

Acoustic microscopy – a powerful tool to inspect microstructures of electronic devices

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ABSTRACT

Due to the requirements of new semiconductor technologies and devices the structures of semiconductor chips are getting smaller and smaller and the layered constructions are getting more complex. The inspection of these small and thin structures leads to new demands on the NDT methods (non destructive testing), especially in lateral and depth resolution. X-ray tomography as one inspection method has limitations to detect special types of cracks and delaminations in general. New developments in Scanning Acoustic Microscopes (SAM) are able to detect cracks, delaminations, and other non homogeneities with improved image quality and resolution. Modern systems use frequencies between 3 MHz and 2000 MHz and are designed to detect defects even in the sub micron and nm range. In combination with new scanning units providing step sizes of less than 0.1 μm , new modified transducers and special software functions, new SAM's inspect microelectronic devices fast, reliable and showing defect resolution and image contrast which have never been observed before.

TECHNICAL OVERVIEW

Scanning acoustic microscope technologies provide systems for low frequency investigations from 1 MHz up to 100 MHz, higher sophisticated systems cover a middle frequency range from 100 to 400 MHz, and finally high end systems up to 2 GHz. Generally, the low frequency SAM's dedicated for volume and depth inspection, where penetration is important, whereas mid and high frequency SAM's can be used for sub surface and low penetration applications with higher resolution requirements. The new application demands caused the development of acoustic objective lenses and new transducer technologies, where the specific selection of frequency, bandwidth, opening angle and the radius of curvature for the focal distance have to be taken into account. Today, the operation of instruments combines a dedicated graphical user interface, special data acquisition and image analysis software (Fig. 1) [4]. User friendly operation is an important key feature for semiconductor failure analysis and process control applications. Acoustic microscopy gives the advantage to inspect samples nondestructively in different "cuts", like the B-scan, which is a cross section through the sample, or the C-scan, which gives an acoustic image of a selected layer. Besides these special scan types, G- and X-scans allow to "cut" nondestructively the samples interior in specific selected layers and therefore provide a precise location method for the defects (Fig. 2). Defects in electronic devices like flip chips, chip-on-board or chip-on-flex are typical samples with layered structures dedicated for SAM inspection (Fig. 3). The new developed instruments have linear motion x-y-scanners combined with optical encoders providing scanning ranges from 250 μm up to 300 mm. Special ultrasonic auto focus systems compensate changes of sample and surface flatness.

These new linear motion scanners achieve scanning speeds up to 1m/sec and 10m/sec² acceleration. New developments acquire images up to 32.000 x 32.000 pixels per image, which provide in combination with new high specific linear scanning systems a resolution from 128 x 128 pixels up to 32000 x 32000 pixels (Fig. 4a/b). Special developed transducers with a center frequency of 200, 300, 400 MHz or higher can be used for best image resolution in combination with this scanner system only.



Fig. 1: SAM EVOLUTION II: Designed to operate in the frequency range from 3 MHz up to 400 MHz. It combines a high-speed high-resolution linear scanning system, a new developed high frequency electronic unit and a user friendly graphical working interface. A set of transducers is available for different types of applications.

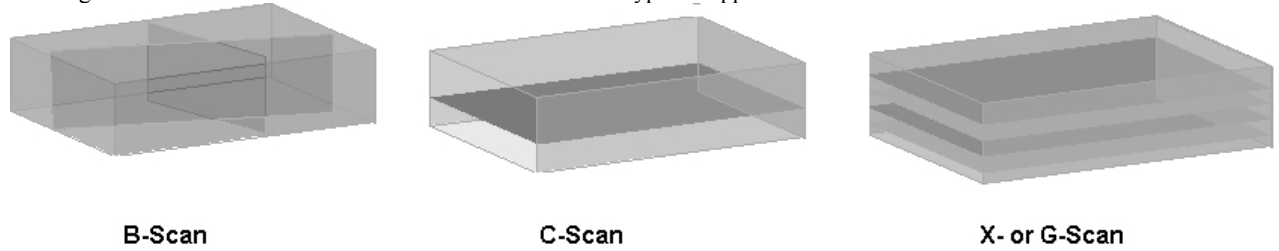


Fig. 2: Schematic drawing of B-, C-, X and G-scans. For X- and G-scans the number and the thickness of the specific layers can be selected by the width and position of the gate in the time of flight window (A-scan).

