Transducer Properties for High-Definition SAT Imaging of Semiconductor Packages

Scanning acoustic tomography (SAT) has been adopted as a prominent, nondestructive inspection technique for microelectronics package quality control and failure analysis. In this article, we review the fundamental parameters of the ultrasound transducers essential to acquiring high-definition images from acoustic tomography.

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Modern electronics continue to shrink in size while their performance improves, as semiconductor packaging evolves from simpler leadframe-based DIPs and QFPs to complicated 3D structures such as system-in-package (SiP) and stacked dies.

To ensure that today's compact but complex electronics function reliably, devices inside are inspected and tested at various stages by applying electronic, visual, optical, x-ray, and acoustic probing technologies.

One standard inspection method for silicon wafers and bare-die is the use of a scanning electron microscope (SEM).

The SEM can detect device dimensional defects and material compositions by imaging the secondary electrons and/or observing x-ray emissions from the specimen.

Finding Flaws

For packaged devices, however, SEMs find very limited application because the electron beam is incapable of probing the flaws which are introduced after dies are encapsulated together with leadframes, wire bonds, solder bumps, etc.

For package interior inspection, x-ray equipment offers real-time projections from virtually any angle. X-ray beams generated from micrometer-size targets can easily resolve gold bonding wires and tiny metal structures without blurring anomalies.

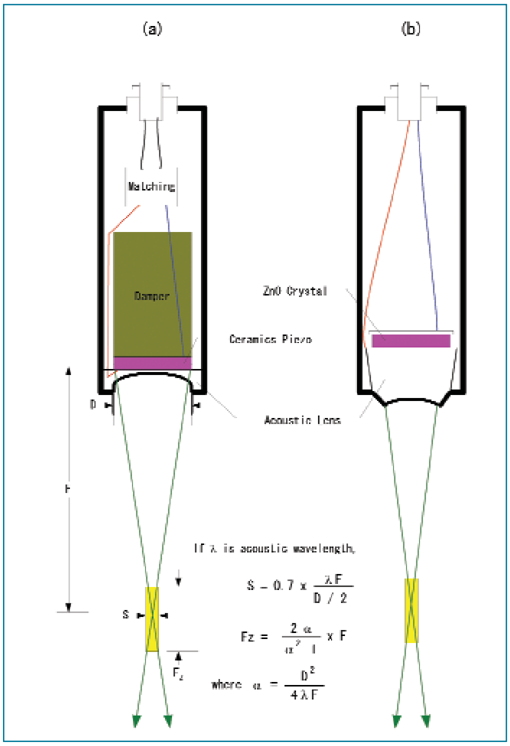
The x-ray, however, is blind to the existence of small air voids or delaminations between two glued material layers where the accumulation of moisture may destroy the device performance overnight.

X-rays may even fail to detect thin layer cracks in stacked dies or multilayer chip structures because these cracks may not induce enough intensity difference to create sufficient contrast in a projected image.

If water moisture and other foreign materials are unintentionally confined inside the package, serious functionality and reliability issues may arise. To prevent this situation, nondestructive inspection by acoustic imaging is often employed in the semiconductor package production line, as well as in the mass production of multilayer ceramic capacitors.

Ultrasound Probe

Most device packages today are built with silicon chips surrounded by various materials, from fine metals to resins and other plastics or polymers to enable electrical operations over a long time. For quality inspection of these packages, imaging with an ultrasound probe is adequate, since this technique visualizes many flaws that are invisible in x-ray images.



Probe designs and parameters

Scanning acoustic probe imaging technology, also referred to as C-mode scanning acoustic microscopy (C-SAM), utilizes the characteristics of ultrasound beams to distinguish a boundary of different materials by observing the amount of energy reflected back from the boundary.

In contrast to continuous x-ray beams, ultrasound beams are usually generated in repeated pulse-train forms. The pulsed beams allow the measurement of time-correlated echo waveforms encoded with valuable information such as layer-to-layer separation, exact depth of voids and their dimensions or volumes.

Because of this time-correlated echo-data availability, we refer to this ultrasonic imaging tool as the scanning acoustic tomograph (SAT).

The information embedded in SAT images is much more than mere planar projection images; since their introduction about 20 years ago, this inspection technology has steadily advanced to become a powerful tool of nondestructive chip inspection.

