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

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ABSTRACT

To increase the efficiency of electronic devices their structures are getting smaller and the layered constructions are getting more complex. The inspection of these small and thin structures gives new demands on the NDT, especially in lateral and depth resolution. High-end X-ray tomography is one inspection method, which allows to detect cracks or delaminations. However, it is time consuming. Ultrasonic techniques are able to detect cracks, delaminations, and other inhomogeneities, too. Acoustic microscopy is the high-end application of ultrasonic techniques. Using frequencies between 1 MHz and 1000 MHz (1 GHz) it is possible to detect defects even in the submicron-range. In combination with scanning units with a resolution of 0.1 µm, modified transducers and special software microstructures of layered electronic devices can be inspected very fast. This method will be presented at several examples of semiconductor devices. It will be shown, that inline-inspection with acoustic microscopy is possible.
Keywords: Ultrasonic techniques, Acoustic microscopy, nondestructive testing, semiconductors

1. INTRODUCTION

Since several decades ultrasonic techniques are wellknown. According to the increasing demands the application fields are wide spread from defect detection in large components to defect detection and characterization in the µm range resulting in a variety of different types of ultrasonic instruments modified for the different demands. Especially for inspection of small structures like in electronic devices the demands in accuracy of the scanning system, as well as in imaging characterization techniques and operation comfort are very high. The acoustic microscopes presented in this paper belongs to the type of microscope with the most efficient scanning systems as well as ultrasonic transducers covering most of the application demands.

2. TECHNICAL BACKGROUND

One can distinguish between acoustic microscopes at lower frequencies starting at 1 MHz to 100 MHz, a middle frequency range from 100 to 400 MHz, and acoustic microscopes in the high frequency range starting at 100 MHz to 2 GHz. Generally, the low frequency acoustic microscope allows to inspect the volume of a component whereas the high frequency acoustic microscope can be used for surface and surface near inspection of components. Beside this the type of the transducer to be used depends on the intended application. Here the frequency, bandwidth, opening angle and the radius of curvature for the focal distance are some of the points, which have to be taken into account. Today, the handling of most of the instruments is computer controlled, as well as data acquisition, analysis and documentation. Some of the acoustic microscopes are controlled by graphical user interfaces (Fig. 1) [1]. This is very comfortable for the user and even allows persons, which are not familiar with the ultrasonic technique quickly to learn controlling the instrument. 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 layer of the interior of the sample. Beside these special scan types, like G- and X-scans allows to “cut” nondestructively the samples interior in layers and therefore to get an overview of the depth and location of defects inside the sample (Fig. 2). Electronic devices like flip chip, chip-on-board or chip-on-flex are samples with layered structures ideally to be inspected by acoustic microscopy (Fig. 3).

2.1 Scanning systems

Most of the instruments have x-y-scanners with scanning sizes between 60 µm and 1 m. The z-direction is moved by hand or is motor controlled with a newly developed ultrasonic autofocus mechanism. The highest positioning accuracy with a motorized mechanic is given with 0.1 µm. Typically step motor scanners were used for standard applications.

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Fig. 1: Acoustic microscope KSI WinSAM Vario III, working in the frequency range from 1 to 400 MHz. It consists out of a high speed high resolution linear scanner system, PC-controlled workstation, and various transducers. The customer can choose the set of transducers and the scanning system individually.

420 000 data points are counted for a distance of 4mm for this high precision stepper standard. Beside the high noise level during operation these scanners are quite rough and due to the typical spindle driver mechanism the mechanical accuracy is limited for high frequency applications and high magnifications.

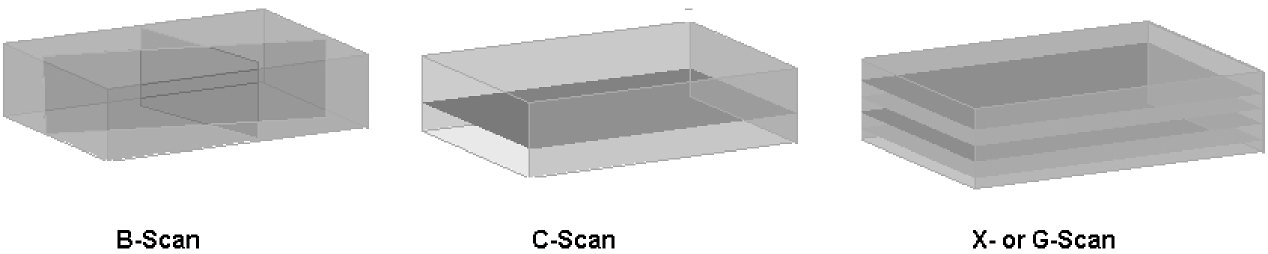


Fig. 2: Different scan types of the KSI WinSAM. A-, B-, and C-Scan are wellknown. The gate settings were done by software. Just two mouse clicks are necessary to determine the gate position and width. For X- and G-Scan the number and thickness of the single scan is given by the gate width of the B- and C-Scan gates.

