Advancements in High Frequency, High Resolution Acoustic Micro Imaging for Thin Silicon Applications

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ABSTRACT

This paper builds upon work first done in a joint project with Intel [1] on high frequency studies of buried silicon interfaces. That paper reported a study on experimentally determined resolution limits for a series of 230 MHz transducers of different focal lengths using specially designed resolution test targets. This paper takes the information learned from the previous study on test targets and applies it to "real world" applications. In addition further developments on higher frequency transducers to increase resolution needed for these applications will be presented.

INTRODUCTION

Recently microelectronics has been miniaturizing structures further and using thinner silicon wafers/die. This is driving AMI technology to develop higher frequency transducers to increase the available resolution in the spatial (x,y) dimension. Acoustic Micro Imaging has been used over the past years to successfully evaluate the quality of various microelectronic components. Acoustic micro imaging uses high frequency ultrasound (5 to 500 MHz) to image the internal features of samples. Ultrasound is sensitive to variations in the elastic properties of materials and is particularly sensitive to locating air gaps (delaminations and voids).

Although higher frequency transducers (400 MHz to 1 GHz) are available the transducer design and limited penetration of the high frequencies in materials has traditionally limited the application to surface and near surface (within a few microns) analysis. However, with the trend being to make the silicon die and other material layers thinner the penetration in the materials is less of a problem (within limits) and applications are widened to include sub-surface features such as flip chips, through silicon vias (TSV), stacked die and MEMs.

The technical issues involved with high frequency /resolution acoustic imaging will be discussed and the results obtained using higher frequency transducers will be illustrated using acoustic images of both test targets and actual applications such as flip chips, stacked die and molded underfill parts.

Key words: Acoustic Micro Imaging (AMI), Acoustic Microscopy, Flip Chip, Molded Underfill

BACKGROUND REVIEW

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.

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:

$$R = I \, \frac{Z2 - Z1}{Z2 + Z1}$$

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.

Interface Scan - C-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

$$\text{Resolution} = 0.707 \times 1.22 \times F\# \times \lambda$$

F# = diameter of the transducer element / focal length

λ = 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 a 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 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. 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 an 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 an 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.

