EMPIR Grant Agreement 14IND07 – 3D Stack

Good Practice Guide: Recommendations on the strategy for measuring the dimensional properties of TSVs based on Confocal microscopy, IR interferometry and optical microscopy traced to a metrological 3D AFM.

Lead Partner: PTB
Contributing partners: CEA, FhG, Fogale

WP3: Towards in-line metrology process control for 3D integration technology
Task A3.3.1:

From the results of A1.2.1, A1.2.4 and A1.2.5, PTB, with input from CEA, FhG and Fogale will produce a Good Practice Guide on the traceable measurement of the dimensional properties (CD, vias diameter, shape, sidewall angle (top and bottom), vias bottom profile, sidewall roughness) of the TSVs before filling.

1. Introduction

As part of the 3D integration technology, the Through Silicon Vias (TSV) are becoming the main structure to electrically connect bonded chips reducing packaging size and improving power consumption and performances. Controlling x,y,z TSV dimensions is key to ensure proper Cu filling and connectivity to the next chip or wafer. To achieve this goal, several methods already exist such as optical profilometry (confocal, interferometry), optical microscopy and AFM. Due to the various TSV dimensions and aspect ratio fabricated as a function of the final device application, different techniques will be used. In this document, we present a Good Practice Guide, which evaluated the possibilities of the different measurement techniques with their capabilities, limitations and traceability with standards and metrological AFM. After optical systems performance assessment in measuring TSV critical dimension (CD) and depth, an overview of TSV measurements using 3D-AFM with various measurement strategies and approaches in realizing traceability available at PTB will be explained.

2. Confocal microscopy and other techniques comparison at Fogale

In TSV middle approach, controlling the TSV depth over the full wafer surface is of high importance to make sure that after Cu filling, the TSV will not be destroyed during the next "nails" reveal process. Indeed, deeper TSVs will be revealed too fast, while too short TSVs might not be revealed. A fast and accurate-enough technique like confocal microscopy seems to be a good candidate to complete this task. But, as demonstrated on the Fogale 4see system, the confocal microscope is not capable of measuring high aspect ratio TSVs such as ones with 10µm diameter by 100µm depth. As shown in Figure 1 no reflection could be detected from the bottom of the 100µm deep vias but only the top wafer surface reflection signal is obtained.

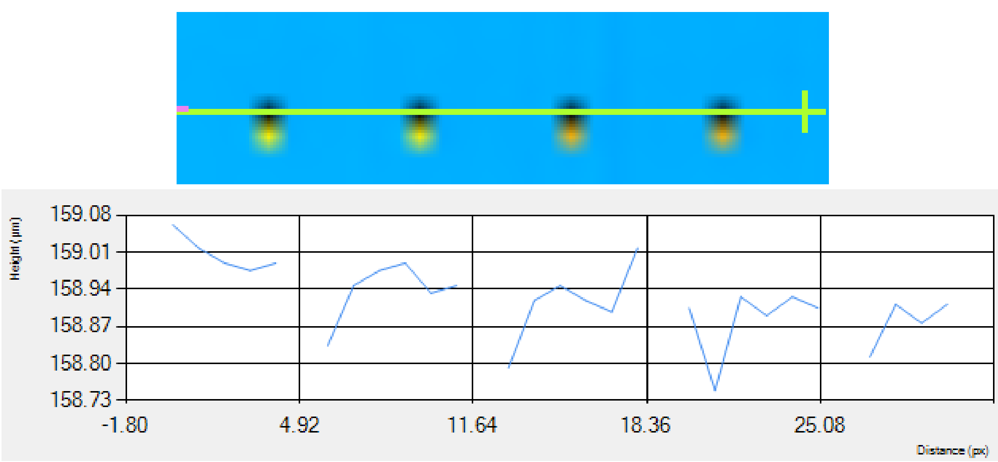


Figure 1. Confocal chromatic Scan line path and corresponding signal along a TSV series.

In the Fogale laboratory, several tests were implemented and applied on various TSV dimensions. It was found that 3D Confocal chromatic analysis, which is the fastest technology, is limited to TSVs with diameter (>5µm) and depth (<70µm). As exposed in Figure 2, other complementary technologies available on Fogale systems were also tested such as visible full field interferometry and IR interferometry.