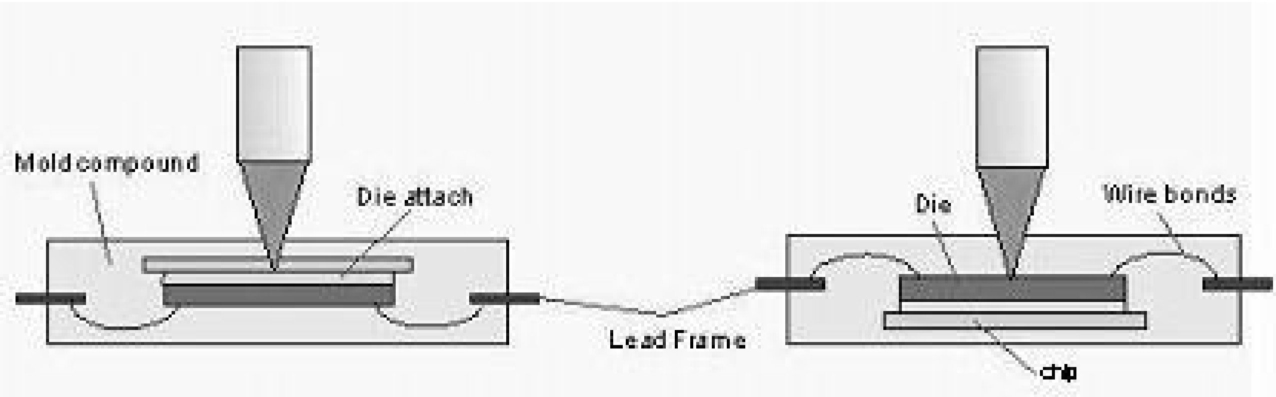
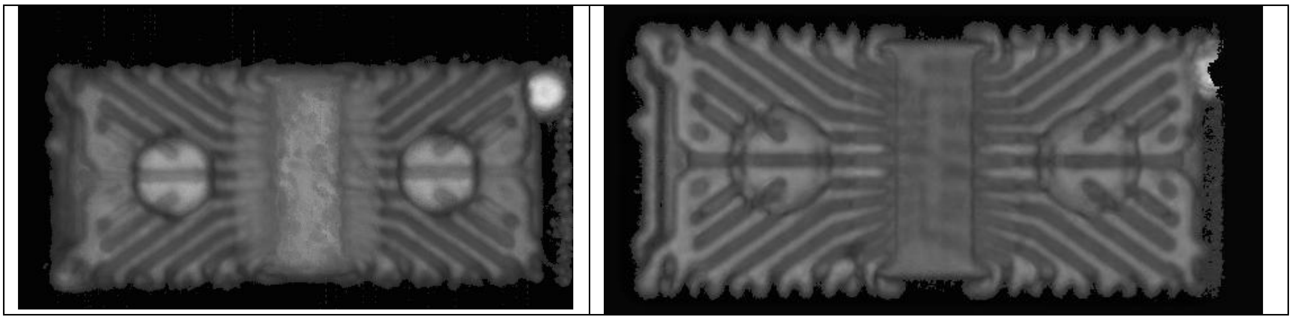


Fig. 3: Ultrasonic inspection of a flip chip is possible from both sides of the sample.

For special applications a new linear driver scanner generation is used. Especially for inspection of small defects the scanner resolution has to be smaller than the smallest defect structure to allow the imaging of the defect. A newer high speed, high resolution scanner generation is a xyz-scanner with a linear motor system giving the SAM unmatched accuracy and robustness. Here, the scanner resolution is better than 0.1 µm for x, y and z direction. The electronic positioning control unit is for all scan areas 4 times better in its internal accuracy for such precise and mechanically stable inertially balanced scanner. This unique scanner has a top speed of 1m/sec and 10 G acceleration. Hence high resolution acoustic micrographs can actually chosen from a spectrum running from 128 x 128 pixel up to 32000 x 32000 pixel per image to see acoustic details that were not viewable before. 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. Suppose you are analyzing a flip chip failure .The solder bump bonds often hold important adhesive data for the analysis. The very high resolution image with a high pixel number itself will look extremely sharp even if the blow up function is used to enlarge for example just one bump bond with true magnification, not just bigger pixels. Tiny voids and microcracks (see fig. 11 and 12) can be detected.

