EMPIR Grant Agreement 14IND07 – 3D Stack

Guide to Conformity assessment for the critical dimensional parameters for TSVs

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

WP3: Towards in-line metrology process control for 3D integration technology
Task A3.2.3:

With inputs from A3.2.1, PTB, with input from CEA, FhG, IMEC, Fogale and METAS will write a Guide to Conformity assessment for the critical dimensional parameters for TSVs and wafer alignment.

1. Introduction

Through Silicon Vias (TSV) are the main structures for electrically connecting bonded chips to reduce packaging size and to improve power consumption and performances. TSV are typically etched with a very high aspect ratio (HAR) – a ratio between the depth and the diameter of the TSV, which may 20:1 or even higher.

To enable a reliable manufacturing and functioning of the TSV structures, several critical dimensions of TSV dimensions need to be controlled, for instance:

- TSV etch depth
- TSV diameter
- TSV etch profile
- etc.

This document presents a guide to conformity assessment for the critical dimensional parameters for TSVs.

2. Metrology Method

2.1 TSV etch depth

To measure the critical dimensions of TSV mentioned above. Various measurement techniques are available, for instance, confocal microscopy, white light interferometry (WLI), infrared interferometry, optical microscopy, scanning particle microscopy (e.g. Scanning electron microscopy and Scanning ion microscopy) and scanning probe microscopy (e.g. 3D atomic force microscopy). Different measurement technique has strength on the one hand, and weakness on the other hand. As an example, Figure 1 illustrates some complementary technologies available on Fogale systems.

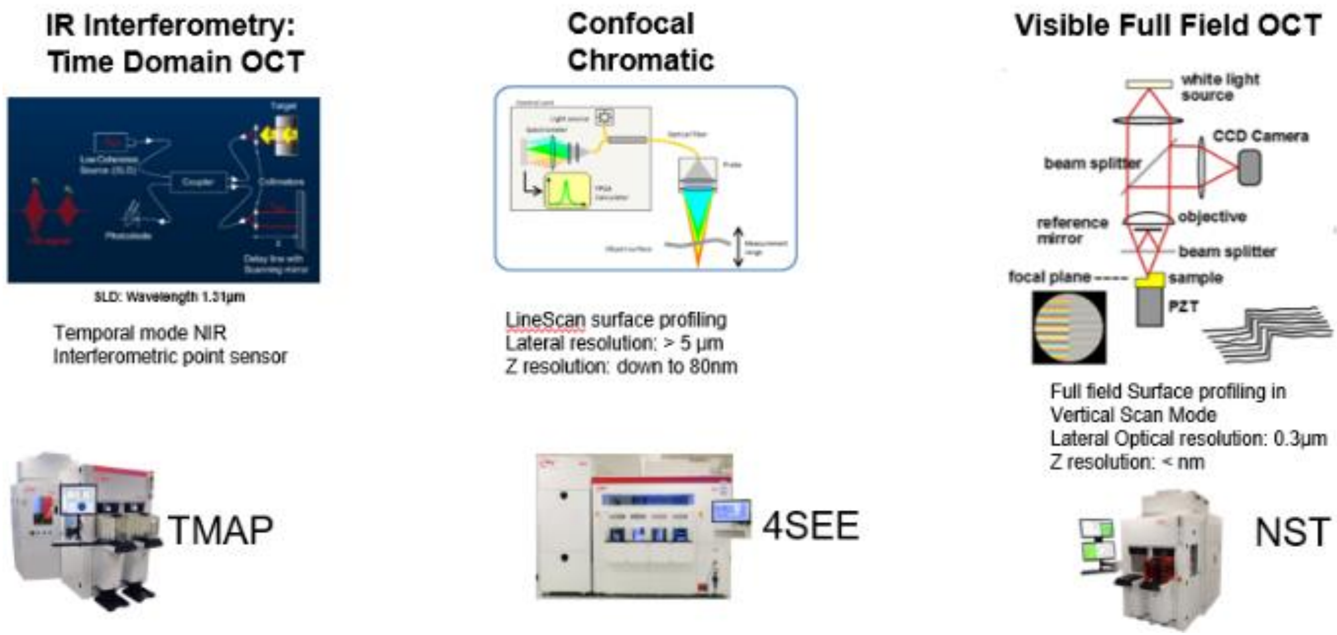


Figure 1. Three complementary technologies used to characterize TSV open in Si wafers.