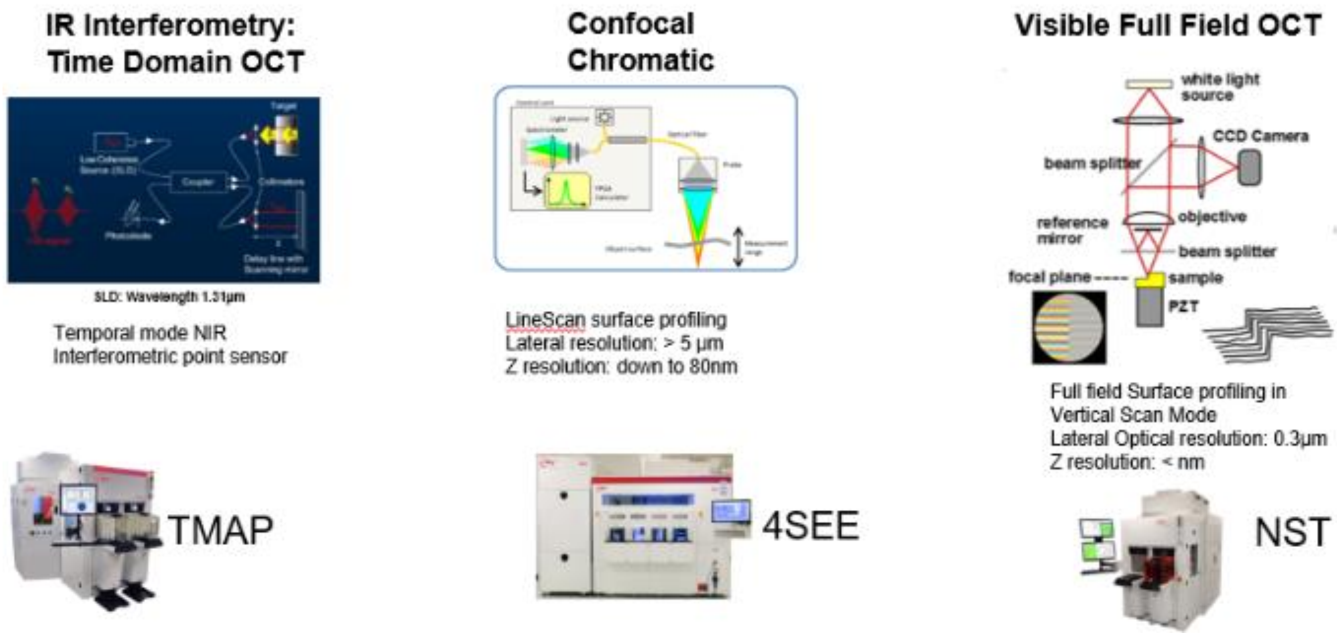


Figure 2. Three complementary technologies used to characterize TSV open in Si wafers.

In Figure 3 the performances of these techniques are compared with SEM measurements on various TSV diameters with 10µm depth. These techniques are full field interferometry, Confocal Chromatic and Time-Domain OCT (IR interferometry). All techniques are providing similar results in depth. Each technique has advantages and limitations. The time Domain OCT based on a new generation LISE-HR sensor developed at Fogale demonstrated capability down to 10 µm of minimum depth and 3 µm of minimum diameter with no limitation in aspect ratio. White Light Vertical Scan Interferometry (VSI) could measure TSV depth down to 3µm wide in diameter with good matching vs SEM.

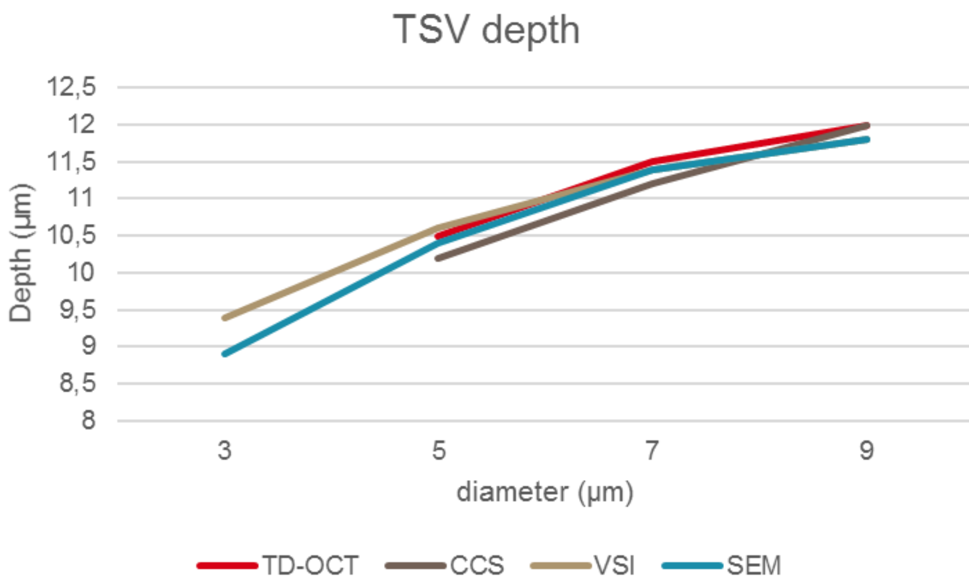


Figure 3: 10µm TSV depth measurement capability as function of diameter for different techniques.