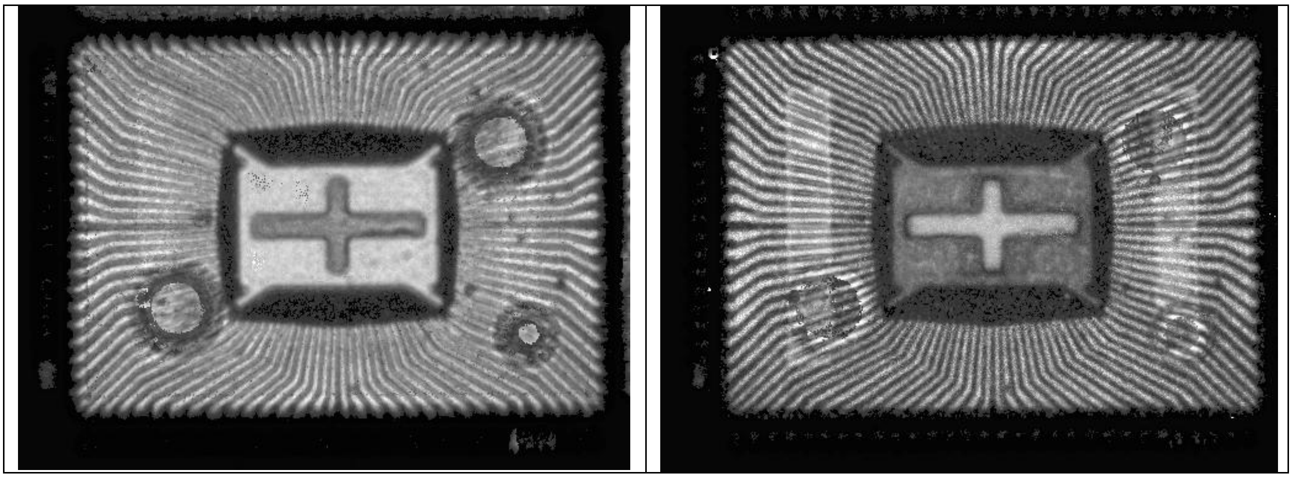
2.2 Instrument settings

Beside the wellknown A-, B-, and C-Scan the WinSAM offer as well other scan types thus as 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 incl. automated gain adjustment due to higher sound wave damping 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 just by software control with one click.



a) b)

Fig. 4: Comparison between a step motor scanner system (a) and a linear motor scanner system (b) WINSAM Vario III. Due to the smaller step width of the linear motor scanner system and its high precision mechanical linear guide ledge, the resolution in the acoustic image is higher than for the commercial step motor scanning systems. 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.

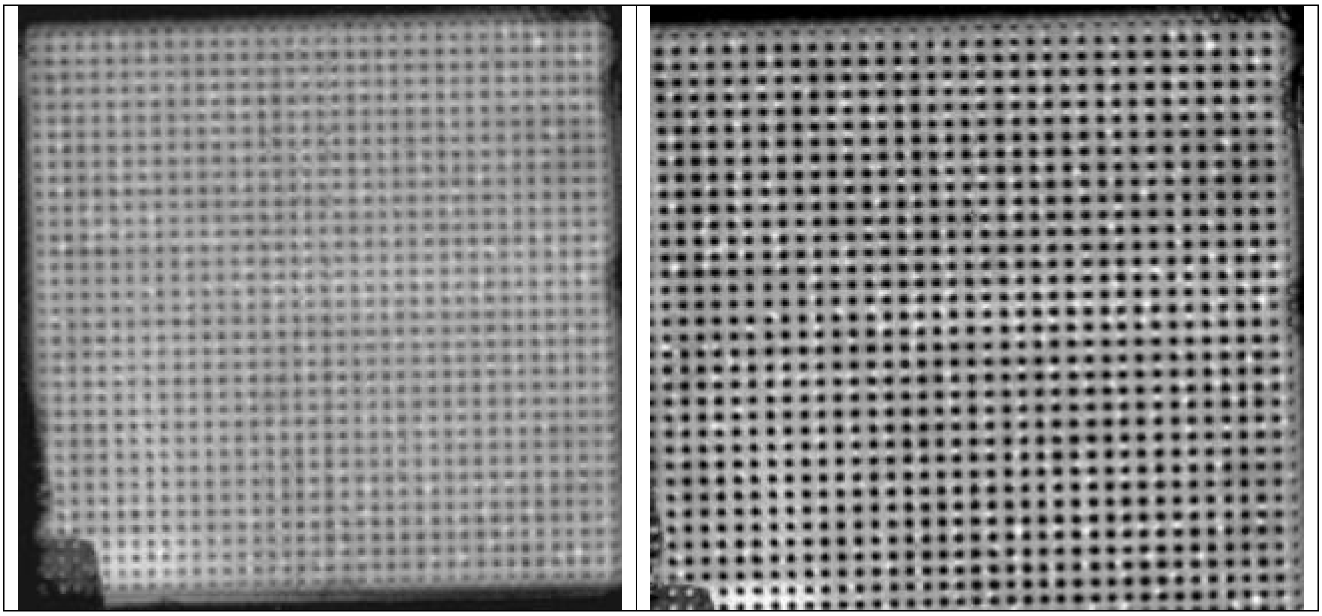


a) b)

Fig. 5: Comparison of acoustic images of an IC (**I**ntegrated **C**ircuit) taking with a transducer of 50 MHz center frequency (a) and 80 MHz center frequency (b). The resolution of the structures of the IC is higher for the transducer with the higher center frequency.

