Experiences and challenges in Multi Material Micro Metrology

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ABSTRACT

The Microsystems Technology manufacturing is expanding into other materials than the silicon. Polymers, metals and ceramics manufactured with micron feature sizes put new demands on metrology systems and a better education of instrument operators. In particular 3D-structured polymers require special care with regard to measurement forces for contacting probes of e.g. coordinate measuring machines. Ceramics tend to scatter light from the bulk, which can introduce off-sets from the true surface position in e.g. optical triangulation systems. Engineered metals tend to have comparatively rough surfaces compared to silicon and this imposes problems when a dimension of a micro feature is to be measured, as the roughness may introduce large local variations in measured size of a particular item. One of the most critical problems is associated with the high aspect ratio features present in micro systems manufacturing. This paper will high-light some examples of metrology problems found within the European 4M Multi Material Micro Manufacturing Network, discuss them, show new surprising results of optical profiling on high aspect ratio features and discuss possible solutions to get around some of the obstacles.

INTRODUCTION

Nano-structure and nano-precision have become a buzzword in many science and engineering areas in the past decade. Researchers and technicians who have been working with nano-features for decades are indeed somewhat surprised about this boost of excitement for a technology and metrology that has been around for many years. In metrology, techniques for measuring surface roughness at nano and even sub-nano levels have been around for several decades, see e.g. Bennett and Mattsson [1] and references therein. The driving force has been the surface quality of outstanding optical components. Nano-manufacturing in the thickness dimension has been around for more than seven decades in the form of thin film deposition and etching and ruling of X-ray gratings. Technique for step height (Z) 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 has been well established since many decades – but often unheard of among mechanical engineers. This knowledge gap is now slowly being bridged as mechanical engineering methods are approaching nano-dimensions. The first truly useful nm metrology tool providing good lateral resolution was the Talystep stylus profiler provided with an inductive probe. [2] It was developed for measurement of step heights of thin films having a maximum assessment length of 2 mm and maximum height range of 12 µm. This has recently been extended in our laboratory to 400 µm by controlling the stylus vertical offset with a high precision inductive probe. The sensitivity and performance of the Talystep 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 the atomic force microscopes. With a stable environment, a root-mean-square noise level of 0.04 nm can be achieved of the present system at KTH and it has been proven by measurements of height steps of atomic planes.[4] The ultimate lateral resolution is dependent on the tip radius and the cone angle of the replaceable stylus. Another advantage of the Talystep is that the stylus force can be set as low as 10 µN. This is to be compared with a typical coordinate measuring machine having 5000 times higher measurement force.

However, when the lateral (X,Y) dimensions of surface features shrinks to micro-meters and the thickness dimension (Z) increases and even surpass the lateral dimensions by large factors, we face the real metrology challenges. Stylus profilers can no longer be applied as stylus cone angles limits the possibilities of measuring in narrow holes and trenches. Typically a 1:1 height/width ratio is the limit for traditional stylus profilers. More specialized styluses with considerably improved high aspect ratio (HAR) performance are being investigated [5,6] and may be a potential solution in the future, at least for atomic force microscopes. For a general review of micro and nano metrology from the mechanical engineering perspective the reader is referred to the recent keynote paper by Hansen et al. [7]. A more specific review of metrology issues related to 3D metrology of micro components in different materials was given recently. [4] One particular issue was the metrology of HARMS (high aspect ratio microstructures)

The performance of optical profilers for HARMS is still to be revealed because the instrument deliverers give no information on the performance of these instruments for deep narrow trenches and holes. This paper will present the first investigation along that line and it has been initiated by the joint research efforts made in the 4M Network of Excellence.[8] Particular results will be presented on measurements of X-ray LIGA structures made available by Forchungscentrum Karlsruhe. We will also mention experiences and results of metrology investigations performed in collaboration with the polymer division of the 4M Network [9].

ERRORS FROM MEASUREMENT FORCE

A micro manufactured item of say 100 x 100 x 100 µm^3, create substantial problems for the metrology engineer. How to attach it and what happens when a tactile probe touches it? Assuming the item to be a freestanding cube of PMMA, the gravity will create a normal force of 12 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 3.6 nN (neglecting the contribution from van der Vaals forces, capillary forces and electrostatic forces), 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. Thus, there is no way a standard CMM probing system can be used for the measurement of free-standing 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.

