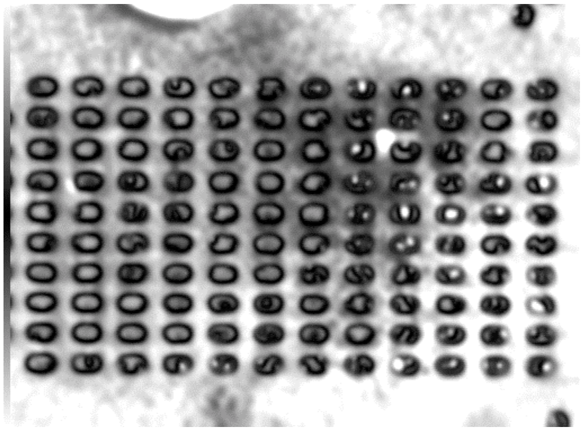

Figure 4a- 180 MHz (circa 1997)

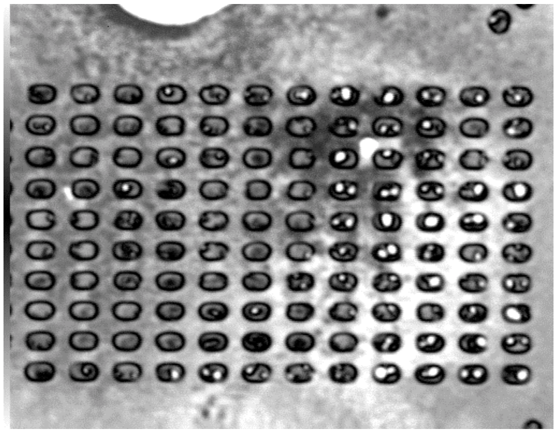

Figure 4b – 230 MHz (circa 1998)

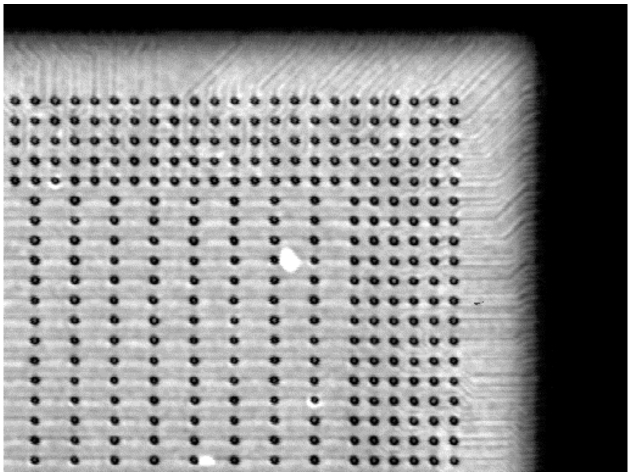

Figure 5a – Image taken with a general purpose 230 MHz transducer. (circa 1999)

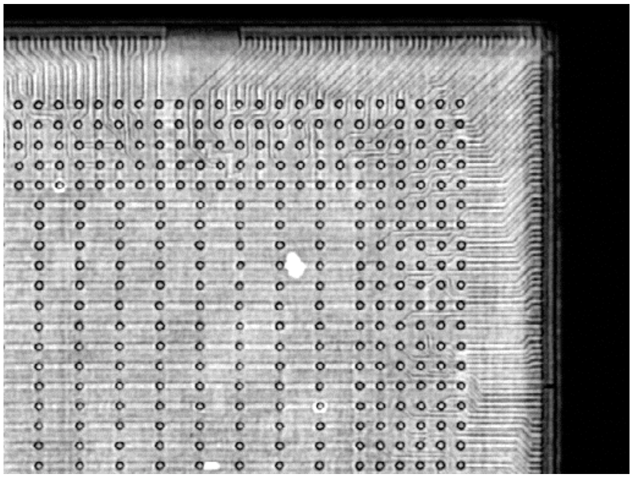

Figure 5b – Image taken with a 230 MHz transducer designed to improve resolution and minimize edge effect. (circa 2000)

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 5a and 5b 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.

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. 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

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