3. White Light interferometry on high aspect ratio TSVs

3.1. Scanning positioning consideration

As the trend for the TSV-mid process is to reduce the TSV dimension, we proceeded with high aspect ratio TSV (10µmx100µm). After assessment of confocal microscopy, measurements were accomplished using white light interferometry (WLI) on a commercial system available at CEA and results were compared to a Fogale system also using interferometry. For the following measurements, the tool available at CEA (tool A) was using WLI and Fogale tool (tool B) was using Near IR interferometry (Low coherence Interferometric Sensor: LISE). In figure 4, a wafer map with the location in the test wafer of the five TSVs measured for this comparison is shown as well as an example of typical interferometric scan line signal.

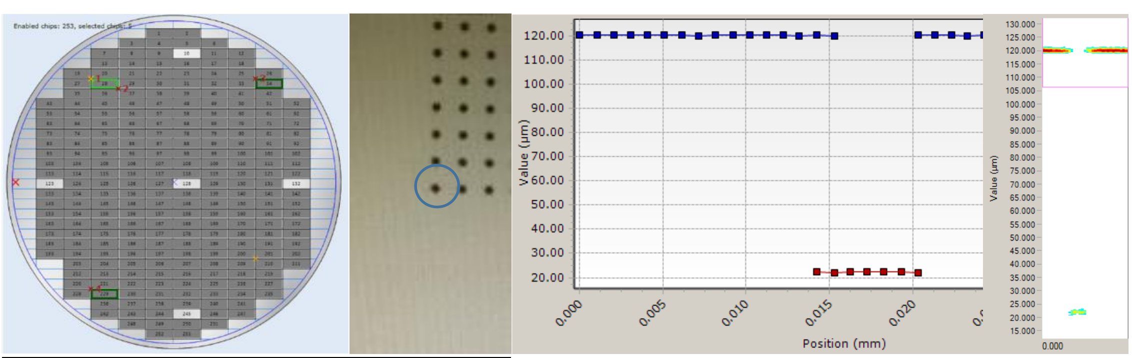


Figure 4. 10µm x 100µm TSVs location and interferometric signal on the CEA test wafer.

The TSV depth measurement from both tools is presented in the bar graph in Figure 5. These results are presented with error bars representing the expanded uncertainty, using a coverage factor of two (which gives a level of confidence of approximately 95 %), which is around +/-0.3µm for both tools. Results are very similar for Center and Right dies, whereas differences in measurements between the other dies can go up to 1%. For these three dies, the standard deviations are bigger for at least one of the tools.

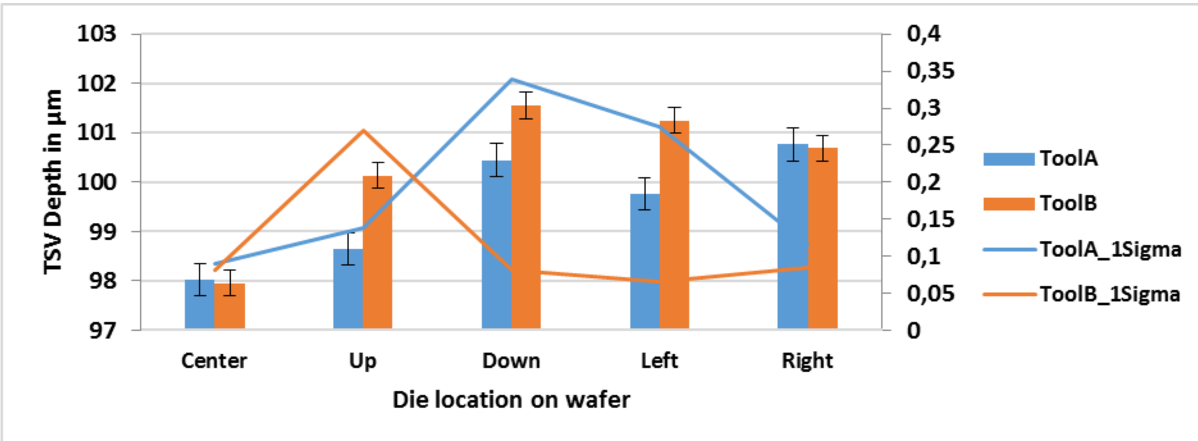


Figure 5. 10µm x 100µm TSVs measurements results for tool A and tool B.

Higher standard deviations can be explained by initial stage positioning or alignment strategy inaccuracies avoiding proper line scan location above TSV center. This positioning is of importance knowing that the TSV bottom is not flat, as shown in Figure 6, which shows a SEM cross section of a 12 µm wide TSV imaged at high resolution (S-5500 tool). Thus, we can assume that measurements will be more stable at the TSV center where the surface is more flat.

