Metrology for MEMS; MEMS for Metrology

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1. Introduction

The emergence of MEMS as a hot item demands for metrology systems which can measure the corresponding dimensional structures in 3 dimension with sufficient accuracy. There is a gap between traditional measurement systems for macroscopic dimension, such as 3-D coordinate measurement machines (CMM’s) and more or less traditional systems for the small dimensions, usual in 2-D, such as microscopes, electron microscopes; and for small dimensions in 3-D, such as interference microscopes and scanning probe microscopes. Deficiencies are in the probe dimensions and the accuracy for the CMM’s in a limited range and 3-D measuring capability for the other instruments. These gaps have to be bridged in two ways: from the one side by the downscaling of CMM’s while improving the design and increasing the accuracy, on the other side by integrating the accuracy in SPM-probes in a 3-D probe system for such a CMM. At the TU/e, several CMM-designs for objects of small dimensions have been prepared, some of which are in a prototype state or even further. In this paper a few examples are given. Also several probes were designed, an overview of the studied possibilities is presented. A special case in the context of MEMS technology is a small probe of a true MEMS design which will be described in detail. For taking this MEMS-based probe into production, a dedicated production facility has been developed, following a modular approach which is fit for being standardised for the production of MEMS in large quantities. Some aspects of this system will be mentioned.

2. Design concepts of MEMS-capable CMM’s

For measuring the dimensions of a MEMS-device, a conventional CMM is not appropriate as its measuring volume is far larger than necessary, its probe and probe tips are generally too large and the uncertainty is larger than the required sub-nm figures. For this reason new CMM-like measuring machines must be designed which fulfill the requirements regarding the measurement uncertainty. With special precautions, great advantages in terms of fulfillment of the Abbe-principle and accuracy in the measurement systems can be achieved. Such systems in our group were e.g. investigated by Vermeulen, Rosielle and van Seggelen [1,2]. Essential in these designs is that the Abbe principle is fulfilled.
in 3 dimensions as closely as possible. Figure 1 gives schematically how this can be achieved in two dimensions: the measurement systems \( M_x \) and \( M_y \) for the x- and y-directions are always in the direction of the probe tip \( P \).

![Figure 1. Schematic of 2-D measurement in Abbe-configuration](image)

The most recent application is for a machine which is dedicated for MEMS-measurements. It has a measurement volume of 50 x 50 x 4 mm and the aimed uncertainty is 25 nm. The basic lay-out, with measuring lines less than 2 mm from the in-Abbe-position, is given in figure 2.

![Figure 2. Lay-out of a CMM dedicated for dimensional MEMS measurements](image)
In figure 2, the structure as in figure 1 can be recognised. In order to exploit the low uncertainty which such a platform permits, new probe designs are necessary, some of which are presented in the next sections.

3. Design concepts of nanometre probing systems

In this section we will shortly discuss some general ideas and principles on which nanometre probing systems can be based. Basically, one type of suspension is used, based on slender rods. This type of suspension is used in earlier probe designs of van Vliet [3], Pril [4] and Peggs [5]. A slender rod is here defined as a rod-shaped elastic element which fixes one degree of freedom. The probe is connected to an intermediate body which is suspended to the probe housing by three slender rods tangentially touching the intermediate body. This suspension has an equal stiffness for all horizontal probing directions. Because of symmetry, the thermal centre is at the z-axis. This suspension is depicted in figure 3. The bending of the three thin elastic elements accomplish that the probe has three degrees of freedom: a translation in the z-direction and two rotations around the x- and y-axis.

