Featured Articles

Ultrasonic Imaging of Microscopic Defects to Help Improve Reliability of Semiconductors and Electronic Devices

—Scanning Acoustic Tomograph—

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OVERVIEW: Hitachi Power Solutions' SAT is an instrument that uses ultrasound to nondestructively detect and image defects such as cracks and delamination in semiconductors and other electronic devices. To achieve high inspection image resolution, it uses an acoustic lens to create a focused beam of ultrasound that is transmitted into the object of inspection. As electronic devices become increasingly compact, measurement images need to have higher resolution and definition. To meet these needs, Hitachi Power Solutions' SAT achieves higher resolution by incorporating an instrument that emphasizes the high-frequency components of the ultrasound transmitted to the object of inspection. This improves detectability from the conventional limit of about 2.5 to 4 µm, to 1 to 1.6 µm. And, by incorporating a process that performs deconvolution by considering the intensity distribution of the focused ultrasonic beam that is transmitted, resulting in a 60% improvement in contrast and a higher-definition inspection image.

INTRODUCTION

TODAY'S ever lighter, thinner, and smaller consumer products are resulting in semiconductors and other electronic devices with increasingly complex and scaled-down structures and package formats. A scanning acoustic tomograph (SAT) uses ultrasound to nondestructively detect cracks, delamination, and voids in these electronic devices, which is crucial for ensuring reliability. However, as electronic devices become smaller, measurement images need to have higher resolution and higher definition.

Hitachi Power Solutions Co., Ltd. has developed and manufactured original SATs to meet these market needs. The fourth-generation of the series was released in April of 2015 (see Fig. 1) and supports 5 to 300 MHz probes.

SAT: scanning acoustic tomograph

Fig. 1—Fourth-generation of Hitachi Power Solutions' SAT.
The photo shows the fourth generation of Hitachi Power Solutions' SAT (with options attached).

OVERVIEW OF HITACHI POWER SOLUTIONS' SAT

Principles of Ultrasound-based Defect Detection

SATs use differences in acoustic impedance (an indicator of how easily sound passes through a medium) to image defects. As shown in Fig. 2, when ultrasound is transmitted into a specimen containing a layer of medium 1 and a layer of medium 2, reflection and transmission occur at the interface between the layers. The reflected wave intensity (R) is given by equation (1) below.

$$R = \frac{Z_2 - Z_1}{Z_2 + Z_1} I \quad (1)$$

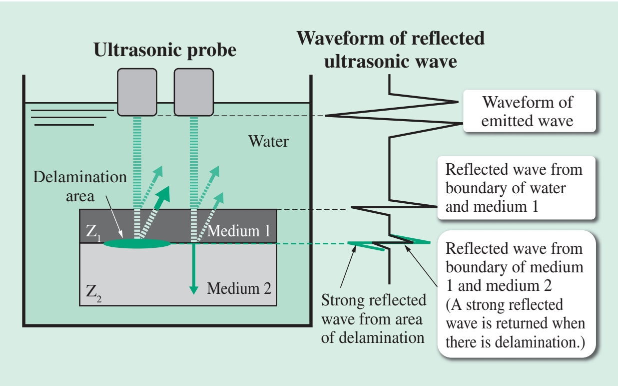

Fig. 2—Principles of Defect Detection Using Ultrasound.
The difference in the intensity of the reflected wave from the boundary between medium 1 and medium 2 is imaged by varying gray scale shades.

Here Z_1 and Z_2 are the acoustic impedances of medium 1 and medium 2 respectively, and I is the incident wave intensity. SATs acquire a measurement image by rapidly scanning the ultrasound while displaying its reflected wave intensity or transmitted wave intensity at each point as gray scale shades. The measurement method using the reflected wave is called the reflection method, and the measurement method using the transmitted wave is called the through transmission method.

Acoustic impedance is highest for solids, lower for liquids, and even lower for gases. The acoustic impedance of gases is more than three orders of magnitude lower than that of solids. Due to this large difference in acoustic impedance, delamination areas, and voids reflect nearly 100% of the incident wave, providing a large contrast with the surrounding area in reflection method images, and making defect detection easy. Gaps of 5 nm in the direction of the delamination depth are considered detectable[1].