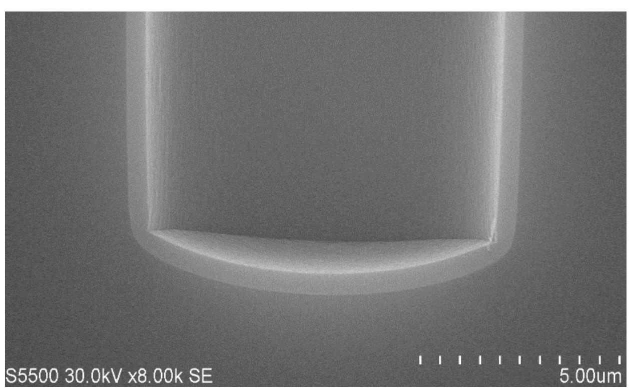


Figure 6. S-5500 SEM high resolution image of 12µm wide TSV bottom.

This hypothesis was confirmed by setting up a multi scans measurements with 1µm steps between scans to cover the full TSV top surface. In this mode, we guaranteed to measure the lowest point of the TSV and therefore a standard deviation of only 20nm was found for eight repeats.

3.2. TSV diameter limitation and workaround with IR interferometry at wafer backside

Another limitation using an interferometric point sensor is the minimum TSV diameter that can be measured. As specified earlier for Fogale system (Tool B) a limitation of 3µm was also found for the system installed at CEA from another company (Tool A). Below this value, there is not enough light returning from the TSV bottom and the measurements standard deviation is multiplied by 20 for 2,5µm and 40 at 2µm compared to larger TSVs of 3µm diameter and more.

In figure 7, TSV arrays measurement results are shown as a function of various diameters from 0,4µm up to 100µm (measurement in arrays was chosen to reduce time to recipe that can be impacted by difficult alignment steps on single TSV). Visible light interferometry curve (orange) demonstrate measurement capability from 100µm down to 3µm TSV diameter with around 50nm standard deviation.

Below 3µm the IR interferometry, with measurement from the wafer backside to collect more reflected light from TSV bottom, allows TSV measurement with diameters down to 0,4µm (single TSV measurement is not demonstrated yet for diameter below 1µm). Note that on a single 10µm diameter TSV, the IR interferometry technique allows similar expanded uncertainty (+/- 0.3µm) and accuracy (1% measured on certified VLSI standards) as for WLI.

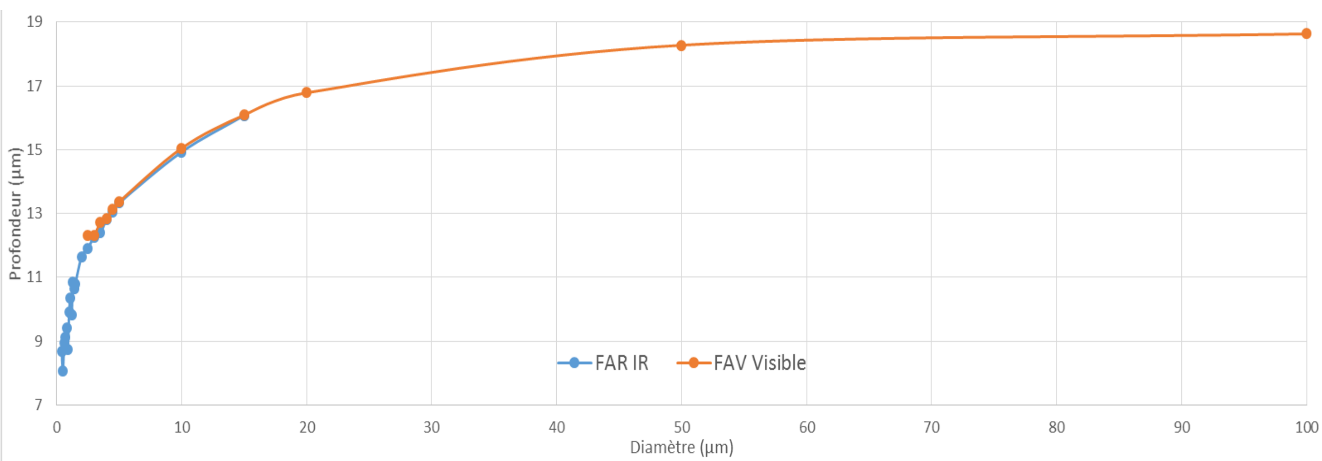


Figure 7. Tool A Visible light (orange line) versus IR interferometric (blue line) TSV depth measurements results as a function of diameters.

4. Critical dimension measurement on TSV opening using optical microscopy

After z dimensions measurement, critical dimensions (x,y) measurement using optical microscopy was evaluated on tool A available at CEA. This system is hosting a 50X objective with 0.4µm optical resolution coupled with CCD camera providing images with pixel size of 0.2µm (size of the corresponding surface on the wafer) . The measurement is performed using a grey scale image where TSV edge is detected at eight angular areas of 10° to fit a circle providing the TSV diameter value (see figure 8). Theoretically (and confirmed on certified standard), the measurement accuracy is two times the optical resolution of the objective, that is to say for 10µm wide TSV a measurement inaccuracy that can be up to 10%.