![Figure 3. Suspension used in probe design. E: elastic elements, B: frame bars (stiff), S: position of piezo-resistive sensors (if applied)](image)

3.2 Capacitive probe

The high resolution of capacitive sensors can be exploited in a probe design. Some problems may be caused by the non-linearity (with distance) of the probes and a limited amount of overtravel when the probes must be positioned at a small distance from the moving parts. This design is based on the measurement of the differential capacitance between the lower- and the upper side. By dividing the areas into four quadrants, two rotations and one displacement can be measured. This is sketched in figure 4. A detailed design of such a system is described by Lu [6],
who calculated in his design a lower limit on the measurement uncertainty of 1.6 nm in the z-direction and 5.3 nm in the x- and y direction.

![Figure 4. Design of probe with capacitive displacement sensing](image)

A related design of this type, was developed by Peggs [5], and achieves uncertainties of about 16 nm per axis.

### 3.2 Optical Position sensing

Van Vliet [3] developed a probe system, designed to be both fast and accurate, based on an optical triangulation measurement. In an adapted design, using a phasegrating to split the beams, the four beams are reflected by a pyramid-shaped mirror which is on top of the probe shaft. The design of this system, which is still under development, is depicted in figure 5 [7].

![Figure 5. Design of probe with optical position detection. D: Laser diode; L: lens; P: phase-grating; Q: quadrant photodiode; M: mirror; E: elastic elements](image)
4. Probe based on elastic elements with integrated strain gages

4.1 Concept design principles

Mechanics

The probe is designed according to the basic suspension depicted in figure 3. It is miniaturised to reduce the measuring force when a probe tip diameter of 0.3 mm is used, and to enable a probing speed of 1 mm s⁻¹ without damaging a workpiece. The stylus length must be at least 4 mm. To enable the integration of sensors, the suspension is made out of silicon; on which aluminium frame bars and the stylus are glued.

Sensors

Poly-crystalline silicon strain gauges were used, as these hardly add any mass or size to the system. By using several evaporation, lithography and etching steps the slender rods, the strain gauges, and their electrical connections can be manufactured in one set-up, and hysteresis is virtually eliminated. This technology in the field of IC- and Micro System Technology (MST) enables the integrated fabrication of mechanics, sensors and electronics on a micrometre scale. Silicon is used as a substrate.

Calculations [8] showed that the strain gages are best placed close to the two ends of the slender rods. The read-out is done by means of Wheatstone-bridges, one bridge per beam, as depicted in figure 6. With this wiring scheme the temperature-dependent resistance of the strain gages is almost eliminated.

Predicted mechanical and electrical behaviour

The calculated stiffness is 800 N/m for the z-direction, and 160 N/m in any direction in the xy-plane. The calculated overtravel range is 0.5 mm (worst case). The natural frequency is 590 Hz in z-direction and 1060 Hz in any horizontal direction.

The sensitivity of the probe system depends on the probing direction. It is highest in z-direction, and lowest in a close to horizontal direction. Assuming that a relative change of the strain gauge resistors of 10⁻⁶ can still be detected, a resolution of 1.2 nm is possible.

Figure 6. Strain gauges on one rod in a top and a side view, with the Wheatstone-bridge scheme
4.2 Probe manufacturing steps

Manufacture of chip containing wiring, slender rods and sensors

Chips are manufactured in the usual way on 3” silicon wafers. The chips are realised in successive steps of illumination, etching and adding insulation layers by CVD. The chip size is 14 x 14 mm. The basic structure, after being cut from the wafer, is shown in figure 7 and in some detail in figure 8.

Mechanical parts

The ball and the stylus are mounted on an aluminium tripod. The tripod and the stylus are very stiff compared to the slender rods. The stylus length is 8 mm.

Gluing

The chips are mounted (glued) in an aluminium housing (see figure 7) and the tripod with the stylus and the ball are mounted on the chip by gluing. Finally a flex cable is mounted to the chip wiring and it is connected to the aluminium housing.

Electronic testing of wiring and sensors

The wiring and the sensors on the chip are tested before and after mounting the stylus with the tripod and the flex cable. The real probe system is depicted in Figure 7.