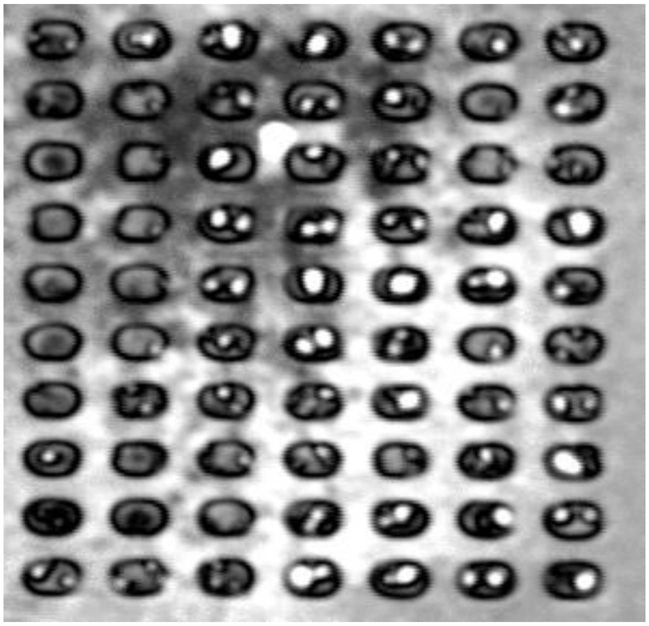

Figure 1a: 230 MHz, F# 2, 9.5 mm fl

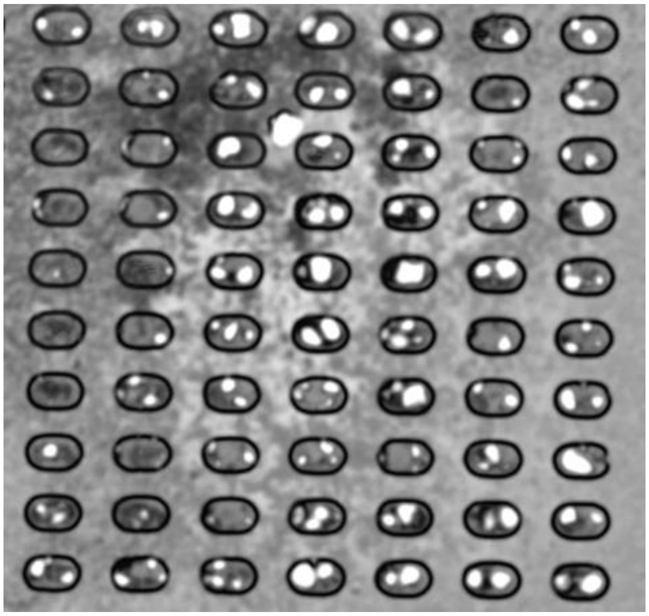

Figure 1b: 230 MHz, F# 2, 3.8 mm fl

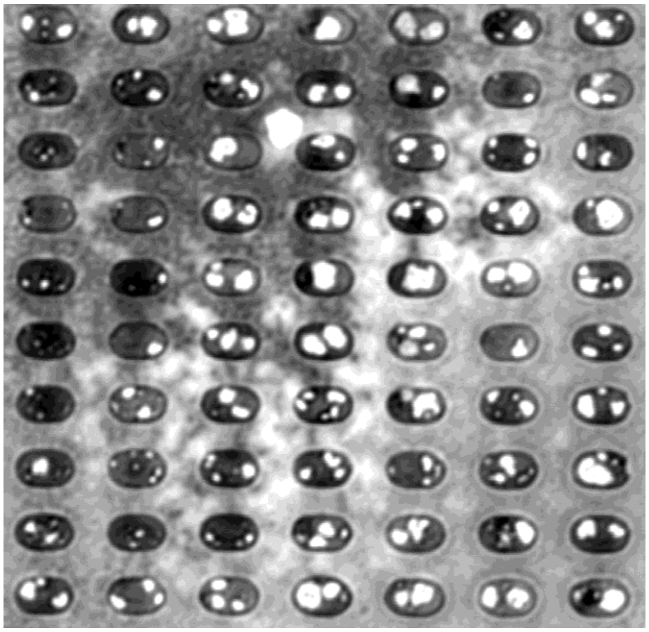

Figure 1c: 230 MHz, F# 0.8, 3.8 mm fl

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.

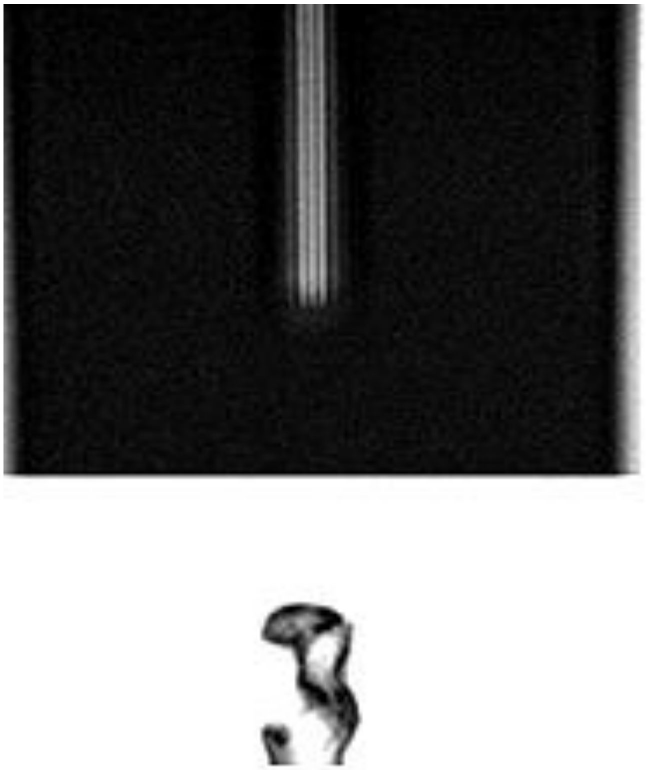

Figure 2: 230 MHz, F# 0.8, 3.8 mm fl

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.