Today, optical techniques such as WLI and IR interferometry can be well applied for measuring etch depth of individual TSVs for 5 micron and larger diameter TSVs with less than 10:1 aspect ratio. However, when TSVs with smaller diameter to be measured, the sensor configuration needs to get paralleled collimated light to able to be reflected down to the bottom TSV. The optical techniques has advantages of fast measurement speed and inline measurement capability. In figure 2, a comparison measurement result of different TSV depth measuring tools is demonstrated.

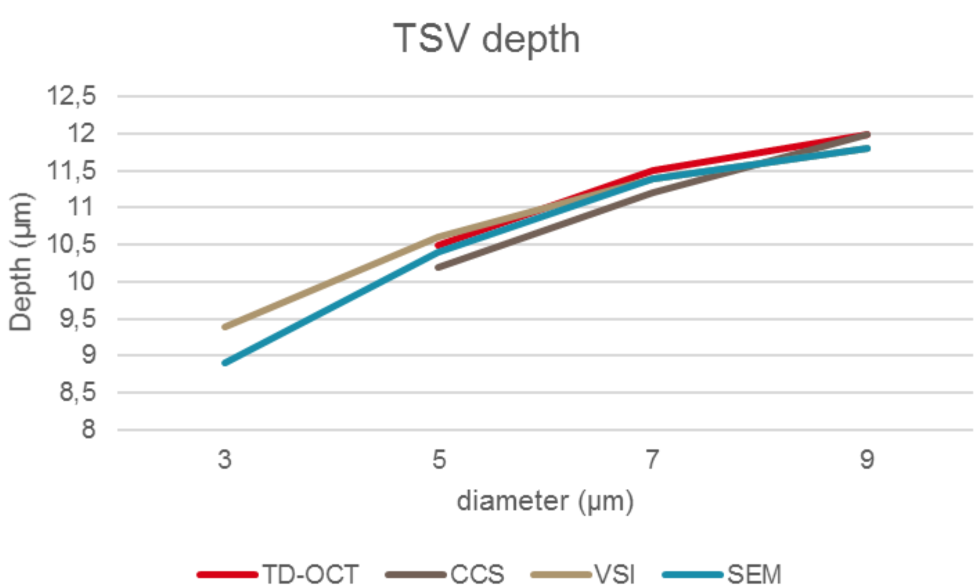


Figure 2: 10µm TSV depth measurement capability as function of diameter for different techniques.

The model-based infrared reflectometry on an array of TSVs could be another alternative for depth measurement of diameter below 5 micrometers at the condition the density of via is high enough to get diffracted signal. This technique is not a direct technique and will require cross-section analysis for calibration.

2.2 TSV diameter

Besides the z dimensions measurement, critical dimensions (x,y) of TSV can be performed using optical microsocpic tools. As an example, measurement using a tool A available at CEA is illustrated in figure 3. 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%.

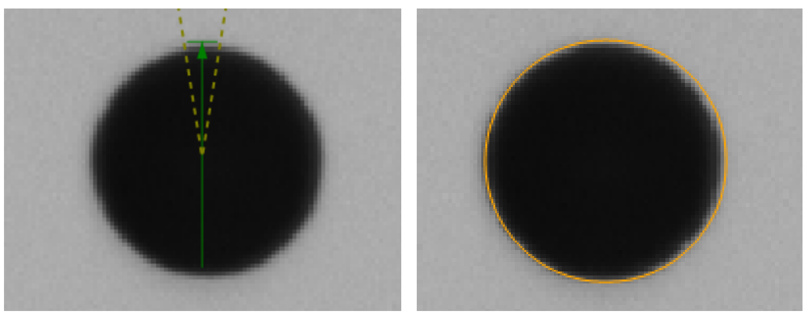


Figure 3. TSV diameter measurement using optical microscopy.

