ARCHIVES OF ACOUSTICS
19, 4, 487–493 (1994)

# SUBSURFACE IMAGING OF SAMPLES WITH SAM

J. LITNIEWSKI

Ultrasonic Department
Institute of Fundamental Technological Research
Polish Academy of Sciences
(00–049 Warszawa, Świętokrzyska 21)

The paper presents unique abilities of the acoustic microscope to penetrate and visualize an interior of materials which are opaque to the light. The construction of an acoustic lens optimized for subsurface imaging is described. The lens enables to achieve resolution of approximately 100 μm at 100 MHz frequency when visualize an interior of aluminum sample. Images of the back side of a coin and of a die attach bond of integrated circuit with ceramic package are presented.

## 1. Introduction

The scanning acoustic microscope (SAM) is one of the most rapidly developing and proven techniques of non-destructive examinations of hard and soft material. It has become well known and unique scientific tool. The physical and technical principles of the microscope have been described by many authors [1, 2]. The use of the microscope significantly extended the possibility of imaging the surface of material, integrated elements and small biological objects. The microscope enables to detect the physical properties of a surface layer by measurements of surface acoustic waves (SAW) velocity and attenuation [3].

Taking an advantage of relatively low attenuation of the ultrasonic waves even at very high frequency, acoustic microscope can penetrate materials that are opaque to the light. The following paper reveals the ability of SAM to visualize unseen internal structures.

## 2. Low frequency scanning acoustic microscope

We have build a scanning acoustic reflecting microscope. The system enables to obtain high quality amplitude and phase images with special resolution 30 μm, 10 μm and 5 μm operating at 35 MHz, 100 MHz and 200 MHz frequency respectively.

When the system operates in visualization option two modes of imaging are possible, C-scan and B-scan. In the C-scan mode the back scattered ultrasound collected by the lens and detected by the transducer is time gated such that only scatter from the focal plane are accepted. The amplitude or phase of the signal is stored while the transducer moves over the sample point by point to produce two dimensional image (Fig. 1). Depending on the focus position, the C-mode allows to visualize the surface or an interior of the sample. The image reflects acoustic properties of the material at the plain perpendicular to the acoustic beam axis.

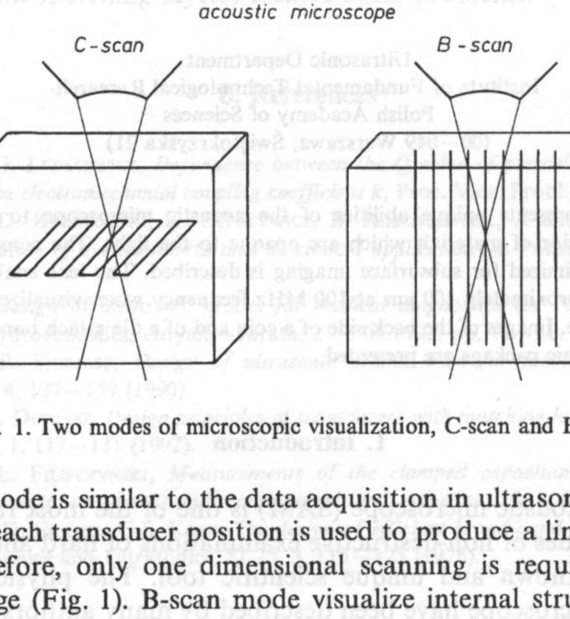

Fig. 1. Two modes of microscopic visualization, C-scan and B-scan.

The B-scan mode is similar to the data acquisition in ultrasonography. The back scatter signal at each transducer position is used to produce a line of information in the image. Therefore, only one dimensional scanning is required to obtain two dimensional image (Fig. 1). B-scan mode visualize internal structures of material. The image corresponds to the crossection of the sample, parallel to the acoustic beam axis.

## 3. The lens for subsurface imaging of a hard sample

Imaging of the interior requires the acoustic beam to be focused under the surface of the sample. In an acoustic microscope the lens is coupled to the sample with a fluid, usually water. The converging acoustic wave transmitted by the lens must penetrate highly refractive interface between water and a sample. In water acoustic waves can be easily focused in a diffraction limited spot. The geometrical aberration is so small that it can be neglected even for a large aperture lenses. In solid materials with a high velocity of acoustic waves, the aberration spreads widely the focal area. The proper choice of a lens aperture limits the degradation of a focus introduced by geometrical aberration.

There are some other reasons which justify the use of small aperture lenses for subsurface imaging. For high angels of convergence the waves can not penetrate the water-sample interface. The high amplitude signal of the waves specularly reflected from the surface masks low amplitude signal coming from the interior. Additionally, waves incident on an interface at critical angels excite a Leaky Surface Waves (LSW) in a surface of the specimen. The LSW in turn excite waves in the coupling fluid at the critical angels. These waves are detected by the transducer and they disturb the signals received from the inside of the sample. The small aperture lenses preclude LSW generation.

