Detection of Local Cu-to-Cu Bonding Defects in Wafer-to-Wafer Hybrid Bonding using GHz-SAM.

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Abstract

This paper demonstrates the application of GHz-SAM for the detection of local non-bonded regions between micron-sized Cu-pads in a wafer-to-wafer hybrid bonded sample. GHz-SAM is currently the only available non-destructive failure analysis technique that can offer this information on wafer level scale, with such high resolution.

Introduction

In 3D technology, thinned Si wafers and/or dies are vertically stacked and electrically interconnected, enabling fast and compact electronic circuits. The stacked dies/wafers and packages are electrically interconnected using micro-bumps, Cu pillars and Cu Through Silicon Vias (TSVs). Various technology options for 3D-integration are described in [1].

An alternative 3D stacking option, which allows obtaining a higher interconnect density with pitches down to 1 μm , is 'hybrid wafer-to-wafer (W2W) bonding', where two wafers containing Cu pads are face-to-face (F2F) bonded [2]. In this bonding process, Cu pads on both sides of the wafer form electrical contacts (Cu-Cu), while bonding outside these pads is done during the same bonding step by dielectric-to-dielectric bonding. For this reason, it is called 'hybrid' bonding. A schematic picture of this process is shown in Fig. 1.

Figure 1: Schematic pictures showing the hybrid wafer-to-wafer bonding process.

After processing wafer 1 and 2, as shown in Fig. 1, with dielectric deposition and damascene Cu pads, they are aligned

and bonded F2F. Thinning of the top wafer to 5 μm reveals the TSV (5 μm diameter), after which a redistribution layer is processed on top. In an alternative process, TSVs can also be fabricated after thinning the top wafer (TSV last).

Figure 2 shows a schematic picture of one such Cu-Cu interconnect. The dashed red line indicates the bonded interface. The bonding and alignment between the two wafers should be perfect, meaning that voids or badly bonded regions should be avoided. This is complicated because different bonding interfaces exist near such an interconnect: dielectric to dielectric, dielectric to Cu, and Cu to Cu (Cu-Cu). The technique currently used to detect possible non-bonded regions is in-line wafer-level scanning acoustic microscopy (SAM), using a 175 MHz transducer. Fig. 3, left, shows a typical in-line SAM result of a bonded wafer showing defective bonding. The white regions indicate that there are air gaps present between top and bottom wafer. The zoom-in on two different dies, die A and die B, on the right side of this figure, using the same system, shows that die B has more unbonded regions than die A. The rectangles which are visible in the left top corner of the dies (indicated by a yellow rectangle) contain arrays of daisy chains.

Figure 2: Schematic image of a single Cu-Cu connection in W2W hybrid bonding.

The in-line SAM clearly indicates defective regions, but it does not give details on which Cu-Cu pads are defective. As such, it does not give information on where best to make a FIB

cross-section to investigate the defect in detail. The purpose of the current work was to investigate whether GHz-SAM [3] can offer more detailed information and possibly even visualize separate single Cu-Cu interconnects within a daisy chain.

Figure 3: In-line SAM image (175 MHz) of a 300 mm wafer (left) and zoom-in on two dies (right; die size 12.6x13.2 mm).

Test samples

Each of the rectangles visible in the SAM images shown in Fig. 3, corresponds with an array of interwoven long daisy chains (DC) containing hundreds of Cu-Cu bonds. Information on the daisy chain number, a design image and a zoom-in on the left-top corner is shown at the bottom of Fig. 4 and in Fig. 5. One 'square' in this design image corresponds with one Cu-Cu top-bottom interconnection.

Figure 4: Top: In-line SAM images (@175 MHz) of die A (left) and die B (right) with indication of the daisy chains DC11, 22, 30 and 40. Bottom: Left: Daisy chain design and detail of the top left corner; right: cross-section image of a single Cu-Cu pad interconnection corresponding with one square in the detail design.

