Development of a Resolution Test Wafer for Use in Acoustic Microscopy of Microelectronic Devices

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ABSTRACT

Acoustic Micro Imaging (AMI) has become an established method to evaluate the quality and reliability of IC packages from the standpoint of package integrity. Ultrasound is sensitive to variations in the elastic properties of materials and is particularly sensitive to locating air gaps (delaminations, cracks and voids). Microscopic feature sizes in flip chip, SOI, and MEMS devices has necessitated imaging at much higher ultrasonic frequencies to improve the axial and spatial resolution. However, sufficient penetration and working distance must be maintained to access the various internal layers of the devices. Higher frequency pulse - echo transducers have recently been developed and are in use. However, factors such as fluid path attenuation and fluid couplant temperature need to be addressed to realize the resolution improvement. The assumption of higher resolution in the images based on higher frequency alone comes from basic theory and the evidence for the improvements has been based on the clarity of details observed in the acoustic images. But no accepted resolution test sample for high frequency resolution tests of ultrasonic microscopes/transducers has been available to provide a quantitative, objective measure of the gains in resolution. Such a sample is important for both determining the minimum flaw or feature size detectable in a device using AMI at a given frequency and for establishing if the acoustic microscope and/or transducer are operating to specified parameters.

This paper will describe the resolution test sample and show the results obtained with high frequency transducers. In addition, example images of actual samples will be shown to illustrate the resolution capabilities of high frequency ultrasound. Too often theoretical calculations state the impossibility of detecting certain defects that are seen by practical applications. The Test Wafer was designed to reduce some complex equations to a solid practical base.

Key words: Acoustic Micro Imaging, resolution test wafer

AMI

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 dependant 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. 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 an 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 element). 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.

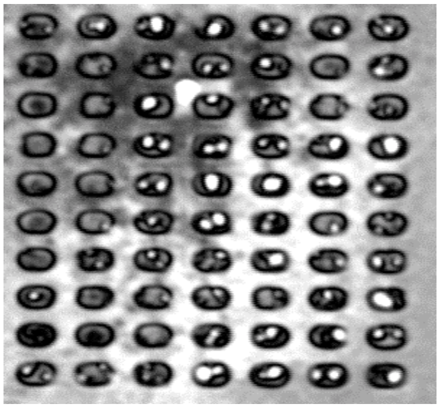

Figure 1a: 230 MHz, F# 2, 9.5 mm fl

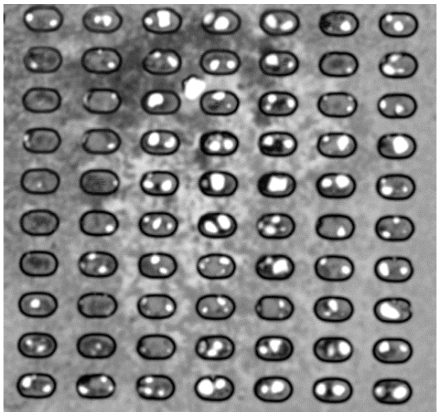

Figure 1b: 230 MHz, F#, 3.8 mm fl

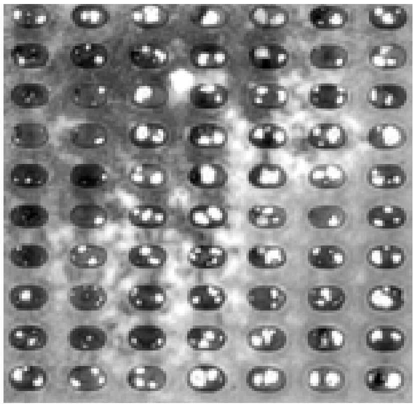

Figure 1c: 230 MHz, F# 0.8, 3.8 mm fl

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 2a and b illustrate the influence of fluid temperature and focal distance on the frequency downshift.