The aim of this work was the construction of the acoustic microscope lens appropriate for optimized subsurface imaging. There was assumed that the microscope operating at 100 MHz frequency should visualize internal structures situated 3 mm under the surface of material with the velocity of longitudinal waves equaled to 6000 m/s.

The simple geometrical analysis of the acoustic system consist of the lens, coupling fluid and a plane sample allows to determine the size of the lens aperture minimizing the aberration and diffraction effects [4].

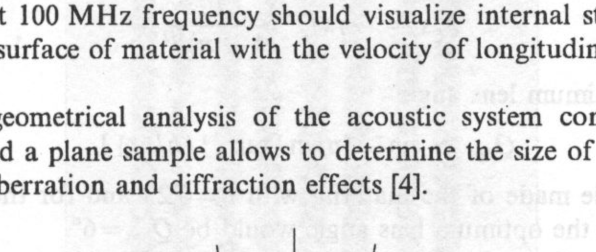

Fig. 2. Rays focusing below the surface of a solid sample, refraction of the interface and an aberration effect.

Using the notation of Fig. 2 one can find that the minimum geometrical aberration is:

$$a = a_G/2 = \frac{h^3\left(\frac{1}{n} - 1\right)^2}{4\,s^2}, \qquad (3.1)$$

where *n* is a refractive index at the water/sample interface.

Diffraction spreads the focal spot into the Airy disc which first minimum can be found at the distance from the axis

$$d = \frac{1.22\,\lambda s}{2h}, \tag{3.2}$$

$\lambda$ — wavelength in the solid sample.

The total size of the focal spot may be written as

$$a_t = (a^2 + d^2)^{1/2}. \tag{3.3}$$

It can be found that a minimum of $a_t$ occurs for

$$h/s = (\lambda/s)^{1/4}\,\frac{1}{(1-n)^{1/2}}, \tag{3.4}$$

what gives an optimum lens angle

$$Q_{\mathrm{opt}} = \sin^{-1}[n \sin\{\tan^{-1}(h/s)\}]. \tag{3.5}$$

For the sample made of the material with $n = 0.25$ and for the focusing 3 mm below the surface the optimum lens angle would be $Q_{\mathrm{opt}} = 6°$.

The total size of the focal spot calculated for the optimum lens amounts to 800 μm. Experimental results will give much better resolution. Though the geometrical analysis do not describe correctly the size of the focus it gives good results in optimizing the lens for aberration.

## 4. Subsurface imaging

We have prepared an aluminum test sample to check focusing abilities of the constructed lens. The B-scan image of the sample is presented in Fig. 3 giving an idea of its geometry. The upper surface of the sample was flat while the opposite surface was shaped in steps. We have made several parallel grooves on the surface of each step. The distance between grooves was approximately 200 μm. The resolution of the lens was checked by focusing ultrasounds at different depth and visualizing the grooves.

The best C-scan image was obtained for focusing at 3 mm under the surface (Fig. 4). The grooves are easily resolved what proves that the lens resolution is of the order of 100 μm (one and half wavelength in aluminum). The resolving power of the microscope is much higher than predicted by geometrical calculations. In calculations it is assumed that a plane uniform amplitude wave is focused by the lens. In the microscope the lens is situated in the transition zone between the far and near field of the transducer. Thus the lens is illuminated with a gaussian beam. Additionally at the lens/water and water/sample interfaces an amplitude of the waves corresponding to high angles of convergence is farther reduced. The natural apodization occurs and the waves are focused much better than the geometrical calculations predict.

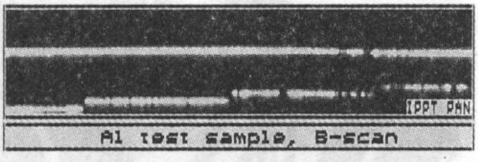

Fig. 3. *B*-scan image of a test sample (image dimensions 12.8 mm × 4.2 mm).

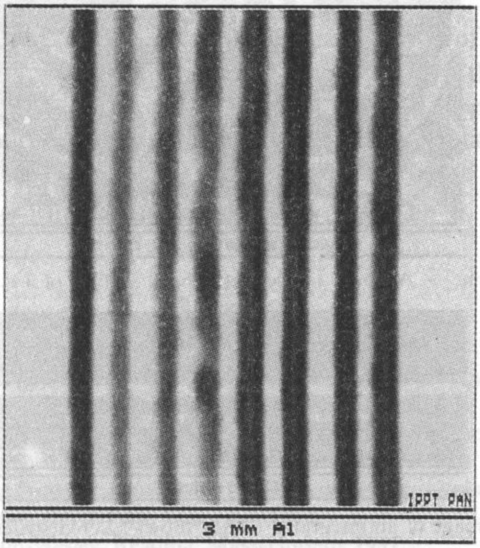

Fig. 4. *C*-scan image of the test sample showing the grooves through 3 mm of aluminum (image dimensions 3 mm × 3 mm). The distance between the grooves — approximately 200 μm.