The daisy chains consist of two interwoven daisy chains, a detail of which is shown in Fig. 5. This results in 180 nm wide cross-like interconnections between the squares. Size information for four tested daisy chains is given in Table I. It is also indicated whether the daisy chain was good (OK) or bad according to the in-line SAM tests.

Figure 5: Design detail showing the interwoven daisy chains. One chain is indicated in red, the other in blue. The top Cu pad (PADD) is indicated by a red open square, the bottom one (PADB) with a blue open square. The metal connecting two pads is 180 nm wide and indicated in red when connecting top Cu pad (MIT) and in blue when connecting bottom Cu pads (MIB).

Table 1: List of daisy chains (DC) that were determined to be good (OK) or defective (BAD) based on in-line SAM results (see Fig. 3 and 4). The width of the Cu pad of the bottom wafer (w_b) and top wafer (w_t), and pitch for the different tested daisy chains is indicated, as well as the percentage Cu in the daisy chain.

Daisy chain: w_b - w_t /Pitch (nm)	Die A	Die B
DC11: 1080-540 /1710 (40% Cu)	OK	BAD
DC22: 1620-540 /2340 (48% Cu)	BAD	BAD
DC30: 2700-900 /5400 (25% Cu)	OK	OK
DC40: 900-900 /2250 (16% Cu)	OK	OK

Acoustic GHz-Microscopy

GHz-SAM [2, 3] inspection applied in the current study was performed at 1 GHz acoustic frequency employing a highly focused acoustic lens of 80 μ m focal length (in water) and a semi-aperture angle of 50°. For coupling the acoustic waves into the sample, deionized and degassed water was used and experiments were performed at 21°C. A schematic of the acoustic GHz-microscope is provided in Fig. 6. Here, the acoustic lens is excited by a tone burst of 20 ns length and an amplitude of 18 V peak-to-peak. The signal is converted into a mechanical wave by the ultrasonic transducer, and transmitted towards the sample where it interacts with the mechanical and elastic properties of the samples internal structure. At each interface between material with differing mechanical/ elastic

properties the acoustic wave is partially transmitted and partially reflected (and scattered, if conditions are fulfilled), depending on the gradient. The echoes are then received by the same transducer and fed into the receiver chain of the GHz-SAM, where they are amplified and pre-processed to provide a signal at each scan-line.

Figure 6: Schematics of the GHz-SAM set-up.

The acoustic transducer is moved parallel to the sample surface by an X-Y stage with a line frequency of up to 50Hz. This setup allows frame acquisition periods of approx. 20s - 30s, depending on the number of frame lines. The ultrasonic transducer consists of a piezo element that, based on electro-mechanical conversion (and vice versa), excites an elastic wave with the shape of the electrical signal. To focus the acoustic waves the lens body contains a small spherical cavity. GHz-SAM data presented here were recorded in $V(z)$ scan-sequences, meaning that acoustic GHz-micrographs were recorded at decreasing distances between the probes tip and the sample surface. This approach ensures that the micrograph with the sharpest contours but also with the most relevant sub-surface features are recorded and can be correlated. However, it also allows the excitation of complementary wave modes like e.g. surface acoustic waves, shear waves, etc. These modes have a different propagation behavior and may allow accessing features and depths which would not be accessible by the pure compressional mode. Acquisition in $V(z)$ mode started with the acoustic focus being 45 μm above the sample surface. The lens was then defocussed towards the sample in steps of 1 μm and continued until the acoustic lens was 5 μm above the sample surface.

Results and discussion

Fig. 7 shows some GHz-SAM images selected from a $V(z)$ scan on a part of daisy chain DC30. This demonstrates that changing the focus clearly reveals new features, and that $V(z)$ scans are required to be able to select the best image of the interface to be studied. In the following discussions, for clarity, images from only one depth offering most information are shown. Each 'dot' visible in these images represents one Cu-Cu connection, indicating that GHz-SAM can indeed distinguish the separate pads. The results obtained for the

different daisy chains listed in Table I are discussed in the following figures.

