Extending Acoustic Microscopy for Comprehensive Failure Analysis Applications

Sebastian Brand, Matthias Petzold Fraunhofer
Institute for Mechanics of Materials Halle,
Germany

Peter Czurratis, Peter Hoffrogge PVA
TePla Analytical Systems GmbH
Aalen, Germany

Abstract:

In industrial manufacturing of microelectronic components, non-destructive failure analysis methods are required for either quality control or for providing a rapid fault isolation and defect localization prior to detailed investigations requiring target preparation. Scanning acoustic microscopy (SAM) is a powerful tool enabling the inspection of internal structures in optically opaque materials non-destructively. In addition, depth specific information can be used for two-and three-dimensional internal imaging without the need of time consuming tomographic scan procedures. The resolution achievable by acoustic microscopy is depending on parameters of both the test equipment and the sample under investigation. However, if applying acoustic microscopy for pure intensity imaging most of its potential remains unused. The aim of the current work was the development of a comprehensive analysis toolbox for extending the application of SAM by employing its full potential. Thus, typical case examples representing different application fields were considered ranging from high density interconnect flip-chip devices over wafer-bonded components to solder tape connectors of a photovoltaic (PV) solar panel. The progress achieved during this work can be split into three categories: Signal Analysis and Parametric Imaging (SA-PI), Signal Analysis and Defect Evaluation (SA-DE) and Image Processing and Resolution Enhancement (IP-RE). Data acquisition was performed using a commercially available scanning acoustic microscope equipped with several ultrasonic transducers covering the frequency range from 15 MHz to 175 MHz. The acoustic data recorded were subjected to sophisticated algorithms operating in time-, frequency-and spatial domain for performing signal-and image analysis. In all three of the presented applications acoustic microscopy combined with signal-and image processing algorithms proved to be a unique tool for non-destructive inspection.

Introduction:

Inspection methods operating non-destructively are required in many applications in the field of failure analysis including quality control and fault localization prior to destructive target preparation for detailed micro-structural investigations. Providing the option of running multiple tests on the same sample these methods also extend the level of investigation and thus, the understanding of defect formation, failures and their root causes. However, non-destructivity is always connected with a trade-off between comprehensive destructive preparations and resolution. Scanning acoustic microscopy employing ultrasonic signals from the MHz-to the GHz-range allow resolutions from the mm-down to the µm range. The final resolution achievable however, is depending on several parameters namely the acoustic frequency, the transducers aperture but also the sound velocity of the material and the depth of the structure under investigation. While the aperture of the inspection transducer can be tailored for specific applications wave attenuation is inevitably proportional to frequency and the materials viscosity [1]. For increasing the penetration depth the acoustic frequency has to be lowered which is related to a decreased lateral resolution. The interaction of acoustic waves with matter is characterized by phenomena like reflection, diffraction and scattering caused by structural, size and mechanical properties. By employing appropriate signal analysis algorithms to time domain echo signals acquired by the acoustic microscope, parameters related to structural and mechanical properties of the inspected sample can be derived. Thus, by analyzing the echo signals comprehensive information on the samples condition and composition can be obtained. In situations were acoustic microscopy is applied for pure qualitative imaging of internal structures, like delaminated spots in a bonding interface, additional image processing and analysis can improve resolution and contrast for revealing and emphasizing various of defects. The current work is focused on the development of a comprehensive analysis tool for extending acoustic microscopy by signal and image processing algorithms, enabling a broad range of applications in the field of failure analysis. In this paper three case studies representing different fields of application are described targeting developments in parametric imaging, defect evaluation and image processing. Signal analysis and parametric imaging is applied for estimating the adhesive condition of a solder tape of PV-solar panel. The solder bump contacts of a flip-chip device were evaluated and classified employing extended signal analysis. Finally, delaminations in wafer-bonded interfaces were inspected and images were processed for increasing the resolution and the contrast. In all three applications the results were improved providing additional information on the defect situation.

Materials and Methods

Data Acquisition

All acoustic data were recorded using an acoustic microscope (Evolution II, PVA TePla Analytical Systems GmbH, Aalen, Germany) equipped with a 175 MHz transducer. The signals had a bandwidth of approx. 50 MHz (@-3 dB) and were sampled with a resolution of 8 bit at 500 MS/s prior to storage on the microscopes internal hard drive.