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

In figure 4, 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.

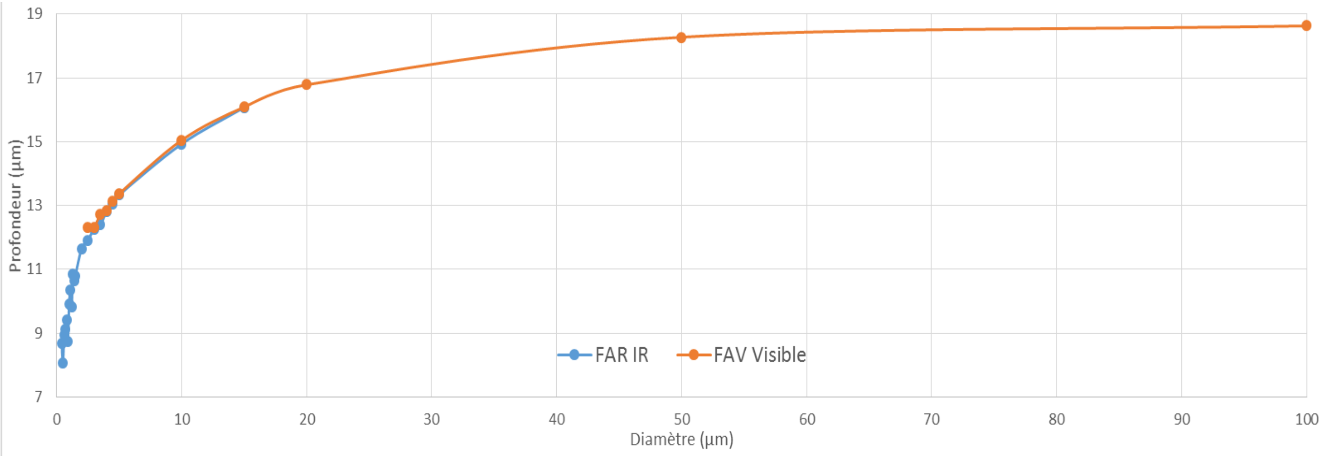


Figure 4. Tool A Visible light (orange line) versus IR interferometric (blue line) TSV depth measurements results as a function of diameters.

2.3 TSV etch profile

Compared to TSV depth and diameter measurement, the measurement of the sidewall profile of HAR TSVs becomes much more challenging. As the sidewall of TSVs are steep, optical beam can be hardly reflected back to detectors in optical tools, lead to measurement problems. In this project, PTB has developed a 3D-AFM which is capable of measuring the TSV profiles. 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 5.

