Metrology of micro-components – a real challenge for the future

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Abstract
Micro manufacturing is steadily advancing from research labs to spin off companies. Products formerly manufactured by thin film technology using semiconductor processes are being replaced by more efficient full 3D micro manufacturing techniques. Materials have expanded to polymers, metals and ceramics. From being wafer based structures of tens of microns in width and a thickness of up to a micron, feature sizes are now a few microns wide and hundreds of microns deep.

This puts very high demands on the geometrical dimensional and roughness measurement tools of the future. This paper gives a review of current metrology tools available for dimensional and surface characterization, and their limitations. It will also present the requirements of future instruments and discuss potential techniques to solve these issues.

Keywords:
Micro metrology, high aspect ratio, CMM, optical probe, surface roughness, micro manufacture

1 INTRODUCTION

The nano-ambitions all over the world have created a big boost for nano-manufacturing and associated metrology. However, it is worth mentioning that nano-manufacturing in the thickness dimension has been around for more than seven decades in the form of thin film deposition and etching. Technique for step height measurements in the nano/sub-nano range, was available already in sixties. Thus, the nano-sensitive technique for thickness and surface roughness measurements of mm-sized components is well established. When the lateral (X,Y) dimensions of components shrinks to micro meters (µm) and the thickness dimension (Z) increases and even surpasses the lateral dimensions by large factors, we end up in so called high aspect ratio structures. This is where the big metrology challenges sets in, and joint research efforts will be needed to tackle these tasks. This is where networking of scientist from different fields gives great benefits.

Multi Material Micro Manufacturing is one such joint effort. [1] It is a joint EC Network of Excellence and it represents manufacturing, assessment, materials and application areas for 3D micro-components, mainly in non-silicon materials. Techniques are applied from many fields, e.g. mechanical engineering, optical fabrication and micro-systems technologies. These techniques and application areas form a joint platform for information exchange. Better ways to manufacture and measure true 3D micro devices and components are the main issues, and it provides a critical mass to efforts previously scattered all over Europe.

This paper will report on the current status of metrology for micro-dimensions and surface roughness of micro-components and devices. Challenges are found in several areas and these will be reviewed.

Historically micro-manufacturing can be associated with watch making and jewellery work, and the metrology tools at that time were the optical microscope and profile projector. Later on came the semiconductor technology with high demands on film thickness measurements and lateral resolution in mask fabrication. Techniques employed were lithography, etching, deposition by evaporation and sputtering The layered 2D-structures were laid down on mm sized wafers to start with. Today they have extended to several hundred millimetres in diameter, and at the same time the lateral resolution requirements are approaching 30 nano-meters (nm). The height dimension is still measured in micrometers (µm) or fractions of µm, with resolution requirements of sub-nm.

Similar requirements came up for more than 50 years ago in the manufacturing of optical components. Extreme demands on surface quality (sub-nm roughness), sub-micrometer form accuracy and nm-thickness uniformity of thin films called for nano-sensitive metrology of film thickness.

The first true nano-metre metrology tool, the Talystep stylus profilometer provided with an inductive probe, [2] was developed for measurement of step heights of thin films using a maximum trace length of 2 mm and maximum height range of 12 um. The sensitivity and performance of this instrument was further developed by Bennett and Dancy [3] and it is still one of the most reliable systems for mechanical profiling, with a z-sensitivity similar to modern atomic force microscopes, as will be shown later in this article. The lateral resolution is dependent on the stylus tip radius, and data acquisition speed when the stylus traverses the surface. Stylus load can be set to fractions of a milligram.

The Nanosurf series of instruments followed up the success of the Talystep by providing lateral traverse lengths up to 50 mm. It was designed for the assessment of X-ray mirror surfaces [4]. Height calibration of these instruments relied on multiple beam interferometry developed already in the 40-ties by Tolansky [5]

If measurement of thin films was the main driver for the development of the nanometre sensitive Talystep in the sixties, there was another drive, gauge blocks, for making nm metrology available already in the thirties. The instrument developed was the Mikrokator, invented by H. Abramsson at gauge block manufacturer CE Johansson in Eskilstuna. It had a resolution of 10 nm/division at its best. The measuring mechanism of this instrument uses a twisted strip of metal. When the strip is stretched, the mid - point rotates, and the pointer moves. Precision, linearity, repeatability and sensitivity are inherent characteristics of the Mikrokator principle. It is still available as an instrument, although the 10 nm resolution has been relaxed to 100 nm resolution and larger measurement ranges. [6] Lateral resolution was never an issue for this instrument which has a several mm radius at the spherical probe tip. The major drawback of the Mikrokator, the high measuring force of 750 mN, reflects its intended use in hard workshop environments. Anyhow, it is a technically sound and robust precision mechanism with frictionless transfer, no inertia, high sensitivity and extremely low hysteresis. Therefore the principle might be considered as a readout device for future precision positioning systems.

