Multiple Depth, Single Crystal Silicon MicroActuators For Large Displacement Fabricated by Deep Reactive Ion Etching

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ABSTRACT

The design, fabrication and testing results of a Single-Crystal-Silicon (SCS) comb-drive actuator fabricated at two depth levels by Deep Reactive Ion Etching (DRIE) are presented in this paper. Prior work on deep microactuators has focused on DRIE or LIGA where the height of the spring is the same as the height of the comb fingers. In this paper, we present a DRIE fabricated comb drive actuator where the height of the spring is significantly less than the height the comb fingers. This gives the benefit of a compliant spring with a large displacement per unit of actuator force. A single mask, multiple depth fabrication allows the spring depth to be controlled independent of the depth of comb fingers, utilizing the loading effect of the Bosch silicon etching process and the masking of released beams using PECVD oxide.

A displacement of 130 μm at 37 volts is achieved on a 4 mm by 4 mm comb-drive actuator, where the comb fingers are 100 μm deep and the depth of folded flexure springs is 22 μm . A resonant frequency of 220 Hz is measured in air. Different suspension systems are evaluated using ABAQUS simulation, and the experimental results of the actuator are shown to be in a good agreement with the simulation.

INTRODUCTION

Bosch silicon etching process [1] is a newly developed deep silicon dry etching technique at room temperature involving a cycle of silicon sidewall passivation and an aggressive SF_6 etch. A typical silicon etch rate is 3.5 $\mu\text{m}/\text{min}$ with a selectivity of 100:1 on oxide and 50:1 on photoresist. The PlasmaTherm SLR-770 (Shuttle Locked Reactor) runs the Bosch process using an inductively coupled plasma source at 2 MHz and an industry standard 13.56 MHz RF source to generate a high density plasma. By controlling more than 15 process parameters during the etch step and the passivation step, we have recently fabricated a wide range of complex 3-D structures that are often impossible to construct using a conventional RIE technology [2].

Bosch silicon etching is ideally suitable for fabricating a large displacement, high force actuator because of its ability to produce straight and deep high aspect ratio fingers. A single mask, multiple depth process allows the spring depth to be controlled independent of the depth of comb fingers, utilizing the loading effect of Bosch silicon etching process and the masking of released beams using PECVD oxide.

In this paper, we fabricated a deep etched comb drive actuator where the depth of the spring is 22 μm and the depth of the comb fingers is 100 μm . It results in a spring stiffness small enough to achieve a significant increase in the displacement per unit of actuator force. A displacement of 130 μm at 37 volts is measured on a 4 mm by 4 mm comb-drive actuator. This device has a resonant frequency of 220 Hz in air. The resonant frequency is expected to increase to approximately 500 Hz with a modified layout in future work.

Such a large linear displacement at a low operating voltage is attractive in x-y microstage applications [3], data storage technology [4-5], and applications that require positioning various nanotools [6].

The two level depth process can easily be scaled for the fabrication of multiple depths of high-aspect-ratio single crystal silicon structures on a single wafer, as will be discussed in the fabrication section. The fabrication of self-aligned, two-level structures is also demonstrated using the same two level depth process flow. This allows the benefit of a compliant spring system coupled to a large capacitance and a high proof mass structure.

DESIGN CONSIDERATIONS

Spring design

To achieve large displacements at low operating voltages, a suspension system must be compliant in the direction of displacement. Stiffness in the orthogonal directions must be high in order to prevent side instability. To design an optimum suspension system, ABAQUS was used to simulate the displacement as a function of the actuator force for three different spring systems: fixed-fixed, crab legs, and folded flexure. In the simulation, three dimensional beam element were used. Materials were assumed to deform elastically. The nonlinear geometry option was used to calculate the large deflection behavior of the beam. Boundary conditions were defined such that the spring was assumed to be clamped at the pad.

At a given spring dimension, the ABAQUS simulation showed that the folded flexure design has the largest deflection per unit of force and the largest linear deflection range, as shown in Figure 1. This result is in a good agreement with a previous work on the evaluation of various suspension systems for large displacement purposes [7].

Figure 1. (a)- (c) Three different spring structures for the simulation.