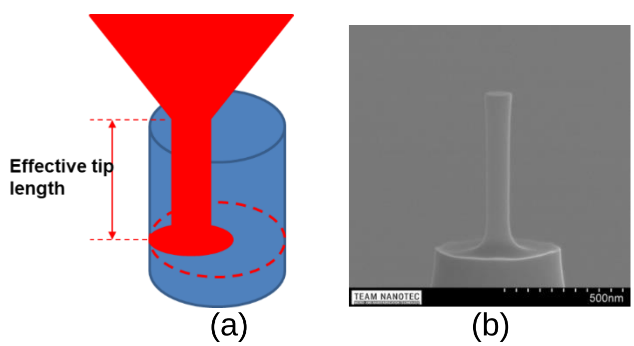
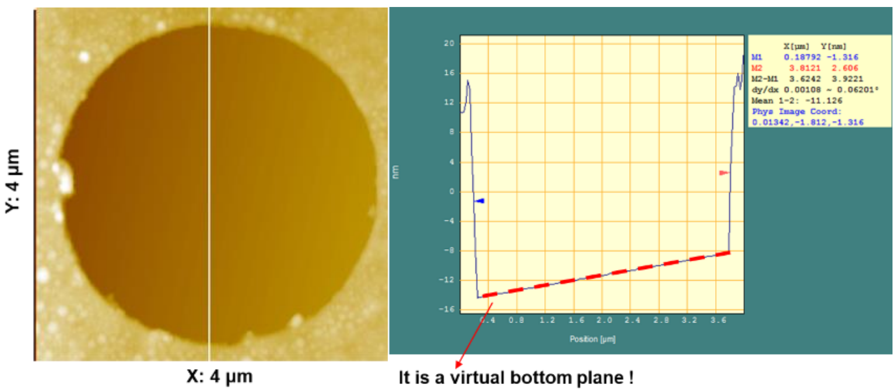


Figure 5. (a) A flared AFM tip for measuring micro and nanoholes; (b) A SEM image of a commercially available flared AFM tip as an example.

Three different measurement modes referred as “top-down imaging “, “sidewall probing” and “XY contour probing” have been implemented in the 3D-AFM. Measurement result of a TSV with a nominal diameter of 3 µm using the ”top-down imaging” mode is shown in figure 6.

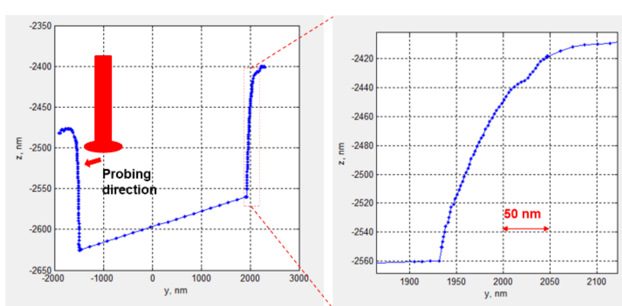
Such a measurement mode is desired for overview measurements of the vias from the top. The AFM probe type CDR70S (nanosensors) is applied in the measurements. Prior to them, the tip width was traceably calibrated as 77.4 nm by a line width reference standard jointly developed by the PTB and the Team 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 6. 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.

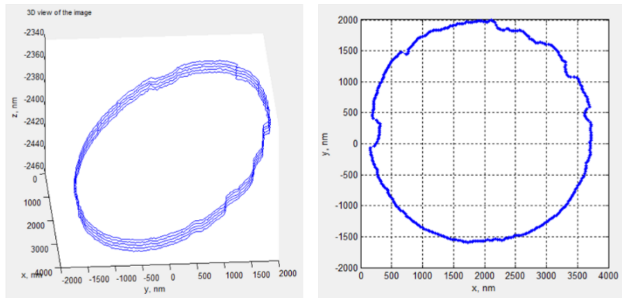
To measure the sidewall profile of micro- and nanoholes, another measurement mode referred to as “sidewall probing” mode is applied. The measurement result is depicted in figure 7. Using this mode, The CDR tip is operated in the so-called 3D vector probing mode, where its probing direction is normal 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 7. 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 8 shows the measurement result of the TSV using such mode.



(a) (b)

Figure 8. XY-contour measurement of the TSV using the “XY contour probing” mode, shown as (a) an 3D view and (b) a xy contour profile.

However, there are two strong limitations on the applications of the 3D-AFM technique. First, the commercially available CD-AFM tip has a length up to 7.5 µm, which limits its measuring depth in TSVs. However, this technical limitation can be solved by applying the state-of-the-art nanomanufacturing to fabricate long CD-AFM tips. The other limit is its relatively low measurement speed. Consequently, such technique is more suitable for measuring individual TSVs only and not suitable for in-line metrology.

Further methods for TSV profile metrology is by using scanning particle microscopy after the TSV is cleaved by e.g. focused ion beam (FIB) tools. The major limits here is that it’s destructive and very long time-to-data.