Probe Resolution

A probe is a device that sends and receives ultrasound by using a piezoelectric element to transform electrical signals into mechanical vibrations, or inverse-transform mechanical vibrations into electrical signals. Since high resolution is required for inspecting electrical devices, the probe has an acoustic lens at its tip that is used to transmit a focused beam into the specimen. The beam spot size diameter in water d_{-6} is given by equation (2) below, from the focal distance F, and the acoustic lens aperture diameter D.

$$d_{-6} = \alpha \frac{\lambda F}{D} \qquad (2)$$

Here α is a coefficient, and λ is the wavelength of the ultrasound in water. The speed of sound in water v and the frequency of the ultrasound f are expressed by equation (3) below.

$$\lambda = \frac{v}{f} \qquad (3)$$

The ultrasound emitted from the probe is not a single frequency. Instead, it has a waveband with a peak at a particular frequency, so f is considered to be this peak frequency.

Equation (2) indicates three methods of improving probe resolution: Reducing the wavelength (i.e., increasing the frequency), reducing the focal distance, and increasing the aperture diameter. However, in practice, two of these methods (reducing the focal distance and increasing the aperture diameter) are sometimes ineffective for nondestructive inspection. When the aperture diameter is increased, refraction will occur according to Snell's law in the course of propagating the ultrasound into the specimen from water. As a result, even if the aperture diameter is increased, only the ultrasound emitted from the center of the lens will actually penetrate into the specimen. Reducing the focal distance is only effective for defects near the surface. Accordingly, frequency is the key to high-resolution/high-definition measurements.

RESOLUTION-ENHANCING TECHNOLOGY

Principles of Resolution-enhancing Technology

As described in the previous chapter, increasing the frequency is the key to enhancing resolution. Hitachi Power Solutions has therefore developed a high resolution (HR) unit that narrows the bandwidth of the frequency components of the ultrasound emitted by the probe and shifts its frequency higher. It can be connected to Hitachi Power Solutions' SATs as an option. Fig. 3 shows a block diagram of when the HR unit is connected. When the HR unit is connected, it is equipped with the standard transmitter along with the HR unit for high-resolution measurement, and is configured to enable either device to be selected from the personal computer (PC) used to set the measurement conditions.

Fig. 4 shows fast Fourier transforms (FFTs) of the reflected wave signal obtained from the same location at the interface between a flip chip/chip scale package (FC/CSP) large-scale integration (LSI) silicon chip and its underfill resin, using a probe with a nominal

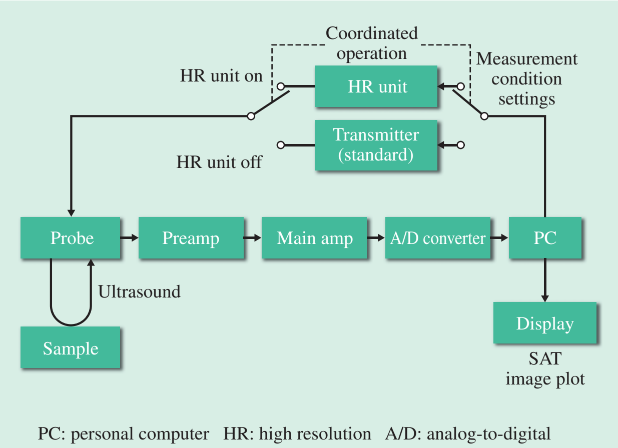

Fig. 3—Block Diagram When Optional HR Unit is Connected.
The HR unit has a function that narrows the bandwidth of the frequency components of the ultrasound emitted by the probe and shifts its frequency higher.

