MEMS 6 Degrees of Freedom parallel micro manipulator for TEM sample manipulation

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Abstract: *Up till now MEMS actuators acted either only in-plane or only out-of plane restricting to 3 DOF manipulation. A design for a millimeter-sized manipulator with 6 degrees of freedom to manipulate a micron-sized substrate at nanometer resolution over strokes of 10 microns with a position stability better than 100 pm over a minute is presented as part of the Multi Axis Micro Stage (MAMS) project of IOP precision technology of SenterNovem. A secondary goal of the project is to generate principle solutions for manipulation and sensing in the micro domain. A parallel kinematic manipulator has been designed in MEMS processes to operate in a TEM environment. The parallel kinematics is used to convert in-plane motion to 6 DOF. For large angles the MEMS device is mounted on a second stage, which is designed with assembly like techniques. Currently the MEMS devices are being processed in the MESA$^+$ clean room.*

Introduction

Manipulation of a sample in a TEM requires 3 translation degrees of freedom of +/-10 µm stroke, one large stroke rotation of +/- 70° and a second of +/- 35°. The large rotations are used for Computer Tomography 3d reconstruction of 2d transmission pictures. The typical size of a semiconductor sample is 20 x 10 x 0.1 µm (Figure 1). The positional resolution should be around 5 nm. When the e-beam is scanned over a sample (STEM mode), the capturing time can take up to half a minute. The resulting resolution of the picture can be in the order of several angstroms if the stability of the e-beam with respect to the sample is better than 0.1 nm/min.

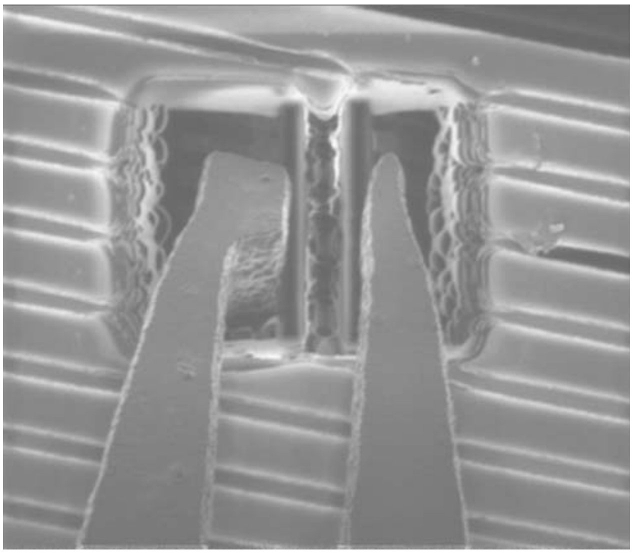

Figure 1: *Semiconductor Silicon sample milled by a focused ion beam, picked by a MEMS gripper (R.Haanstra).*

Currently positioning micron-sized substrates within several nanometers accuracy seems to require a macro system. The relatively large dimensions of the system result in typical drawbacks such as thermal drift, compromised dynamics and obviously space problems. Potential solutions for miniaturizing can be found in Micro Systems Technology (MST) or Micro Electro Mechanical Systems (MEMS), which make use of IC-technology based processes to manufacture micron-sized features. However classic IC based technology also has its limitations, such as the typical 2.5D stacked layer approach and the small signal to noise ratio with respect to sensing. The demand for precision micro manipulators however is becoming more urgent with the global trend towards MEMS systems and research for nano-technology.