2.3 Transducers

Depending on the critical defect size and defect depth the working frequency and transducer design have to be chosen. Here, some influence parameters are: the bandwidth corresponding to the depth resolution, the center frequency responsible for the lateral resolution (Fig. 5) as well as the focal length corresponding with the penetration depth possible [2]. To detect small surface defects special transducer with a large opening angle to generate surface acoustic waves (SAW) are necessary. However, beside 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.



a) b)

Fig. 6: 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 KSIanalysis image anlaysis software for acoustic microscopy. The delaminated areas are stronger in contrast. All delaminations are still visible without loosing sharpness and resolution.

2.4 Imaging and filter software

The data acquisition and documentation is computer controlled. Beside the typical instrument format "SAM" where all scanning and gate setting parameters are stored with the acoustic image as well other formats like bitmap or tiff are possible. The time to make an acoustic image depends on the mechanical scanning speed, the scanning size and the pixel number of the acoustic image. Typically the scanning time is approximately a minute for a scan size of 20 x 20 mm². Images with a size up to 32,000 pixels a line are possible depending to PC RAM.
To increase the contrast of weak structures or defects in the acoustic image a number filters are available, like the median filter for noise reduction and smoothing the image, edge enhance filter for contrast increase of edges, emphasis filter, the DCE filter, the Emboss filter, the contour filter for sharpening the contours of the structures. A combination of the different filter types one after the other is possible. Some of the filters can be set thus they were used automatically after finishing the scan (Fig. 6).

Advantageous is the possibility to investigate **all layered structures** like in electronic devices during **one scan**. This allows a fast inspection of the whole interior of the sample (Fig. 7). The defect depth and location can be determined immediately. As well as a characterization of defect type is possible due to its shape and influence on the ultrasonic signal, like a phase shift due to delaminations or voids.

3. APPLICATION EXAMPLES

There are several different types of defects, which are of interest in the semiconductor industry. Here, some examples and comparison of transducers and instrument settings are presented. **Flip chips** were just turned over and its active side connected by solder bumps. This increases performance and saves space because you don't need bond wires. These advantages are making flip chips an increasingly popular package on modern boards. Yet the flip chip design has a fundamental drawback: by placing the chip face down, its interconnects become hard to inspect. Solder bump bonds, the solder bumps themselves, and the underfill, which is usually present, are all sites for potential problems. A solder bump can be partly or entirely disbonded and underfill can be delaminated from a surface or contain voids. These defects, however, possess a common characteristic in that they consist of an air-filled discontinuity (or gap) in the material.

Fortunately for inspection purposes, such air-gap defects are the domain of acoustic microscopy. Normal interfaces (a good solder bump bond, for example) reflect a part of the ultrasound to permit imaging. But an air gap, a disbond, a delamination, a void or a crack reflects all of the ultrasound. In the corresponding acoustic image display this makes defects highly visible.

Because echoes from various levels within the flip chip package arrive back at the transducer at slightly different times, electronic gating can be used to restrict the acoustic image to specific levels within the package. For example, only the interface at which the solder bumps are bonded to the die face. In fact, this fine gating and high resolution is why acoustic microscopy is so useful for evaluating flip chips. As acoustic frequencies increase, lateral resolution increases, while penetration ability drops off. But flip chip packages have tiny internal features, and so require a high frequency with good penetration ability.

There are about a dozen types of package defects, which can affect flip chip package reliability. These defect types are in addition to more or less universal package defects like molding compound cracks, and occur as a result of various processing errors. All of them have been imaged successfully by scanning acoustic microscopy.

To image extremely small defects, like defects inside individual solder bumps, including voids and cracks, acoustically, a transducer with a frequency of 200 MHz or more must be used, and gated within the bulk of the solder bumps, excluding the bonding interfaces at the chip level and at the substrate level (Fig. 8).