Fig 1. (d) ABAQUS simulation results for maximum deflection versus applied force. Three different spring systems are simulated and compared. The simulated beam depth, width and equivalent modulus are 20 μm , 3.05 μm and 92.3 Gpa, respectively. The linear deflection range of folded flexure is shown.

Stability and Design Parameters

The movable fingers of the comb drive are centered between the fixed fingers. This gives a zero resultant force along the direction perpendicular to the stroke avoiding a failure mode of movable fingers touching the fixed fingers. Any deviations from the perfect symmetry will cause the movable fingers to move perpendicular to the stroke direction. Side stability has been investigated previously [7-8]. Actuation stability is a function of several design parameters and can be summed up by the following expression, where a deflection greater than $Y_{critical}$ will cause side instability:

$$Y_{critical} = g \sqrt{\frac{k_x}{2k_y} - \frac{y_0}{2}} \quad (1)$$

where g is the finger gap, y_0 is the initial comb finger overlap, and the direction of actuation is in the y direction. The equation (1) indicates that actuators with smaller finger gaps become unstable at smaller displacements than those with the larger gaps, side instability is proportional to the overlap length and increases with applied voltage because the spring constant of folded flexure in the x -direction decreases with increasing beam displacement in the y -direction. For folded flexure system, spring constants in x and y directions are given by:

$$k_x = k_{x1} k_{x2} / (k_{x1} + k_{x2}) \quad (2)$$

$$k_y = \frac{2 \cdot 2Ehb^3}{L^3} \quad (3)$$

where h is the height of springs, L is the length of springs, b is the spring width, k_{x1} is the axial spring constant at zero-deflection, and k_{x2} accounts for the reduced axial spring constant as the lateral deflection increases,

$$k_{x1} = \frac{2 \cdot 2Ehb}{L} \quad (4)$$

$$k_{x2} = \frac{2 \cdot 200EI}{3L\delta_y^2} \quad (5)$$

A factor of 2 is included in each equation since there is a folded flexure spring at both ends of the backbone. At the stability limit, k_x is approximately equal to k_{x2} , and deflection in beam segment δ_y is approximately equal to $Y_{critical}$. By substituting (2) and (3) into (1), we obtain:

$$(Y_{critical})^2 + \frac{y_0}{2}(Y_{critical}) - gL\sqrt{\frac{25}{18}} = 0 \quad (6)$$

Figure 2 shows a plot of $Y_{critical}$ as a function of folded flexure spring length, comb finger gap, and initial finger overlap. The graph shows a design space of these three parameters that satisfies the stability criteria given in equation (6). For a given value of desired displacement, various combinations of finger gap, spring length and overlap length can be selected. Actuators with smaller gaps become unstable at smaller displacements compare to actuators with larger gaps. Consequently, actuators with smaller gaps require a large value of L , increasing the ratio of k_x/k_y to compensate for the effect of small g , as shown in equation (1).

In practice, two physical limitations restrict the length of springs and the size of finger gaps. As in a conventional RIE, Bosch etching is limited to an aspect ratio of about 30:1. Consequently, a limited range of finger gap sizes is available for a desired displacement based on the aspect ratio requirement. Secondly, thin PECVD oxide and Al films on a released silicon spring structure creates an intrinsic stress. As the length of the released springs increase, the displacement due to the intrinsic stress becomes greater, and a better design is needed to keep the spring planar [9]. Therefore, possible ranges of finger gaps and spring lengths are limited by the fabrication and physical constraints.

Figure 2. $Y_{critical}$ as a function of the folded flexure spring length, initial finger overlap, and the comb finger gap. Units are in micrometers. Y_c is the critical deflection, L is the length of spring, and Y_0 is the initial finger overlap.

Design Parameters

In our initial design, we selected the folded flexure spring system based on comparisons in the previous sections. The comb actuators are attached to two folded flexure springs at each end of the backbone. We specified the depth of the comb fingers and the depth

of the backbone to be 100 μm . The silicon spring width and depth are 2 μm and 22 μm respectively. The initial finger overlap is 30 μm and the targeted displacement is 130 μm . As shown in Figure 2, the necessary finger gap is 14.5 μm for a spring length of 1100 μm to achieve $Y_{critical}$ of 130 μm . The fabricated actuator is shown in Figure 3.