Materials characterisation is another area which has constantly been pushing the metrology instrument manufacturers to their limits. The highest resolution instruments, the scanning electron microscope and the scanning probe microscope, e.g. the atomic force microscope are both able to measure nm sized features in all three dimensions.

With increasing demands of the manufacturing systems for integrated circuits, there has been a continuous development of metrology tools dedicated to wafer inspection and measurement of sub-µm line widths (often referred to as critical dimension – CD, for a reliable functioning of an integrated circuit), side walls and thickness of layered structures. At an early stage the need for nm-height sensitivity measurements over entire wafer surfaces was obvious and stylus profilometers with fixed stylus and traversing wafer holding stages became the solution to that. Optical, microscope based profiling systems have also been developed for wafer assessment. Although faster in data acquisition they need to stitch several images for obtaining data over larger areas. For on-line monitoring of the multiple processes in the integrated circuits fabrication light scattering has been the obvious choice. By utilizing specially designed grating structures on selected areas on the wafers, the process parameters can be checked by comparing the scattering patterns vs. libraries of calculated scattering distributions. The technique is now becoming one of the most important tools for critical dimension measurements of the upcoming nm-nodes.

Medicine and biology have been main drivers for developing optical microscopy and in particular the confocal microscopy for 3D-mapping of tissue. After establishing the technique and improving its speed by multiple pin-hole imaging or matrix detectors it has been widely accepted as one of the most promising techniques for 3D-metrology of micro components.

Fig.1 summarises the application areas that have been the main drivers for micro/nano-measurement technologies, and it also indicates the resolution routinely obtained today in lateral x,y directions and in height, the z-direction.

Micro-component metrology benefits from the advancement in all these application areas, and it becomes very cross disciplinary in its nature. At the same time it requires a broad view to collect information about instrument developments in such a large field. The 4M Network of Excellence has the advantage of bringing scientists from many different fields and is therefore an excellent platform in this process. Instrument performance data is also being collected from the partners, for easy access to the best performing instrument for a particular measurement task in this distributed European Center of Metrology.

Early application areas of metrology tools and today's associated resolution in x,y,z

Mechanical engineering
Mechanical comparator (-,-,nm)
Coordinate Measuring Machine (µm,µm,µm)

Optics
Interferometer (µm, µm,nm)
Step height profile (um,-,nm)

Materials
Scanning Electron Microscope (SEM) (nm,nm,nm)
Atomic Force Microscope (nm,nm,nm)

Semiconductor
Large area profiler (µm,µm,nm)
Scatterometers (µm,µm,nm)

Medical/Biological
Confocal microscope (µm,µm,nm)

Figure 1: Summary of application areas that have been driving instrument development towards nano-sensitivity and a rough estimate of current resolution of the instruments in x,y,z. (x,-,z) refers to a line profile with no y-information obtained from the measurement.

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2 CHALLENGES IN MULTI MATERIAL MICRO-METROLOGY

2.1 Measurement force

With a size of a manufactured item of say 10 x 10 x 10 μm^3, there will be considerable problems of handling and manipulating it. How to attach it and what happens when a tactile probe touches it? Assuming the device to be a freestanding cube of dense Tungsten, the gravity will create a normal force of 0.2 nN. With a friction coefficient of 0.3 we end up in requiring the measurement probe force in the lateral direction to be less than 60 pN (neglecting possible stronger adhesion forces with such a small footprint), to avoid movement of the item to be measured. This is to be to be compared with a trigger probe force of 50 -100 mN of a standard coordinate measuring machine. That force corresponds to the friction force of a Tungsten cube of 1x1x1cm^3! And even worse, the overtravel force obtained immediately after the trigger has detected the surface, may exceed the trigger force by 2-5 times depending on machine type and probe mass. Thus, there is no way a traditional CMM probing system can be used for the measurement of freestanding micrometer sized features. If tactile probing systems would be used they have to have a very very sensitive system for detecting contact with the surface.

