Flip Chips and Acoustic Micro Imaging: An Overview of Past Applications, Present Status, And Roadmap for the Future

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Abstract

Acoustic Micro Imaging has been used over the past years to successfully evaluate the quality of flip chip underfill and interconnect bonds. Flip chip technology is steadily progressing toward smaller devices and higher IO count which leads to smaller bumps and bonds. In many instances the small bumps are in close proximity to the edge of a relatively thick silicon chip which leads to information being obscured by edge effects. This is driving AMI technology to provide higher resolution images with improved clarity of information at the edges in order to evaluate the devices. This paper will present an overview of AMI flip chip applications from the inception to the present and include a roadmap for future AMI developments to meet the challenges presented by changes in the design and manufacturing of flip chips.

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 from reflected signal and 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. The geometric focus of the acoustic beam is 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, 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 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 $d_{\text{Resolution}} = \frac{1}{\sqrt{2}} 1.02 \lambda F^{\#}$ (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 IC package 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 [1].

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 flip chip devices.

The following section provides examples of applications that describe the progression of AMI technology to provide more information and better resolution for flip chip evaluation.

Progression of flip chip applications

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 1) and 230 MHz (Figure 2). 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.

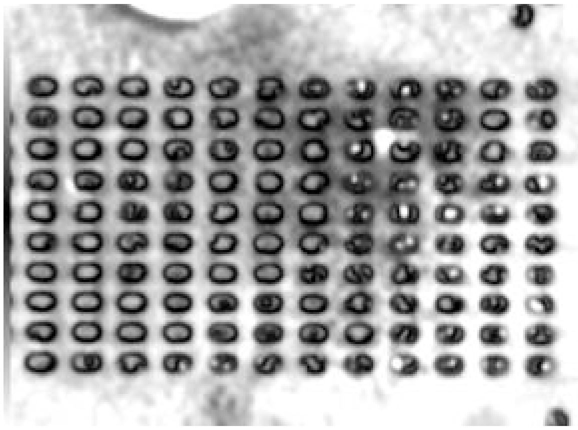

Figure 1- 180 MHz (circa 1997)

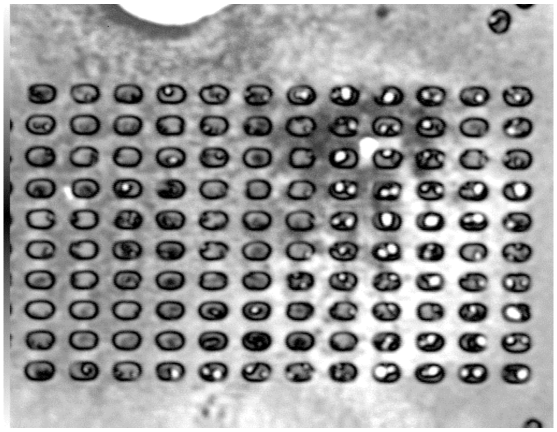

Figure 2 – 230 MHz (circa 1998)

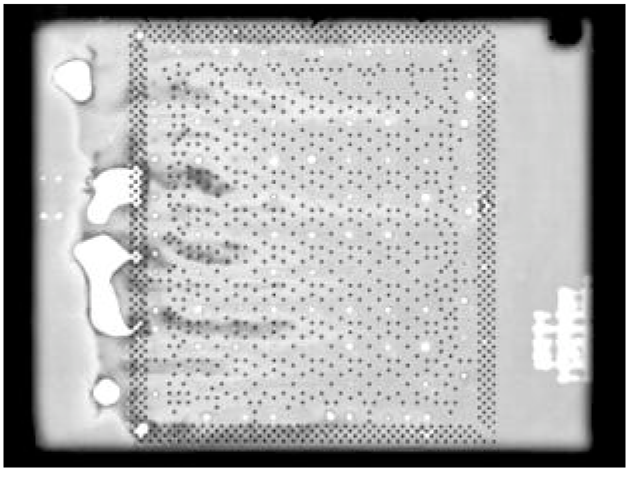

Figure 3 – chip to bump and underfill interface (1999)

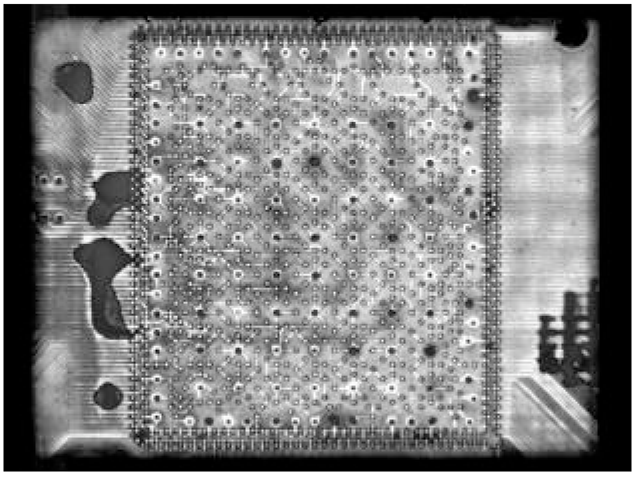

Figure 4- Bump and underfill to substrate interface (1999)

The device shown in Figure 3 and Figure 4 illustrates an example of underfill analysis although information on the solder bump bonds is also available from the images.

In the underfill features that can be determined from the acoustic images include the dispense pattern of the underfill, filler particle distribution and/or settling [2][3], 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 surrounding the bump. Delaminations of the underfill that result from thermal stress have also been detected [4]. 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 leads 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.