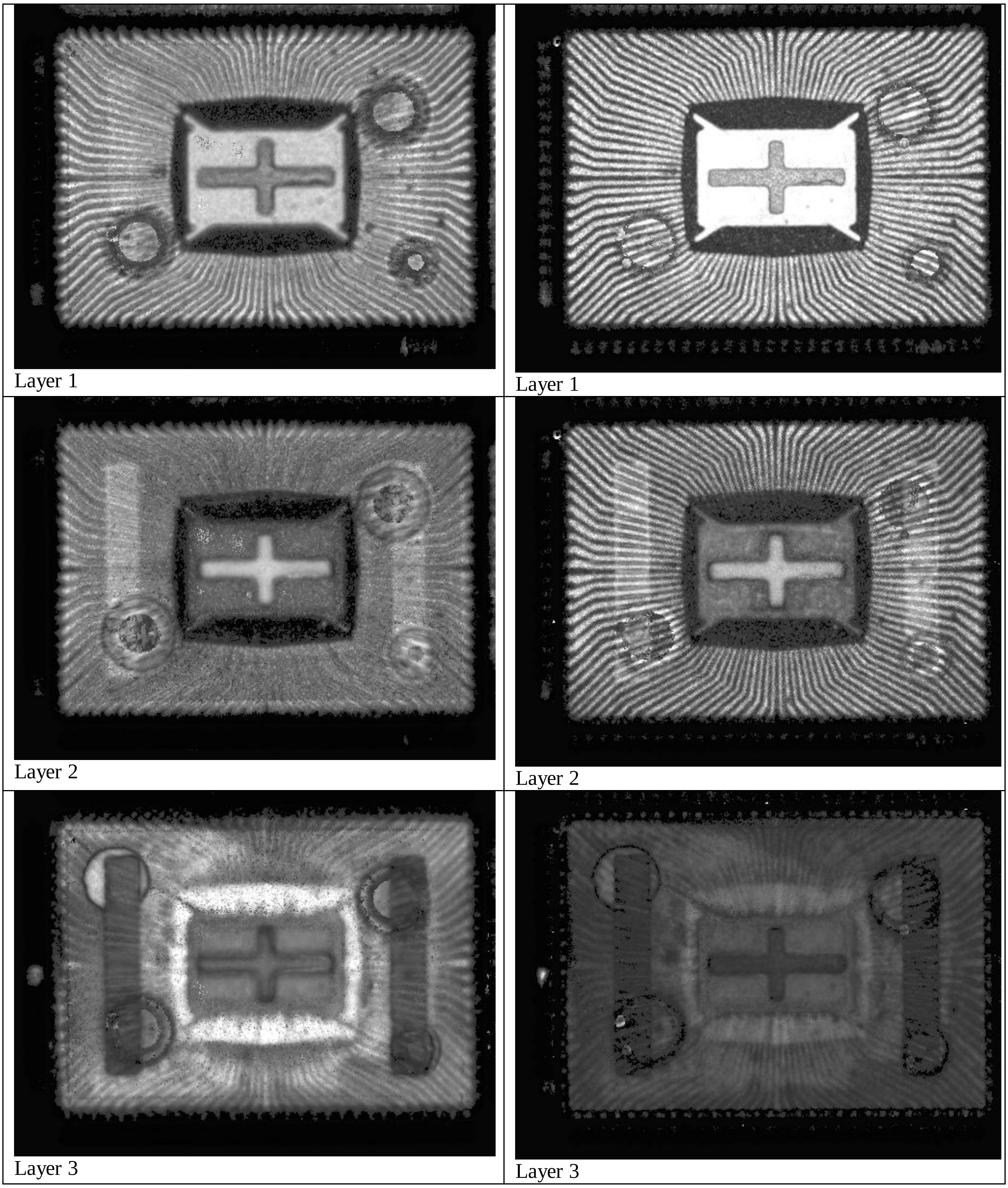


Fig. 7: Layered structure of an IC. The gates are set thus all layers are inspected separately during one scan. The scanned area is 22.7 x 17.1 mm². The center frequencies of the transducers used are 50 MHz (a) and 80 MHz (b).