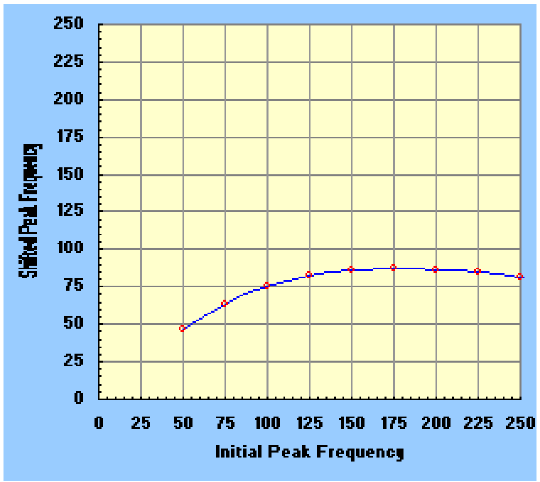

Figure 2a: 15^0 C fluid, 9.5 mm water path

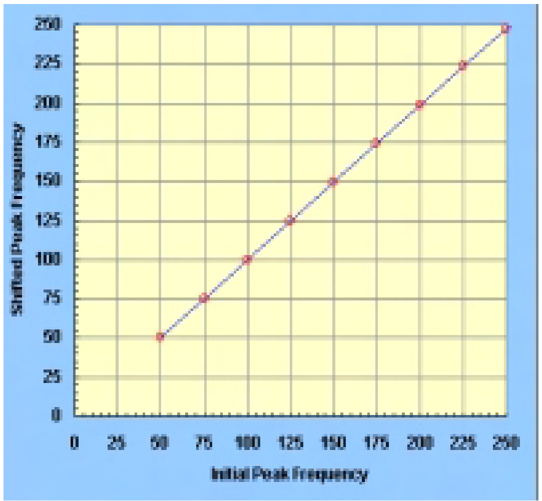

Figure 2b: 50^0 C, 0.5 mm water path

A-Scan Storage and Frequency Domain Imaging

Currently a new method is used that stores the A-scan information for each x-y point in a scan. From the stored information images of depths within the device not included in the original gate for the image can be recreated and/or waveforms (echoes) can be viewed for analysis without rescanning the sample. In addition to this the echoes can be digitally processed, frequency filtered, etc., to extract further information about the condition of the sample, or extract information at or slightly beyond the limits of conventional AMI.

Frequency Domain imaging is one method that can extract further information by using the frequency content of the signal. In this technique each A-scan of the image relates to the localized frequency response of the corresponding pixel in the sample. For reference, the conventional image is a time domain image in which each pixel relates to the magnitude of a return echo [3].

The transducers used in AMI range in center frequency from 5 MHz to 300 MHz and above. In conventional acoustic imaging, the choice of transducer determines the spatial resolution, penetration, and other parameters. These transducers typically have highly damped waveforms in order to achieve better resolution, both spatial and axial, using time domain imaging. Figure 3 displays an A-scan with typical echoes (pulses) as seen in the time domain. However these highly damped waveforms contain broad-spectrum frequency information that can be displayed in the Fourier (frequency) domain. When using time domain imaging at a center frequency of 50 MHz, one can not manipulate the image data to produce a 30 MHz image or a 75 MHz image, because in the time domain the acoustic pulses themselves do not have sufficiently wide frequency content. However, the data file including the stored A-scans makes this kind of manipulation possible, within limits.

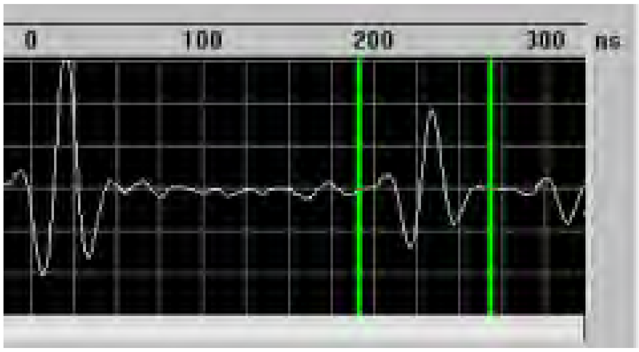

Figure 3: A-scan displaying typical waveforms (pulses) in the time domain.

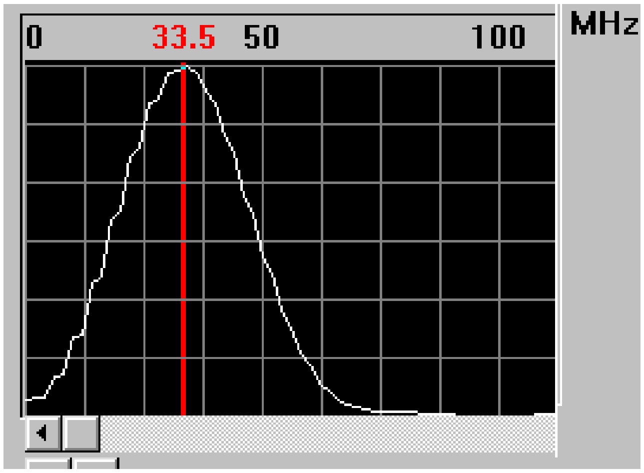

Figure 4: Broadband pulse content in the frequency domain for the echo within the gate on the A-scan in Figure 1.