Figure 3. SEM of the deep etched microactuator

FABRICATION

The fabrication sequence for a large motion in-plane actuator is illustrated in Figure 4. A 2 μm thick PECVD oxide layer is deposited on a (100) P-type silicon wafer. This oxide thickness is needed since the typical selectivity of silicon to oxide in DRIE is 100:1. An additional 1 μm of oxide is conservatively added to protect silicon structures during the isotropic silicon etch for release. The oxide is patterned using OCG 897-21i resist on GCA 6300 i-line stepper, and the pattern is transferred to the SiO_2 film using CHF_3 plasma in a Magnetron RIE etcher as shown in Figure 4b.

A first deep silicon etch is performed using the PlasmaTherm SLR-770 for the first 22 μm . The patterned silicon structure is conformally passivated with PECVD oxide [Figure 4c]. After clearing the floor oxide using another CHF_3 plasma etch, a second deep silicon etch is carried out for an additional 30 μm , making the height of silicon structures thus far 50 μm [Figure 4d]. A time-controlled SF_6 plasma selectively releases the spring system since the width of silicon springs is 2.0 μm , whereas the silicon width of the remaining beams of the actuator is 4 μm . Only silicon beams with previously deposited PECVD oxide are protected during this step. Thus the springs are limited to a height of 22 μm [Figure 4e].

Once the springs are released, a third silicon etch step continues an additional 50 μm , making the comb fingers 100 μm tall [Figure 4f]. In order to release the movable fingers and the backbone, another layer of PECVD oxide is deposited. After the floor oxide etch, a 30 μm silicon etch is performed to facilitate the release of silicon structures using the isotropic SF_6 etch. Finally, aluminum is conformally sputtered for metallization [Figure 4g]. The electrical isolation is provided by a PECVD oxide overhang, where a portion of inner silicon core is etched out during the release process. This overhang isolates metal from the silicon substrate [10].

Figure 4. A schematic summary of process flow for two level depth large displacement microactuator.

The first isotropic SF_6 etch step produces a notch on wider beams that are not released. This may prevent a continuous metallization on the sidewalls. Therefore, it is important to minimize the first SF_6

etch time. There are three ways to ensure the minimal undercut. Taking advantage of the loading effect inherent in the Bosch process, the undercutting effects are minimized by the geometrical condition that the comb fingers are placed in a more confined area than the springs. Secondly, a time-controlled SF_6 etch is characterized so that the etch time is enough to release only the springs. By using a re-entrant profile, the width is reduced, requiring a shorter release time. These factors contribute to reducing the notching on the sidewall of deeper structures and permit a continuous metal film on the sidewall. The re-entrant profile of comb fingers in conjunction with the effects of the first two factors is shown in Figure 5.

Figure 5. Re-entrant profile of comb fingers to minimize the first SF_6 etch time.

Figure 6(a). A 22 μm deep spring is attached to a 100 μm deep actuator.

Figure 6(b). A closer view of 6(a)

Fabrication of SCS structures on a single wafer can easily be scaled from the two level depth process into multiple levels. In the two level fabrication, a smaller depth structure is made possible by selecting a narrow silicon beam width in an open space whereas the deeper structures are designed with a larger silicon beam width in a more confined space. For the case of a three level process, the deepest structure is fabricated by designing the silicon width to be more than the width of the less deep structures in a confined space.

In conjunction with the multiple depth fabrication, it is possible to fabricate multiple level structures [11] using the same process flow shown in Figure 4. For example, a released spring from 4(e) can serve as a mask for a shadow mask for producing an underlying structure. Since the Bosch Silicon etching is not based on a high degree of anisotropic bombardment of ions as in the standard RIE, the distance between the end of the released mask and the beginning of the substrate with respect to its open space must be optimized. If this distance is too large and/or its surrounding spacing is not confined enough, the substrate is exposed to the Bosch etching and the silicon underneath the masking silicon structure will be etched away. Self-aligned, two-level comb fingers are shown in Figure 7.

(a)

Figure 7. (a) SEM picture of self-aligned two level comb fingers fabricated by the two level process.

