Fabrication technique for microelectromechanical systems vertical comb-drive actuators on a monolithic silicon substrate

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This article presents a technique to fabricate a microelectromechanical systems vertical comb-drive actuator on a monolithic silicon substrate. This technique employs only two photomasks. The first photomask defines all the critical patterns, including a set of movable upper hollow comb fingers, a set of fixed lower comb fingers, and a suspension spring to avoid the alignment problem and maintain a small finger gap. The second photomask selectively covers the upper fingers to obtain the released upper hollow fingers. The vertical comb-drive actuator is fabricated by deep reactive ion etching process on a monolithic silicon wafer using these uniquely designed photomasks to avoid the residual stress and stiction problems. Different lateral gaps between the adjacent lower solid and upper hollow fingers are obtained with various finger widths. The height of the comb fingers is 10.0 µm. The vertical offset between the two sets of comb fingers can be adjusted by controlling the process conditions. Both symmetric and asymmetric staggered comb-drives are achieved through process modifications. The mechanism of notching effect is discussed and addressed by multiple spacer oxide deposition. Silicon residue effect, which occurs during the lowering down etching process, is investigated from the fabrication aspect and resolved by combining isotropic and anisotropic etching processes. This kind of vertical comb-drive actuator can be widely applied in optical switches, scanning micromirrors, and sensors. © 2005 American Vacuum Society. [DOI: 10.1116/1.1835291]

I. INTRODUCTION

Comb-drive structures are widely applied in microelectromechanical systems (MEMS) devices for electrostatic actuation and capacitive sensing. In general, the comb-drive actuators can be divided into two broad categories according to the direction of the motion: (1) in-plane interdigitated comb-drive and (2) vertical comb-drive actuator. The vertical comb-drive actuator is developed to generate out-of-plane or torsional motions, and is widely used in high-speed and high-resolution optical scanning and switching applications. The vertical comb-drive actuator consists of two staggered sets of comb fingers. One set is fixed and stands on the wafer substrate. The other is movable and supported by a suspension spring. However, the fabrication of such a vertical comb-drive actuator on a single crystalline silicon wafer is a challenging task as the conventional microfabrication methods basically define only the planar geometry.

The vertical comb-drive actuator fabrication can be classified into three different research methods. The first method is by combining surface micromachining and bulk micromachining technologies, in which the vertical comb array microactuator is developed by trench etching in bulk silicon and trench filling of polysilicon. In addition, an electrostatic torsional actuator is fabricated on silicon-on-insulator (SOI) wafer by using polysilicon surface micromachining and deep reactive ion etching (DRIE). The second method is based on single-crystal silicon developed either on SOI substrate or by employing wafer bonding, such as employing double-sided process on SOI wafer and developing comb structures on two wafers and assembling them by wafer bonding. As the alignment between upper and lower comb is difficult, self-aligned method is studied to minimize the planar gap and to generate high electrostatic actuation in low operating voltages. In further efforts, Jeong _et al._ developed a self-aligned vertical comb-drive actuator on a single layer of SOI substrate where vertical offsets are realized by using bimorph cantilevers bending or thick photoresist hinge reflowing. In the latest research, Kim _et al._ proposed the surface/bulk micromachining technology on (111) single-crystal silicon substrate and Chu _et al._ used boron etch-stop-assisted lateral silicon etch on a (111)
wafer. These two approaches employ multiple masks and deep trench etching steps to form silicon beams with offset and utilize alkaline solution to release the vertical comb structure in which the spacer oxide or boron diffusion play the role of sidewall protection.

These techniques have their individual drawbacks and shortcomings. Generally, they suffer from some of these problems: (1) alignment and bonding difficulties when wafer bonding and multiple-layer techniques are employed, (2) inherent residual stress problem when polysilicon is used as structure material, (3) photoresist residue problem in high aspect ratio features, and (4) stiction problem when the wet release process is carried out. After all, the fabrication of a single-crystal silicon vertical comb-drive actuator on a monolithic silicon wafer with a simple process seems to be the most attractive.

This article proposes a simple fabrication technique to realize the vertical comb-drive actuator on a monolithic single crystalline silicon substrate by employing two uniquely designed photomasks and multiple DRIE process to avoid the stiction, stress, bonding, or alignment problems. The design of the vertical comb-drive actuator and the photomasks are described in Sec. II. The fabrication process and results are discussed in Sec. III. The analysis of the notching effect and the silicon residue effect is presented in Sec. IV. The last section presents some brief conclusions.