Signal Processing

Signal processing was performed using custom-made MATLAB (The Mathworks, Natick, USA) software. The algorithms developed during this work were combined in an analysis toolbox that can be applied for performing comprehensive and complex analyses on acoustic data and images. The entire software was compiled using the MATLAB compiler and thus, can be run on any Microsoft Windows based computer.

Signal Analysis and Parametric Imaging (SA-PI)

For optimizing acoustic images using appropriate processing and analysis algorithms, the echo signals were subjected to a cepstral analysis [2]. The cepstrum-domain represents the periodicity of the spectrum which is related to the spacing between pulses in the time domain signal. From the computed cepstra the position of the first maximum was extracted and further used for parametric imaging. This data analysis was particularly used for the inspection of electrical interconnects on a solar panel. It consisted of polycrystalline silicon with a thickness of 220 µm. For electrical connectivity a copper tape of 100 µm thickness and 5 mm width was soldered on top of the panel. The solder had a thickness of approx. 30 µm on each side of the tape.

Signal Analysis and Defect Evaluation (SA-DE)

A CPU device manufactured in flip-chip technology was investigated for evaluating and classifying the condition of the solder bump contacts. The solder bumps connected the 750 µm thick silicon die with the organic substrate of the CPU device. The solder bumps had a lateral diameter of 80 µm. The echoes occurring at the chip/interconnect interface were analyzed using wavelet-, pulse separation-and backscatter amplitude integral analysis (BAI) [3]. By specifying appropriate parameters, the flip-chip contacts could be localized and distinguished from the silicon/unterfill interface. Further analysis allowed to classify the contacts into intact and void. For a simplified visual assessment of the voids, intact contacts are indicated green while voids are marked red in the acoustic image (Fig. 4). For estimation of the accuracy of the developed method, the derived data were compared to X-ray-analysis and scanning electron microscopy (SEM) results.

Image Processing and Resolution Enhancement (IP-RE)

Acoustic micrographs were recorded at the interface of two bonded wafers. Both wafers had a thickness of 500 µm and were originally prepared and patterned for mechanical strength testing. Bonding was based on a plasma-activated low temperature silicon direct wafer bonding process. Prior to the tests, samples were inspected using acoustic microscopy to investigate the geometric accuracy of the bonded structures which is relevant for the mechanical tests. Acoustic micrographs were then processed using image processing filters for blind deconvolution [4], a Gaussian filter and a Sobel filter for emphasizing edges. Image contrast was adapted manually for matching the gray levels to the dynamic range of the images appropriately.

Results and Discussion

Signal Analysis and Parametric Imaging (SA-PI)

The connectivity of a solder tape on top of a solar panel was assessed by computing the position of the first cepstral maximum from time domain signals acquired using acoustic microscopy. Figure 1 shows a regular acoustic micrograph of the solar panel with the solder tape in the vertical center. The time domain signals are plotted as a cross section in Figure 1 (bottom). This cross section corresponds to the red-marked line in Figure 1 (top).

It can be seen that the echo distribution is not homogeneous over the cross section. On the left side the solder tape is detached (delaminated) from the bus bar of the solar panel which causes multiple reflections of the acoustic signal in the tape. By applying a cepstral analysis the echo separation and periodicity was extracted. The parameter matrix containing the position of the first cepstral maximum is plotted in Figure 2. This parameter map corresponds well to the location of the defects enabling a simplified assessment of the solder quality of the contact tape.

Signal Analysis and Defect Evaluation (SA-DE)

Figure 3 shows a cross section through the CPU device investigated for the development of an automated inspection/classification method for flip-chip contacts. The corresponding interfaces are indicated by the schematic to the left of the cross section. The echo pulses in the red-marked time-range were applied to further inspection using wavelet-, pulse separation and BAI analysis. It was found that in case of a void wavelet coefficients were distributed almost equally over the scaling factors and the wavelet positions, while intact connectors only showed a narrow distribution. The separation of echoes (entrance/exit of the flip-chip contact) obtained at intact interconnects were up to 20 ns smaller than for voids, also BAI values were observed to be significantly higher at intact connectors than at voids. All three parameters were combined in a classifier and applied to the acoustic data recorded from the CPU. The automated operating tool indicated intact contacts in the BAI image by a green mark, while voids are marked red. Figure 4 (right) contains the result of the automated classification. For verification X-ray and SEM analyses were performed on the device. In Figure 4 (left) yellow marks indicate voids detected by the acoustic method developed here. Each of the void which was confirmed by X-ray is indicated red. Two rows containing the majority of defects were cross-sectioned and imaged by SEM. Voids confirmed by SEM are indicated by a white circle. From Figure 4 (left) it can be seen that 13 voids were confirmed by SEM and that five voids have not been found by X-ray. However, two false positive and one false negative classification occurred, resulting in an overall success rate of 90.3% for the acoustic detection method.