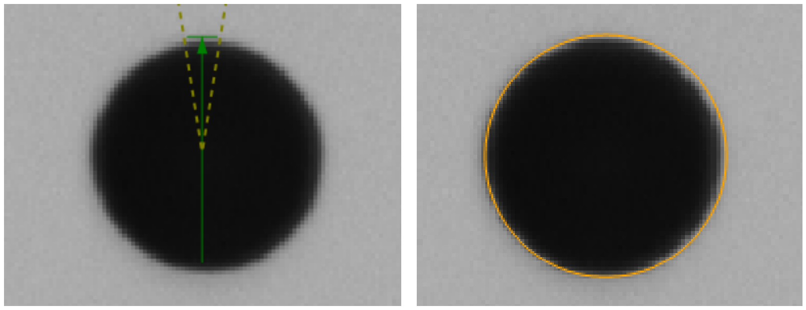


Figure 8. TSV diameter measurement using optical microscopy.

Note that the expanded uncertainty, using a coverage factor of two is only 7,6nm. Although the accuracy of measurement is relatively poor for 10µm wide TSVs, the repeatability is very good.

5. Various techniques comparisons for TSV dimensions characterization

In figure 9, a summary table is presented for six techniques evaluated for CD measurements in upper row and depth measurements in lower row. Different aspects are assessed such as throughput, measurement range, resolutions and dimensional type of output (scan or area). Even if some limitations were previously highlighted, white light interferometry is the more versatile technique for TSV dimensional characterization.

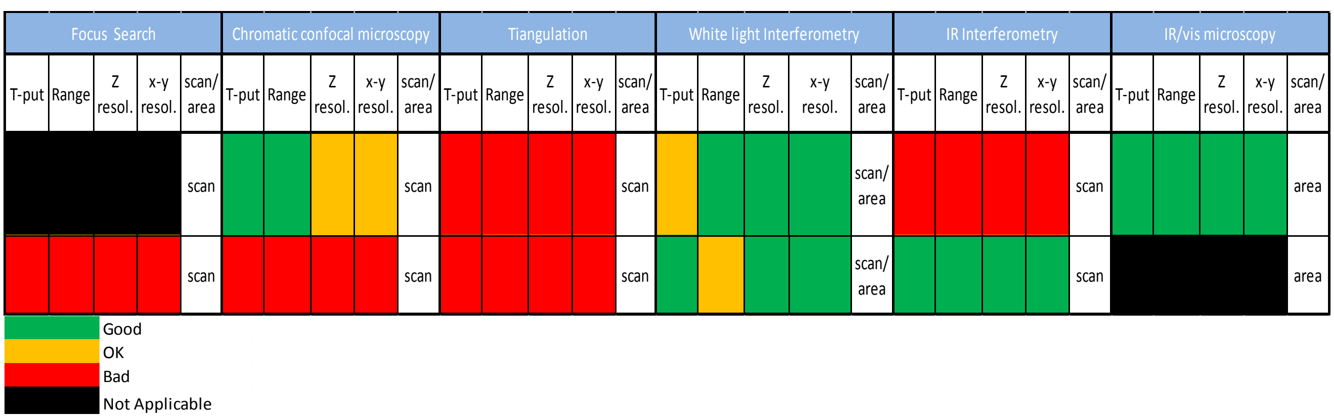


Figure 9. Benchmarking comparison between technologies for TSV CD and depth measurements.

Note that WLI makes use of phase differences of light reflected from different depths. However, any transparent film present on a sample will also induce a phase shift of the light. If this film is present at some parts of the surface and not present at other parts, this might provide false height information. As such, it is best to apply this technique for depth-measurements of TSVs before any different transparent layers are processed on the wafer surface, or for sure be aware of this issue. An experiment performed at imec where this issue became very clear, was when measuring Cu pumping, i.e. the height of the Cu of a filled TSV after it has seen a high temperature step, such as typically applied when further processing the back-end-of-line layers. As observed in figure 10, WLI measurements indicated that the top of the TSV was not flat, while from SEM and AFM measurements, it was clear that the top is flat and the WLI gave wrong results. Two effects played here: the presence of oxide on top of the Cu (a transparent film with varying thickness) and edge effects near the sharp edge of the Cu extrusion.

