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Design and modeling of a six DOFs MEMS-based precision manipulator

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ABSTRACT

In this paper a design is presented for a precision MEMS-based six degrees-of-freedom (DOFs) manipulator. The purpose of the manipulator is to position a small sample ($10\,\mu m \times 20\,\mu m \times 0.2\,\mu m$) in a transmission electron microscope. A parallel kinematic mechanism with slanted leaf-springs is used to convert the motion of six in-plane electrostatic comb-drives into six DOFs at the end-effector. The manipulator design is based on the principles of exact constraint design, resulting in a high actuation compliance (flexibility) combined with a relatively high suspension stiffness. However, due to fabrication limitations overconstrained design has been applied to increase the stiffness in the out-of-plane direction. The result is a relatively large manipulator stroke of 20 μm in all directions combined with a high first vibration mode frequency of 3.8 kHz in relation to the used area of 4.9 mm × 5.2 mm. The motion of the manipulator is guided by elastic elements to avoid backlash, friction, hysteresis and wear, resulting in nanometer resolution position control. The fabrication of the slanted leaf-springs is based on the deposition of silicon nitride (Si_xN_y) on a silicon pyramid, which in turn is obtained by selective crystal plane etching by potassium hydroxide (KOH). The design has been analyzed and optimized with a multibody program using flexible beam theory. A previously developed flexible beam element has been used for modeling the typical relatively large deflections and the resulting position-dependent behavior of compliant mechanisms in MEMS. The multibody modeling has been verified by FEM modeling. Presently only parts of the manipulator have been fabricated. Therefore, a scaled-up version of the manipulator has been fabricated to obtain experimental data and to verify the design and modeling.

1. Introduction

In the future, the precision manipulation of small objects will become more and more important for appliances such as (probe-based) data storage, micro-assembly, sample manipulation in microscopes, cell manipulation, nano-indenting, manipulation of optical beam paths by micro-mirrors and manipulation of electron beam paths by phase plates. At the same time, there is a drive towards miniaturized systems. An example can be found in the manipulation of samples in a transmission electron microscope (TEM). The relatively large dimensions of ‘conventional’ TEM sample manipulators result in typical drawbacks such as thermal drift and compromised dynamics. Especially the requested stability of 0.1 nm/min requires a new manipulator concept. Miniaturization creates the opportunity to fix the manipulator directly to the column which guides the electron beam, isolating external thermal and vibration noise. Secondly miniaturizing the manipulator generally results in enhanced stability because of increased natural frequencies, decreased thermal drift and in small thermal time constants of the manipulator. Potential solutions for miniaturizing can be found in Micro Electro Mechanical Systems (MEMS). MEMS devices comprise micro-sensors, actuators, mechanisms, optics and fluidic systems. They have the ability to integrate several functions in a small package. Precision manipulation in MEMS seems sparse however.

Combining design principles, a mature design philosophy for creating precision machines, and MEMS fabrication, a technology for miniaturization, could lead to micro-systems with deterministic behavior and accurate positioning capability. However, in MEMS design trade-offs need to be made between fabrication complexity and design principle requirements. A micro-mechatronic design of a parallel kinematic six degrees-of-freedom MEMS-based preci-

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sion manipulator is presented. Although presently only parts of the fabrication process have been tested [1], the conceptual manipulator design is verified by measurement data on a scaled-up version. The research, design and fabrication of a multi-DOFs micro-stage will be continued.

2. Requirements

The requirements of the manipulator are based on a next generation TEM sample manipulator. First, the manipulator has to operate in an ultra high vacuum (10^{-8} to 10^{-9} mbar) and should not interfere with the electron beam. The maximum displacement should be enough to examine a sample. A semiconductor sample is typically 20 μm × 10 μm × 0.2 μm. Therefore, the *x*- and *y*-strokes of the manipulator should be about 20 μm. For the focusing of the electron beam, the *z*-stroke should be about 20 μm also. Once an area of interest is found on the sample, the TEM sample manipulator should be able to find this area again with a translational repeatability of about 10 nm. Extremely fine positioning is possible by manipulating the electron beam itself. The MEMS-based manipulator will be used for small correction angles up to several degrees only. The rotational repeatability needs to be better than 0.05°.

Some TEMs can be used in a scanning TEM (STEM) mode, where the beam can be scanned across the sample to form the image. Taking a picture in the STEM mode can take up to half a minute. This fact, combined with the possible image resolution of 0.08 nm, results in an extreme stability requirement of 0.1 nm/min for the sample with respect to the electron beam. This stability should be reached within 10 s after the manipulation of the sample. Because of the high resolution capability of the TEM, sound and the vibrating surroundings cause the TEM column to vibrate, which could lead to blurred images. Therefore, the sample needs to be fixed dynamically stable to the TEM column. Therefore, a next generation manipulator requires a lowest vibration mode frequency of more than 1 kHz. A summary of the main specifications is given in Table 1.