Unfortunately, there are no in-line TSV etch profile metrology tools available which are suitable for high-volume manufacturing. The international technology roadmap for semiconductors 2.0 (2015 edition, metrology) has mentioned that the through-focus scanning optical microscopy (TSOM) method shows potential for this application. It demonstrated good sidewall angle (or 3D shape) sensitivity for TSVs/HAR targets. It is a non-destructive method with high-throughput and hence suitable for high volume manufacturing. Improved sidewall sensitivity can be expected using IR wavelengths that can penetrate much deeper into Si. Both isolated and multiple repeated TSV/HAR targets could be measured using the TSOM method [1]. However, these topics are beyond the scope of our project.

2.4 Comparison of different techniques

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.

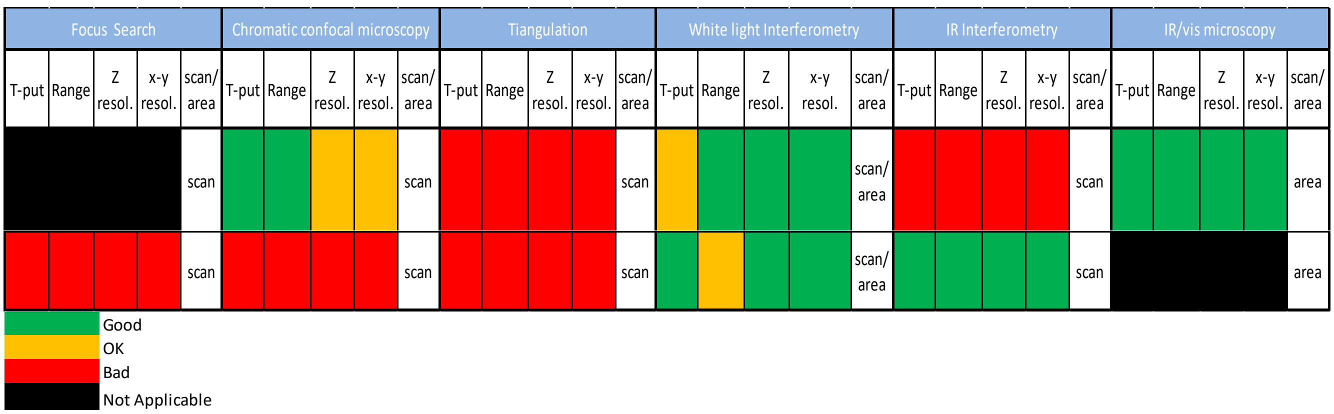


Figure 9. Benchmarking comparison between technologies for TSV CD and depth measurements.

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.