Many micro-items being produced for micro-fluidic applications are not freestanding but bound to a wafer surface. 100 um deep channels, separated by walls, only some ten um wide, are not uncommon. They might be produced by etching in silicon, or replicated from Ni-moulds into plastic materials. Let us consider a 100 µm tall pillar with a square section of 50 x 50 μm^2 made of PMMA plastic material. With a standard CMM probe force of 50 mN acting from the side at the top of the pillar, the pillar will bend by approximately 10 µm, causing very erroneous measurement results. If the pillar is made in silicon the displacement would be about 0.3 µm. Thus, the 4M concept of multi materials, including metal, ceramics and polymers create a lot more challenging metrology problems from the probe force point of view than formerly found in microsystems based on silicon.

2.2 Compression by probe force

Another problem associated with the probe force is the elastic, or in worst case plastic, deformation induced by a contacting probe tip. The small size of the items to be measured requires the probe tip to be small enough to yield relevant measurement data. Unfortunately that will lead to higher risk of compression deformation at the interface between the probe tip and the item to be measured. The amount of elastic deformation between a spherical tip and a flat surface, Δ, can be calculated by the Herz equation for contacting surfaces [7].

$$\Delta = \left\{ \frac{9P^2\left(1-\nu_{eff}^2\right)^2}{4E_{eff}^2 R} \right\}^{1/3} \qquad (1)$$

The effective stiffness in (1) is obtained from

$$\frac{\left(1-\nu_{eff}^2\right)}{E_{eff}} = \frac{1}{2}\left\{ \frac{\left(1-\nu_1^2\right)}{E_1} + \frac{\left(1-\nu_2^2\right)}{E_2} \right\} \qquad (2)$$

P is the applied force, ν_1 and ν_2 are the Poisson ratios and E_1 and E_2 are the Young's Modulus of the materials in the tip and the planar surface respectively. *R* is the radius of the tip.

A common material for injection moulding of micro devices is polypropylene. If a probe tip of 20 μm diameter is contacting a polypropylene surface, the expected compression deformation Δ is about 5 μm for a trigger force of 50 mN. Again it is obvious that big measurement errors will be introduced by conventional CMM probes.

The conclusion is that in the design of micro-structures, there is a need for not only geometrical dimensions and tolerances on the drawing, but also maximum permissible measurement force associated with the tolerance.

2.3 Probe access

In order to measure micro components and devices in all three dimensions, access is required to all surfaces having dimensional tolerances specified. Top surfaces (marked A in Fig. 2) are normally easy to reach by a contacting probe-tip or a non-contacting optical probe. Outer (vertical) sidewalls (marked B) may also be accessible by tactile probes. But inner sidewalls (marked C) surrounding narrow holes or trenches are exceedingly difficult to get access to unless the item is destroyed by cutting it apart. The same applies to bottom surfaces in narrow trenches and holes (marked D), in particular if the aspect ratio (height/width) is getting high. Undercuts in deep narrow trenches (marked E) are practically impossible to get access to by non-destructive methods.

A realistic design can have a trench width of 20 μm, trench length 2 mm and the depth can be 100 - 300 μm. An ultimate challenge for metrology of holes have been presented by the Sodick company, who reports the possibility to machine a hole of only 2.9 μm diameter by electro discharge machining. [8]

For tactile probes it is rather easy to calculate what features can be measured by simply analyzing possible access ways and assuming that the items are manufactured according to the specifications.

For optical probes the task is much more difficult, as very little is known about their performance when the numerical aperture is strongly reduced in one direction, as will be the case of the deep trench in Fig. 2. The question is - will it appear as a reduced signal to noise ratio only, or will the path length, as measured by an interference microscope, be affected by reflections in the side walls?

For a confocal microscope – can we trust the position of the focal point when the aberrations are strongly disturbed in a non-symmetric way by cutting down the numerical aperture along the slit? What difference does it

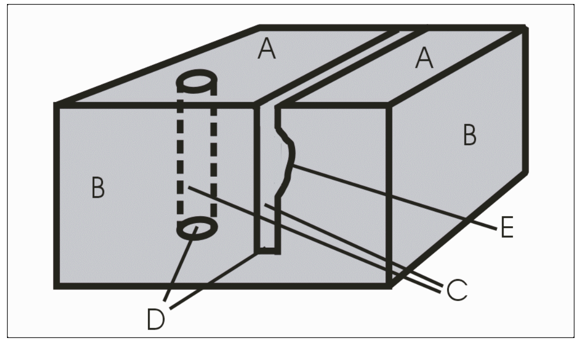

Figure 2: Surfaces that might be specified regarding dimensional tolerances or surface roughness. The deep trench and hole are examples of high aspect ratio features, making measurements practically impossible if the width is getting too small.

make to the optical probe if the micro feature is transparent, highly scattering or absorbing? And what about the influence of corner and edge radius? At what angle will the reflected light disappear, and be interpreted as the "true" edge?.