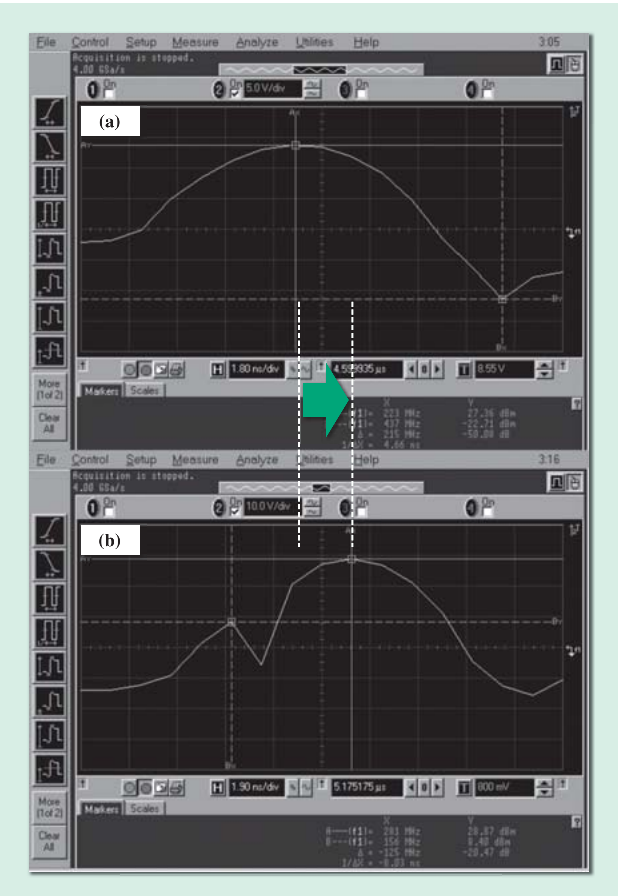

Fig. 4—Narrowing Bandwidth and Increasing Frequency of Transmitted Ultrasound Using the HR Unit.
The graphs above show fast Fourier transforms (FFTs) of the spectrum of the reflected wave signal obtained from the same location at the interface between a flip chip/chip scale package (FC/CSP) LSI silicon chip and its underfill resin, using a probe with a nominal frequency of 250 MHz and a focal distance of 2.9 mm. Graph (a) is the graph obtained when the HR unit is off. Graph (b) is the graph obtained when the HR unit is on.

frequency of 250 MHz and a focal distance of 2.9 mm. When the HR unit is used [Fig. 4 (b)], the peak frequency shifts to 281 MHz, compared to 223 MHz when it is not used [Fig. 4 (a)].

Benefits of Resolution-enhancing Technology

Fig. 5 shows the cross-section of a sample of bonded silicon wafers used to evaluate the HR unit. The sample was created by making grooves 170 nm deep and 1 to 300 µm wide on a silicon wafer, and bonding another silicon wafer on top of the first wafer. Fig. 6 shows the SAT image measured by switching from the standard transmitter to the HR unit during measurement of the bonded silicon wafer sample. The probe used had a nominal frequency of 250 MHz and a focal distance of 1.2 mm, and was focused on the bond interface. The HR unit improved the signal to noise ratio, and improved the contrast between bonded and unbonded parts (indicated by the ellipse in the diagram). As a result, the 2.5 µm and narrower grooves that were almost undetectable without using the HR unit could be detected by using the HR unit (indicated by the circle in the diagram). However, since the 4 µm and narrower grooves were smaller than the ultrasound's beam spot diameter, they all appeared to have the same width.

Fig. 7 shows the SAT image created by observing the interface between the FC/CSP LSI silicon chip and its underfill resin under the conditions of Fig. 4. The image acquired when using the HR unit [Fig. 7 (b)] has detected a more minute defect (indicated by the circle in the diagram) than the image acquired without using the HR unit [Fig. 7 (a)].

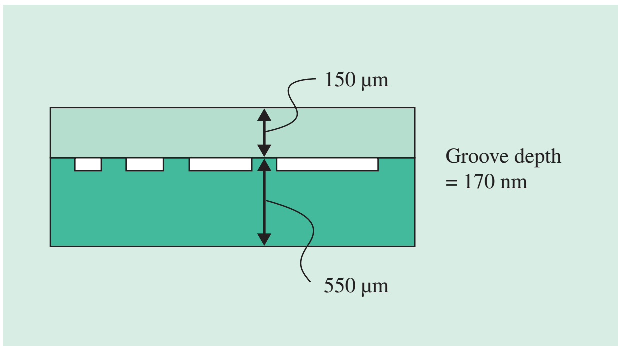

Fig. 5—Cross-sectional Structure of Bonded Silicon Dummy Sample.
The sample was created by making grooves 170 nm deep and 1 to 300 µm wide on a silicon wafer, and then bonding another silicon wafer on top of the first wafer.