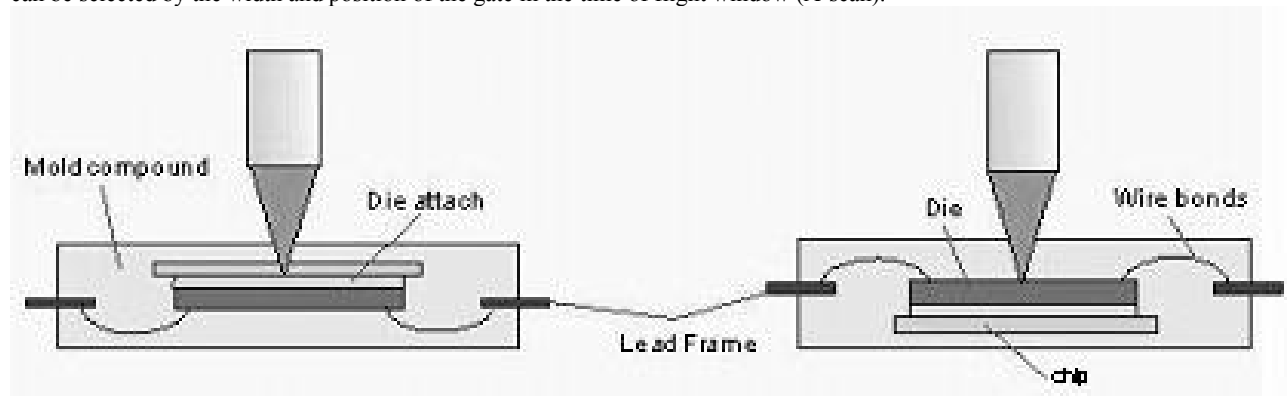
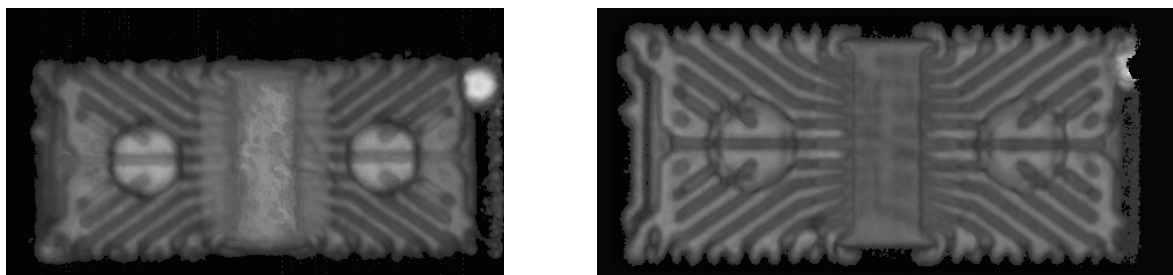


Fig. 3: Ultrasonic inspection of a flip chip from both sides of the sample.



a) b)
 Fig. 4: Comparison between a conventional stepper motor scanning system (a) and a new developed linear motion scanner system. Due to the smaller step width of the linear motor scanner system and its high precision mechanical linear guide ledge, the resolution of the acoustic image (b) is higher than the image (a) taken with a commercial step motor scanning system. For both images the same transducer (50 MHz center frequency) and the same gate settings were used. The scanning area is 18.2 x 8.5 mm².

2. RESULTS

In addition to the well known A-, B-, and C-Scans the new generation of SAM offers also other scan types like the X-Scan and G-Scan. Here, the sample interior is “cut” in layers during the scan. The signals are determined depending on the time gate settings. For the G-Scan the gate settings can be chosen individually including automated gain adjustment due to higher sound wave absorbability inside a specimen. Due to the software the number of scans for the X-Scan is defined by the width of the B-Scan gate divided by the width of the C-Scan gate. The gate settings for the different scan types can be chosen in the respective time of flight information.

Depending on the critical defect size and defect depth the working frequency has to be chosen as well as the transducer design. Important parameters are: the bandwidth corresponding to the depth resolution, the center frequency responsible for the lateral resolution (example in Fig. 6) as well as the focal length corresponding with the penetration depth possible [2]. To detect very small defects, special transducers and under certain circumstances acoustic objective lenses with a large opening angle to generate surface acoustic waves (SAW) are useful. However, besides the frequency, the material depending attenuation of the ultrasonic wave is another influence. The attenuation increases with the square of the frequency resulting in a reduction of the penetration depth into the sample at higher frequencies.