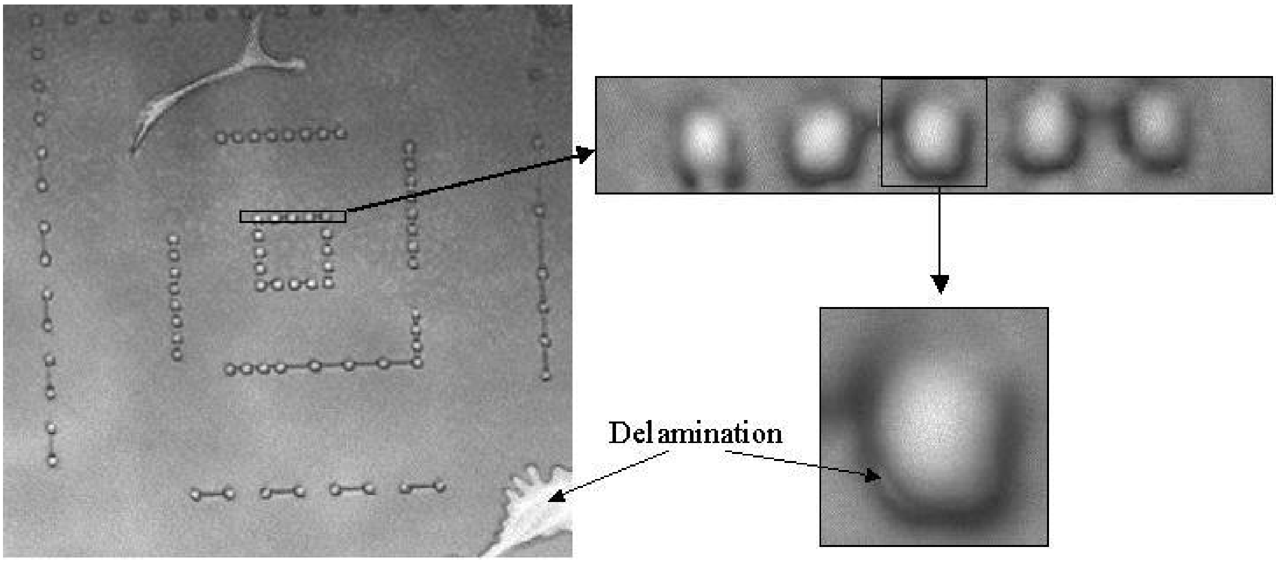


Fig. 8: In the overview image delaminations between the two Si-layers are visible, as well as the solder bumps. In the magnified images of the solder bumps, small delaminations at the edges of the bumps were detected. The transducer used has a center frequency of 100 MHz . Even the connecting wires between the bumps could be imaged, thus bridging defects can be detected if present. The scanning size for the overview image is: 6.7 x 6.3 mm².

Due to the extremely thin solder bumps, the ultrasonic signal has to be very small, this means very broadband high frequency transducers have to be used. The failures might happen during initial bump deposition, are significant because they can grow spatially after repeated thermal cycling and cause the bump to become intermittent or to fail completely.

Special demands to the resolution in the µm-range of the acoustic microscope are given by detection of bridging of adjacent solder bumps, dendrite growth of solder between adjacent solder bumps, failed solder bump bonds, especially after thermal testing since this testing sometimes initiates disbonds, and lateral cracks in the passivation layer above a solder bump.

As well as incomplete underfill, voids in the underfill, irregular distribution of filler particles, and halo delaminations around solder bumps have to be detected and classified by acoustic microscopy. Chip-on-Board (C.O.B.), Chip-on-Flex, and Flip Chip are among the fastest growing and most challenging technologies in the electronic assembly industry. In addition to die placement, wire bonding, and testing, manufacturers must also be skilled at the delicate procedure of encapsulating the die.

Proper **encapsulation** requires that encapsulants, which are viscous liquid epoxies, be applied to substrates, circuit boards, of flexible circuits in precise amounts using heat to ensure complete flow and adhesion. Properly applied, encapsulants offer low thermal expansion and resistance to moisture and chemicals. Typical defects here, are delaminations between encapsulant 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. 9).

4. SURFACE AND NEAR SURFACE DEFECTS

Due to the so called death zone of the ultrasonic signal, it is very difficult with ultrasonic techniques to detect small defects at the surface or in the surface near region. For example during the wafer grinding process small scratches may result in fine cracks, which occurs to catastrophic failure in the brittle material silicon. The detection of these fine cracks especially at the edges of the wafer is very difficult with conventional ultrasonic transducers.

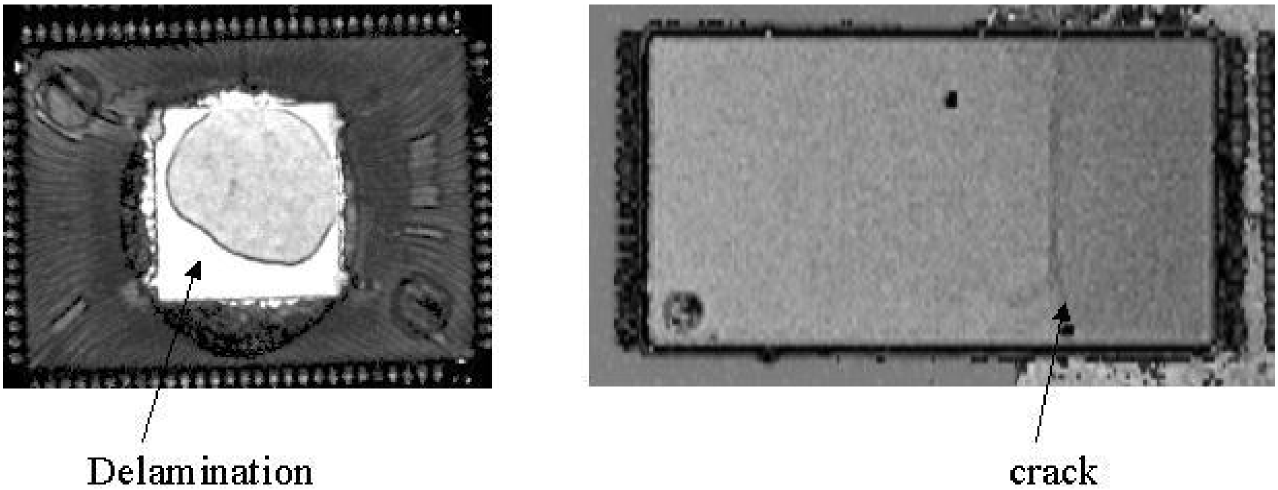


Fig. 9: Defects in the encapsulation: a) Is showing a delamination between the die top and the encapsulant, where the thermal heat exchange is disturbed. b) presents a surface crack in the encapsulant, where aggressive fluids might penetrate.