Fig. 8 shows images selected from a $V(z)$ -scan taken at the top side of the daisy chain DC11 for die A and die B. Die A was found to be non-defective in the in-line SAM, and also with the GHz-SAM no defects are observed. The large fringes which are visible in the GHz-SAM image are caused by interference effects. Die B, which was diagnosed to be defective in the in-line SAM, shows circle-like features at many positions of the GHz-SAM image, indicating defects. Each of these circles corresponds with a single Cu-Cu interconnect, showing that the GHz-SAM can detect single interconnects and distinguish between defective (containing air-gaps) and non-defective ones. Figures 9 to 11 shows similar images, but for arrays DC22, DC30 and DC40, respectively. DC22 (Fig. 9) was found to be defective for both die A and B, and this is confirmed by the GHz-SAM images. Circle like defects are clearly visible.

Figure 7: GHz-SAM images of DC30 taken during a $V(z)$ can, with from left to right a deeper focus inside the sample, showing the top part of daisy chain DC11 for die A and die B.

Figure 8: GHz-SAM images of the top part (yellow square on the design shown left) of DC11, die A and B.

Figure 9: GHz-SAM images of the top of DC22, die A and B.

Figure 10: GHz-SAM images of the top of DC30, die A and B.

Figure 11: GHz-SAM image of the top of DC40, die A and B.

The array DC30 (Fig. 10), however, was indicated to be non-defective (OK) based on the in-line SAM measurements, for both chips A and B, but the GHz-SAM images do show clear deviations at some positions in both chips, more in B than in A. This shows that a sample can pass the in-line SAM analysis, but still be defective. Fig. 11 shows the results for DC40. In this array with smallest Cu pad size (see Table I), no clear defects are observed by GHz-SAM tests neither on die A or B. The small black dots are resulting from particles on the surface of the top wafer.

To confirm that the observed local structures in the GHz-SAM are caused by non-bonded local regions near the Cu pads, an in-depth analysis was done on daisy chain 30. Fig. 12 shows a zoom-in on the bottom region of array 30. One can clearly distinguish circle-like (donuts) features, but also positions where the Cu-Cu pad shows brighter GHz-SAM images.

Figure 12: GHz-SAM image showing the bottom part of daisy chain DC30, die B, and some special locations.

Focused Ion Beam (FIB) cross section analysis was made at positions 1 to 3 as indicated on the zoom-in image from Fig. 12, shown again in Fig. 13, top. The results indicate that the bright spots observed in the GHz-SAM correspond with non-bonded regions between the bottom Cu pad and the dielectric on top, as indicated by the black arrows in Fig. 13, for bumps 1 and 2, respectively. The size of this non-bonded region is about 1 μm , which falls just within the detection limit of the GHz-SAM. Bump 3, which does not show a bright GHz-SAM image, only has a small non-bonded dielectric-dielectric region at the top edge of the bottom Cu. The same small edge issue is also seen at the other bumps. This was not detected in the GHz-SAM. Its width is about 280 nm, which is clearly beyond the detection limit of the GHz-SAM. Although this could not be confirmed yet, the donut-like features (circle) observed in several of the GHz-SAM images indicate most likely non-

bonded regions at the full bottom-Cu/dielectric interface, so, extending all around the top Cu pad.

Figure 13: FIB-SEM cross-section images taken at bumps 1 to 3 as indicated on the zoom-from Fig. 12. Daisy chain DC30.

Conclusions

The unique strength of GHz-SAM for detection of air gaps with a high sensitivity and μm resolution is demonstrated. At this moment, no other technique exists that can visualize these defective bond areas in such a W2W bonding application. The technique can visualize single Cu-Cu interconnects (micron sized features) within a daisy chain structure, and distinguish which interconnect has a defective bonding, i.e. an air gap.

Acknowledgments

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