Even if the micro structure to be measured is attached to a solid base, e.g. an injection moulded part, we will have problems. Let us consider a 100 µm tall pillar with a square section of 50 x 50 µm^2 made of PMMA and sticking out from a base surface. 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, (see Fig.1) causing very erroneous measurement results. In addition to the bending of the structure there will be an indentation error also. This error can be estimated from the Herz equation for contacting surfaces [10] If the pillar had been made in silicon, the bending displacement would have been significantly smaller, 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 technology.

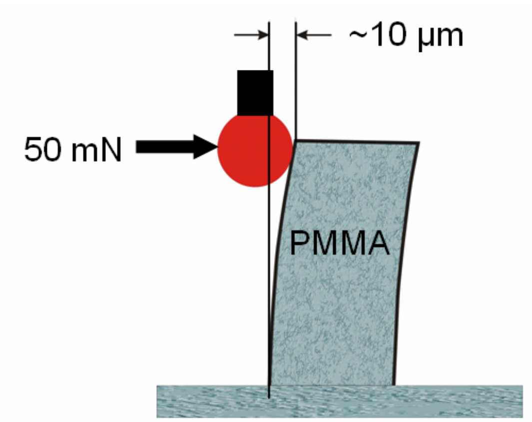

Fig.1. Illustration of the error introduced by the measurement force of a typical CMM on a 100 µm tall PMMA pillar with a 50 µm x 50 µm base.

It is obvious that large measurement errors will be introduced by conventional CMM probes if used on polymer structures. 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.

LIMITED 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 are practically impossible to get access to by non-destructive methods.

A realistic HARMS design can have a trench width of 20 µm, trench length 2 mm and the depth can be 100 - 300 µm. 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, which is far from true when structures in the micrometer range is to be machined.

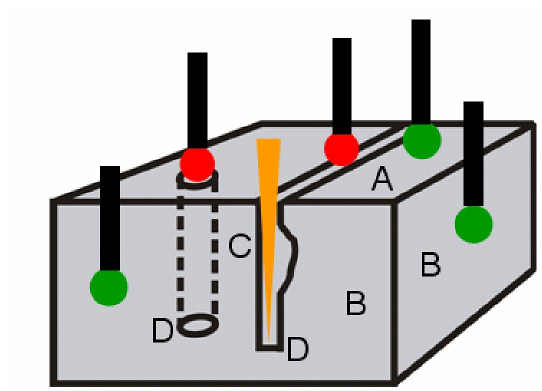

Fig. 2. Ball probe access is limited by deep and narrow holes and trenches and optical profilers can only get a limited amount of light to the bottom in the narrow structures.

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 make to the optical probe if the micro feature is transparent, highly scattering or absorbing? Will the bulk scattering present just below the surface be interpreted as the surface? 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 has been demonstrated as having adverse influence on the output data from auto-focusing optical profilers. [11]

3D-SIEMENS STAR HARMS METROLOGY TEST TOOL

Within the 4M Polymers division a very complex Ni-mould has been produced by both UV-LIGA and X-ray LIGA techniques. An X-ray LIGA sample made by Forchungszentrum Karlsruhe [12] provided to be an ultimate test sample for optical metrology systems. The item used is shown in the SEM picture of Fig. 3. It consists of a Siemens Star, 2 mm in diameter and divided into 36 sectors, yielding a micro land-groove (high-low carpet structure) with 87 µm wide land and 87 µm wide grooves at the outer edge, and separated in height by 184 – 190 µm depending on how well the Ni-deposition process worked out. At the inner edge the land width and grove width was designed to be 2.2 µm, and should in principle have the same height difference of 190 µm. In practice difficulties prevented the Ni-layer to be as perfect as designed, and even some of the vertical walls suffered from lack of Ni deposit, making them shaped as a U-beam profile in cross-section. In some grooves there was also residues left from the X-ray lithography structured PMMA.

Fortunately these defects were all bonus details on the specific sample as it gives the opportunity to test effects of side wall reflections and rough bottom areas in the grooves. With a continuously increasing aspect ratio from 2.1 to – in principle - 86 this is the ultimate tool for testing performance of optical profiler with respect to their response in measuring depths of narrow trenches. In addition to this Ni-star, a pure PMMA Siemens star with the same pitch was also used. With a height difference of close to 400 µm the possible aspect ratios were increased by a factor of two.