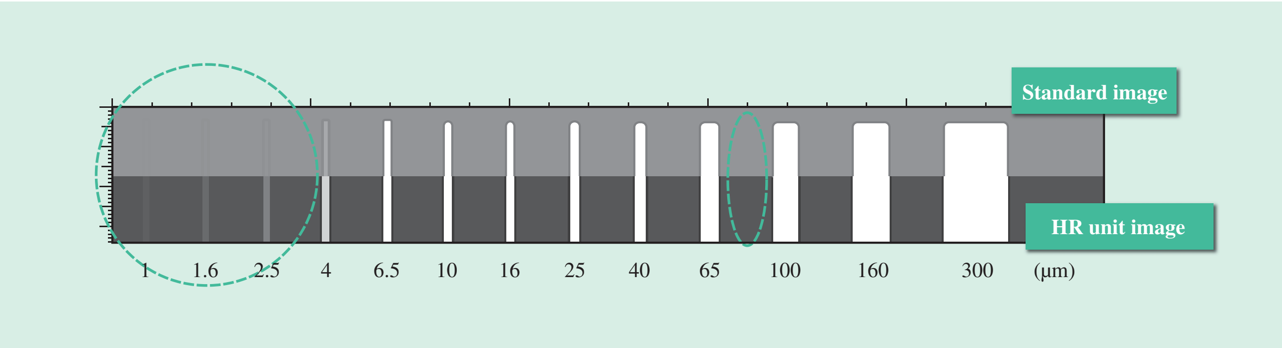

Fig. 6—Improved Detectability Using the HR Unit.
The diagram shows example observations of the bonded silicon sample made using a probe with a nominal frequency of 250 MHz and a focal distance of 1.2 mm. During measurement, the measurement method was switched from the standard method to measurement using the HR unit. The top half shows the standard measurement results. The bottom half shows the results of measurement using the HR unit.

IMAGE RESTORATION TECHNOLOGY

Principles of Image Restoration Technology

High-definition image acquisition is achieved by reducing the beam spot diameter given by equation (2). However, even when the beam spot diameter is reduced, the outlines displayed in SAT images are blurred as a result of the ultrasound intensity distribution in the diameter direction. This blurring results in small defects being missed. To address this problem, Hitachi Power Solutions has developed image restoration technology that is provided as an optional function. It uses image processing to remove blurring from SAT images.

The SAT image $O(x, y)$ can be modeled by the following equation[(2)]:

$$O(x, y) = G(x, y) \otimes X(x, y) + N(x, y) \quad (4)$$

Here x, y are the coordinates in the image, $X(x, y)$ is the ideal image that should be obtained, $N(x, y)$ is noise, and $\otimes$ is an operator that performs position convolution. $G(x, y)$ is the ultrasonic intensity distribution (the point spread function, PSF) of the beam spot that causes blurring. The beam spot diameter d_{-6} can be calculated from equation (2) using the specifications of the probe used to acquire the image, and $G(x, y)$ can be approximated by the Gaussian distribution given by equation (5) below.

$$G(x, y) = \frac{1}{2\pi d_{-6}^2} exp\left(-\frac{x^2 + y^2}{2d_{-6}^2}\right) \quad (5)$$

The ideal image with blurring removed $X(x, y)$ is obtained by removing the noise $N(x, y)$ from the SAT image $O(x, y)$, and using the PSF to perform deconvolution[(3)].