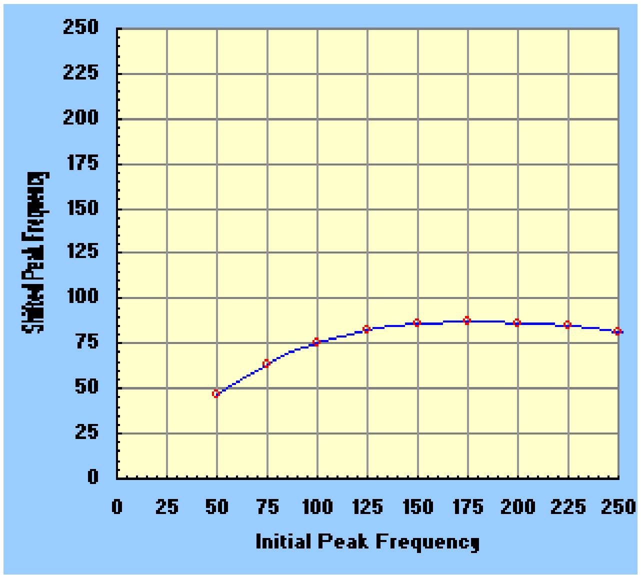

Figure 3a: 15^0 C fluid, 9.5 mm water path

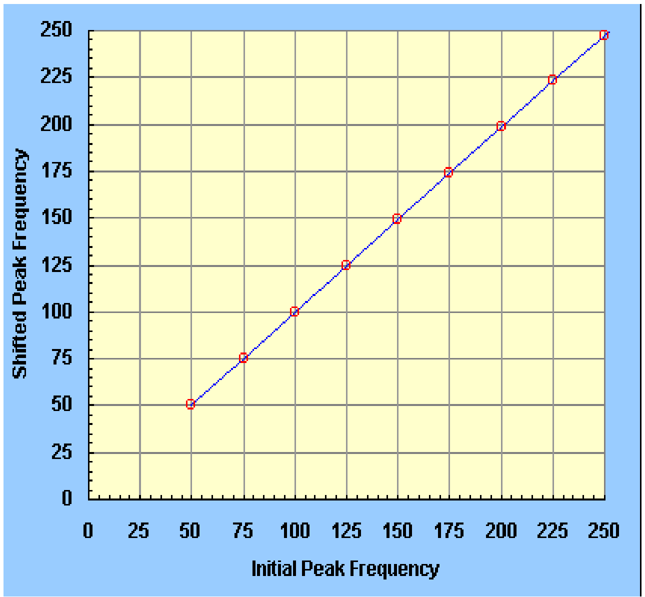

Figure 3b: 50^0 C, 0.5 mm water path

APPLICATIONS

Un-encapsulated flip chip and stacked die:

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 re-distribution 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.