Light scattering effects from local slopes and edges in the surface can have severe influence on the output data from auto-focusing optical profilers, as demonstrated by Mattsson and Wågberg.[9] In a recent study of shallow grating structures by Vorburger et al, it was found that optical profilers suffered lack of accuracy in certain height ranges, in particular for Ra values around 100 nm. [10]

2.4 Materials related problems

In addition to the materials related problems of measurement force and compression of surfaces/probe tips already discussed, there is a specific problem for optical profilers based on interferometry. If a micro device is made up of different materials, e.g. metal surfaces and dielectric surfaces facing the optical probe, the phase change upon reflection will be different for the two types of materials. As the analysis programs of interferometers interpret phase changes as height variations, the output data will be a topographic map showing height variations of up to 50 nm despite being perfectly flat. [11]

Optical profilometers relying on surface scattering may have severe problems with locally tilted but smooth surfaces, as they do not back-reflect sufficient amount of light into the microscope objective. This will be particularly pronounced for optical quality surfaces, e.g. micro lens arrays.

2.5 Semiconductors toward atomic sizes

The micro-metrology of semiconductors is facing severe challenges for the future according to the SEMATECH roadmap for metrology. [12] A reason is that a variation in features size of one tenth of the nominal dimension often results in significant changes in device properties. With the advancement towards the 32 nm generation, this means that thin film and interfacial layer thickness as well as line width variations, are approaching near atomic sized requirements. As the industry moves further into nanoelectronics, metrology, including materials characterization, will take on greater challenges and become even more critical. As discussed in the previous section physical access becomes an important point also in semiconductor circuits. One particular gap is the ability to measure properties as thickness on the sidewalls of densely patterned features such as gates and trenches.

The fundamental challenge for factory metrology will be the measurement and control of atomic dimensions while maintaining profitable high volume manufacturing.

2.6 Surface roughness

Measurement of surface roughness, e.g. the arithmetic mean deviation Ra of the assessed profile, of micro-machined micro devices is far from straight forward. The overall size of the component might be just a tiny fraction of a standardised roughness sampling length of 0.25 mm or 0.8 mm, depending on the roughness. [13] The former is used for a surface roughness interval of 0.02 µm < Ra < 0.1 µm and the latter for 0.1 µm < Ra < 2 µm. The standardised Ra, normally requiring 5 sampling lengths at different places, might therefore be severely limited and yields a larger uncertainty. This limitation imposed by the standard for macro components may be circumvented by working with ISO defined primary profiles, i.e. sampling lengths specifically tied to the component. [14] The primary profile is the deviation remaining after subtracting the nominal shape.

This fact that macro defined roughness may loose its meaning as the lateral scale shrinks is another problem. Depending on the size of the component, the same topographical structure might be interpreted as surface roughness for a big work piece, waviness for sub-mm sized and form deviation for the tiny micro component. For future work it is important to take the functional description of the surface into account when new parameters are being proposed. Knowledge along that line is in progress [15, 16]

2.7 Standards and traceability

None of the ISO standards for tolerances of form, orientation, location and run-out are readily available for components being a few micrometers in size. The same applies for surface texture measurement. The 3D areal surface roughness standards are still being prepared in the ISO task groups. Hopefully these will be more biased towards metrology of small size features than the existing line profile standards. The main challenge in traceability is to manufacture suitable artefacts with nano to sub-nano accuracy. Essentially this means artefacts prepared and measured down to atomic size levels.

