Scanning acoustic GHz-microscopy versus conventional SAM for advanced assessment of ball bond and metal interfaces in microelectronic devices

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1. Introduction

In spite of alternatives such as laminate or flip chip packages classical wire bonding is still essential for microelectronic packaging. The assessment of quality and reliability of the wire bond interconnects is usually conducted by pull and shear tests of ball bonds and wedges. However, those destructive mechanical test methods only provide information about the required forces and the sites of the interconnect breakdown but do not allow direct access to information about the condition of the bond interfaces themselves. Moreover, for modern (fine pitch) Cu wire bonding and sensitive pad metallizations the pull and shear values strongly depend on the applied decapsulation process which is a prerequisite for providing access to the wire bonds [2,3].

Commonly in failure analysis additional inspection methods like mechanical or focused ion beam (FIB) cross-sectioning combined with subsequent SEM imaging are used. However, these methods enable a detailed local assessment only along certain cross-sectioned interfaces but do not provide information on the complete bonding area.

As an alternative approach of ball bond quality assessment also the intermetallic phase formation between ball and pad can be analysed. While the necessary selective removal of the ball bonds is widely established, e.g. for Au or Cu wires on Al pads [4], this method naturally cannot be applied on homogeneous interconnects formed e.g. by the upcoming Cu to Cu wire bonding.

Conventional high frequency back-side scanning acoustic microscopy (SAM) can be employed for analysing bond interfaces of various geometries [5]. However, the resolution achievable using conventional ultrasonic transducers in the frequency range of up to 230 MHz is approximately 20 μm depending on the lenses’ numerical aperture and the required analysis depth inside the specimen. This, however, is not nearly sufficient for a precise and accurate assessment of wire bond interconnects, especially when considering today’s small wire bonds with diameters of a few 10 μm.

The current paper presents experimental results obtained from the inspection of wire bond and metal interfaces employing an innovative ultra-high resolution acoustic microscopy setup. This GHz-SAM combines up to 2 GHz acoustic frequency with ultra-short focal lengths of the acoustic lenses leading to an outstanding increase of the achievable lateral resolution with an extreme sensitivity to surface and near-surface features. Data obtained from ball bond and power metal interfaces are compared to the results recorded by conventional acoustic microscopy in combination with a 300 MHz transducer.

2. Materials and methods

2.1. Sample preparation

For high and ultra-high resolution back-side acoustic microscopy analysis of ball bond and metallization interfaces close access from the chip back side is required. For a common plastic package as shown in Fig. 1a this can be achieved in a multi-step preparation sequence. At first the lead-frame and the die attach materials such as solder or glue have to be removed employing standard wet-chemical etching.

In general, for conventional back-side SAM applications in the frequency range up to 300 MHz it is already important that the thickness...
of the Si chip is adapted to the focal length of the employed ultrasonic transducer. Usually, thinning of the die is necessary which can be achieved by mechanical polishing of the die in its original package. For the conventional 300 MHz ultrasonic transducer with 2.5 mm focal length applied here, a Si thickness below 200 μm has been prepared (Fig. 1b).

In contrast, for ultra-high frequency GHz-SAM analysis with its extremely short focal lengths at most a few μm of Si can be left on the chip back side. For the experiments presented here, all remaining Si was removed employing a selective SF6-based plasma etching process stopping at the oxide layers of the back-end-of-line (BEOL) stack.

2.2. Conventional high resolution SAM analysis

Conventional high frequency SAM operates in the frequency range between 100 to 300 MHz. Acoustic transducers at those frequencies commonly have focal lengths between 2.5 and 10 mm. In the experiments described here, a 300 MHz transducer with 2.5 mm focal length has been used within a commercial Sonoscan Gen5 acoustic microscope allowing for a lateral resolution in Si of 10–15 μm. Acoustic inspection was performed in pulse-echo mode with water heated to 40 °C acting as the couplant between the acoustic lens and the specimen. For imaging, the acoustic transducer was scanned laterally over the sample while recording the reflected intensity.

In general, for the reflection of an ultrasonic pulse at the interface between two materials the reflected portion \( R(\phi) \) is determined by the incident angle and the mismatch in acoustic impedance of the adjacent materials. The reflectivity of an interface can be described by [6]:

\[
R(\phi) = \frac{Z_2 \cos \phi - Z_1 \cos \phi'}{Z_2 \cos \phi + Z_1 \cos \phi'}
\]  

(1)

Here, \( Z_1 \) and \( Z_2 \) represent the acoustic impedances of the involved materials. \( \phi \) and \( \phi' \) are the angles of the incident and the refracted wave components. The acoustic impedances of the involved materials are given by the product of the material’s mass density and the corresponding wave velocity. Eq. (1) shows that the intensity reflected at a certain interface is strongly angular dependent but also increases with the mismatch of the involved acoustic impedances. In the case of a void or a gap within a solid material, which corresponds to \( Z_2 \approx 0 \), total reflection of the incoming signal and a negative sign of the reflectivity is observed (\( R \approx -1 \)). Consequently, delamination within a metallization stack or reduced adhesion between a ball bond and the underlying metallization can be detected by a clear increase of the reflected acoustic intensity.

