

# Design and fabrication of an overhanging *xy*-microactuator with integrated tip for scanning surface profiling

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## Abstract

This paper presents a microsystem consisting of an overhanging *xy*-microstage with integrated tip and comb actuators for scanning surface profiling. The design is optimized with respect to precise *xy* positioning at low drive voltages and accurate detection of vertical deflection. The structure is micromachined in monocrystalline silicon, requiring only three masks and combining various techniques such as KOH and sacrificial layer etching, silicon fusion bonding and wet isotropic and dry anisotropic etching.

## 1. Introduction

The invention of the scanning tunneling microscope (STM) in 1982 [1] and its brother, the atomic force microscope (AFM) [2], has been of considerable interest for use in surface analysis, and later also in other domains like data storage or motion detection [3–6].

For all these applications of the STM or AFM principle, the basic requirements are the same: the accurate moving and position detection of the sharp sensing tip. This led to the development of various actuation and sensing devices, among which micro-machined structures are promising candidates, since they do not need any assembling of hybrid elements and, in addition, their sensitivity to thermal and vibration noise decreases with their dimensions [6–9].

For scanning force microscopy (SFM), an extended version of the AFM where the tip on the cantilever support is scanned over the sample, high sensitivity and noise reduction are major conditions [2]. Recently, technological progress has led to the concept of integrated SFM devices satisfying these requirements [10].

This paper presents the realization of a new overhanging *xy*-microstage with integrated protruding tip and comb actuators for scanning surface profiling. In the next section the structure will be described and the design will be discussed with regard to the oscillation and displacement characteristics of the structure. In the third section, the detailed fabrication sequence is presented, followed by concluding remarks on the first realized prototype.

## 2. Structure design and operation principle

### 2.1. Description of the structure

Figure 1 shows a schematic view of the microstage. It consists of two beams crossing each other at their center where the sharp tip is integrated. The ends of each beam are attached to comb actuators driven electrostatically. Four actuators are necessary because they can only be used in pulling mode [11, 12]. The actuation of two of the four interdigitated combs allows a positioning of the tip in the *xy* plane.

The combs are electrically isolated from the substrate by a silicon dioxide layer. The drive voltage is applied on the pads, which are not connected with the tip, so that perturbations due to electrostatic effects are kept as small as possible [3].

Further, the substrate wafer has been etched through, leaving the microstage overhanging a via hole. Thus, the vertical displacement of the scanned probe can be optically detected [3].

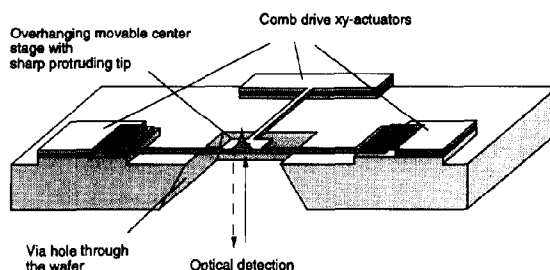


Fig. 1. Schematic view of an overhanging *xy*-microactuator with an integrated sharp protruding tip and a via hole for optical detection.

## 2.2. Design considerations

In SFM the microstage has to satisfy various conditions [13]. For the described structure, the following three requirements are the most important. First, the first resonance frequency has to be high enough ( $> 10$  kHz), i.e., beyond the noise range. Secondly, the beams of the cross must have a low vertical spring constant in order to be sufficiently sensitive (flexible) to atomic, electric or magnetic forces that are typically of the order of  $10^{-9}$  N. Finally, the horizontal spring constant (in the  $xy$  plane) has to be small to enable electrostatic actuation by the combs.

To estimate the vertical spring constant of the cross, we assumed that the ends of the beams are fixed (i.e., the contribution of the comb suspensions to the vertical stiffness of the microstage is neglected in this approximation). Further, we assumed that the spring constant of a cross with beams having a width  $w$  is the same as that of a beam with width  $2w$ .

Using these assumptions, the first resonance frequency of the cross for free vibrations perpendicular to the substrate ( $z$  direction) can be calculated as follows [14]:

$$f_1 = 1.03/L^2(Eh^2/\rho)^{1/2} \quad (1)$$

where  $\rho$  is the density of the material ( $2300 \text{ kg/m}^3$  for silicon),  $L$  and  $h$  are the length and the thickness of the beams, respectively, and  $E$  the Young's modulus of the material (assumed to be  $1.7 \times 10^{11} \text{ N/m}^2$  for silicon). If the beams of the cross have a length of  $600 \text{ }\mu\text{m}$  and a thickness of  $4 \text{ }\mu\text{m}$ , a value of about  $100 \text{ kHz}$  is found, which is far beyond the noise.

With the same assumptions as above, the vertical spring constant of the cross,  $c_z$ , is calculated employing the expression [15]

$$c_z = 16Eh^3w/L^3 \quad (2)$$

where  $w$  is the width of the beams. With the values mentioned above and  $w = 2 \text{ }\mu\text{m}$ , the vertical spring constant becomes  $3.2 \text{ N/m}$ , leading to a vertical displacement of a few angstroms for an applied force of  $10^{-9} \text{ N}$  (Hooke's law), thus lying within the sensitivity range of optical detection systems.