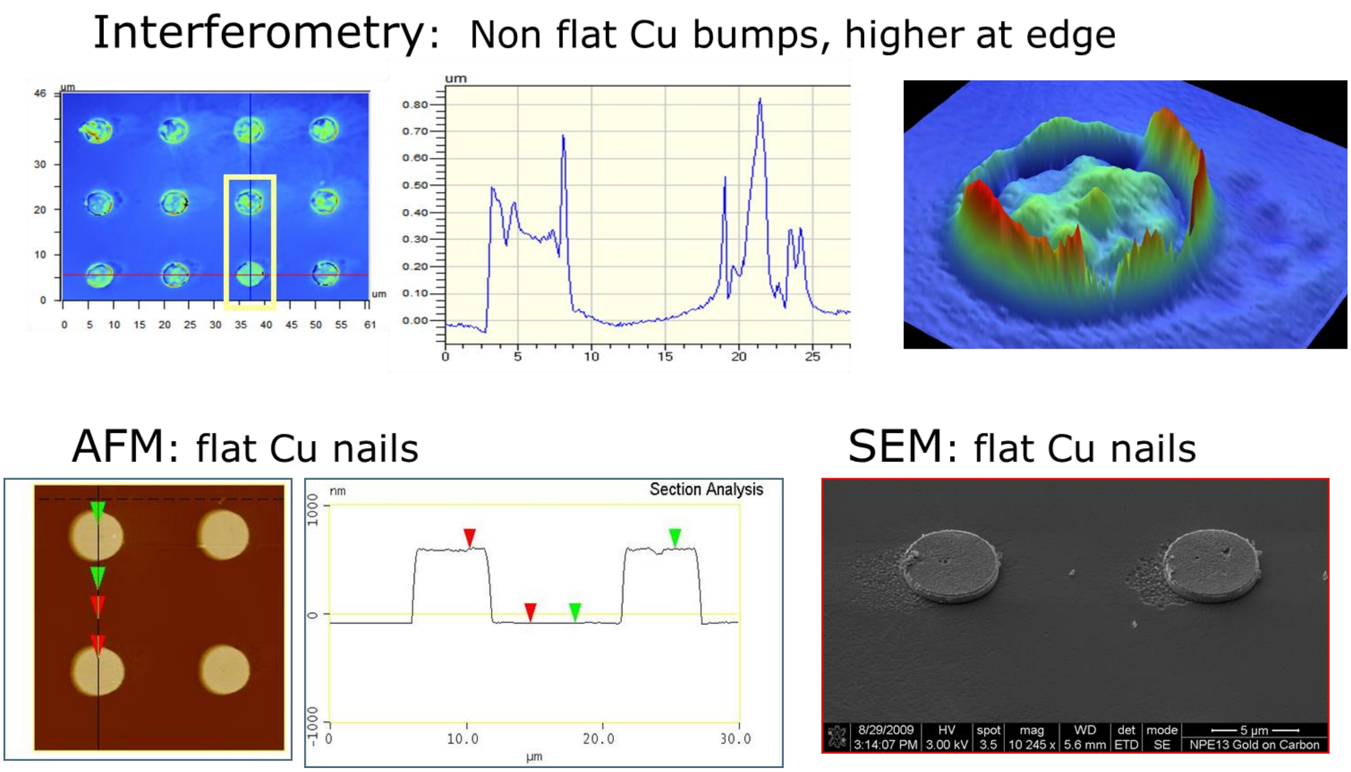
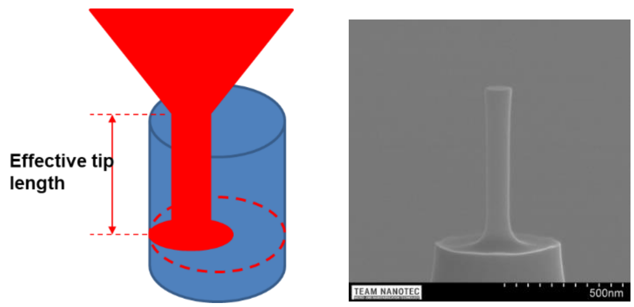


Figure 10. Issues that can falsify the WLI results: transparent layers on top of Cu nails, with varying thicknesses (after annealing for example) and sharp edges.

6. 3D-AFM for non-destructive measurements of dimensional properties of TSVs

Atomic Force Microscopy (AFM) is a well-developed technique widely applied for characterizing versatile nanostructures today. However, AFM usually applies conical or pyramidal shaped AFM tips. As a result, images generated by an AFM are the dilated result of the real structure by the tip geometry. Consequently, the steep sidewalls of micro and nanoholes cannot be properly measured by the conventional AFM technique, since the tip geometry prevents its contact with those regions. Therefore, the conventional AFM technique is not capable of measuring the TSVs dimensions directly due to almost vertical sidewall structures of TSVs. Of course it is possible to measure TSVs by conventional AFMs after TSVs are cleaved by e.g. Focused Ion Beam (FIB) devices. However, this is a time-consuming and destructive procedure.