2.3. Ultra-high resolution GHz-SAM analysis

For the inspection of ball bonds and power metal interfaces resolutions in the range of 1–5 μm are strongly required for inspecting features of relevant size in that kind of sample structure. This requirement, however, highly compromises capabilities of conventional acoustic microscopy. Increasing the acoustic resolution firstly requires an increase in acoustic frequency and secondly a specific focusing of the acoustic lens. The GHz-SAM setup employed here (see Fig. 2) was developed in close collaboration between the Fraunhofer IWM (Fraunhofer Institute for Mechanics of Materials, Halle, Germany) and PVA TePla company (PVA TePla Analytical Systems GmbH, Westhausen, Germany). The GHz-SAM allows the application of acoustic frequencies of up to 2 GHz.

It should also be noted that acoustic attenuation increases exponentially with frequency. As an example the round trip attenuation through the couplant is 35 dB at 1 GHz and a focal length of 80 μm [7]. Therefore, and to increase lateral imaging resolution specifically adapted acoustic lenses were employed in the current work. These were an acoustic lens operating at 1.12 GHz with opening angle 100° and a free working distance (focal length in water @ 21 °C) of 76 μm, a 400 MHz acoustic lens with opening angle 60° and a free working distance of 200 μm, and a 200 MHz lens with opening angle of 60° and 500 μm focal length. The large opening angles of these acoustic transducers result in large numerical apertures and thus enable a highly extended imaging resolution, superior to conventional acoustic microscopy. Fig. 3 contains a schematic of the strongly focusing lenses employed in the acoustic GHz-microscope. The large opening angles lead to large phase shifts of the acoustic wave components across the aperture and result in a strongly focused acoustic beam. The increase in acoustic frequency leads to reduced wavelengths. Both phenomena result in the superior lateral resolutions achievable with the acoustic GHz-microscope.

In addition, the acoustic GHz-microscope is specifically adapted (as shown in Fig. 2) to phenomena occurring at the extremely high frequencies employed. In contrast to conventional SAM excitation of the acoustic lens is performed in burst-mode to provide sufficient energy in the acoustic pulse to overcome the increased acoustic attenuation. Also the GHz-SAM contains an analogue pre-processor unit which allows for a high degree of lateral oversampling in order to increase the signal-to-noise ratio of the received data without the need of sequential averaging [8].

Image acquisition in the acoustic GHz-microscope usually requires 15–20 s, depending on the number of image lines. The GHz-SAM provides a maximum scan range of 2 mm × 2 mm which can be reduced down to 10 μm by 10 μm. For large area screening the scan range can...
be extended artificially by employing an automated operating sequential scan mode. Line repetition frequency can be set up to 50 Hz allowing for rapid frame acquisition with pulse repetition frequencies of up to 350 kHz to provide sufficient spatial oversampling. For the acoustic inspections performed here a 1 GHz, a 400 MHz, and a 200 MHz lens were used. For optimized imaging multiple frames have been acquired automatically at decreasing distances between the acoustic lens and the specimen.

3. Results and discussion

3.1. Small ball bonds in LQFP package

For the inspection of small ball bonds by back-side SAM analysis a test chip in a standard PG-LQFP-176 package with 25 μmCu bond wires on an unstructured Cu metallization was used. Fig. 4 shows the back-side SAM reflection image of the entire chip obtained by conventional acoustic microscopy recorded with a 300 MHz (FL 2.5 mm) transducer. All ball bonds are clearly resolved but there are several balls with pronounced irregularities within the outer ball ring (bright areas indicating insufficient adhesion). Pull and shear analysis applied on a similar sample confirmed the observation that balls with reduced adhesion are exclusively found within the outer ball bond ring. FIB cross-sectioning performed for a “good” and a “bad” ball clearly showed an extended irregular interface between the ball and the pad metallization only for the “bad” ball bond as shown in Fig. 5.

After selective dry-chemical removal of the Si the same test chip has been investigated by ultra-high resolution GHz-SAM using a 1.12 GHz acoustic objective with a focal length of 80 μm and an opening angle of 100°. A direct comparison of the respective results is provided in Fig. 6. An impressive increase in imaging resolution can be noticed clearly: For all three “bad” balls in the left row some residual adhesion at the right ball edges is shown by both images, but the adhering area appears very small and well defined in the acoustic micrograph recorded at 1.12 GHz acoustic frequency (Fig. 6b).

On the other hand, for the “good” balls no details are resolved by the 300 MHz transducer at all, only showing diffuse dark areas, whereas the GHz-SAM image reveals small embedded areas with obviously decreased adhesion. The dimensions of these well resolved areas are in the range of only a few μm as shown by the close-up image Fig. 6c.