MEMS have been around for more than half a century starting with pressure sensors. By measuring the strain piezo resistively of a micron thick membrane the pressure difference was determined. Commercialization started in the mid 70s, with applications for car manifold pressure sensing especially. Acceleration sensors for airbags, inkjet print heads and the digital mirror device commercialized at the turn of the millennium. Next generation mems will possibly bring Radio Frequency (RF) MEMS for telecom and radar, valves for micro fluedics, micro flown for measuring gas speed, angular rate sensors for vehicle stability, switches and variable capacitances ,and gas/chemical sensors. A true mechatronic MEMS example is the acceleration sensor. The position of a proof mass is measured (Bosch, electrostatic gap closing) and kept constant by actuation (Bosch, electromagnetic). The actuation force is proportional to the acceleration. An even more challenging example is the rate sensor which has the same function as a gyroscope. The Coriolis effect is used to amplify the forces caused by an angular rate. A high frequent elastic translation of a proof mass radial to the rotation axis causes Coriolis forces tangentially.

Today most MEMS are used for sensing purposes. This while accurate sensing of small structures is not straightforward as the small signals are easily deteriorated in for example the interconnection.

Up till now MEMS actuators acted either only in-plane or only out-of plane restricting to 3 DOF manipulation. In the 6 DOF micro manipulator focus is on manipulating both in-the-wafer plane and out-of-the wafer plane.

The TEM manipulator

For high resolution pictures it is of paramount importance to guarantee a positional stability between the e-beam and the sample better than 0.1 nm/min. Stability by active feedback would require position sensing with an accuracy of a ridiculous 0.02 nm. Relying on passive stability however requires especially a thermal stable design, necessitating a small thermal loop from the sample to the e-beam. Dynamic stability requirements result in a lowest natural frequency higher than 1 kHz.

In the TEM the beam is directed by coils and soft magnetic poles. For high resolution scans the distance between the lens poles should be down to 5 mm. However currently there is no manipulator available which can rotate at large angles within such a small gap.

A combination of a MEMS manipulator and a rotation stage (an assembly of precision engineered parts), can facilitate the requirements on low and high frequent stability, and the large rotation. The mass and size of the total manipulator will be small enough to couple the stage to the TEM poles directly, minimizing disturbance from external vibration sources (sound and air pressure changes), internal vibration sources (pump), and external thermal sources.

System design

The large-rotation stage exhibits movement freedom like a cardan joint, stacking two rotations. A combination of inertia sliding (PZT) piezo actuators and capacitive differential sensors should position the MEMS stage within 50 μRad. The material choice for the high vacuum ($<5.10^{-8}$ mbar) compatible sliding bearings, as elastic joint are obsolete, is under investigation at the moment, candidates are ruby, sapphire, MOST and DLC. The inertia sliding motion is modeled using Simulink.

The MEMS stage is designed like a parallel manipulator. Parallel manipulators in general have a large stiffness (mainly tensile / compressive stress) to mass ratio resulting in high natural frequencies and short settling times. However parallel kinematics facilitate 6 (or more) actuators to be made in-plane of the wafer, using a mechanism to direct the motion out-of-plane (of the wafer) to obtain 6 DOF. In this way one technology can be used to manufacture the actuators.

Actuation and sensing

Several physical principles are used for actuation of MEMS devices: Piezo, Electrostatic, Thermal, Electromagnetic, Chemical, SMA. The first four are the most commonly used. **Electromagnetic** actuators are often applied in actuator systems larger than 10 mm^3, because of their large stroke at moderate forces, low voltage, easy electronics and easy manufacturing. However because of the small work density (especially in small volumes) they are not commonly used in MEMS. For example a typical 30 μN over 30μm ≈ 10^{-9}J, requires about 5.10^{-12} m^3 of total magnetic actuator volume. (Lorentz actuator, using SmCo magnet, permalloy soft magnetic material and the rise of the temperature above ambient limited to a large 200K!). PZT **piezo** exhibits a large work density (table 1), but is incompatible with MEMS technology. AlN piezo is currently still in the research phase. Both piezo's output a small stroke, which needs to be amplified. **Thermal** actuators can work well in MEMS (many inkjet print heads) and can have a large work density. The time constant can be small enough if the volume is small. However in this case the stroke also needs to be leveraged. Also a heat source in a precision manipulator is not advantageous for stability. **Electrostatic** actuators are relatively easy to manufacture in MEMS. Basically only conductors and insulators are necessary. The stroke force combination can usually be directly utilized. In a gap closing actuator parallel plates are attracted to each other as a result of the voltage difference over the plates. This actuator type exhibits non-linear transfer of voltage to force and position to force. Comb drive actuators exhibit position independent force (Figure 2). Though used frequently the work density remains a drawback requiring relatively large areas in MEMS structures. A very big advantage of electrostatic atuation is the possibility of using the structure as a sensor [1]. The capacitance can be measured by super positioning a high frequent (e.a. 1 MHz, 1V) signal on the actuation signal.