Because the A-scans for each point in the image are collected with the image changes in frequency that may occur during reflection can be analyzed. For example, a pulse of 15 MHz ultrasound launched toward a material interface (such as molding compound to die) may be reflected with a different frequency content than originally pulsed, and this change – not otherwise detectable – may be indicative of the interface condition. The gated echo(es) from the stored A-scans can be filtered by means of a Fast Fourier Transform (FFT), also called a Frequency Domain algorithm, to isolate a given frequency. The Fourier transform decomposes the selected waveform(s) into sinusoids of different frequencies. The FFT identifies the different frequency sinusoids and their respective amplitudes. Figure 4 shows the frequency content distribution of the gated echo shown in Figure 1 in the frequency domain. Images can then be reconstructed from components of the frequency information. Specific features may yield more information at one frequency than another. Therefore, FFT filtering of the echo can bring out image detail that may not be visible with conventional time domain imaging.

Advancements have been made in recent years with respect to higher resolution in the acoustic images by increasing the frequency/design of the transducers. However there is a point where the thickness and type of material in the packaging will limit the use of even higher frequency ultrasound even though package features are becoming increasingly smaller and internal layers increasingly thinner. Frequency domain (FFT) analysis of the waveforms has been used in the past to measure bond line thickness and has shown the capacity of measuring to thickness well beyond the axial resolution limit of a given frequency [4]. Frequency domain imaging can be used to improve detection/resolution in the lateral dimensions by removing the low frequency component from the image. Figure 5a shows the time domain image of a flip chip at the chip/bump interface. The bump bonds can be seen as well as an associated laminar crack next to one of the bumps. The evidence of the metallization on the chip is faintly visible in some areas. The frequency domain image using the higher frequency portion of the signal (Figure 5b) shows the metallization clearly.

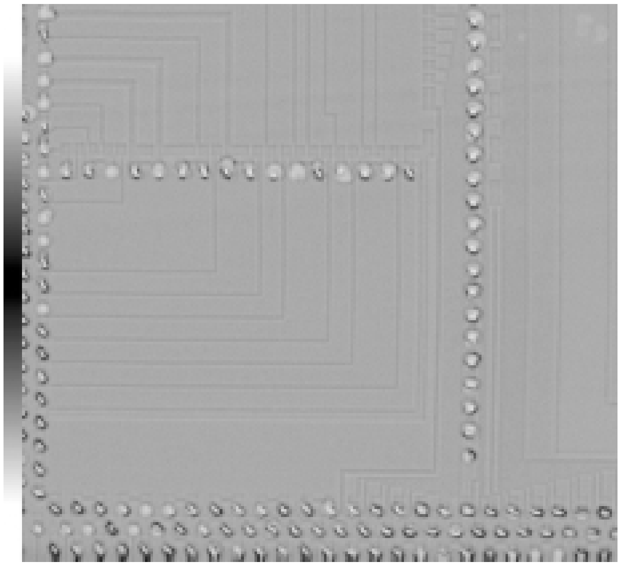

Figure 5a: Time domain image of flip chip

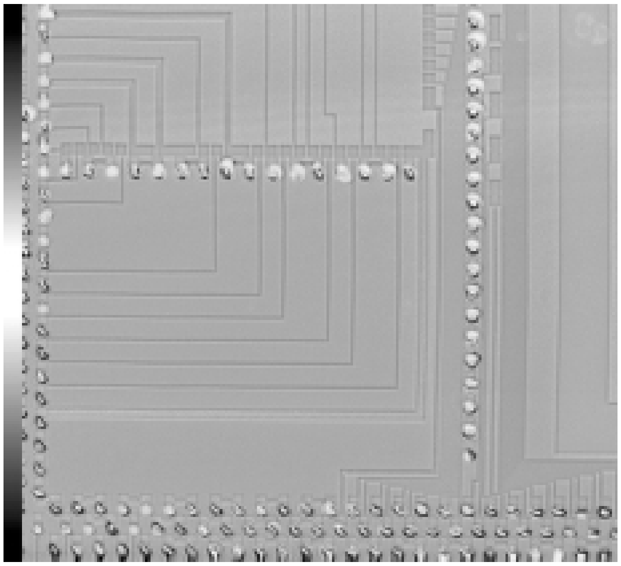

Figure 5b: Frequency domain image of flip chip

RESOLUTION TEST WAFER

One option that was considered in finding an appropriate resolution test sample was to use test targets or calibration samples used for other imaging methods. Optical test targets such as those used for light microscopes or scanning electron microscopes could be used however, these are only useful for measuring the resolution at the surface of a sample instead of inside it. What was needed was a sample that would approximate the conditions experienced in actual applications such as flip chip evaluation.