The data acquisition and the image analysis are embedded in the graphical user interface software. All scanning and gate setting parameters are stored with the acoustic image information. The time to collect an acoustic image depends on the scanning speed, the selected scanning size and the pixel number of the acoustic image. Typically the acquisition time is approximately 30-60 seconds for a scan size of 20 x 20 mm². Images with a size up to 32,000 pixels for one line can be collected with additional hardware expansion (memory).

To increase the contrast of weak structures or defects in the acoustic image new software embedded filter functions are available, like a median filter for noise reduction, smoothing, sharpening, DCE, Emboss or edge enhancement. (Fig. 5).

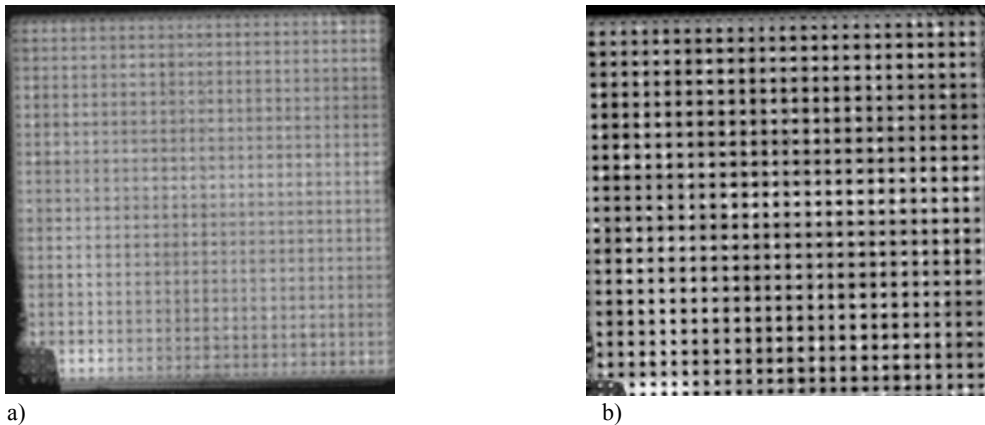
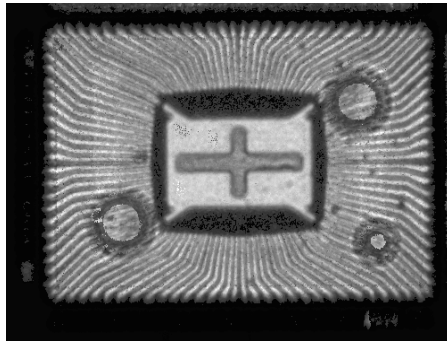
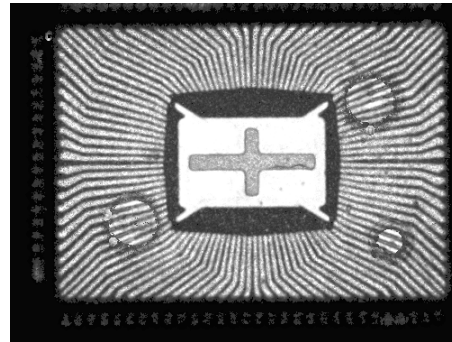


Fig. 5: Acoustic image of a flip chip. The left image (a) is the original acoustic image. Bright areas represent delaminated areas of the flip chip. The right image (b) is the modified acoustic image using a special developed image algorithm to highlight defects using SAM image analysis software for acoustic microscopy. The delaminated areas are stronger in contrast. All delaminations are visible.

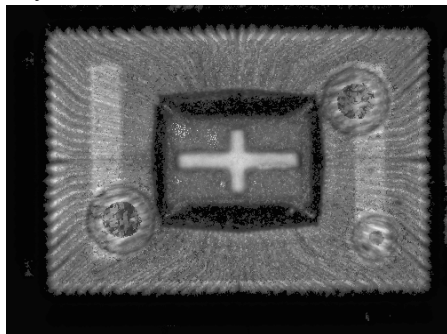
One of the most important functions is the possibility to investigate **all layered structures** in an electronic device during **one scan** using the **X-scan** or **G-scan** function. This allows the fastest inspection of the whole interior of the sample (Fig. 6). The defect depth and location can be determined immediately as well as a characterization of defect type due to the respective shape of the ultrasonic signal. Delaminations or voids are indicated by a phase shift of the ultrasonic signal.