Image Processing and Resolution Enhancement (IP-RE)

Image processing was applied to acoustic micrographs recorded from the bonding interface of wafer bonded structures. The acoustic micrographs did not show sufficient contrast and sharpness to clearly evaluate defects located at the bonding interface. In Figure 5 the acoustic micrographs prior to the image processing are plotted in the upper row. Performed was blind-deconvolution for increasing the sharpness of the images. Additionally, a Sobel filter was applied to the region of interests (ROIs) in the left and right images in Figure 5. A Gaussian Filter was applied to the central image in Figure 5. In all three cases the visualization of defects in the bonding interface was optimized. The lateral dimensions and the shape of the defects are clearly visible.

Conclusions

The signal-and image analysis toolbox developed for improving the performance of acoustic analysis showed positive results. It was possible to extend the application of acoustic microscopy from pure qualitative imaging to parametric imaging and thus, semi-quantitative parameter estimation applicable in a broad range of different application fields. Additionally, an automated operating method for defect evaluation of interconnects was developed, based on acoustic microscopy data. Finally, the combination of acoustic imaging with image analysis and processing also proofed successful for increasing image detail and contrast. Further image processing filters will be included stepwise into the analysis toolbox in the near future, for extending the optimization of the acoustic micrographs.

References

1. A. Briggs, Advances in Acoustic Microscopy. New York and London, Plenum Press, 1995.

2. K. Zieger, “Cepstrum Analysis of Voice Disturbances”, *Folia Phoniatrica et Logopaedica*, 1995, Vol. 47, No.4, pp210-217.

3. K. Raum, A. Ozguler, S.A. Morris and W.D. O'Brien, “Channel defect detection in food packages using integrated backscatter ultrasound imaging.” *IEEE Transactions on Ultrasonics Ferroelectrics and Frequency Control*, 1998, Vol. 45, No.1, pp. 30-40.

4. M. Cannon, “Blind Deconvolution of Spatially Invariant Image Blurs with Phase”, *IEEE Transactions on Acoustics, Speech and Signal Processing*, 1976, Vol. 24, No.1, pp. 58-63.

Contact author information:

Sebastian Brand Fraunhofer Institute of
Material Mechanics Walter-Huelse-Str. 1
06120 Halle, Germany

Sebastian.Brand@iwmh.fraunhofer.de
+49 345 5589 193 +49
345 5589 101 FAX

Images:

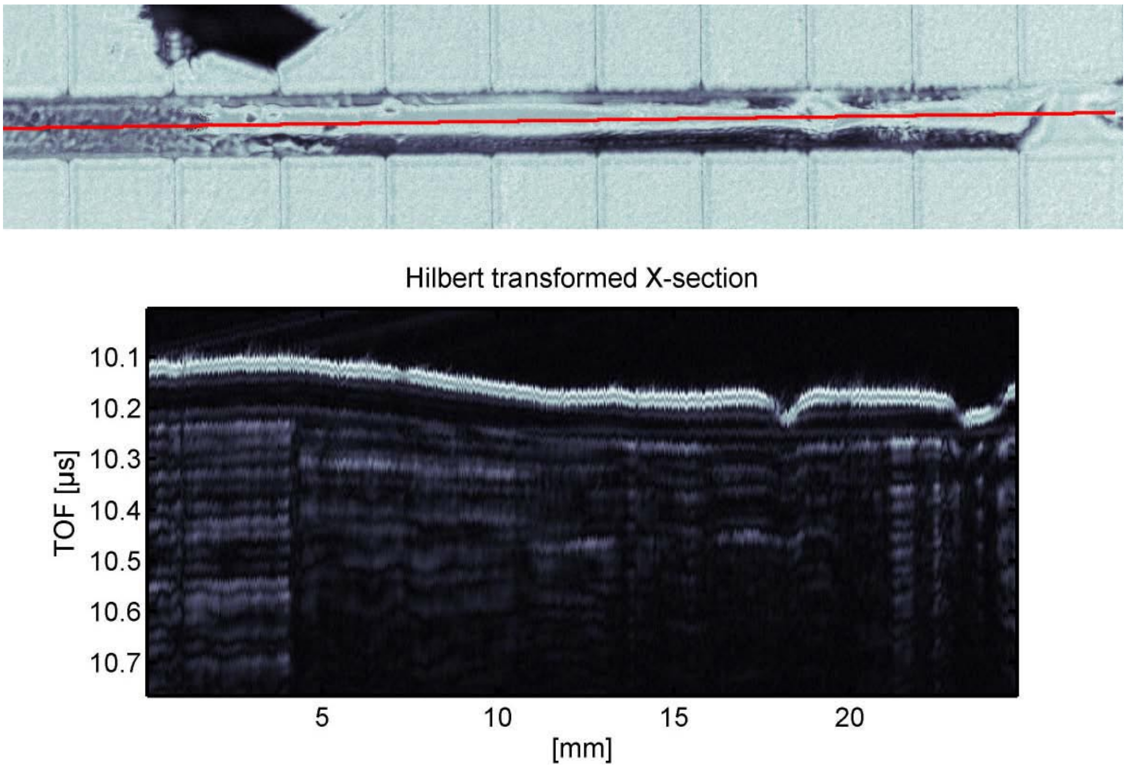

Figure 1: Top: Acoustic micrograph of a solar panel showing the solder tape in the vertical center. The gray values correspond to the magnitude of the surface echo. Bottom: Cross section of the solder tape along the red-marked line in the Top image. Echoes occurring below the surface are characterized by the structure of the solder tape and the solder and thus contain information on the solder adhesion.

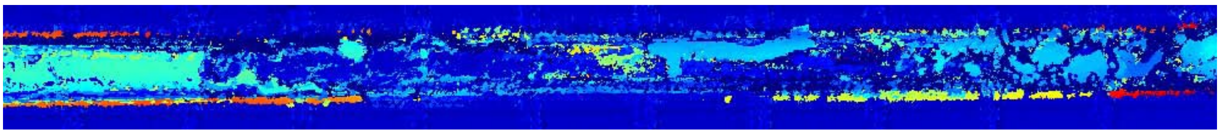

Figure 2: Parametric image computed from the echo signals obtained by acoustic microscopy. By performing a cepstral analysis signal features related to the solder connection of the tape can be extracted. The positions of the first cepstral peak are plotted using the color coding. This parameter can be converted into pulse spacing. On the left the solder tape is delaminated from the underlying solar panel.

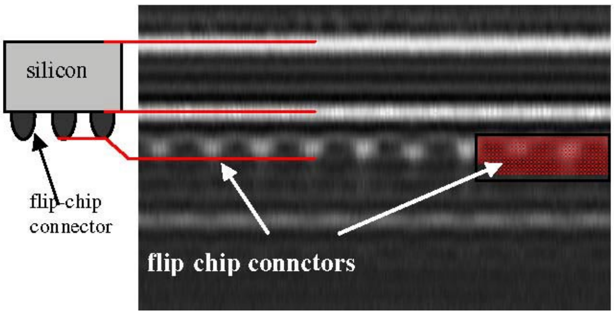

Figure 3: Sample description. The schematic on the left illustrates the 750 µm thick silicon die with flip-chip solder contacts (80 µm lateral diameter) underneath. On the right a cross-sectional B-mode image through the CPU-device is shown. Boundaries and corresponding echoes are indicated by red lines. The red rectangle shows the time range for estimating BAI values.