To achieve true 3D measurements of dimensional properties of TSVs, a 3D-AFM has been further developed and optimized at the PTB. The 3D-AFM uses flared tips. Such a tip has an extended geometry near its free end which enables the probing of steep and even undercut sidewalls of micro and nanoholes, as illustrated in figure 11a.



(a) (b)

Figure 11. (a) A flared AFM tip for measuring micro and nanoholes; (b) A SEM image of a commercially available flared AFM tip as an example.

Today, various flared AFM tips are commercially available, with tip diameters ranging from 15 nm to 850 nm and effective tip length ranging from 130 nm to 7500 nm. Such probes allow measurements of very small holes. However, a limitation of such a probe is that the depth of holes measurable is limited to the effective tip length, as shown in figure 11a. To measure deeper holes, AFM tips with longer tip length are needed. This is technically feasible to be realized by the state-of-the-art micro and nano-manufacturing techniques such as etching and focused ion beam (FIB) induced deposition.

The photo of the developed 3D-AFM is shown in figure 12. The instrument works in the so called “scanning AFM head” principle. In measurements, the AFM head (together with the AFM tip) is positioned by a 6-axis flexure stage with a measurement volume of 15 μm × 45 μm × 45 μm (x, y and z), large-size samples such as 12-inch wafers can be measured. The instrument Nanostation 300, which has an air bearing stage with a travel range of 550 mm × 300 mm, is applied for coarse positioning of the sample. For AFM measurements, the air bearing is deactivated for eliminating the vibration noise of the air bearing stage.

The 3D-AFM uses the classic optical lever technique to detect the bending and torsion of the cantilever. The AFM measurements are mostly performed in the intermittent-contact mode, where the amplitude modulation technique is applied for detecting the tip sample interaction. For achieving a better 3D measurement performance, new probing and measurement strategies have been developed. For instance, the tip is capable of probing surfaces with a vertical and/or a torsional oscillation to enhance the 3D probing sensitivity; a “vector approach probing” (VAP) method has been applied for enhancing the measurement flexibility and for reducing the tip wear as well.

There is a big difference between conventional AFMs and the 3DAFM concerning the measurement strategy. Conventional AFMs usually measure in a scanning manner, where the tip is scanned along a lateral axis, while servo controlled in the z-axis to keep the tip sample interaction to be constant. Measurement points are typically taken with quasi equidistance in the lateral axis. Such a measurement strategy is well applicable for measuring e.g. surface textures, however, it is not suitable for measuring true 3D features (for instance, at the steep sidewalls). Instead, in 3D-AFM measurements sample features are probed in a point-wise manner by an AFM tip approaching along a 3D vector path, which is typically given by the normal vector of the surface. Measurement points can be flexibly defined, for instance, to obtain high density points at areas of interests. In other words, the 3D-AFM works as a touch-trigger CMMs for 3D measurements at the nanoscale.

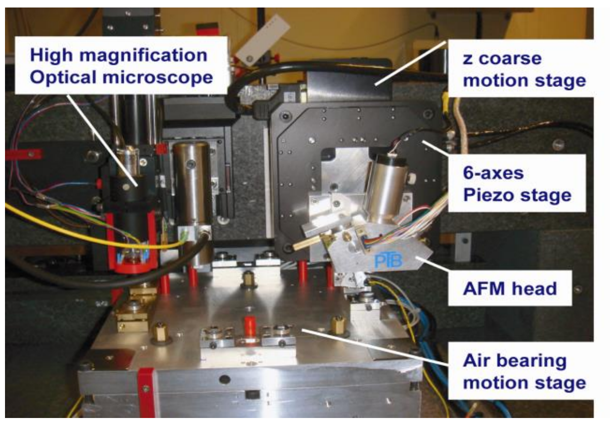
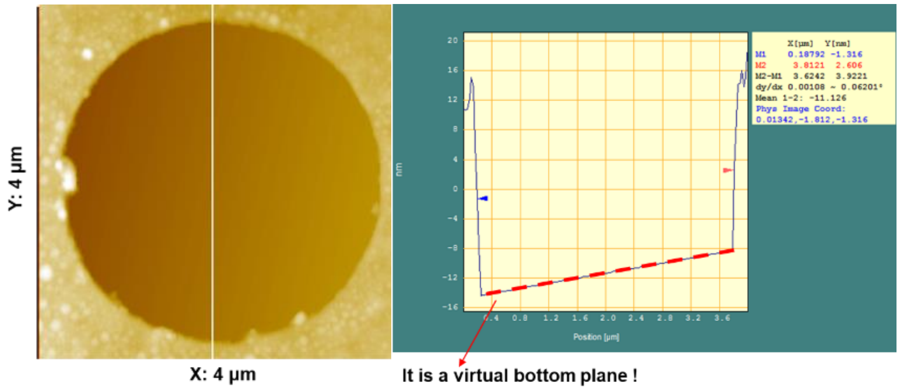


Figure 12. Photo of the developed 3D-AFM at PTB.