In a similar way, the horizontal spring constant of one beam of the cross in the  $x$  direction,  $c_{xb}$ , is estimated:

$$c_{xb} = 16Ew^3h/l^3 \quad (3)$$

Using the values mentioned above, a result of  $0.4 \text{ N/m}$  is found.

For the horizontal stiffness of the comb suspension,  $c_{xs}$ , the following formula is employed [16]:

$$c_{xs} = 2Ew^3h/l^3 \quad (4)$$

where  $l$  denotes the length of a beam element, two of which form a folded suspension, and  $E$ ,  $h$  and  $w$  are

as defined in eqns. (1) and (2). For  $l = 200 \text{ }\mu\text{m}$ , a comb suspension stiffness of  $1.4 \text{ N/m}$  is obtained.

The total horizontal spring constant of the structure sketched in Fig. 1 can then be calculated. Since the suspension of the active comb, that of the passive comb actuator and one deflected beam of the  $xy$  cross are assumed to have their ends fixed, they can be considered as three springs connected in parallel. Thus, the resulting total spring constant becomes

$$c_{\text{tot}} = 2c_{xs} + c_{xb} \quad (5)$$

For the described structure, we find a value of  $3.2 \text{ N/m}$ , which has to be compared with the force created in the combs. For small displacements, this force is given by [11, 17]

$$F_c = n\epsilon V^2/g \quad (6)$$

where  $n$  is the number of fingers,  $\epsilon$  is the permittivity of the air gap,  $V$  the applied voltage and  $g$  the gap between the fingers. For a driving voltage of  $30 \text{ V}$ , a value of  $0.23 \text{ }\mu\text{N}$  is obtained, which allows the microstage to be moved about  $72 \text{ nm}$  in each direction, while a displacement of  $1 \text{ }\mu\text{m}$  requires a voltage of  $110 \text{ V}$ . Larger displacements at lower drive voltages are achieved, for instance, by increasing the flexibility of the beams. From eqns. (3) and (4) it can be seen that a large flexibility is obtained when the beam lengths of the cross and comb suspensions are increased (enhanced the risk of sticking of the beams to the substrate) or when the width of the beams is diminished. A rise of the beam thickness leads to a larger electrostatic driving force (see eqn. (6)) which, however, is compensated by a lower flexibility of the beams (see eqns. (3) and (4)). In addition, an enhanced stiffness in the  $z$  direction results from an increased beam thickness (see eqn. (2)), thus lowering the sensitivity but on the other hand reducing the sticking. In conclusion, a compromise between features like high sensitivity or low drive voltage has to be found by choosing an appropriate structure design.

## 3. Fabrication sequence

The challenge was to realize the structure of Fig. 1 using micromachining batch processing. The detailed fabrication sequence, which requires only three masks, is shown in Fig. 2.

Two highly boron-doped silicon  $\langle 100 \rangle$  wafers with a bulk resistivity of  $0.06 \text{ }\Omega \text{ cm}$  are used in order to obtain a conductive suspended structure. First, a thermal silicon dioxide ( $\text{SiO}_2$ ) of  $1.5 \text{ }\mu\text{m}$  thickness is grown on each wafer. The backside oxide of both wafers is then patterned using photolithography and etching in buffered hydrofluoric acid (BHF). On the lower wafer, this