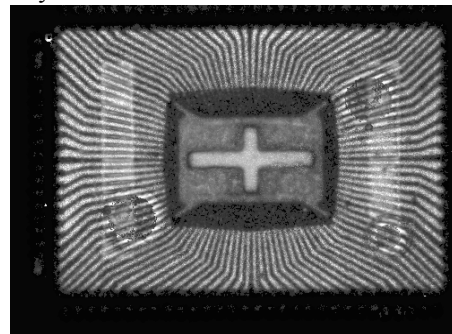
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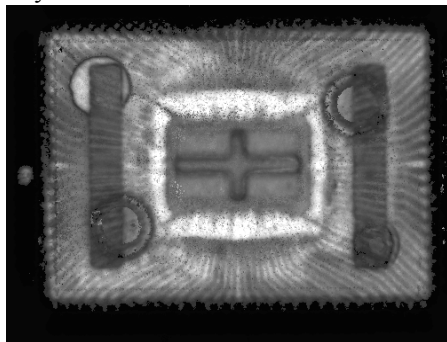
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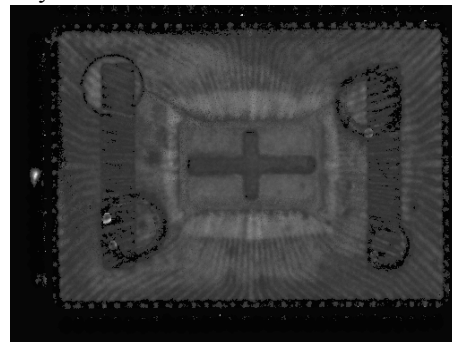
Layer 2 a



Layer 2 b



Layer 3 a



Layer 3 b

Fig. 6: Layered structure of an IC. The gates are set so that all layers are inspected separately during one scan. The scanned area is 22.7 x 17.1 mm². The center frequencies of the transducers used are 50 MHz (a) and 80 MHz (b).

Proper **encapsulation** requires that encapsulates, which are viscous liquid epoxies, are applied to substrates, circuit boards, or flexible circuits in precise amounts using heat to ensure complete flow and adhesion. Properly applied, encapsulates offer low thermal expansion and resistance to moisture and chemicals. Typical defects here, are delaminations between encapsulates and substrate reducing the thermal heat exchange, cracks and voids in the epoxy allowing the penetration of aggressive fluids into the sample and causing corrosion of the electronic device (Fig. 7).

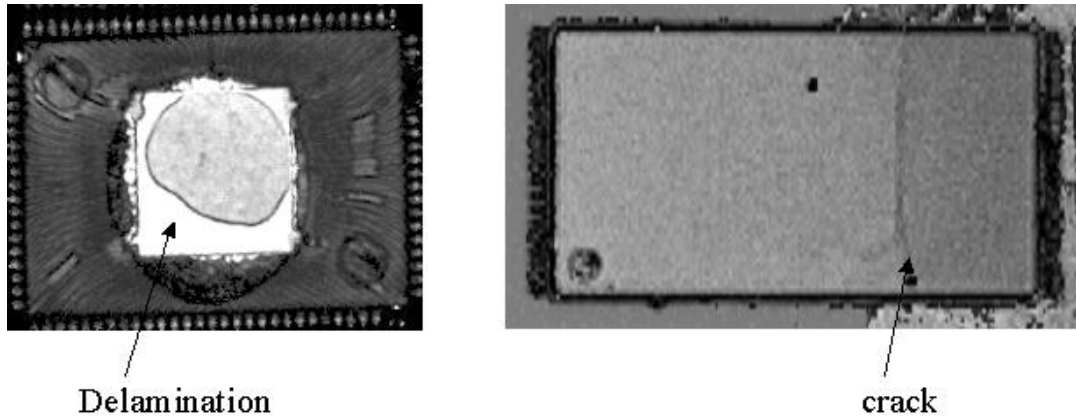


Fig. 7: Defects in the encapsulation: a) shows a delamination between the die top and the encapsulates, where the thermal heat exchange is disturbed. b) Presents a surface crack in the encapsulates, where aggressive fluids might penetrate.

Using a special transducer lens design with a large opening angle of the curvature, surface acoustic waves (SAW) were generated, which are very sensitive to surface and surface near defects (Fig. 8) [3]. These transducers are available up to 2 GHz. Distilled water usually is used as the coupling medium. Depending on the material under investigation, other fluids are possible.