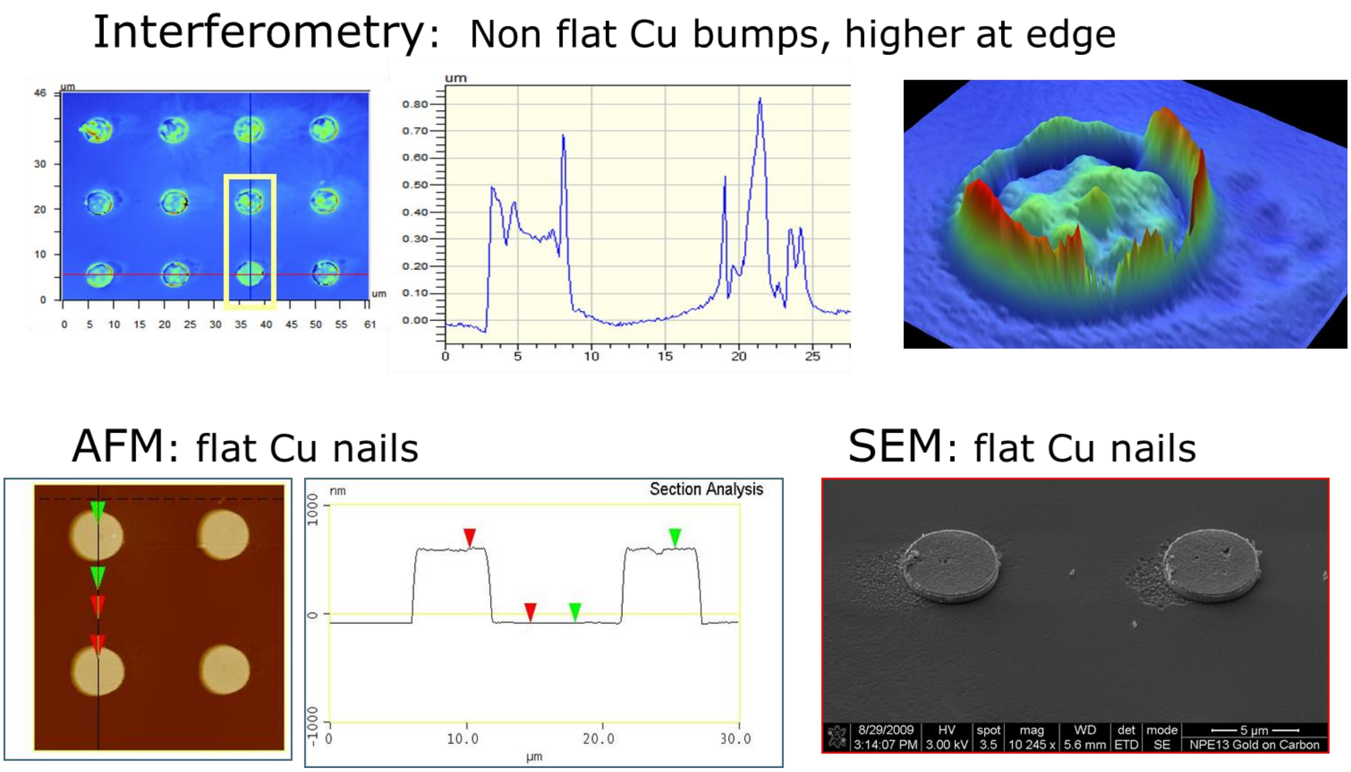


Figure 10. Issues that can falsify the WLI results: transparent layers on top of Cu nails, with varying thicknesses (after annealing for example) and sharp edges.

3. 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.

TSV etch depth, TSV diameter and TSV etch profile are critical dimensions need to be measured for ensuring reliable manufacturing. Today, various techniques such as confocal microscopy, white light interferometry (WLI), infrared interferometry, optical microscopy, scanning particle microscopy (e.g. Scanning electron microscopy and Scanning ion microscopy) and scanning probe microscopy (e.g. 3D atomic force microscopy) are available. Each technique has its advantages on one hand, but disadvantages on the other hand.

Optical tools such as WLI, confocal microscopy offers fast and accurate measurements capability in the TSV depth measurements, however, has a limit to TSV with a diameter down to about 3 µm. For smaller TSVs, model-based infrared reflectometry on an array of TSVs could be another alternative solution, however, the technique is not a direct imaging based method and thus requires cross-section analysis for calibration

Besides the z dimensions measurement, critical dimensions (x,y) of TSV can be performed using optical microsocpic tools. 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%.

Compared to TSV depth and diameter measurement, the measurement of the sidewall profile of HAR TSVs is still very challenging. The project has proposed an idea of using 3D-AFM, however, has still limitations of (1) the limited tip length and (2) the limited measurement speed. Therefore, the method is more suitable for reference metrology. It may offer calibrations for potential inline and fast optical methods such as through-focus scanning optical microscopy (TSOM).

Besides the critical dimensions mentioned above, TSV liner, barrier, seed thickness as well as voids are important aspects for reliable TSV manufacturing. These aspects are not covered in this report.