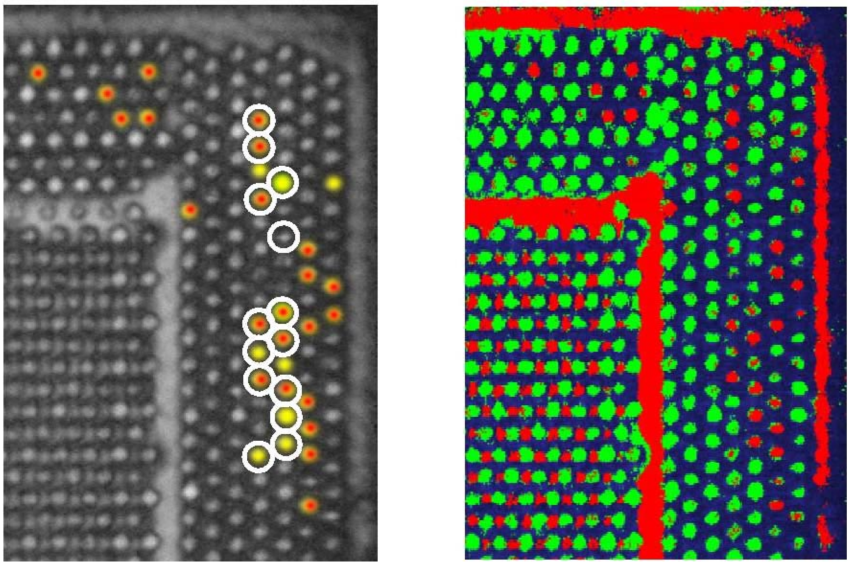

Figure 4: Classification results and evaluation of void detection. Right: green indicated are detected flip-chip contacts. Red connectors were classified as voids based on the wavelet coefficients and pulse separation characteristics at the interface silicon/ solder bump. Left: BAI-parametric image with indication of detected voids. Yellow marks correspond to voids detected using acoustic microscopy data. Red marks show where voids have been confirmed by X-ray microscopy. White circles show where defect connections were verified by cross-sectioning and SEM imaging. SEM investigations were only performed on column 3 and 4 (counted from the right-hand-side of the device).

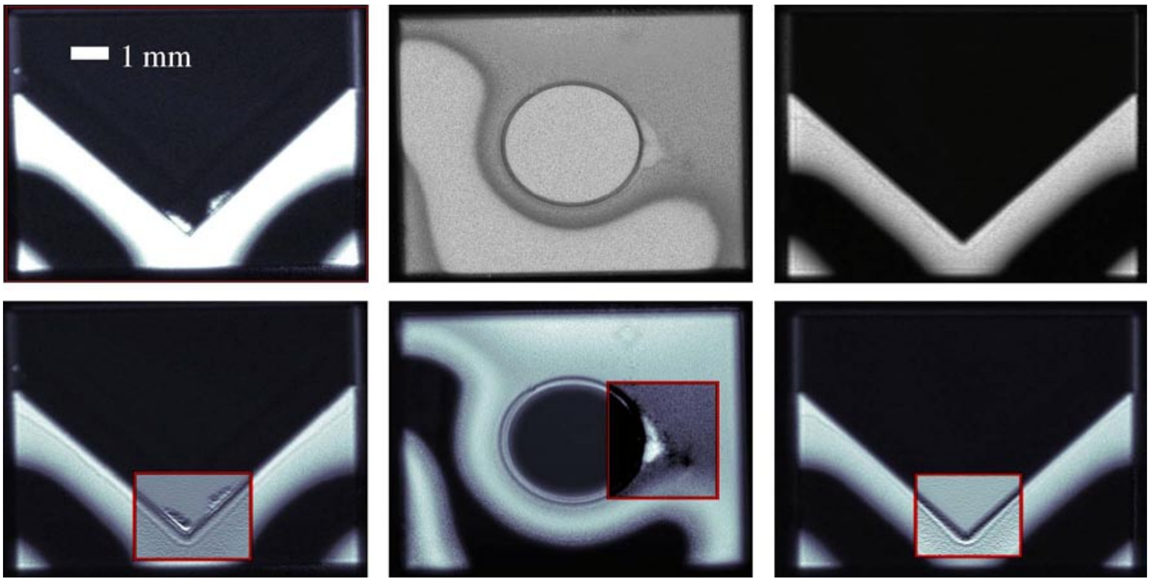

Figure 5: Image analysis applied to acoustic micrographs. Top: pure intensity images obtained by an acoustic microscope. Bottom: processed acoustic images. Image filters for blind-deconvolution and a Gaussian filter were applied to emphasize the defect and for increasing the resolution. A Sobel filter was applied in the lower left-and right images for detecting the contour and orientation of the defects.