Acoustic Imaging Systems

Industrial applications for ultrasound begin at a frequency range of 1MHz and above. There are two types of SAT systems currently available. The first is the conventional "single transducer system," consisting of an ultrasonic probe attached to a precision *xyz*-axis scanning mechanism.

This mechanism is controlled by a computer, which also serves as the image-acquisition controller, together with ultrasound generation and echo detection circuits, advanced digital signal processing algorithms and image analysis software.

Figure 1 shows an ultrasound probe attached to a three-axis scanner system being readied to scan a sample immersed in a water medium.

Recently, the second type, a new class of SAT with electronically scanned transducer array, was reported by Takishita et al. This SAT has multiple transducers along the *x*-direction to eliminate time-consuming mechanical travels and thus dramatically improves throughput, satisfying a major requirement of manufacturing lines today.

Three-Axis Scanner

The conventional three-axis scanner offers great flexibility and will accommodate varying sample sizes from tiny chip condensers to over 14-feet FPD sputtering target materials. Regardless of what the sample *XY* size is, the depth of interest in a sample determines the adequate probe frequency and the focal length to be used.

For inspecting molded semiconductor packages, DIPs and QFPs for example, ultrasound frequencies up to 75MHz cover all the requirements for quality assurance and failure analysis purposes.

In the research and development of advanced package designs, including flip chip, CSP, SiP, MEMS and stacked die, however, probe parameter requirements vary, depending on actual sample structure and material combinations.

The user has to select from a wide range of available probe frequencies and focal lengths. General purpose probe frequencies range up to 75MHz, while special high-resolution probes are available from frequencies of 85 to 300MHz. To clarify probe parameter selection, the design basics of two different acoustic probes are described below.

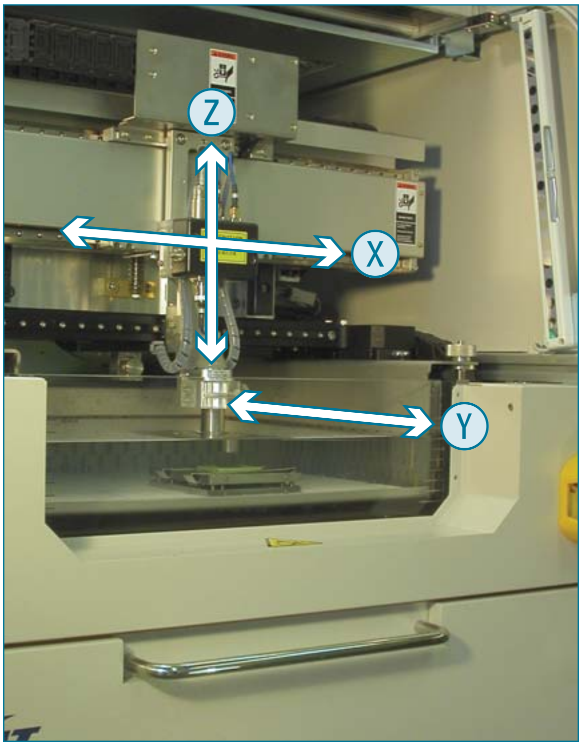


Figure 1. A 3-axis mechanical scanner SAT system; the sample is usually immersed in water and the acoustic probe scans *X-Y* directions to acquire a plane image. When focused cross-sectional images or S-images are acquired, the *Z* direction is also scanned.

Probe Design Parameters

The lead graphic, probe designs and parameters, illustrates the ultrasound transducer for a general-purpose probe and a high-resolution probe, respectively.

A general-purpose probe typically features a fixed-frequency output in the range of 5 to 75MHz, and its piezoelectric material is either ceramics, lead zirconate titanate or another functional polymer that generates ultrasound waves when excited by a hundred volts of electrical pulses.

Since it is ideal to generate one wavelet of ultrasound per electrical excitation pulse, a damper cushion or backing material is usually attached at the back of the piezo material to suppress the after-ringing reflections.

With a carefully designed damper, these lower frequency probes can practically achieve 3 cycles of wavelets per excitation pulse. The effective width of such a pulse-train generated by a 25MHz probe, for instance, is 120ns. This duration essentially determines the *z*-axis resolution, or whether the separation of layers in a given sample would be possible.

Constructing a High-Resolution Probe

To construct a high-resolution probe (as shown in part (b) of the lead image), ZnO crystals are best-suited for generating acoustic frequencies higher than 75MHz.