Using a special transducer 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. 10) [3]. These transducers are available up to 2 GHz. As coupling medium usually distilled water is used. Depending on the material under investigation also 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 objetives in optical microscopes. Therefore, the ultrasound is focused to nearly one point, resulting in a resolution of approximately λ, 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 θ_R for most of the materials. An ultrasonic wave incident under the critical angle generates a surface wave, usually a Rayleigh wave (Fig. 10).

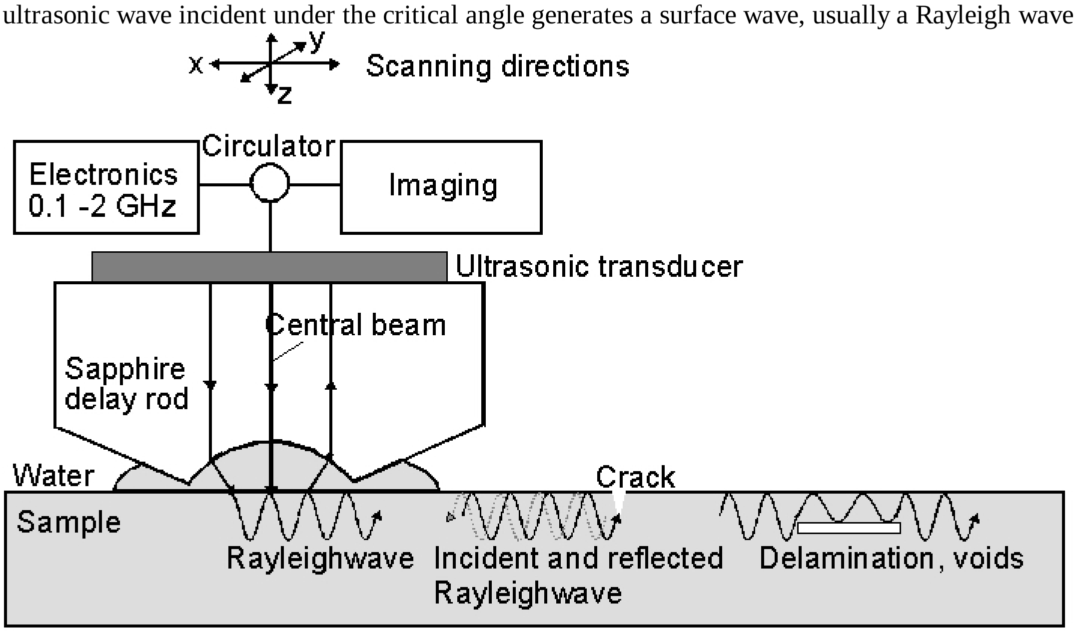
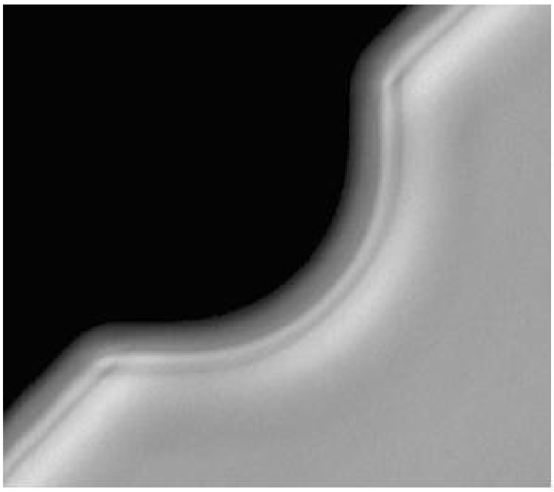