3 PROGRESS AND FUTURE WORK IN MULTI MATERIAL MICRO-METROLOGY

3.1 Reduced measurement force and accessibility

As stated in the preceding paragraph, there are multiple challenges facing the developers of future micro-metrology systems. Many research groups are devoted to bridging the gap between traditional coordinate measuring machines and atomic force microscopes. The probing force has been tackled by Schwenke et al [17] by making use of a thin optical fibre with a tiny spherical ball at the tip. The technique has been commercialised by Werth [18] as the Fiber Probe WFP 3D, and provides measurement forces in the sub-µN range. At the same time the challenge of accessing micro holes and narrow trenches has been addressed by providing cm long shafts and ball tips down to a size of about 20 µm diameter [19]

The other commercial low force CMM type system, UMAP103, has been developed by Mitutoyo [20]. It couples a vision measuring system with an ultrasonically activated vibrating probe. As the probe contacts with the workpiece the amplitude of the ultrasonic signal is damped, and at a predetermined level, the probe is considered to have touched the surface of the workpiece. The contact force is generally around 1 µN. The smallest probe tip is 30 µm in diameter and it is available on shaft lengths of 2 or 12 mm. [19]

A very low force principle was presented by Takaya et al. [21] A laser-trapped microsphere in air is forced to vibrate in the transverse direction using an oscillating laser beam. By studying the frequency and phase delay response of the optically vibrated microsphere with a position sensitive detector the viscous drag coefficients near the surface can be found and used as trigger. The target resolution of the system is 10 nm with a probing force determined by a spring constant of 10 µN/m giving an exceptional low measuremet force. The proposed probe sphere diameter is 10 µm.

Several other references to nano-CMM:s are reported by Leach et al. who gave a thorough analysis of the requirements for measuring micro-structures. [22]

Accessibility of optical probes in micro components has been discussed very little in the literature, and instrument deliverers have so far not presented performance data for high aspect ratio structures where the light cone of the objective is strongly blocked. Within the 4M Network of Excellence we will be addressing this issue, and compare performance between different instruments, including the Werth fiber probe, confocal and interference microscopes as well as imaging systems. An example of the type of artefact we intend to use in this study is shown in Fig 3. It is an X-ray LIGA manufactured Ni-surface with 100 µm high bars in a star shaped pattern. The aspect ratio can then be continuously changed from 1,1 – 11 or even higher by imaging different parts along the radial direction. Other areas of the Ni-surface contain trenches, ridges, grating structures, square holes and square pillars of different sizes.

3.2 Traceability

Leach et al. have addressed the issue of traceability at the nano-scale dimension. [23] They conclude that their upcoming work needs to be focused at traceable measurement of thin film thickness, research into critical dimension metrology with atomic force microscopes (AFM, including high-aspect-ratio probes using carbon nanotubes), extension of the low mass scale, further developments of optical, contacting and hybrid probes for use with micro-CMMs and research into methods critical to the development of advanced MEMS sensors.

Usually the height sensors of the AFM:s are calibrated using step height specimens ranging from about 10nm to a few µm, A natural sub-nm calibration standard is a

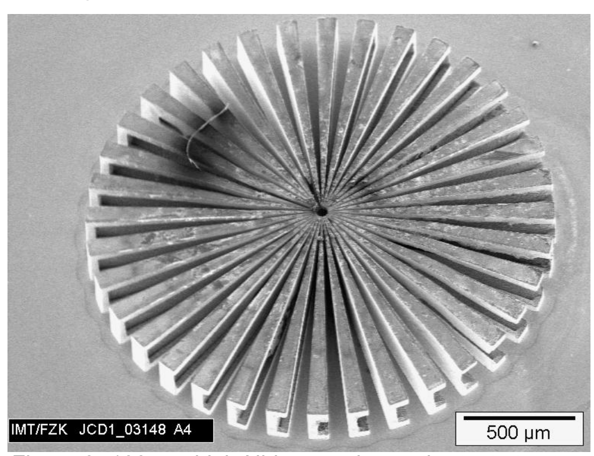

Figure 3: 100 µm high Ni bars make up the test structure manufactured by X-ray LIGA technique. The star shaped structure provides a convenient tool for testing the measured depth vs increasing aspect ratio for optical probes and microscopes.

surface with atomic steps. If separated well enough, the atomic planes can also be measured with sub-Ångsröm sensitive mechanical probes. An attempt to calibrate the Talystep surface profiler at KTH, Stockholm in this way was performed already in 1989, thanks to a specially cut silicon 111 wafer surface provided by Wacker Chemitronics, Burghausen. The levelled profile is shown in Fig. 4. Four steps can be distinguished, and the average step height was determined to be 0.22 nm. The measurement was performed using a shovel shaped stylus, with a minimum radius of 0.1 um. The applied stylus force was approximately 1.5 µN. The static noise level of the system, provided with software and hardware upgrade from Bennett [3], was at that time equivalent to 0.04 nm rms roughness. The measurement was carried out at 2 am in the morning to avoid noise impact from activities in the surroundings and from the subway.