The resolution of the microscope is determined by the refraction index n of the sapphire delay rod and the used coupling medium. It is given by the ratio of the longitudinal sound velocities of both materials. For distilled water $n = 11.2 / 1.5 \approx 7.5$, much larger than that of objectives in optical microscopes. Therefore, the ultrasound is focused to nearly one point, resulting in a resolution of approximately $\lambda/4$, the wavelength in the coupling medium. At 1 GHz the wavelength λ is 1.5 μm . The opening angle of the acoustic lens is 100° , enclosing the critical angle λ_R for most of the materials. An ultrasonic wave incident under the critical angle generates a surface wave, usually a Rayleigh wave (Fig. 8).

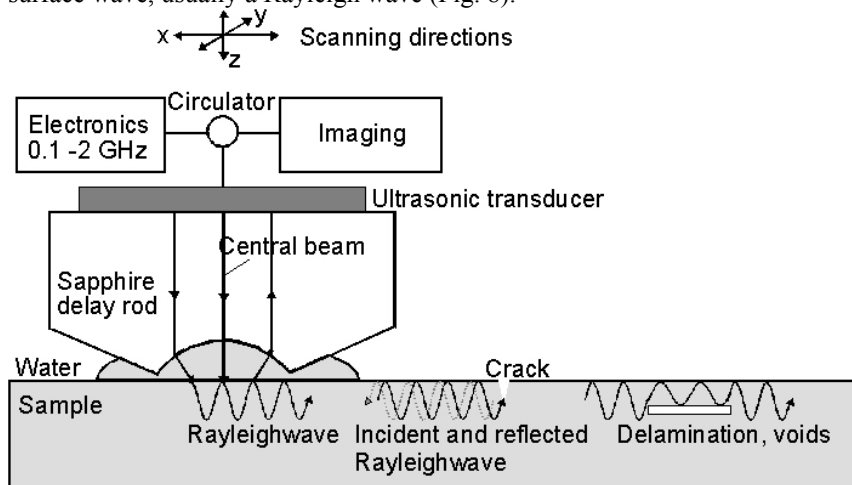
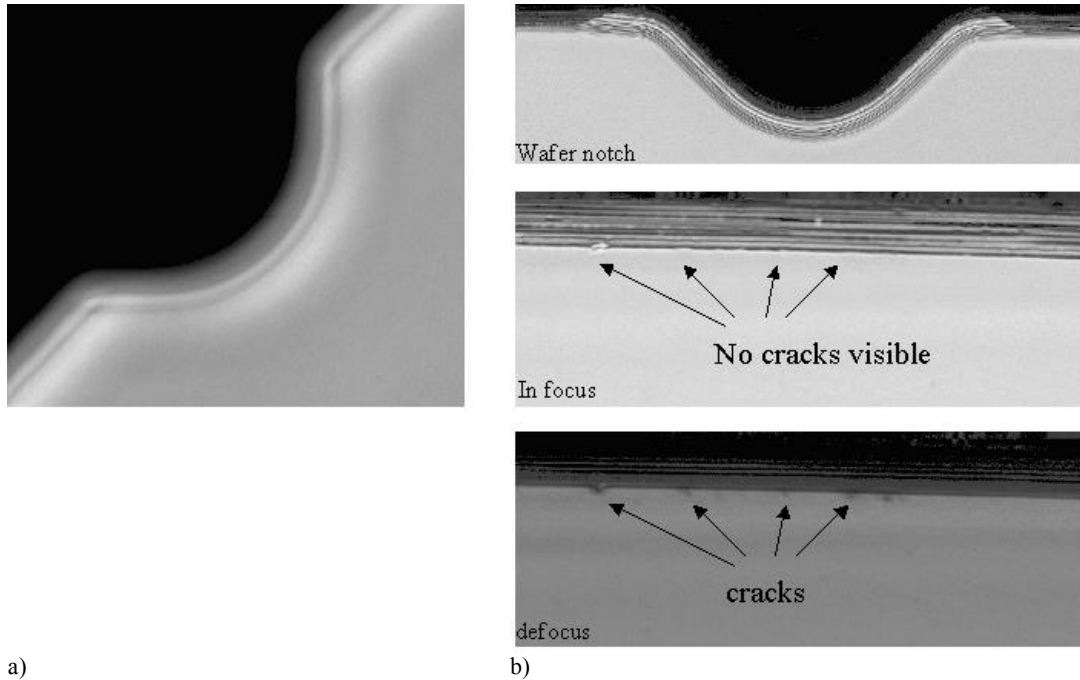
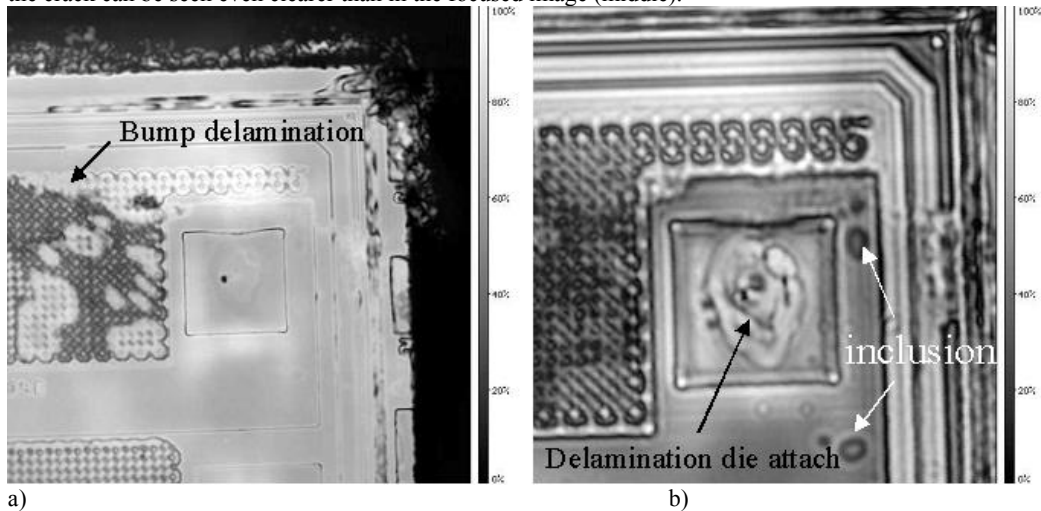