Based on the image of the chip/underfill level (Figure 3) the dispense pattern in the sample was a single pass along the right edge of the chip. Darker streaks can be seen streaming towards the center of the device in the image from the left side of the sample (opposite the dispense side). A knit line from a second fill pass merging with the edge of the first mold front is seen as a line at the left side of the part. Voids are present in the underfill and appear as white features. The large voids at the left of the device appear to be trapped between the mold fronts. The flip chip bump bonds appear as dark spots in the image indicating they are bonded at this interface. There is no difficulty with edge effects in the image of the bumps in this device.

The image at the bump and underfill to substrate interface shows the voids from the previous interface as dark shadows. Metal traces can be seen on the substrate. Interface scans are level specific and several images are required to cover the entire volume of the device. This is usually not a major issue with regard to flip chips as the pertinent information for evaluation of the underfill and bump quality is contained in the images of two interfaces as discussed in the previous example. However, there are instances where additional information can be useful. By using 3V (Virtual Volumetric Viewing) 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.

This method also has utility for automatic (user independent) set-up of the acoustic microscope. The challenge is still the interpretation of the information contained in the images, which relies on the capability of a trained investigator.

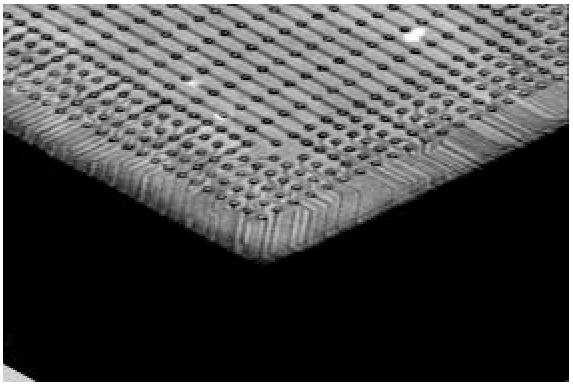

Figure 5 - The image displays the reconstruction before sectioning. The chip to underfill and bump level is displayed showing the metallization on the chip and bond sites. White features indicate voids at the interface. (1999)

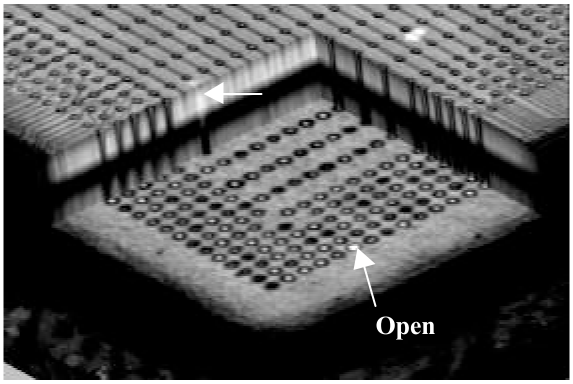

Figure 6 - A cutout of the "virtual" flip chip now reveals a void below the chip/underfill interface and an open connection at the bump/substrate level (1999)

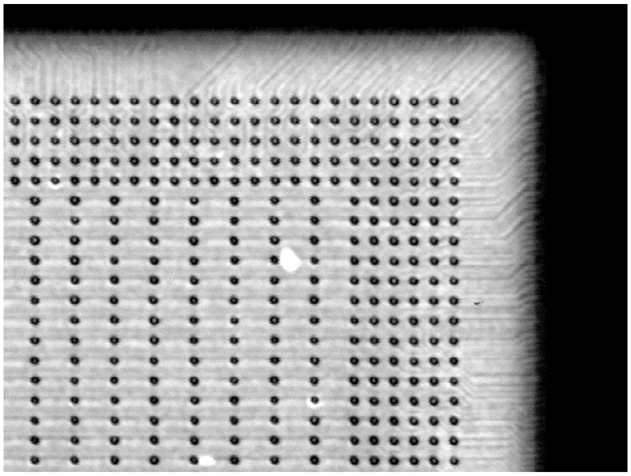

Figure 7 – Image taken with a general purpose 230 MHz transducer. (1999)

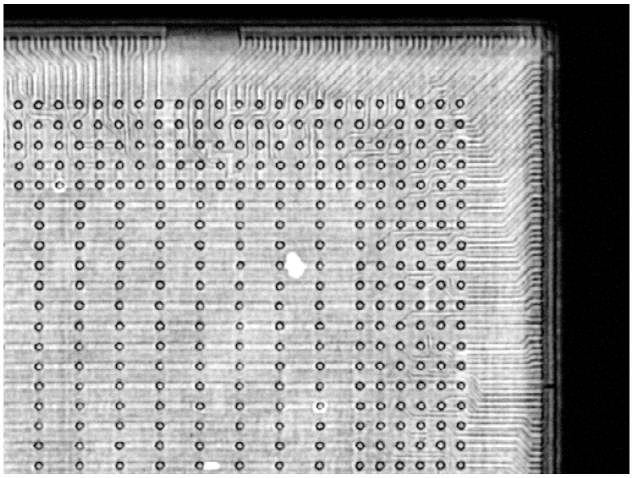

Figure 8 – Image taken with a 230 MHz transducer designed to improve resolution and minimize edge effect. (2000)

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 7 and 8 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

The roadmap for future developments in AMI analysis of flip chips will closely follow the roadmap for advancements in flip chip design and manufacturing. The trend is leading to increasingly smaller bonds which will force the development of higher resolution transducers to keep pace with the flip chip developments. Also the transducers will have to be more sample specific in as far as focal length/working distance in order to derive the optimum frequency performance from the transducer.

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