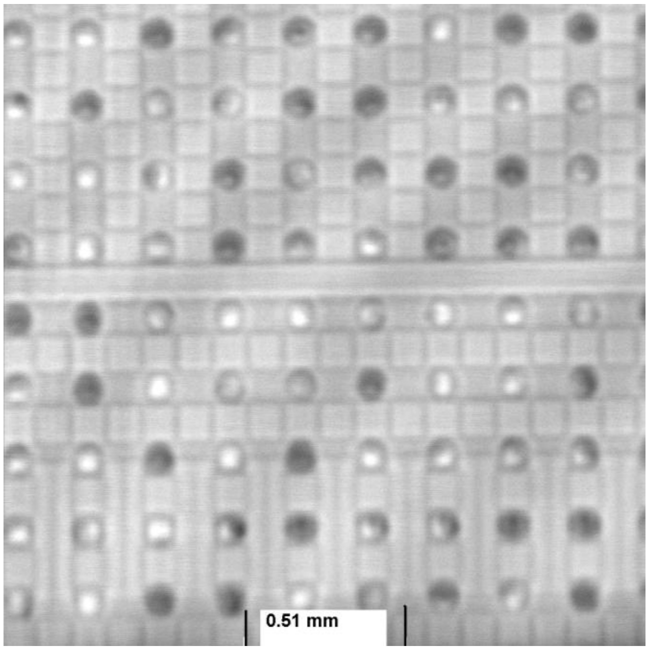

Figure 4: 300 MHz image of flip chip device with some bump bond delaminations

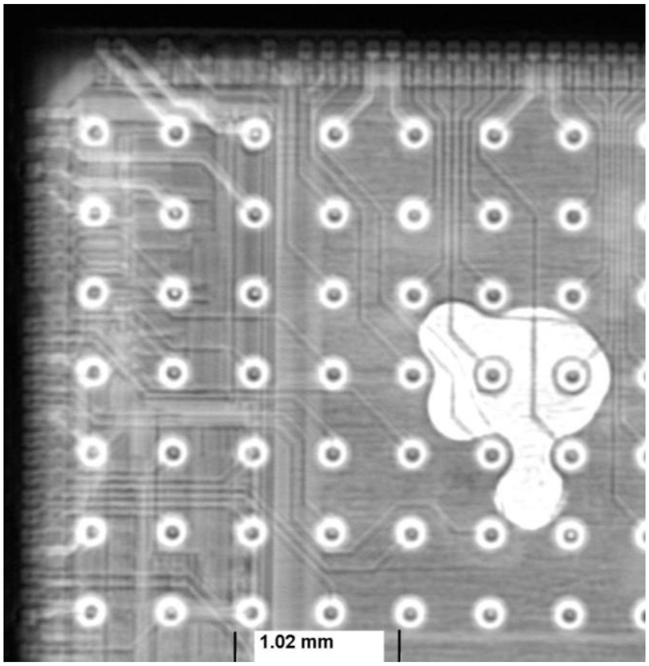

Figure 5: 300 MHz image of flip chip device with re-distribution layer and a large void

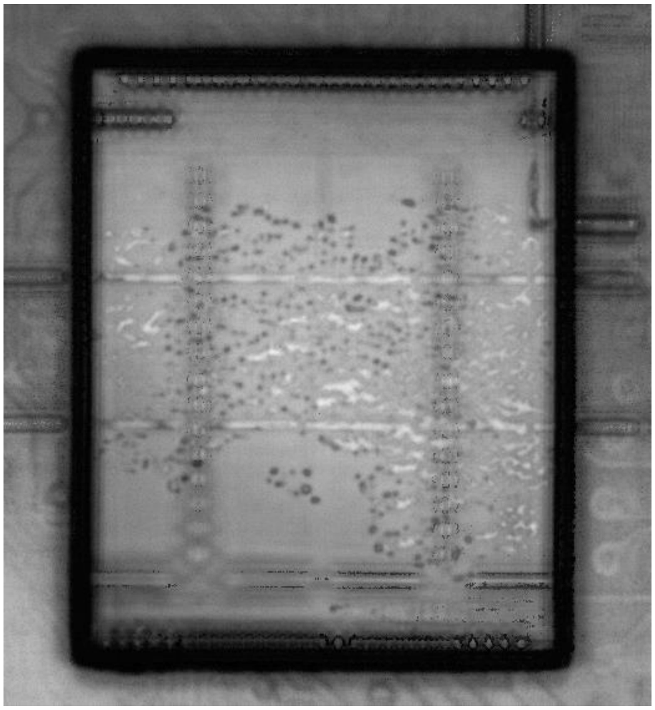

Figure 6: 230 MHz image of un-encapsulated stacked die

Figure 6 shows a 230 MHz image of the die attach of the top die in an un-encapsulated stacked die sample. This die had a 100µ thickness. Metallization on the die is visible as well as voids in the die attach.

Encapsulated stacked die and molded underfill devices

In some applications it is not possible to view the devices prior to encapsulation. For example in stacked die devices inspection is required of the finished product rather than at some earlier stage of assembly. 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 high resolution imaging. Plastic materials are more absorbing of high frequency ultrasound and the filler particles in the material cause scattering. Often the filler particles are of a size close to the resolution of the smaller features that need to be detected in the devices. In addition 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.

Figure 7 shows the same type of stacked die device that was imaged in the un-encapsulated state. This molding compound necessitated using a lower frequency transducer (100 MHz) as higher frequency ultrasound was absorbed by the material and did not penetrate to the die stack level.