Figure 7. (b) Schematic cross-section of the device

RESULTS AND DISCUSSIONS

For a dc driving voltage, the displacement is given by:

$$d = \frac{nh}{2gK_y} V^2 \quad (7)$$

where n is the number of fingers, h is the height of comb fingers, g is the gap between comb fingers, k_y is the spring constant in the direction of displacement and V is the applied voltage. For this tested large displacement comb drive, there are 310 comb fingers and each finger is 100 μm tall with 15 μm gap spacing. The folded flexure spring is a composite material wherein the silicon core is surrounded by a layer of PECVD oxide and a layer of aluminum, as shown in Figure 8. For the calculation of k_y , a composite modulus needs to be approximated using the following equation [12],

$$E_{eq} = \sum \frac{E_i (h_i^3 - h_{bi}^3)}{h_T^3} \quad (8)$$

where, h_i is a lateral distance from the center of the beam to the end of i layer, h_{bi} is a lateral distance from the center of the beam to the beginning of i layer and h_T is a half of total width of the beam. The equivalent modulus of 92.3 GPa is calculated for an effective spring width of 3.05 μm.

Figure 8. Cross-section of beam at the end of process.

A displacement of 130 μm is measured at 37 volts. Motion of the comb fingers under an optical microscope is shown in Figure 9. ABAQUS simulated values are shown to be in good agreement with the experimental results as indicated in Figure 10. The comparison of calculated and measured displacement shows that the small deflection theory is valid for displacements up to roughly 90 μm, which is approximately 8% of the spring length. This range of linearity for a folded spring structure is reasonably consistent with the work done by Legtenberg et al [7].

Figure 9. Optical microscope pictures. (a) The initial position of comb finger. (b) Displacement of 83 μm at 28 volts

Figure 10. (a) Comparison of measured, simulated and calculated displacement as a function of voltage squared. (b) Actuator force as a function of applied voltage. There are 310 comb fingers, each with 15 μm finger gap, 30 μm initial finger overlap and 100 μm depth. The length of folded flexure spring is 1100 μm. They are 22 μm deep and the effective width is 3.05 μm.

Resonant frequency is expressed by:

$$f_r = \sqrt{\frac{k_{sus}}{m_{moving}}} \quad (9)$$

where m_{moving} is the mass of the moving structure and k_{sus} is the spring constant of suspension. The calculated value of resonant frequency is 198 Hz which is in reasonable agreement with the experimental measurement of 220 Hz. The discrepancy is most likely due to inaccurate measurements of the width of composite layers. A perfect rectangular cross section of deeper silicon structures is not possible due to the release of shorter beams as discussed above. Also, the etch profile tends to get slightly tapered as the aspect ratio increases. All these factors contribute to the difficulty of estimating the accurate mass of moving structures. For an accurate estimation of k_{sus} , the effect of small out-of-plane curvature on the spring needs to be accounted for, as the spring is not perfectly planar. A higher resonant frequency is possible by minimizing the dimensions of the actuator.

Future Work

Currently, we are working on the design of a large linear displacement x-y stage with a low operational voltage that can move more than a 100 μm in both x and y directions. The x-y stage is driven by four large displacement actuators. A mechanical coupling of suspension systems and the decoupling of x and y directions are carefully being investigated for stable operation.

Webb et al. have demonstrated isolated released silicon segments, allowing the use of the silicon core as a conductor and eliminating the aluminum layer [13]. Work is being done on implementing this approach for a two level depth actuator design.

Fabrication of a Z-motion actuator has been carried out. A multilevel depth fabrication enables the use of shorter springs as well as fabrication of movable fingers at a different height than the fixed fingers. As in the case of a spring system, this can easily be done by designing the width of a shorter finger to be less than the width of the taller one. Thus, narrower beams will be released before the wider beams. This vertical asymmetry in the comb finger design has a vertically asymmetric electric field acting on the movable fingers. Consequently, there will be a net vertical force creating a static displacement or a vibrational excitation of the comb fingers [14].

CONCLUSION

We have demonstrated the fabrication and operation of a two level deep etched microactuator. The single crystal microactuator has 22 μm deep folded flexure springs and 100 μm deep comb fingers. A displacement of 130 μm at 37 volts was achieved. A resonant frequency of 220 Hz was measured. The experimental data matches well with the ABAQUS simulation.

The two level depth process can easily be scaled for the fabrication of several depths of high-aspect-ratio single crystal silicon structures on a single wafer. The fabrication of self-aligned, two-level structures is also demonstrated using the same two level depth process flow.

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