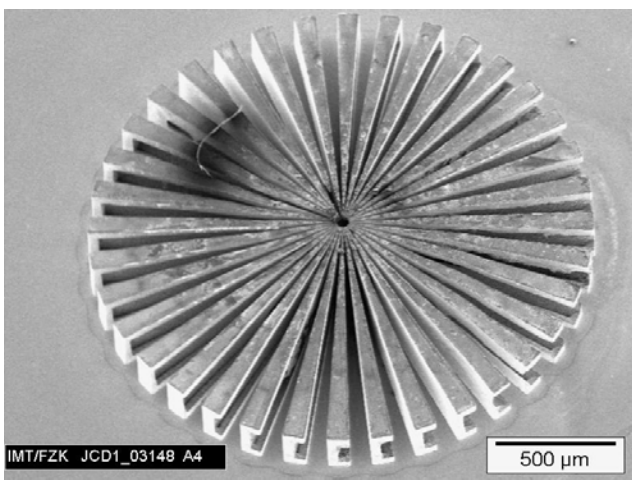

Fig. 3. X-ray LIGA Siemens star – the ultimate sample for testing the HARMS response of optical profilers. Aspect ratio varies from 2 - 80. SEM picture, Forchungszentrum Karlsruhe [12]

In Fig. 4 a part of the Siemens star is imaged by a standard optical microscope provided with a 12X/0.16 numerical aperture objective. The focus is set at the land top level (brighter sectors) of the Ni-surface. PMMA residues within the grooves appear black in this image. The slightly rounded edges of the top Ni surface appear black, which makes it difficult to accurately determine the widths of them.

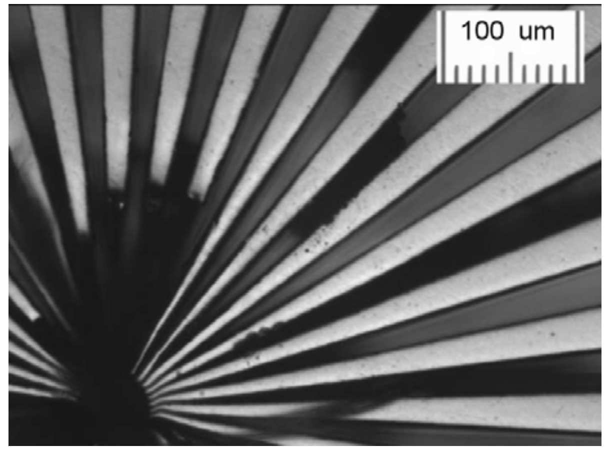

Fig. 4. Optical micrograph of the central part of the 190µm deep Siemens star. The land (bright top of Ni-surface in focus) and groove (grey) are approximately of the same widths. The dark patches within the grooves are residues from PMMA.

For a more accurate determination of the land-groove widths at the top level, Talystep measurements were performed with a 60º stylus cone with a 0.3 µm tip radius. The result 225 µm out from the center of the star is shown in Fig. 5. Corrected for the stylus tip radius and the non-perpendicular trace across the land sectors, the land – groove width came out as close as 0.5 µm from the design value of 19.6 µm. As can be seen in the graph the land levels are flat within 0,25 µm.

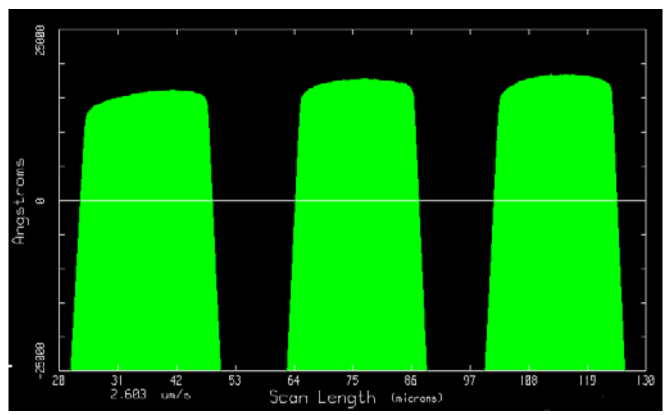

Fig. 5. Talystep trace across three land sectors of the Siemens star, 225 µm from the centre of the star. Full scale in vertical direction is 5 µm in this graph and 110 µm in the horizontal direction. The apparent slope of the side walls is entirely given by the cone angle of the stylus sliding on the edges and has nothing to do with the real angle of the vertical walls.