The crystal is grown on a sapphire lens structure to achieve an excellent 4-cycle pulse-train without a damping effort. The pulse width is about 40ns at a center frequency of 100MHz, which effectively enables separating top and bottom echoes of a resin layer as thin as 0.1mm.

Although beam spot size *S* is a prime parameter in determining the lateral resolution of a SAT image, several factors remain that influence the image definition and quality.

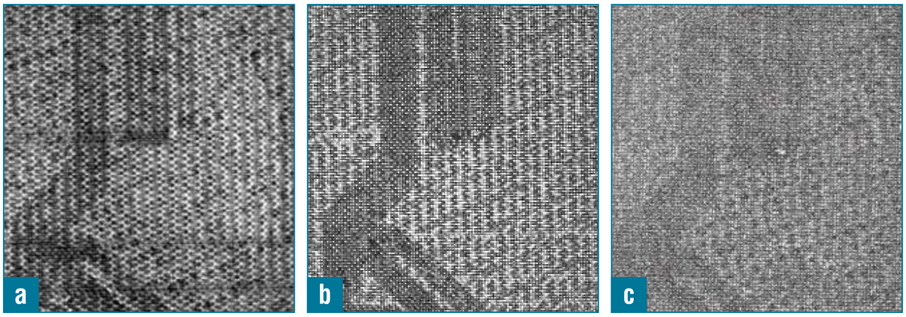


Figure 2. High resolution images of underfill layer using (a) 50MHz, (b) 85MHz, and (c) 200MHz probes

Other than the damping efficiency, which is inherited from the physical design, the total system response—comprised of the sensitivity in detecting low-level echo signals, attenuations of frequency and intensity while traveling in water; signal-to-noise ratio, sampling rate and digital signal processing techniques play crucial roles in constructing informative images.

As a general rule for inspecting today's flip chips and CSPs, the higher frequency probes offer better images to evaluate patterns and voids in underfill and other imperfections around the solder bumps. A perfect acoustic probe should have sufficient depth penetration while it generates pulse-trains narrow enough to separate congested material layers when desired.

The volumetric scan mode opens up a new horizon in the acoustic imaging technology to view the interior of 3D packages from any angle or arbitrary cross-sections, similar to what the medical micro CT tools can do.

Figures 2(a), (b), and (c) show the underfill conditions of a flip-chip package with 725μm silicon die thickness at the probe frequencies of 50-, 85- and 200MHz.

As seen in these images, the reflections from patterns on lower organic substrate layers become weaker as the probe frequency increases, resulting in images with purer signals from the underfill region.

Identifying Small Voids in Underfill

To identify small voids in the underfill material, these images are acquired at fairly high resolution: 10μm pitch or 1800 x 1800 pixels out of the highest possible resolution (8192 x 8192) pixels-per-image.

The 200MHz image 2(c), for example, can be further enlarged and processed to highlight small voids at the middle of adjacent bumps as seen in Figure 3.

At lower frequency inspections, shown in both Figures 2(a) and (b), these very same voids appear together with other signals that originated from upper and lower layers. The blending is because lower frequency probes have wider pulse width and longer depth of field causing the echos of adjacent layers to superimpose on each other.

An alternative analysis technique to cross-check such *z*-axial confusion employs a depth-profile analysis that color-codes the signal peaks to represent the differences in their arrival times. This time based analysis of lower frequency images also clarified the existence of very same voids in between the bumps.

Probe Frequency

If probe frequency is lower, the penetration depth is deeper and the focal length and depth of field are larger, resulting in easier image acquisition.

The first disadvantage of a lower frequency probe is that it has a larger beam spot size, and thus offers lower lateral resolution. Second, the image tends to be a result of superimposed signals from adjacent layers that appear in a wider pulse-width interval.

When *z*-directional resolution is low, the extraction of desired information from the image may be difficult without using an adequate time-resolved signal analysis procedure like the depth-profile analysis.

If a well-designed higher frequency probe is used, image resolutions in all *x-y* and *z* directions are improved, owing to smaller beam spot size and narrower pulse width.

The disadvantages are lower penetration power and shorter focal length. At a frequency of 300MHz, the acoustic waves of normal power and focal length would not reach to the bottom of a few-hundred-micrometer silicon die.

Such very high frequency probes, however, are particularly useful to inspect subsurface flaws, as shown in Figure 4, where surface inspection with optical microscopes and SEMs would have difficulty in finding these flaws.