3.2. Power metallization

Whereas a ball bond interface is related to the top side of a thick pad or power metallization, the corresponding bottom side also represents an important interface in terms of reliability topics. For example, reduced adhesion or other alterations of the metallization layer can be detected by high-resolution SAM analysis. To evaluate the potential of conventional acoustic microscopy and GHz-SAM a sample with a bottle-shaped power metal finger structure with a layer thickness in...
the 10 μm range was investigated. Bond wires with a diameter of 30 μm were bonded onto this power metallization.

Fig. 7 shows the comparison between conventional SAM and an image series recorded from different acoustic lenses using the GHz-SAM setup. Here, Fig. 7a represents conventional SAM (300 MHz, FL 2.5 mm) while Fig. 7b was obtained from the GHz setup using an acoustic lens with slightly lower frequency (200 MHz) but much shorter focal length (FL 500 μm). Despite the nominally lower frequency a clearly increased resolution is found for the GHz setup both for the power metal structure and the ball bond interfaces. This result impressively confirms the decisive role a short focal length plays for the ultra-high resolution acoustic microscopy in addition to a higher frequency commonly applied.

Employing different acoustic lenses with increasing frequency in combination with decreasing focal length at the GHz-SAM setup (Fig. 7b–d), a clear increase of the achievable resolution is found. On the other hand, since the signal attenuation exponentially increases with the frequency, the penetration depth decreases drastically. Whereas the ball bond interfaces on top of the thick power metallization are clearly resolved and focusable for the 200 MHz lens (Fig. 7b), the metallization layers beneath the power metal layer become visible for the 400 MHz lens (Fig. 7c), while the signal from the ball bond interfaces becomes weaker. Finally, for the 1 GHz lens (Fig. 7d) the even further decreased penetration depth does not allow a proper imaging of the ball bonds on the metallization top side anymore. However, when focusing on the bottom side of the power metallization at the interface to the underlying signal metallization an outstanding lateral resolution is obtained. Therefore, for frequencies in the GHz range the maximum resolution can only be achieved for surface and subsurface features of a given sample, which requires very close access to the interface of interest.

Thus, employing the GHz-SAM at 1.12 GHz acoustic frequency and focusing on the bottom side of the power metal it is easily possible to

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Fig. 6. Comparison of back-side SAM micrographs of ball bonds formed from a 25 μm Cu bond wire. Images were recorded by (a) a conventional 300 MHz transducer with 2.5 mm focal length and (b) an ultra-high resolution 1 GHz acoustic lens with 80 μm focal length. Bright areas within the ball interfaces represent reduced adhesion. These well-defined features also shown in the close-up image (c) represent an outstanding lateral resolution in the 1 μm range for the GHz setup.

Fig. 7. Comparison of back-side SAM micrographs of a bottle-shaped power metal finger structure with ball bonds formed from 30 μm bond wires. Image (a) recorded by a conventional 300 MHz transducer with 2.5 mm focal length. Images (b)–(d) obtained from the ultra-high resolution GHz setup using acoustic lenses with frequencies of 200 MHz, 400 MHz and 1 GHz and corresponding focal lengths of 500, 200 and 80 μm, respectively.

Please cite this article as: G. Vogg, et al., Scanning acoustic GHz-microscopy versus conventional SAM for advanced assessment of ball bond and metal interfaces in microelectronic devices, Microelectronics Reliability (2015), http://dx.doi.org/10.1016/j.microrel.2015.06.066
resolve the signal reflected from the metallization layers beneath the power metal as shown in Fig. 8a, which is a close-up of Fig. 7d. Moreover, comparing the GHz-SAM image with the corresponding layout displayed in Fig. 8b it can be seen that the power vias linking power metal and signal metallization are clearly resolved. This demonstrates that a feature size of 2 μm representing both via diameter and corresponding pitch can be resolved well by the GHz-SAM setup. For illustration, a mechanical cross section through the analysed power via structure is shown in the inset of Fig. 8b.

4. Conclusion

The current work demonstrates that the use of ultra-high frequency scanning acoustic microscopy operating in the GHz frequency range allows a drastically improved lateral imaging resolution compared to conventional high resolution back-side SAM. For inspecting ball bonds and power metal interfaces the acoustic GHz-microscope proved to be a highly valuable tool. With an imaging resolution in the 1 μm range new applications such as a real 2-dimensional assessment of small ball bond interfaces are possible. These new options of semi-destructive inspection will become extremely valuable e.g. for the assessment of modern Cu to Cu wire bond interconnects which cannot be achieved by other inspection methods operating non- or semi-destructively.

Acknowledgements

This work has been performed within the CATRENE project Master-3D/3D-InnoPro. In that project Fraunhofer IWM and Infineon were funded by the German “Bundesministerium für Bildung und Forschung (BMBF)” under contracts 16ES0069 and 16ES0067K, respectively.

References