Fig. 8: Principle of surface acoustic wave generation and defect detection. Due to the large opening angle of the curvature surface acoustic waves were generated under the material characteristic critical angle. Surface acoustic waves are very sensitive to surface non homogeneities like cracks or surface near delaminations. However, surface roughness disturbs the surface acoustic wave leading to multiple reflection of the SAW. Therefore, the sample surface should be polished and be flat and even, ideally.

Its penetration depth is approximately one wavelength corresponding to a few microns at 1 GHz. Thus even defects in the sub micron range can be detected. However, due to the high frequencies used, this transducer application is limited to the surface or surface near region of the sample. Special demands on the surface topography are given as well. To get best results the surface has to be well polished and flat and even. These demands are fulfilled for wafers ideally. With this technique it is possible to find cracks with crack openings smaller than 1 μm . Surface near in homogeneities like cracks, delaminations, voids, or inclusions are, due to their different elastic properties from the surrounding material, disturbances for the ultrasonic wave. For example, the ultrasonic wave is reflected at open cracks, where the crack walls are not in contact (Fig. 8). The reflected ultrasonic wave interferes with the incident ultrasonic wave resulting in interference fringes around the crack. Even cracks with crack openings smaller than the resolution of the acoustic microscope can be detected if the crack length and depth is larger than the resolution. Some of the cracks detected with acoustic microscopy were optically not visible (Fig. 9). Delaminations or inclusions at the die attach or bumps could be detected (Fig. 10).



a) b)
 Fig. 9): Inspection of a wafer with a) a conventional transducer (center frequency 80 MHz) and b) a SAW transducer (center frequency 100 MHz). The crack cannot be detected with the conventional transducer, but a SAW transducer (100 MHz center frequency) is able to image cracks clearly, even if the crack opening is smaller than 1 μm . In the defocused image (bottom) the crack can be seen even clearer than in the focused image (middle).



a) b)
 Fig. 10): Inspection of a wafer with defects in the die attach a) In the near surface area image delaminations around the bumps are detected. b) A large delamination with an inclusion is under the die attach, which can be seen in the defocused image of the interface of the die attach. The inspection frequency was 400 MHz. The image size is a) 500 x 500 μm^2 and b) 312 x 312 μm^2 .

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