Recent availability of high resolution probes with long focal lengths greatly enhances the flexibility in SAT imaging

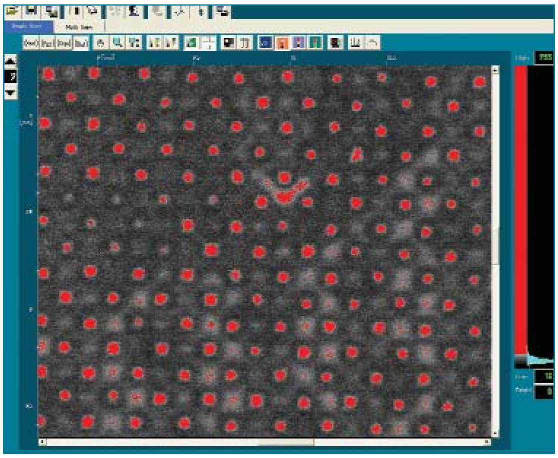


Figure 3. Process screen of 200MHz image in 2(c); Original high-definition image is zoomed in and intensity leveling is applied to highlight underfill voids in the middle of neighboring bumps.

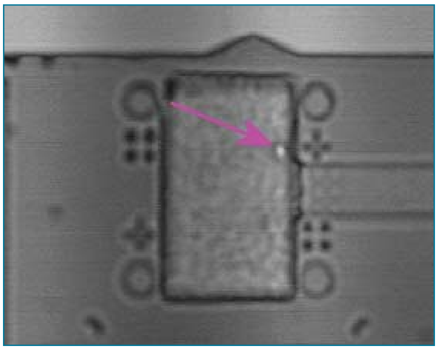


Figure 4. A sub-surface flaw was inspected using a 300MHz probe on the pattern of a silicon IC. The arrow points to a micron-sized flaw on the chip. The arrow length is 200μm.

of thin die flip-chip and Si subsurfaces.

Due to significantly higher ultrasound speed in solid materials, such as silicon crystals compared to the water medium, the effective focal length for a flip chip or CSP-like sample is much shorter.

If voids in underfill below a silicon thickness of 725μm are of interest, it is desirable to use a probe with a focal length more than 7X the die thickness in a flip chip.

The images of Figures 2(c) or 3 are acquired from the thick-die, flip-chip structure with a 200MHz probe with 8mm focal length. Extra attention is required to design such high-frequency output as well as a long focal length probe in its physical structure and beam optics.

It is also important not to compromise the small beam spot size offered in the high frequency region. As a convenient way to evaluate the beam spot size together with the damping efficiency of 200MHz probe, we have inspected a patterned silicon surface drilled with small holes of 1, 2, 3μm sizes by focused ion beam (FIB) apparatus.

Figure 5 shows the SAT image which clearly identifies the 1μm FIB hole and fine lines on the wafer surface. This image confirms that the acoustical beam spot size is smaller than 2μm in diameter.

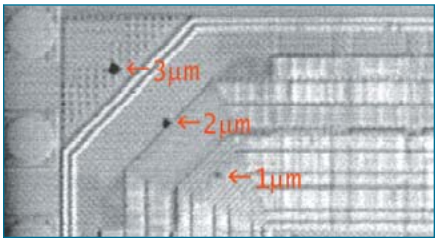


Figure 5. A high-definition image of silicon surface features as acquired by using a 200MHz ZnO probe is shown. A 1μm focused ion-beam-created flaw can be easily seen.

Frequency Selection

In selecting probe frequency for a flip chip, CSP or stacked-dies evaluation, die surface warpage should be taken into consideration. When the arrival time differences across the interface become comparable to the cycle time of wavelets, formations of larger peaks or valleys in the echo waveform occur due to constructive or destructive superimpositions. Acoustically flat surfaces should show no interference from one interface.

Figure 6 demonstrates a real-time volumetric scan of a flip chip visualizing slightly warped die top and bottom interfaces over the organic substrate. In the 3D volumetric scan mode, all waveforms are recorded in digital form, and the images can be reconstructed at any time. This development opens up a new horizon in the acoustic imaging technology to view the interior of 3D packages from any angle or arbitrary cross-sections, similar to what medical micro CT imaging tools can do.