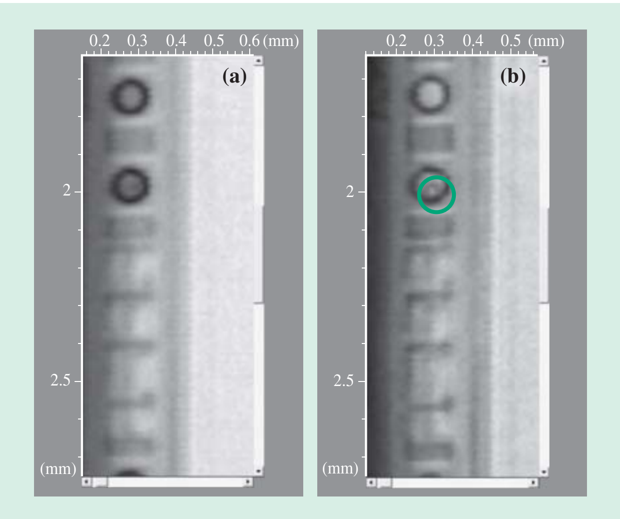

Fig. 7—Improved Detectability on Actual Sample Using the HR Unit.
The images above show the results of example observations of the interface between an FC/CSP LSI silicon chip and its underfill resin, made using a probe with a nominal frequency of 250 MHz and a focal distance of 2.9 mm. Image (a) shows the result of standard measurement. Image (b) shows the result of measurement using the HR unit.

Benefits of Image Restoration Technology

Figs. 8 (a) and 8 (b) show a SAT image, and the restored image created from it, using image restoration technology. The SAT image was created by observing the interface between an FC/CSP LSI silicon chip and its underfill resin, using a probe with a nominal frequency of 200 MHz and a focal distance of 6.9 mm. Figs. 8 (c) and 8 (d) show the signal strength distribution between points A and B in the images of Figs. 8 (a) and 8 (b). The round shapes in the SAT

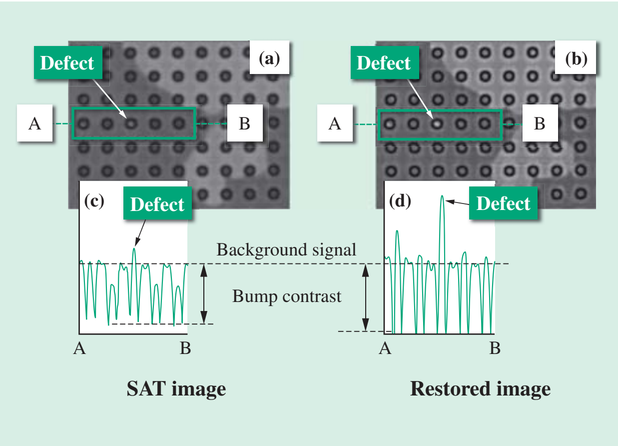

Fig. 8—Using Image Restoration Technology to Reveal Defects.
The images above show the results of applying image restoration technology to the result of an observation of the interface between an FC/CSP LSI silicon chip and its underfill resin, made using a probe with a nominal frequency of 200 MHz and a focal distance of 6.9 mm. Image (a) is the SAT image before applying the image restoration technology. Image (b) is the restored image after applying the image restoration technology. Graph (c) shows the signal strength distribution between points A and B in the SAT image before applying the image restoration technology. Graph (d) shows the signal strength distribution between points A and B in the restored image after applying the image restoration technology.

image [Fig. 8 (a)] represent solder bumps. The area displayed as a defect in Fig. 8 (a) appears slightly lighter than the other bumps, representing a cracked bump. As shown in Fig. 8 (c), it has about the same signal strength as the background signal strength, making it difficult to identify as a defect. However, as shown in Fig. 8 (b), it was possible to find a clear bright spot in comparison to the background image in the restored image created using image restoration. The background signal strength shown in Figs. 8 (c) and 8 (d) is the same, however, the signal strength of the defect was found to be 60% higher.

CONCLUSIONS

This article provided an overview of Hitachi Power Solutions' SAT, and discussed the resolution-enhancing technology and image restoration technology it uses. These technologies improve the detectability of defects that were previously difficult to detect with conventional technology.

The electronic devices used as specimens are expected to become smaller, more multilayered, and more complex in the future. Hitachi Power Solutions plans to continue improving their product's hardware and software and developing new technologies to enable increasingly difficult-to-detect defects to be reliably identified.

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