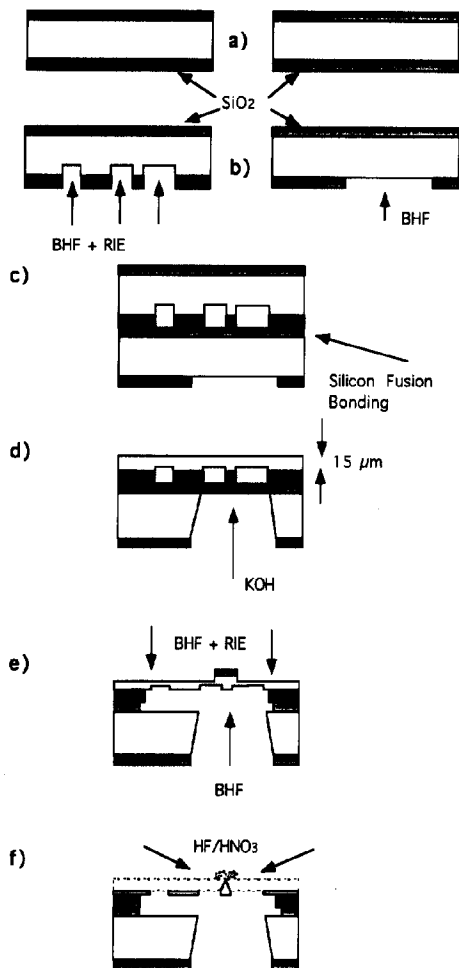


Fig. 2. Detailed fabrication process of the overhanging *xy*-microstage: (a) thermal oxidation (1  $\mu\text{m}$  layer) of a pair of silicon wafers; (b) photolithography and BHF etching for patterning the  $\text{SiO}_2$  of the lower side of both wafers; RIE ( $\text{C}_2\text{ClF}_5/\text{SF}_6$ ) prestructuring of the upper wafer; (c) aligned prebonding followed by fusion bonding; (d) etching of the via holes (lower wafer) and thinning of the upper wafer in KOH solution; (e) oxidation; upper oxide patterning and etching of the interface oxide layer where it is accessible through the via holes; RIE on the upper side to form the columns for the tips; (f) wet etching to pierce the membrane and form the sharp tip.

pattern will be used as the etch mask for the via holes. On the upper wafer, the pattern serves as a mask for the subsequent reactive ion etching (RIE) in a  $\text{C}_2\text{ClF}_5/\text{SF}_6$  plasma to prestructure the *xy*-microstage. The RIE process allows high aspect-ratio beams with fairly vertical side to walls to be produced [12, 18]. After a careful cleaning procedure, high-precision double-sided alignment ( $<2 \mu\text{m}$ ) on a commercial mask aligner [19] for prebonding is performed. Then the wafers are sealed together by means of fusion bonding on their  $\text{SiO}_2$ - $\text{SiO}_2$  contact areas by a 4 h anneal at  $1100^\circ\text{C}$  [20–22].

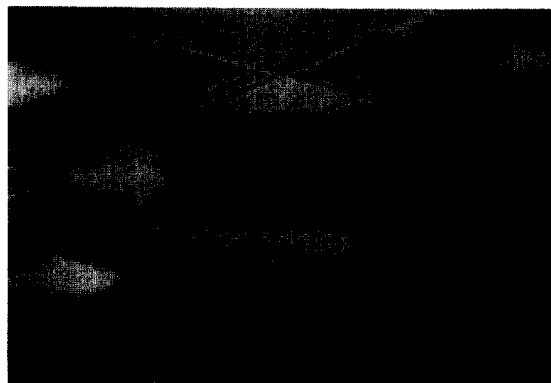


Fig. 3. Top view (SEM) of the microfabricated silicon *xy*-microstage.

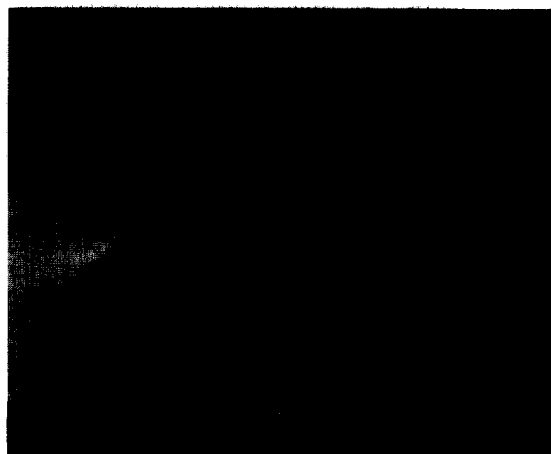


Fig. 4. Close-up view (SEM) of a protruding silicon tip (height 8  $\mu\text{m}$ , radius 40 nm) integrated on the center table.

Although the contact areas cover only a small portion of the whole wafer surface, a rather good homogeneity of the bonding has been achieved. In the next step, via hole etching of the lower wafer and thinning of the upper wafer are carried out in potassium hydroxide (KOH), until a  $10 \mu\text{m}$  thick membrane remains. Afterwards, a  $1 \mu\text{m}$  thick oxide layer is thermally grown and the upper side is protected with photoresist. The original oxide layer of the interface of the wafers, which is now accessible through the via holes, is removed using BHF etching. Next, the oxide on the upper side is patterned to form the caps for the tips. Silicon columns of about  $8 \mu\text{m}$  height under the  $\text{SiO}_2$  caps are then etched by RIE out of the membrane, whose thickness is thereby reduced to a few micrometers. Wet etching in an  $\text{HF}/\text{HNO}_3$  mixture is employed to pierce the residual membrane and to form the tips. This combination of dry and wet etching has proved to be most successful for creating sharp protruding silicon

tips [9]. Finally, the sacrificial bonding oxide under the movable part of the comb actuators is laterally etched.

Figures 3 and 4 show a perspective view and a detail of the first prototype of such a microstage, fabricated by means of the described processing sequence [23].

#### 4. Conclusions

We have demonstrated the design and fabrication of an overhanging xy-microstage with integrated tip for an SFM. In particular, a combination of several micromachining techniques (wet and dry etching, KOH etching and silicon fusion bonding) has been successfully applied. Mainly due to sticking problems, reliable displacement versus voltage measurements have not yet been performed. Thus, the next generation of structures will concentrate on that processing detail. Furthermore, we shall decrease the width of the beams to obtain larger displacements at lower drive voltages.

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#### Biographies

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