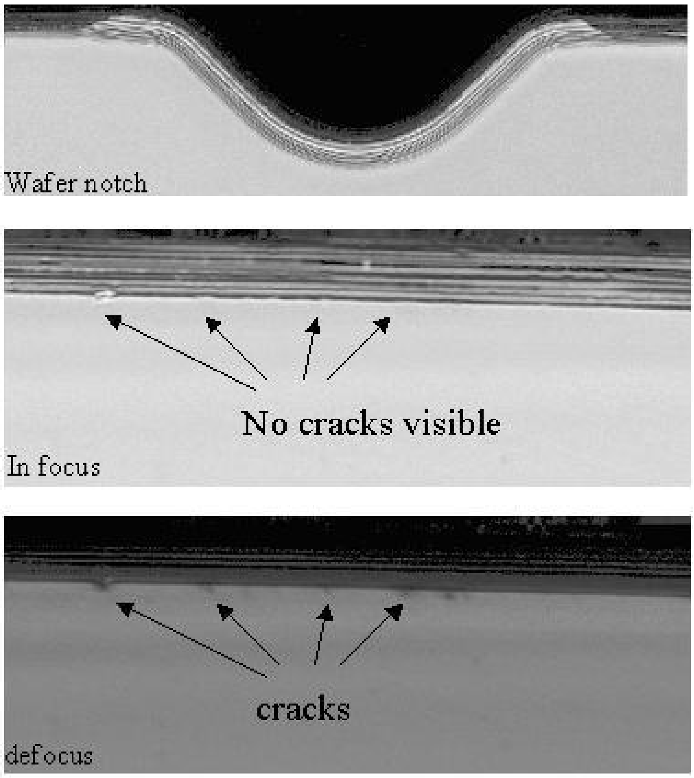
Fig. 10: Principle of surface acoustic wave generation and defect detection. Due to the large opening angle of the curvature surface acoustic waves were generated under the material characteristic critical angle. Surface acoustic waves are very sensitive to surface inhomogeneities like cracks or surface near delaminations. However, roughness disturb of the surface acoustic wave resulting in 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 submicron 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. As well special demands on the surface topography are given. 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 opening smaller than the 1 µm. Surface near inhomogeneities 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. 10). 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. 11). As well as delaminations or inclusions at the die attach or bumps could be detected (Fig. 12).

5. IN-LINE INSPECTION

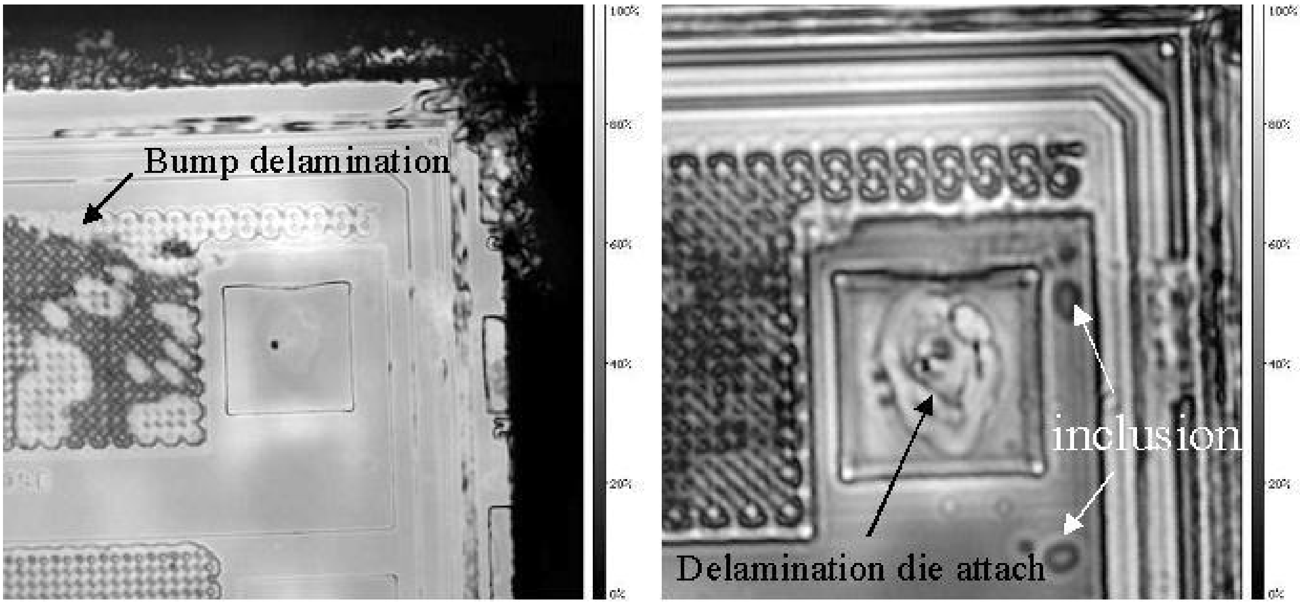
All acoustic microscopes presented in this paper can be modified for an inline inspection easily. The samples are mounted in trays, which can be moved to the acoustic microscope by robots optionally. All gate settings for the individual inspection of a device type are saved and just by loading the corresponding file all parameters are available for automatic inspection including auto focus of the transducer.





a) b)

Fig. 11: Inspection of a wafer with a) a conventional transducer (center frequency 80 MHz) and b) a SAW transducer (center frequency 100 MHz). The crack can not 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 even be seen clearer than in the focused image (middle).



a) b)

Fig. 12: Inspection of wafer with defects in the die attach a) In the surface near image delaminations at 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 µm² and b) 312 x 312 µm².

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