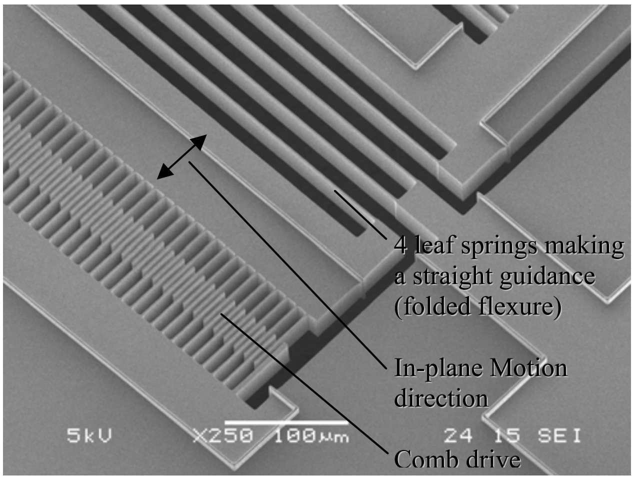

Figure 2: *SEM picture of a Deep Reactive Ion Etched (DRIE) comb drive with folded flexure suspension (E.Sarajlic [2]).*

Kinematics

To facilitate out-of-plane motion with in-plane actuators an out-of-plane geometry is needed. A KOH etched Silicon (Si) pit with compensation structure, results in a chopped pyramid. The top of the chopped pyramid will become the platform which can move in 6 DOF (Figure 3). The 4 sides of the pyramid, are used to structure 4 silicon rich nitride (SiRN) leaf springs on. At the bottom of the SiRN leaf springs, torsion hinges release the in-plane rotations which SiRN the leaf springs constrain. The out-of-plane rotation which is also constrained by the SiRN leaf springs is released by the axis of intersection of 2 Si leaf springs (Figure 5). These Si leaf springs also couple the linear translations of 2 comb drives to two actuated DOF at the base of SiRN leaf spring.

The kinematics of the platform is best explained by looking at the movement of the SiRN leaf spring bases. These are actuated each by 2 comb drives and are constrained in 4 DOF (3 translations and one rotation). The SiRN leaf spring transfers 2 constraint DOF to the platform. The platform is twice over constraint. However, because the actuators have a very small stiffness, the resulting stress will be small. In plane motion (3 DOF) is obtained by moving the pyramid as a rigid body. In plane translations require the SiRN leaf spring base to move with the same amount in the same direction. Rotation around the out-of-plane axis requires the SiRN leaf spring base to move tangentially to the axis of rotation. Out-of-plane translation is derived by moving the bases in radial direction. In-plane rotation requires the one base pair consisting of one front and rear base to move opposite to the second base pair, the left and right one.