This paper describes a resolution test sample consisting of a glass wafer bonded to a silicon wafer and having the resolution targets/features at the interface between the two wafers. This closely simulates the conditions in which the high frequency systems and transducers are used in actual applications.

The resolution targets/features size(s) on the silicon wafer are verified and documented using SEM microscopy prior to bonding of the glass wafer. After bonding the glass wafer side allows for direct viewing of the features at the interface using high power optical microscopes.

Figure 6 shows a cross sectional view of the construction of the sample.

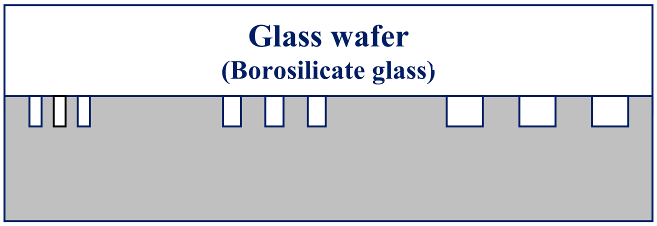

Figure 6: Cross sectional view of test wafer construction

Figure 7 shows an acoustic image of the entire sample for an overview of the feature layout. Figures 8 ,9 and 10 display enlargement of details of the resolution lines. Notice that the 3μ resolution lines with 10μ spacing are visible using 230 MHz. This is beyond the resolution limit that would be expected at this frequency through a glass wafer.