In the other area of applications, lower frequency probes are desired with an efficient damping capability that is able to detect various flaws at very deep levels. To confirm this property, we used a unique two-level flip-chip sample structure in which a 600μm-thick ceramics slab was sandwiched between a 750μm silicon die and an organic substrate. A 50MHz probe with 25mm focal length was used to image the silicon/ceramics and ceramics/organic interfaces.

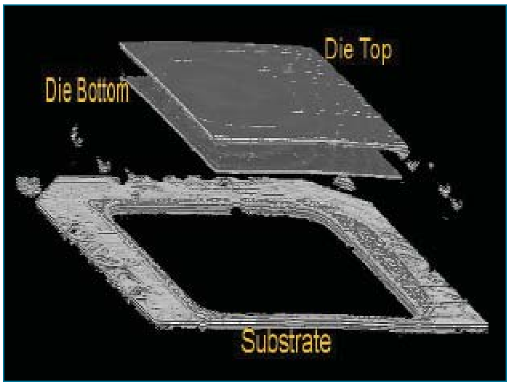


Figure 6. A real-time display of a volumetric scan visualizing flip-chip die top and bottom interfaces is illustrated. All waveforms are recorded in this scan mode to be further processed with advanced analytical techniques like short-time FFT.

The preliminary image of ceramics/organic level exhibited no distinguishable signature to confirm if the probe was adequate for very deep-level imaging. To clarify this, we introduced a flaw at a deeper level by carefully drilling a small hole from the substrate side.

As shown in Figure 7, the drill hole in the organic substrate was detected in the SAT image from the top. This is direct evidence that the bump features in this plane image were from the deep-level ceramics slab and organic substrate interface.

Since imaging multilayer samples always involve multiple reflections, individual interface imaging will be feasible only when acoustic probes with a sufficiently long focal length, the smallest possible beam spot, and high damping efficiency are utilized.

Multiple reflections, interferences, and other ghostly artifacts are much more severe in imaging stacked packages. To image each boundary separately, advanced acquisition techniques involving analysis of high frequency harmonics riding on lower frequency echo waveforms may be required. Therefore, wide system bandwidth that assures high frequency echo detection and a high sampling rate are important parameters to capture all information

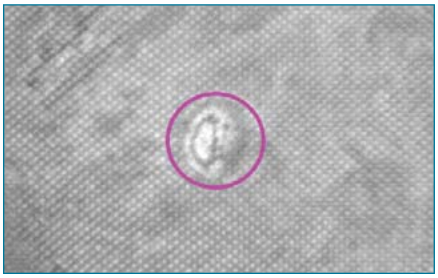


Figure 7. This image of a created deep-level flaw was acquired by using a mid-frequency, long focal length, high-damping efficiency probe.

carried by the reflected acoustic waves.

A waveform data sampled at 2GHz rate and recorded on a hard disk allowed us to retrieve 3D views, as well as to perform powerful spectroscopic techniques such as short-time FFT and Haar wavelet transformation, relative phase-shift, etc., making ready to extract more information from SAT images of complex structures.

Conclusion

We have presented the fundamental parameters of acoustic transducer designs for high-definition SAT image-acquisition technology.

An acoustic probe must have a small beam spot size, excellent damping efficiency and a focal length that is long enough to acquire high-definition images with the needed information.

For a particular package structure, the selection of a proper probe frequency combined with intensity and time-correlated echo waveform processing routines characterizes the details embedded in the SAT images. Several flip-chip packages and silicon dies were inspected using different probe parameters to demonstrate the probe selection criteria.

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References

Y. Takishita, H. Kino, S. Yamaguchi, A. Iwasaki, and N. Yamamoto, "*Development of High-Speed Ultrasonic Testing Device Using Electronic Scanning*," *Acoustical Imaging*, Vol. 22, Plenum Press, New York, 1996.

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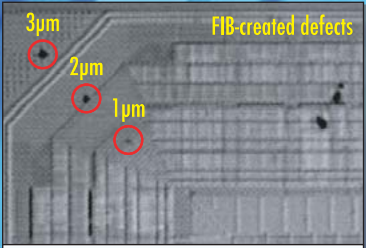

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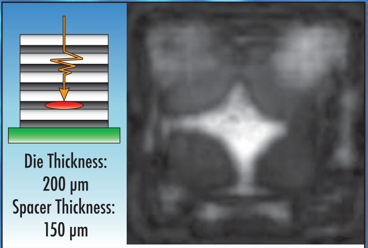

FineSAT image of a multi-layer SIP-style package with an intentionally-introduced delamination

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