Although fine detail such as the metallization on the die is not resolved in the image voids in the die attach and some metal traces on the substrate can be detected easily.

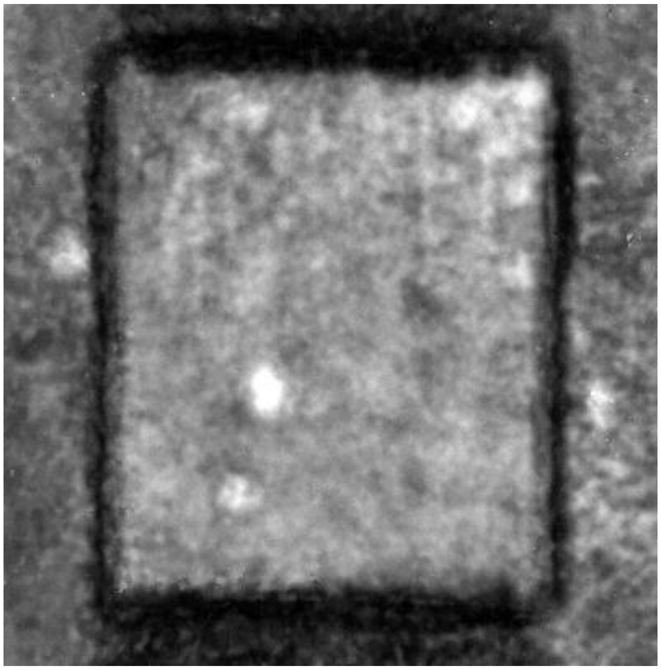

Figure 7: 100 MHz image of encapsulated stacked die with voids in die attach

Figures 8a and 8b 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.

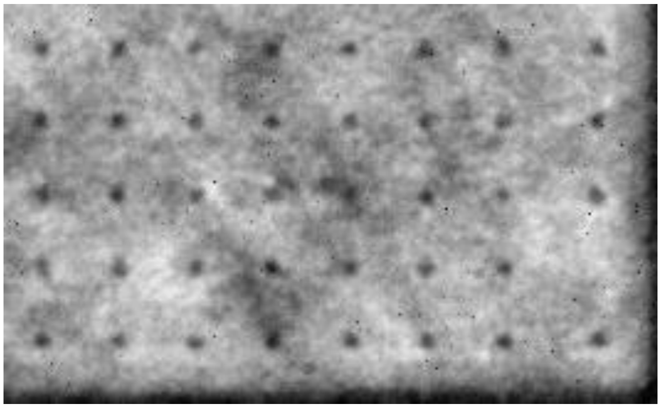

Figure 8a: 120 MHz, 3.8 mm fl

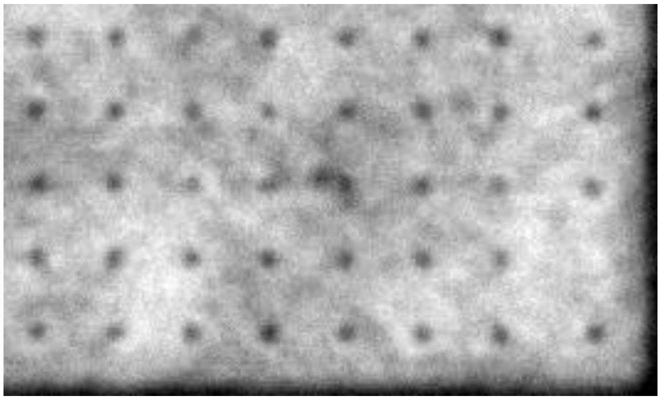

Figure 8b: 120 MHz, 7.9 mm fl

CONCLUSION

For exposed silicon applications increasing the frequency response of the transducer will increase resolution in the images. The challenge here is to deliver the high frequency ultrasound through the specified thickness of the material to the interface of interest.

In encapsulated devices the encapsulation material adds another degree of difficulty to accessing the depth of interest. However a frequency/F#/focal length combination can be found to render the features of interest detectable.

In either case continuing developments in the design of the transducers will keep pace with the developments in the device design and manufacturing processes.

REFERENCES

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