TESTING OF OPTICAL PROFILERS – PRELIMINARY RESULTS

The first tests performed on the Ni Siemens star were made with an optical coordinate measurement machine specially designed for point by point measurement of tiny parts. An operator from the instrument deliverer performed the measurements to reduce possible instrument operator mistakes. The principle of operation is based on sensing the contrast of a projected pattern onto the surface to be determined as the Z-level of the surface.

This instrument managed to detect surfaces in the bottom of the Ni-star structure down to a groove width of 35 µm, i.e. an aspect ratio of 5.5, with correct height data. For narrower grooves the instrument reported measurement error, and gave no false height information. Increasing the magnification of the objective did not improve the performance.

The second instrument to be tested was a white light interferometer operating at 20X + 2X. A trained PhD student, very familiar to the instrument performed the measurements. The response of the system is shown in Fig. 6, where red is the land (top level Ni-surface) and blue is the bottom of the grooves 184 µm below the land level. Black represents the no-measurable signal condition, and is particularly present in two of the grooves clogged with residue. The narrowest grooves giving back a signal representing the correct height across the groove was found to be about 9 µm, illustrated by the position of the yellow line. The surface profile shows the slope at the edges to be 184 µm/1 µm.

However, take a look at the width of the land to the width of the groove at the yellow line, 160 µm from center and at nominal aspect ratio 13.6. The land width is 19 µm while the groove is 9 µm. The nominal width of both is 14 µm. The profiler overestimates the land width by 5 µm, and underestimates the groove width by the same amount! As a result a lateral measurement error of 36% (5/14) is introduced.

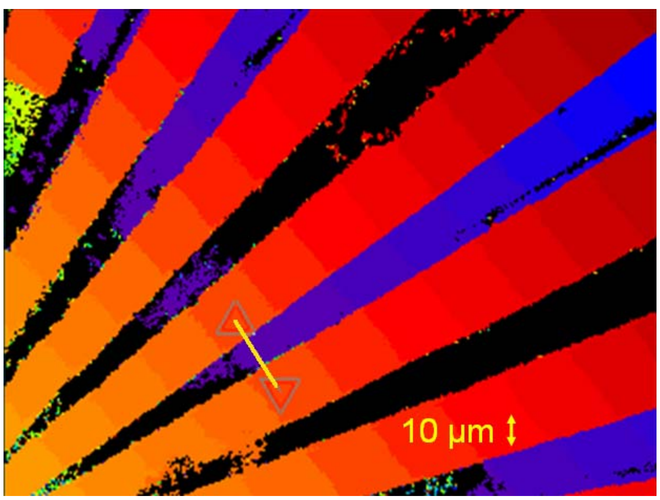

Fig. 6. Height distribution of the Ni-Siemens star as obtained with the white light interferometer. Red represents the land and blue the groove bottom 184 µm below the land level. Black areas lack measurable signal. Note the distorted land - groove widths!

Measurements at 265 and 435 µm from the center at nominal aspect ratios 8.3 and 5.0 yield lateral measurement errors of 3 and 2 µm respectively, i.e. 13% (3/23) and 5 % (2/38) of the nominal value.

The third profiler to be tested was a confocal microscope. Again, an operator with vast experience of the equipment was chosen from the instrument deliverer. Data were initially obtained with a 10X objective, and a typical example of a profile that still gave a correct height value (187 µm) is shown in Fig. 7. At 225 µm from center and at a nominal aspect ratio of 9.7 the groove width at the top is 10 µm and 4 µm at the bottom, indicating a side wall slope of 187 µm/3 µm. These results were obtained at the same position and sector as shown in the Talystep trace of Fig. 5.

As seen from Fig. 7 the land width is strongly overestimated also with the confocal microscope. With a land width of 29 µm and groove width at top of 10 µm the lateral measurement error corresponds to 9.5 µm or 48% of the nominal width of 19.5 µm. The middle groove of Fig. 7 shows that a residue was left in this groove in the manufacturing process. In the white light interferometer this groove returned no signal, (black groove pointing North-East in Fig. 6)

