MEMS based 6 Degrees-of-freedom parallel kinematic precision micro manipulator

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Abstract

A design is presented for a 6 Degree-of-freedom parallel kinematic precision micro manipulator comprising 3 translations of 20 μm stroke, and three small correction rotation strokes of 5°. The elastic deformations of the manipulator have been optimized for minimal elastic energy storage at a large guiding stiffness. The parallel kinematics facilitates 6 electrostatic lateral comb-drive actuators to be made in-plane of the wafer, using a mechanism to direct the motion to out-of-plane to obtain 6 DOF. One single technology can be used to manufacture the actuators and mechanisms. The fabrication involves deep reactive ion etching with a back-etch release process, offering great design freedom, resulting in a compact design.

Introduction

The relatively large dimensions of 'conventional' transmission electron microscope (TEM) sample manipulators results in typical drawbacks such as thermal drift and compromised dynamics. Especially the crucial stability of 0.1 nm/min requires a new manipulator concept. It creates the opportunity to fix the manipulator to the heart of the electron beam source, one of the TEM poles, isolating external thermal and vibration noise. Secondly the manipulator can be made more stable. Miniaturizing potentially increases the natural frequencies, decreases the thermal drift and decreases the thermal time constant of the manipulator. Potential solutions for miniaturizing can be found in Micro Electro Mechanical Systems (MEMS) [1],[3]. Precision manipulation in MEMS seems sparse however. In this paper a 6 Degree-of-freedom (DOF) precision MEMS based manipulator is presented.

The typical size of a semiconductor sample is 20 x 10 x 0.1 μm. The sample can be manipulated in 3 translations of 20 μm stroke, and three small correction rotation strokes of 5°. The positional resolution of the sample in the TEM should be around 5 nm. The positional stability however demands less than 0.1 nm/min movement of the sample with respect to the E-beam. The overall dimensions of the manipulator are 4.9 x 5.2 x 0.5 mm.

System concept

The MEMS stage is designed like a parallel manipulator. Parallel manipulators in general have a large stiffness to mass ratio resulting in high natural frequencies and short settling times. In this case the parallel kinematics facilitates 6 actuators to be made in-plane of the wafer, using a mechanism to direct the motion out-of-plane to obtain 6 DOF. In this way one single technology can be used to manufacture six of the same type of electrostatic lateral comb-drive actuators as shown in figure 1. Electrostatic comb-drives are linear motors that utilize electrostatic forces that act between two conductor combs. In a lateral comb-drive actuator the fingers are typically arranged so that they can slide past one another until each finger occupies the slot in the opposite comb. These comb-drives exhibit a good displacement to force ratio for this application and are relatively easy to manufacture. Furthermore they can be combined with capacitive sensing by super positioning a high frequent signal on the actuation signal. The comb-drives are each straight guided by four folded flexures. The folded flexures consist of 4 reinforced leaf-springs. In comparison to a 14% shorter non-reinforced leaf-spring the straight guiding compliance and stress are equal. The tensile stiffness however is increased 300%, which is very beneficial regarding the side pull-in stability [2]. The six comb-drive actuators are arranged in pairs. Within a pair, one comb-drive is connected to the other with a silicon leaf-spring, an intermediate body and a second leaf-spring. The silicon leaf springs are 1000 x 35 x 2 μm thick. Each intermediate body can be manipulated in the xy-plane, and is constrained in z, Rx and Ry direction. A silicon rich nitride (SiRN) leaf-spring, 0.7 μm thick, connects each intermediate body to the end-effector releasing 3 degrees-of-freedom of the 5 at the base. Each actuator pair, with intermediate body and SiRN leaf-spring, controls 2 DOF of the end-effector, making the end-effector exact kinematic constraint. The end-effector is towering a 460 μm above the base. Because the total mechanism movement is achieved by purely elastic movements, and the mechanism is nearly exact kinematic constraint the positional hysteresis will be extremely low. A planar linear static equilibrium model has been set up for determining the energy storage and stress in the elastic elements, the displacements of the actuators and the end-effector. The model has been used to optimize the dimensions of the leaf-springs for minimal elastic energy storage at a relatively large guiding stiffness.