Recently, the same kind of atomic steps with natural oxide, were measured by a calibrated AFM and found to be 0.304±0.008 nm. [24] Considering the age of the Talystep, developed already in the early sixties and calibrated with a 36 nm step height specimen, it is surprising how well it performed, with its inductive probe.

The result of Orji ett al [24] , was obtained with an CAFM with direct traceability to the definition of length. It is also used to calibrate standards for other AFMs. To validate the use of the Si 111 specimens a comparison was performed among AFM vendors and semiconductor device manufacturers. The average standard deviation was 6pm, and indicates that atomic steps on Si 111 surfaces could be used for sub-nanometer height calibrations.

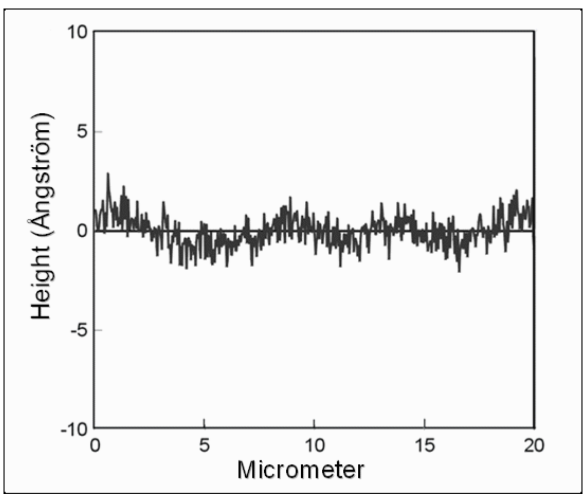

Figure 4: Line profile of a specially cut Si 111 wafer, yielding long terraces between each step. The profile was obtained using a 0.1 um shovel shaped stylus applied to the Talystep setup at former Surface Evaluation Laboratory, Institute of Optical Research, KTH, Stockholm. It was calibrated with a 36 nm reference step height standard provided with the instrument by Taylor Hobson.

3.3 In line micro-metrology

So far this presentation has been devoted to laboratory metrology, where the detailed structures can be measured and examined, independent of time. For efficient production in the future, techniques and systems have to be developed that facilitate rapid in-line, process assessment and dimensional measurements. That means that scanning mechanical touch probe systems will be surpassed by non-contact imaging systems or scatterometry systems. Scatterometry refers to both single wavelength—multi angle optical scattering and to multi-wavelength—single angle methods. In the semi-conductor fab scatterometry has moved into manu-facturing, and does provide line shape metrology.[12] For micro-metrology in multi materials there is a big lack of knowledge of scattering profiles for different features, sizes and materials. Wavelengths have to be selected to minimize the effect of bulk scattering in e.g. ceramics. Modeling software has to be developed from existing simulation packages, like Grace [25] for example, which has been developed for modeling of light interacting with paper surfaces and fiber structures of micrometer size.

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4 SUMMARY

This paper summarized the challenges existing in 3D metrology on micro devices and components. In particular high aspect ratio measurements of trenches and holes are major obstacles to overcome for non-destructive measurements. For tall and narrow pillar type structures and soft materials low measurement forces are of utmost importance. It is therefore proposed that in the design of micro-structures, there is a need for not only geometrical dimensions and tolerances on the drawing, but also maximum permissible measurement force associated with the tolerance. Small measurement forces are being addressed by many groups active in bridging the gap between the atomic force microscopy and traditional coordinate measuring machine technology. Development of µN force probes gives promises for the future, and accessibility is improving thanks to smaller and smaller probes. Optical probes and microscopes needs to be evaluated for high aspect ratio trenches and holes. Technique for doing that is advised and is based on high quality X-ray LIGA test surfaces. Traceability is discussed and performance of both AFM and the old Talystep surface profiler is presented for single atomic steps, 0.3 nm high, on Si-wafers. For batch production of micro-components, new rapid assessment methods have to be developed. Most likely they will be based on optical imaging and scatterometry. The latter has succeeded well in semiconductor manufacturing. However obstacles are much larger for true 3D micrometer structures that also have large variations in optical properties and surface roughness. Considerable efforts are therefore needed to pursue this task.

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