7. Three novel measurement strategies for measuring TSVs

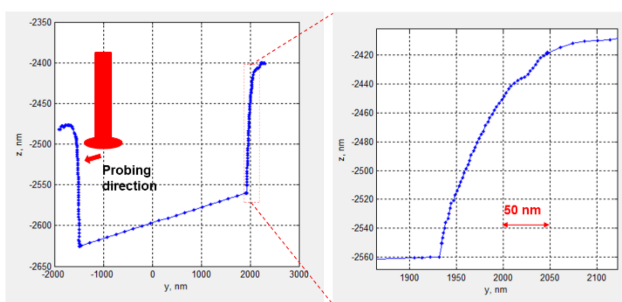
For non-destructive measurement of dimensional properties of TSVs, three different measurement modes referred as “top-down imaging “, “sidewall probing” and “XY contour probing” have been developed. Measurement result of a TSV with a nominal diameter of 3 µm using the ”top-down imaging” mode is shown in figure 13. Such a measurement mode is desired for overview measurements of the vias from the top. The AFM probe type CDR70S (nanosensors) is applied in the measurements. Prior to them, the tip width was traceably calibrated as 77.4 nm by a line width reference standard jointly developed by the PTB and the Team Nanotec GmbH. As the depth of the hole is much larger than the effective tip length, a virtual bottom plane is applied in the measurement software. In such a way, the tip does not go below the virtual plane in measurements for protection of tip damage.



(a) (b)

Figure 13. Measurement result of a TSV with a nominal diameter of 3 µm measured by the 3D-AFM in the top-down imaging mode, shown as (a) an AFM image and (b) a cross-sectional profile at the marked position.

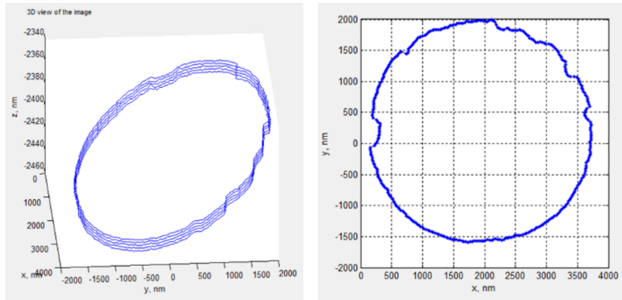
To measure the sidewall profile of micro- and nanoholes, another measurement mode referred to as "sidewall probing" mode is applied. The measurement result is depicted in figure 14. Using this mode, The CDR tip is operated in the so-called 3D vector probing mode, where its probing direction is normal to the sidewall surface, offering the best 3D probing sensitivity. The sample density at the sidewalls and top/bottom surfaces can be set individually, thus the sidewalls can be measured with high pixel density with reduced measurement time.



(a) (b)

Figure 14. Measurement of sidewall profile of the TSV using the "sidewall probing" mode, shown as (a) a sidewall profile measured in the xz plane and (b) a zoomed-in view at the marked position.

To measure the roundness and diameter of micro- and nanoholes, the third measurement mode called as "XY contour probing" mode can be applied. Figure 15 shows the measurement result of the TSV using such mode.



(a) (b)

Figure 15. XY-contour measurement of the TSV using the "XY contour probing" mode, shown as (a) an 3D view and (b) a xy contour profile.

8. Conclusion

As a critical part of 3DIC's product manufacturing, TSVs dimensions must be characterized and monitored during their process flow. For example, during a typical TSV middle process flow, the following points should be verified.

First, after TSV etching step using the Bosh process, the TSVs depth should be measured. The previous techniques assessments confirmed that interferometry is the most efficient method to characterize depth of TSVs with high aspect ratio, more a full field IR interferometer measuring from the wafer backside would ensure the best results in term of accuracy, stability and capability for small diameter TSVs below 3µm. At this process step, TSV top CD can be measured using optical microscopy with high throughput and good repeatability but with poor accuracy compared to the metrological 3D AFM developed at PTB with the top-down imaging mode or X-Y contour probing providing accurate TSV roundness and diameter measurements.

Note that TSV bottom CD measurement would also be of interest to verify that TSV nails will be large enough for good electrical connectivity, but except full-field IR microscopy with high magnification objective, there is no non-destructive method to achieve this goal (wafer cleaving).

Second, after CVD Liner, PVD Barrier and Seed deposition, the internal TSV surface rugosity/uniformity should also be characterized to verify that the TSV is properly electricaly isolated from the bulk Si. At this step, no non-destructive method like FIB cut was found. But, the 3D AFM from the PTB with sidewall probing mode or XY-Contour probing mode can give interesting information of possible sidewall undercut and CD reduction near TSV top that can be one of the main detractors for voids creation during the next Cu ECD filling process.