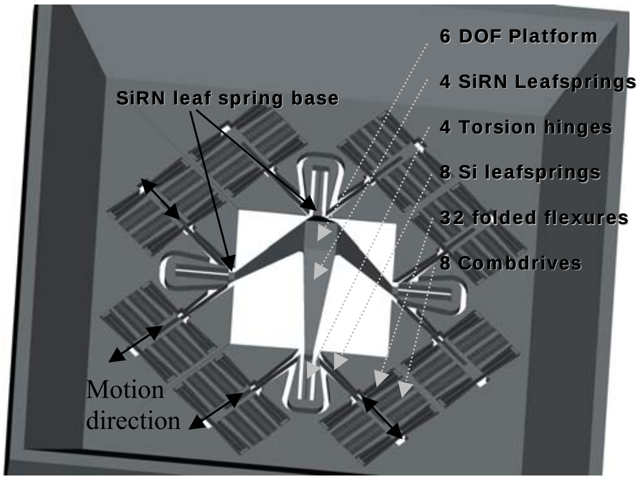

Figure 3: *SolidWorks overview of the MEMS manipulator*

The platform is 150 x 150 x 50 μm. The SiRN leaf springs are 550 μm long and 0.5 μm. The platform is towering a 460 μm above the base. The torsion hinges are built up of two intersecting plates. The in-plane plate is of the SiRN type and is 0.5 x 30 x 270 μm the out of plane plate is Si and is 2 x 40 x 270 μm. The stiff horseshoe shaped Si positions the intersection of the Si leaf springs close to the out-of-plane rotation. The Si leaf springs are 516 x 40 x 2 μm. The comb drives are each suspended by 4 folded flexures, the straight guidance of the comb drive, consisting each of 4 leaf springs 200 x 40 x 2 μm. Each comb drive consists of 112 comb teeth (48 x 40 x 2 μm) pair, resulting is a maximum force 12 μN at 35V. The comb drives are of the push-pull type delivering a bidirectional displacement of 30 μm.

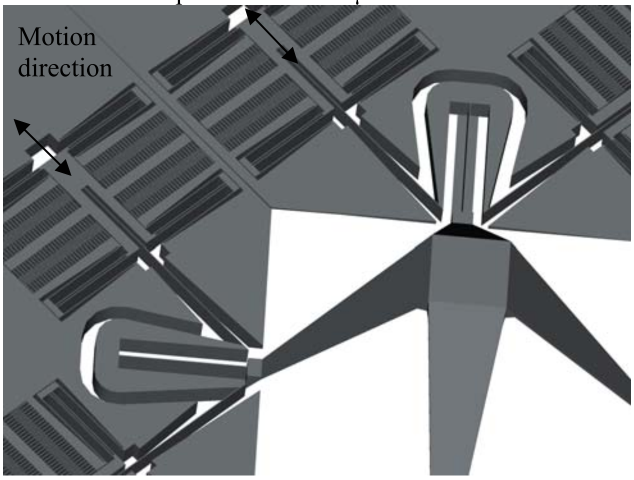

Figure 4: *SolidWorks overview 2 of the MEMS manipulator*

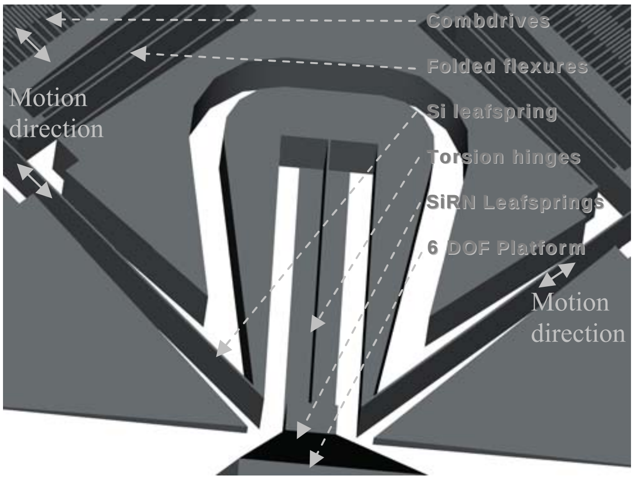

Figure 5: SolidWorks detail of MEMS manipulator

Calculations

When assuming small geometric changes during manipulation, the Jacobian matrix J_{act} transfers the position and orientation of the platform (6 DOF) to the positions of the 8 actuators:

$$X_{act} = J_{act} \cdot X_{pl}$$

The deformation of the elastic elements (36 DOF) is also coupled to the platform position and orientation:

$$X_{el} = J_{el} \cdot X_{pl}$$

The force and or moments in the elastic elements are calculated by multiplying the stiffness matrix with the deformation matrix of the elastic elements.