![Realised probe](image)

Figure 7. Picture of the realised probe

Figure 8 gives a detail of a slender rod with the position of the integrated strain gauges and electrical connections, as sketched in figures 6 and 7.
Figure 8. Slender rod with the position of the integrated strain gages (S). The cross-section is 100 µm x 40 µm

4.3 Calibration of the probing system

4.3.1. Calibration strategy
In order to calibrate a probe in 3 dimensions, ideally a reference system which is able to position a probe in 3 dimension with nanometre-accuracy is needed. While such a system was not available we used the alternative of doing 1-D calibrations against a 1D nano-actuator.
A 1D calibration set-up can be used if the probe system is positioned on the calibrator at several different orientations. The 1D actuator consists of a platform to which the probe system to be calibrated is be attached, and a moving surface actuating the probe, mostly in the centre of the platform. The displacement of the moving surface relative to the platform is determined by an accurate measurement system [8].
Comparable devices have been designed by Wetzels [9] and Haitjema [10,11].
A 1-D calibration set-up can be used along a line in the x-, y- and z- directions. From that we derive what the combined uncertainty in any direction should be.

4.3.2 Measurement set-up principle
A HP 5528 laser interferometer system is used as measuring instrument offering a low uncertainty, rather direct traceability and high resolution. A differential flat-mirror design is used in which dead-path effects are almost completely eliminated. The optical scheme is depicted in figure 9.
In the figure, S_i is a polarising beam splitter, S_{cc} is a corner cube and the other mirrors denoted by S are flat mirrors. The assembly S_{b1} with S_i may be the same as the so-called angular interferometer. The probe rests on mirror S_m which can move upwards in a parallel way over 30 µm relative to the reference mirror S_r. Over this range the mirror moves parallel within 0.2 arc seconds.
4.3.3 Results of the probe calibration
The AC impedance of the strain gauge resistors has been tested as a function of the frequency of the applied voltage. This revealed a resistive behaviour up to about 40 kHz. The probe displacement was calibrated with the instrument described in section 4.2. We give one example here: the calibration in the z-direction. The result of the calibration in the z-direction is depicted in figure 10. The figure shows that the output of the bridge is very linear with the displacement; the residuals being in the 10 nm range. Also hysteresis is virtually absent due to the integration of the strain gauges.

Figure 10. Residuals of the excitation of the bridges as function of the imposed displacement in the z-direction after subtracting of best fitting straight lines.
The rod number is indicated on the right side of the plot. Results of rod 2 and 3 are shifted. Calibration of the linearity deviations for a displacement along a line in the x-y plane gives a similar figure, where we observe residuals of the order of 30 nm at maximum. Although some interdependence in the 3 directions still has to be figured out, it is evident that we have achieved a unique probe with unprecedented low uncertainties.

### 4.4 Probe manufacture in a matching production network

In order to standardise microsystems manufacturing processes, Gutierrez’ microbrick design architecture has been expanded with elements of the production of microsystems [12]. The resulting process is depicted figure 12, the “Microbrick Production Framework”. This is an expansion of the modular design approach with an adjusted modular way of production. It concentrates on the interfaces of the microbricks from the “Design Architecture” in an elementary way. For example: Die-bonding would be split up in the processes, (1)parts feeding, (2)dispensing, (3)pick and place and (4) curing. The elementary processes are provided in modular way by a black box approach, the so-called “Process Modules”. The last step is that the Process modules are combined in a standard (public domain) cell concept. By combining the right modules together, a tailor made production system can be combined in a quick and flexible way. The whole system should be reconfigurable so after a certain production time it can be rebuilt for the production of different microsystems, or future generations of the same product. In the same way that re-use of technological knowledge can be increased in the design process, it will be possible to re-use knowledge about production processes.

![Microbrick Production Framework](image)

Figure 12. Schematic of the Microbrick Production Framework
This system has been realized in a prototype for the assembly of the probe which is described in sections 4.1 and 4.2.

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References