3. Background of multi-DOFs positioning in MEMS

To develop an idea of the state of the art of precision positioning in MEMS, a small survey is presented with respect to existing examples of multi-DOFs devices in MEMS. The MEMS-based manipulators are distinguished with respect to systems for planar positioning, systems for out-of-plane positioning and combinations of both. For positioning repeatability it is important that the mechanism used in a manipulator does not have friction, play or backlash [2–8]. Many solutions for multi-DOFs hinges offering large freedom of movement show play and friction in the hinges [9–12]. This is a large drawback for precision applications and is therefore not regarded. Compliant mechanisms using elastic hinges generally do not suffer from friction, play and backlash and are far more suited to precision manipulation. However, the displacements are limited compared to the size of the mechanism.

Table 1
Specifications for a next generation TEM sample manipulator.

Property	Value
Stroke *x*, *y*, *z*	20 μm
Repeatability *x*, *y*, *z*	10 nm
Rotational stroke (any 2 DOFs)	3°
Rotational repeatability	0.05°
Stability[a]	0.1 nm/min
1st vibration mode frequency	>1 kHz

[a] Value should be reached within 10 s after manipulation.

3.1. In-plane positioning

A 2 DOFs planar manipulation platform is presented by Sarajlic et al. [13]. The platform is actuated by electrostatic comb-drives. The 2 DOFs of the planar manipulator are generated by a series coupling of movements of about 20 μm in both directions. The positioning resolution is limited by the resolution of the amplifier. The system is fabricated by a bulk micro-machining process in single crystal silicon. Etching in the bulk wafer is called bulk micro-machining. In the case of a silicon wafer, it results in single crystal silicon as a structural material. Bulk micro-machining allows high aspect-ratio structures, for example leaf-springs with a thickness of 2 μm and a height of 40 μm. Using comparable fabrication technology, an example of a parallel 3 DOFs planar manipulator has been fabricated by de Jong et al. [14]. The manipulator uses a compliant mechanism of the parallel kinematic type to convert the motion of 3 stationary actuators to 3 DOFs of the platform. The translational strokes are 20 μm and the maximum rotation is 4°. Stepper or inchworm actuators are also found in the micro-domain. Examples of electrostatic parallel plate actuators for clamping and displacement are given by Tas [15] and Patrascu et al. [16] for single DOF displacement and by Sarajlic et al. in [17] for 2 DOFs displacement.

3.2. Out-of-plane positioning

In [18] a 3 DOFs out-of-plane manipulation stage is presented applying three identical linear motors consisting of a slider and a pair of thermal bimorph actuators. The motors are radially positioned around a platform with 120° pitch and push radially inward. The propulsion is based on friction, which is generally a drawback for precision positioning. Another 3 DOFs out-of-plane stage applying the same kinematic principle is presented in [19]. Here electrostatic scratch-drive actuators are applied. A scratch-drive actuator is a kind of stepping electrostatic actuator. For this stage, hinges are used with play instead of hinge flexures. A 3 DOFs out-of-plane stage with compliant hinges made from polydimethylsiloxane (PDMS) is presented in [20]. Out-of-plane actuation is based on a mechanism, built up out of PDMS, transforming the in-plane motion of comb-drives to out-of-plane displacements of a platform.

3.3. Combinations of in- and out-of-plane manipulation

In [21], Sarkar et al. present various multi-DOFs manipulators for inspection inside a TEM or SEM. These are based on compliant mechanisms and driven by thermo-mechanical bimorph actuators made in a surface micro-machining process. Culpepper et al. [22] have designed a symmetric flexure mechanism for six DOFs manipulation called HexFlex. In [23] a MEMS version of this mechanism is presented driven by 12 thermo-mechanical actuators arranged in 6 pairs. The choice for this type of thermo-mechanical actuators allows relatively simple fabrication. However, the system is over-actuated and the thermal heat influences the position stability of a TEM system. Ando [24] has presented a compliant mechanism 3 DOFs stage with strokes of 1.0, 0.13 and 0.4 μm in the *x*-, *y*- and *z*-direction. Inclined leaf-springs are used fabricated by focused ion beam milling. Liu et al. [25] reported a 3 DOFs manipulator with strokes of 25, 25 and 3.5 μm in the *x*-, *y*- and *z*-direction. The positioning repeatability open-loop is better than 17.3 nm along all three axes.

3.4. Assembly of MEMS devices

The literature describes many examples of wafer-bonding of MEMS devices. A very nice example of assembly by wafer-bonding