$$F_{el} = C_{el} \cdot S_{el}$$

$$F_{pl} = J_{el}{}^{T} \cdot F_{el} = J_{act}{}^{T} \cdot F_{act}$$

$$F_{act} = J_{act}{}^{-T} \cdot J_{el}{}^{T} \cdot C_{el} \cdot J_{el} \cdot X_{pl}$$

The force the actuators have to deliver is now coupled to the position of the platform. The stress in the elastic elements is calculated by multiplying the force or moments with the inverse section modulus, Wb, in the elastic elements:

$$\Sigma_{el} = Wb^{-1} \cdot F_{el}$$

$$\Sigma_{el} = Wb^{-1} \cdot C_{el} \cdot J_{el} \cdot X_{pl}$$

The lowest natural frequencies are obtained by transferring the stiffnesses which are significant for the actuation direction into a stiffness matrix C_{act}, which acts as if located and oriented like the actuators. The out-of-plane stiffness of the SiRN leaf spring base for example is transferred to a spring which is located at the two connecting actuators. The mass of the system is concentrated in a mass matrix acting on the middle of the platform:

$$eig(J_{act}{}^{T} \cdot C_{act} \cdot J_{act}, M)$$

More detailed calculation using a Spacar model, a combination of finite elastic elements and rigid bodies with large deformations, is being worked on.

Process

The process is explained roughly as follows. The first steps are based on the trench isolation process, which basically consists of DRIE 40 mm deep trenches and refilling them with SiRN [2]. By LPCVD a SiRN mask with compensation structures for KOH etching is deposited. The pyramids are etched by KOH. A buried mask for the comb drives and the torsion hinges is deposited in TEOS SiO2 and covered by a layer of PECVD SiRN. An aluminum mask for structuring the SiRN leaf springs and the torsion hinges is evaporated through a shadow mask from the back side. The Al mask is copied in the SiRN backside by SF6 etching. The base of the pyramid, a layer of SiO2 and SiRN is opened by DRIE. An PECVD SiO2 is added to the back side for protection of the SiRN leaf springs. TMAH etching excavates the pyramid leaving the SiRN leaf springs un harmed. The top layer of SiRN removed and the buried mask is opened. The comb drives and torsion hinge structures are etched by DRIE. BHF is used to remove SiO_2, and the structure is released.

Results

Currently the MEMS devices are being processed in the MESA$^+$ clean room of the University of Twente.

Conclusions

A design for a millimeter-sized manipulator with ≥5 degrees of freedom to manipulate a micron-sized substrate at nanometer resolution over strokes of 10 microns with a position stability better than 100 pm over a minute is presented. A parallel kinematic manipulator has been designed in MEMS processes to operate in a TEM environment. The parallel kinematics is used to convert in-plane motion to 6 DOF. A large angle rotation stage based on assembly like techniques facilitates the large angles.

Designing a micro system requires knowledge of especially mechanical design principles and process technologies next to transducer science, signal processing and control technique making it an into the micro domain extended micro-mechatronic design approach.

References

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Acknowledgments

First I'd like to thank the people who contributed directly to the project:

G.J.M Krijnen[1], M.J. de Boer[1], J.W. Berenschot[1], H.V. Jansen[1], J.van Dijk[2], J.B. Jonker[2], M. Kruizinga[2], J.A. Deijnen[2], S. Stramigioli[3], W. Zhau[3]

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Second I'd like to thank IOP precision technology of SenterNovem by the name of C.J.G.M. Langerak and A. Hulst who made this project financially possible.