The following two examples show possible applications of SAM for subsurface imaging.

A spectacular image can be obtained when imaging the back side of a coin. The microscope working at 100 MHz frequency can easily penetrate 3 mm of aluminum and the image reveals the topography of the coin (Fig. 5). The image is of a good quality and small surface structures can be resolved. The influence of a coin front surface on imgage is of a minor importance.

The second example comes from micro electronics. In the integrated circuit package the heat must be dissipated to stabilize the electrical behavior of the semiconductor. The poor quality of the die attach bond can be detected with ultrasounds. The bright areas in the microscope image correspond to the high acoustic reflectivity due to the lack of bonding between the die and ceramic.

B-scan acoustomicroscopic image shows layered structures of integrated circuit (Fig. 6). The ceramic substrata, lead frame and die attach bond can be resolved in the acoustic crossection of the chip (E-prom memory).

Fig. 7 shows C-scan image of an interior of the same integrated circuit. The time gate and the focus were located at the die attach bond, approximately 2 mm below

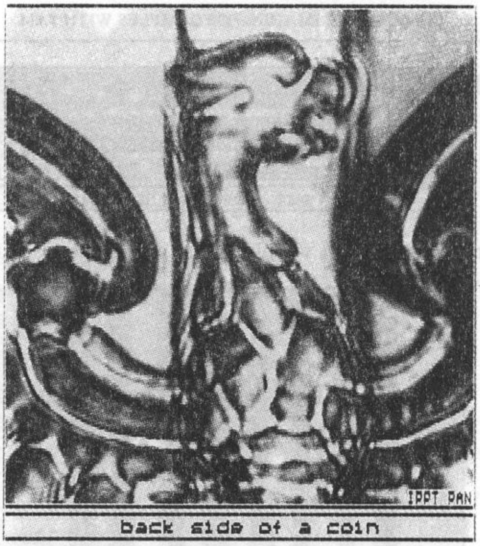

Fig. 5. Acoustic image of the back surface of a coin.

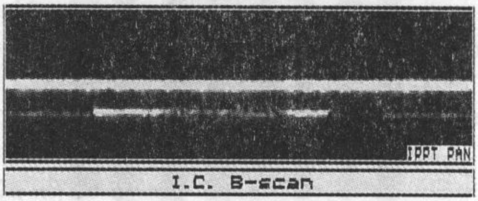

**Fig. 6.** *B*-scan image of an integrated circuit shows layered structure **of a the chip.**

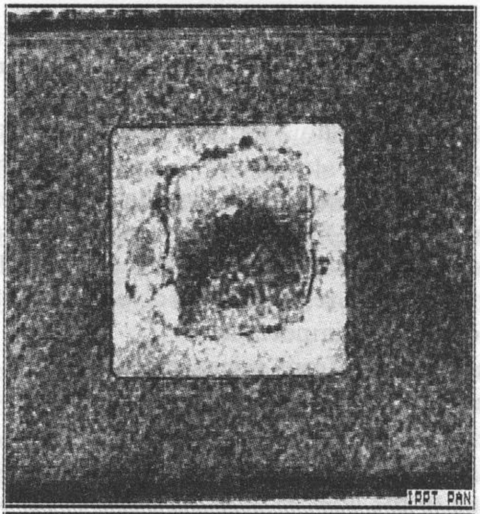

**Fig. 7. An interior of an integrated circuit. The C-scan image shows a die attach bond inside the ceramic package (approximately 2 mm below the front surface).**

the ceramic base. The central part of the bond image is black. This area indicates a good bonding. Ultrasonic waves penetrates the interface almost without any back reflections creating a black area in the image.

## 5. Conclusions

Scanning acoustic microscope can visualize an interior of the samples made of a hard material. It is possible to achieve resolution of the order of a single wavelength. Low aperture lenses must be used to avoid spreading of the focus because of the aberration and generation of LSW which can disturb subsurface image. At 100 MHz frequency depth of several millimeters can be achieved and visualized.

## References

[1] C.F. Quate, A. Atalar and H.K. Wickramasinghe. *Acoustic microscopy with mechanical scanning: a review*, Proc. IEEE 67, 1092–114 (1979).

[2] G.A.D. Briggs, *An introduction to scanning acoustic microscopy*, Royal Society Handbook, 12, Oxford University Press, Oxford 1985.

[3] J. Litniewski, *Acoustic microscope signal for defocusing conditions — application to biological image interpretation*, Ph. D. thesis, IFTR PAS, Warszawa 1990.

[4] E. Hecht, *Optics*, Addison-Wesley, Reading, Massachusetts 1987.