Fabrication

A silicon pyramid is made by KOH etching the silicon along the <111> crystal planes. Compensation structures are used to preserve the instable pyramid edges during etching. The <111> leaf-springs are made out of SiRN which is deposited by a low pressure chemical vapor deposition (LPCVD) on the pyramid. The silicon inside of the pyramid is etched away at a later stage. The leaf-springs are structured by covering them partially with a protective layer by shadow-mask deposition and etching away the exposed SiRN parts. The lateral comb-drives are made by first making electrical isolated sections by DRIE trenches which are refilled with SiRN. High aspect ratio (1:20) deep reactive ion etching enables fabrication of trenches 2 μm wide and 40 μm deep. Then the comb structures are etched by DRIE. Finally the comb structures are released by etching away the backside. The process combines bulk micromachining in standard p^+ doped, conductive silicon wafers by combining vertical trench isolation and backside etching. The process allows trenches of various widths (thus various etch rates) as over etching is no problem. For this reason the design freedom for complex elastic mechanism is guarantied.

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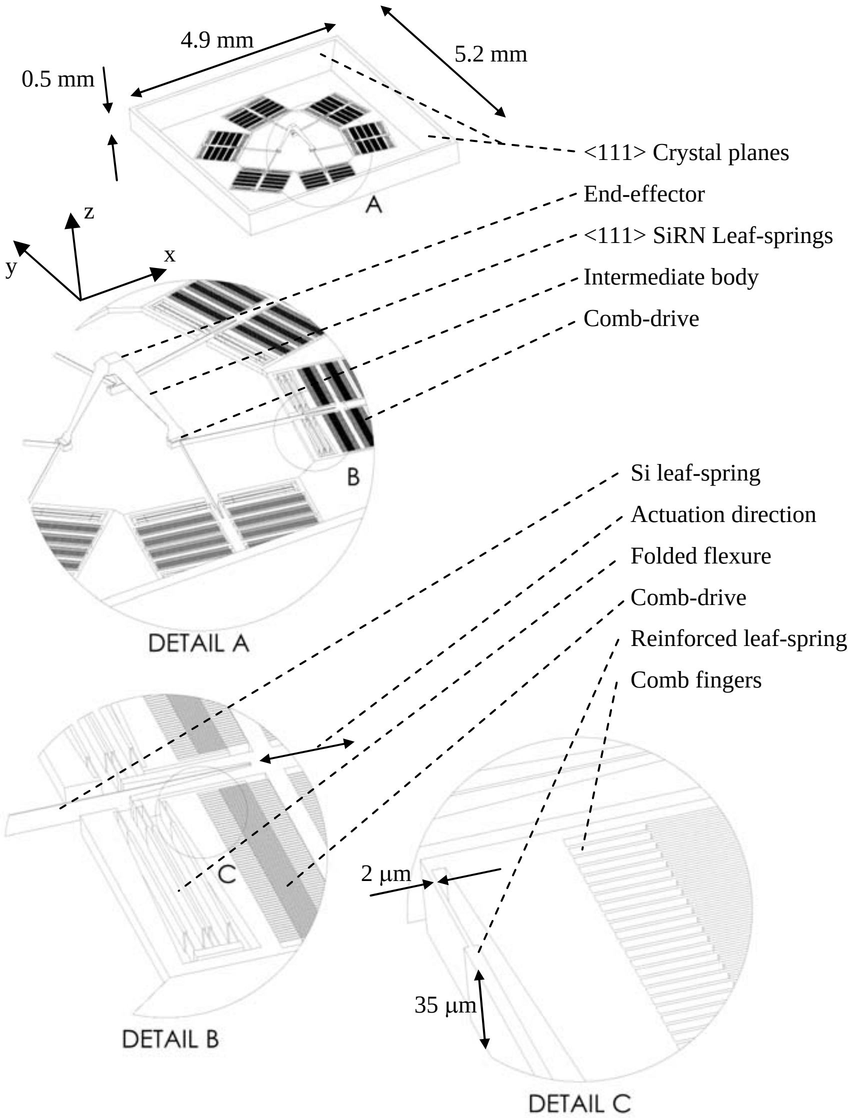

Figure 1: 3D CAD drawings of the MEMS 6 Degrees-of-freedom parallel kinematic precision micro manipulator