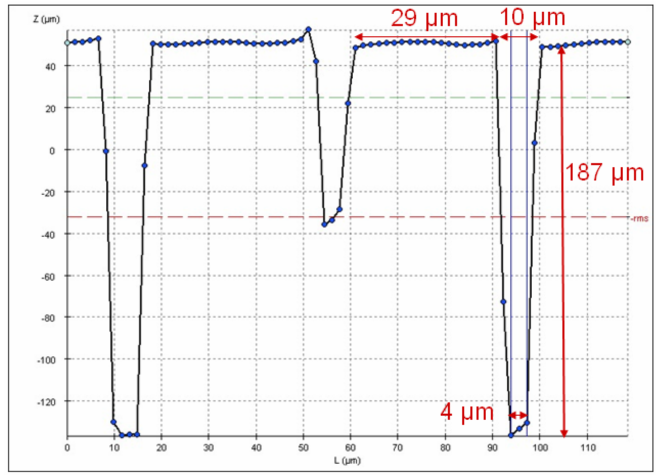

Fig. 7. Profile obtained with the confocal microscope on two land sectors and three grooves of the Siemens star, at a position 225 µm from the centre, were the height measurement still gave reliable results..

Tests performed with the 20X objective indicated the presence of a 20 µm edge artifact never seen on the Talystep traces. This might be caused by misinterpreted light scattering from the edge of the land sector. Another phenomenon that must be attributed to the detection system of the confocal microscope is a strongly non-uniform resolution in different directions. In the 400 µm deep Siemens star made of PMMA it rendered a big difference of how far the groves could be traced at the bottom level. For X-aligned grooves this ended at 550 µm from the centre, while Y-aligned grooves could be traced to 150 µm from the centre. The right hand groove of Fig. 7 corresponds to an angle from horizontal of 34º and is therefore an intermediate resolution example.

DISCUSSION

Table 1 sum up the high aspect ratio performance of the three tested optical instruments without taking into account the lateral measurement errors apparently introduced by the high aspect ratio features. The reason for their existence can only be answered by the manufacturers of the instruments, but a reasonable guess is that the algorithms used for interpreting the images and the strong out of focus conditions of the upper highly reflecting land sectors play a major role. The broadening was so unexpected that neither the operator nor the author running the high aspect ratio test noticed it when the measurements were being recorded. It was not until the analysis of the data and comparison with the Talystep profiles, it was discovered, despite very obvious when looking at the recorded images. These findings will therefore need more systematic measurements and contacts with the manufacturers of the profilers to elucidate and hopefully eliminate some of the laterally introduced errors.

The consequences of the lateral top widening of high aspect ratio structures do not only introduce a false shape of the 3D-structure, but it might also influence the surface roughness value by widening the top levels and suppressing the grooves in a rough, grinded surface, and thereby reduce the roughness value in comparison to the true one. In particular metrology operators having the option of measuring surface roughness with different profilers recognize problems of getting similar results out of optical and mechanical profilers. This is well known and even on sinusoidal low aspect ratio profiles remarkable differences are observed. [14]

Table 1. Max aspect ratio yielding reliable groove depths of the 190 µm thick Ni Siemens star.

Optical CMM	5.5
White light interferometer	13.6
Confocal microscope	9.7

From the table above we see that the white light interferometer is capable if retrieving data in a groove width of 14 µm of the 187 µm deep grove provided the bottom of the grove is sufficiently flat not to cause the reflected light to bounce into the side walls before being captured by the microscope objective. The confocal microscope is in the intermediate resolution direction able to operate down to groove widths of 19 µm. On the other hand it gives measurable signal of non-flat bottom surfaces, e.g. the residue shown in the middle groove of Fig. 7. The correctness of this value is nothing we can confirm at present, as we have not measured it with any other probe yet. For ~190 µm deep grooves as narrow as 14 µm and 19 µm we have no contacting probes available today that can access the bottom, and confirm the heights we measure. We must trust the scanning electron microscopy images showing no residue in most of the grooves and the X-ray LIGA process conditions giving a reasonable uniform thickness of the Ni-layer. The latter can be measured and confirmed at the top level by e.g. the Talystep as seen in Fig. 5.

CONCLUSION

This paper has pointed out critical issues related to metrology of micro structures, in particular structures made of materials other than silicon. Access of mechanical probes in high aspect ratio grooves is very limited and a test was therefore performed for analyzing the performance of optical profilers. The test sample, a 190 µm thick 2 mm diameter Siemens star made in Ni, revealed that optical profilers can yield relevant height/depth data up to an aspect ratio of ~14. However, the lateral, in-plane, measures of the widths of the grooves were strongly diminished at the expense the top land sectors that were interpreted as much wider, causing lateral measurement errors of up to 50% of the nominal widths. Further measurements and analysis needs to be done in close collaboration with the instrument manufacturers to determine the cause of this previously unknown effect.

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