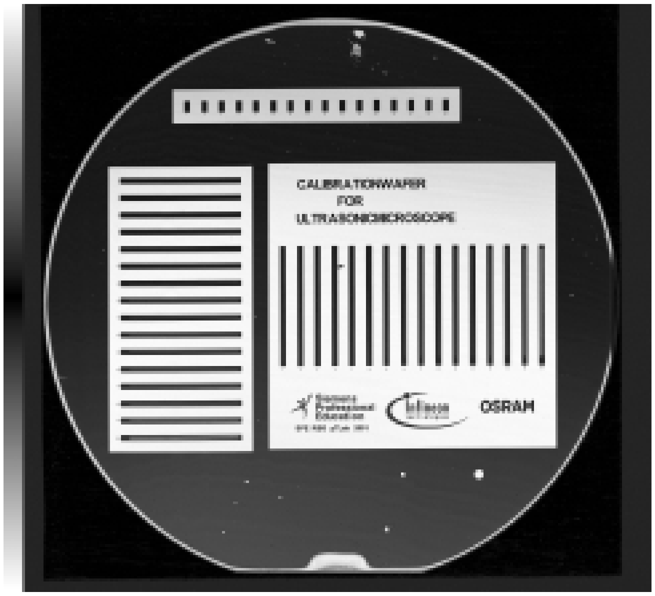

Figure 7: Overview of resolution wafer at 230 MHz

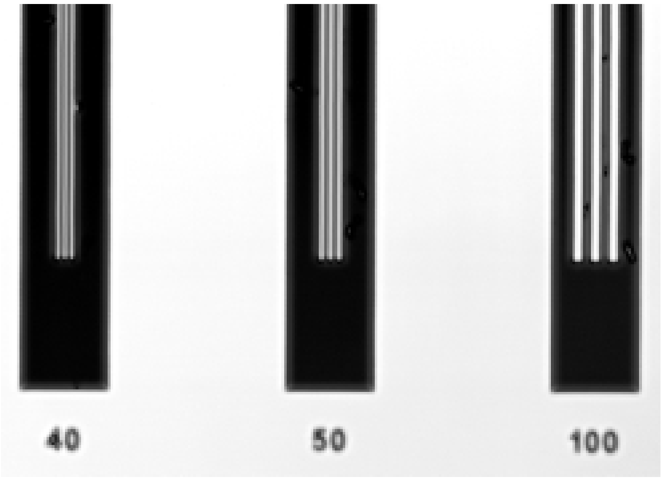

Figure 8: Enlargement of resolution lines 40μ to 100μ

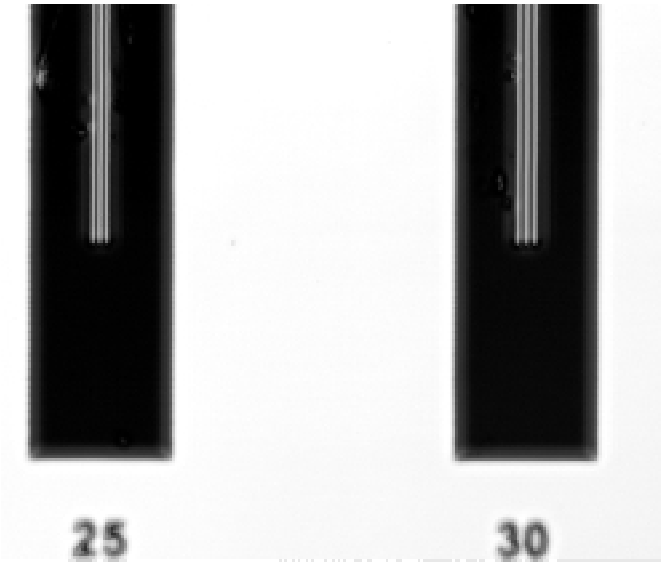

Figure 9: Enlargement of resolution lines 25μ and 30μ

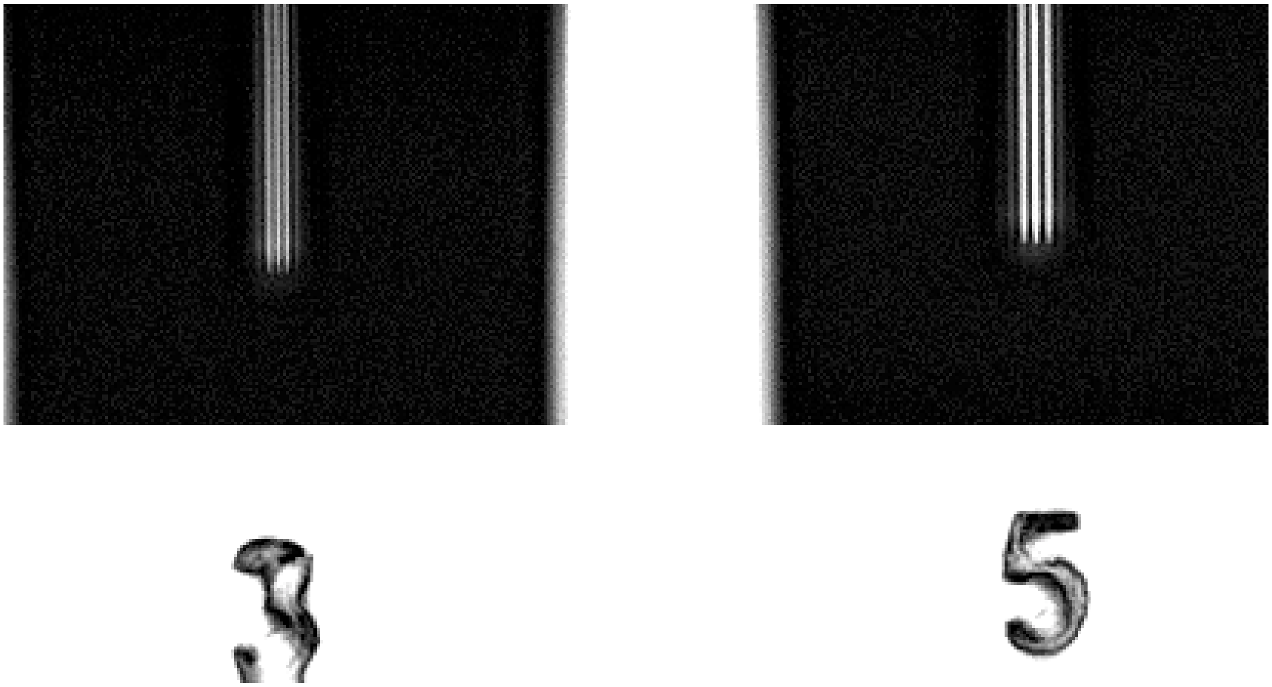

Figure 9: The 3μ and 5μ resolution lines (with 10μ spacing) are shown using a 230 MHz transducer.

SUMMARY

The background provided here discusses the various factors for improving resolution and the improvements in image clarity provide empirical verification. The newly designed resolution test wafer now provides a valid and realistic method of quantifying the improvements. Also, the results with this calibration wafer for acoustic microscopy show that features have been detected beyond what would be expected from simplistic ultrasound theory. The fact that these small features can be detected in a controlled application lends confidence that these size flaws may in some cases be detected in actual devices.

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