II. THE UNIQUE DESIGN OF THE PHOTOMASKS

The proposed vertical comb-drive actuator consists of a set of fixed lower solid comb fingers, a set of movable upper hollow comb fingers and a suspension spring that provides supporting and counteracting forces. Figure 1(a) shows the schematic overview of the actuator and (b) is the cross-sectional view of the comb fingers. The actuation is operating when a voltage is applied between the comb fingers. During this process, the upper beams are pulled toward the substrate with the respective fixed solid fingers. This motion is the result of fringing electric fields, which depend on the electrostatic force and the torsional stiffness. The driving force is determined mainly by the relative position of the movable and fixed comb fingers. The relation between the actuating force and the relative position is simulated by ConventorWare, as illustrated in Fig. 2, where the height of the fingers is 10.0 μm. The result shows that the force approaches maximum when the initial offset is zero and it has no significant change until the engagement between the two sets of comb increases to half of the beam height. After this critical point, the force drops rapidly. Obviously, the initial offset is an important parameter for the vertical comb-drive actuator. In addition, the height of the comb fingers is another critical parameter for consideration to achieve large operating range. To suppress the motions along other directions, the precise alignment between the two sets of fingers and uniform gap between them are important.

To realize such kind of actuator, two pieces of photomasks are involved in the fabrication. The first photomask comprises the frame of the hollow fingers and solid fingers as illustrated in Fig. 3(a), which is used to define the two sets of comb on the hard mask layer. This one mask patterning will help to avoid the alignment problem and maintain small finger gap. The second mask [see Fig. 3(b)] is to accomplish the hollow fingers by covering the overall hollow fingers. The top and the cross sectional views of the relative position between the two photomasks are shown in Figs. 3(c) and 3(d), respectively. By employing these uniquely designed photomasks, the deep trench etching process is divided into two steps and two trenches with different depths are achieved. The detail of the fabrication will be described in the following section.

The relative position between the two masks is very important in the photomask design. The patterned width of the second mask must not be narrower than the width of the
hollow finger defined by the first mask. Otherwise, the hollow fingers cannot be fully covered in the etching down process, which may lead to the damage of the upper fingers. However, the misalignment tolerance between the two masks induced by the process can be as wide as 0.2 \( \mu \text{m} \), which depends on the lithography machine and undercutting during the DRIE etching.

The width of the comb fingers and the lateral gap between the fingers depend on the photomask design and are constrained by the process capabilities as well. Expanding the gap and finger width makes the fabrication easy at the cost of enlarging the operating region. On the contrary, the size of the device can be reduced, but the dimension is limited by the fabrication facilities. Additionally, the depth of the fingers and the motion range will be sacrificed. As a result, there is a trade-off between the overall size of the device and the fabrication process. From the design aspect, narrowing the hollow finger width is the most effective method to reduce the overall size because it is wider than the solid finger. However, the width of the inner trench as shown in Fig. 3(a) is limited by the fabrication, which makes it difficult to obtain deep fingers and hard to realize the spacer oxide deposition. The width of the hollow finger frame also restricts the finger depth due to the unavoidable undercutting and/or the sloped beam profiles.

After considering for the simulation results and the fabrication process, the width of the hollow finger is allowed to vary from 3.0 to 7.5 \( \mu \text{m} \), whereas the width of the inner trench is allowed to vary from 1.0 to 2.5 \( \mu \text{m} \), and the width of the frame beam is from 1.0 to 2.5 \( \mu \text{m} \). The solid comb finger is designed to have a width of 2.0 \( \mu \text{m} \) with different planar gaps of 2.0, 2.5, and 3.0 \( \mu \text{m} \). The vertical offset between the two sets of comb fingers is adjusted through process control, which may be positive, zero, and negative.

III. FABRICATION PROCESS

The process flow is outlined in Fig. 4 that is started with a 6 in. (100) single-crystal silicon wafer. The fabrication processes of the asymmetric and symmetric vertical comb-drives using the uniquely designed masks are described below. The fabrication results are discussed with main highlight on the hollow comb fingers.

A. Asymmetric vertical comb drive

First, a 2.0 \( \mu \text{m} \) plasma-enhanced chemical vapor deposition (PECVD) tetraethoxysilane (TEOS) oxide was deposited onto a cleaned wafer as hard mask layer. This thickness should be as thin as possible to reduce the stress effect in the silicon structure, but should also be sufficiently thick to resist the multiple times of DRIEs. Then the first photomask was employed to define both the hollow and solid fingers. These patterns were then transferred to the hard mask layer by 2.0 \( \mu \text{m} \) oxide RIE etch in the Applied Materials P5000 etcher using CH\(_4\), CHF\(_3\), and argon as etching gases [see Fig. 4(a)]. After photoresist strip and wet cleaning the wafer, the second photomask was used to selectively cover the hollow fingers by a 2.0 \( \mu \text{m} \) thick photoresist as a soft mask while...
exposing the other microstructures. This prepattern technology avoids resist spinning on high aspect ratio structures. Next, a time-controlled oxide trimming was carried out to etch away 8000 Å oxide by employing the Applied Materials P5000 etcher with the same etchants. This trimming process reduced the thickness of the hard mask layer over the solid fingers with a consequence of different oxide thicknesses on the hollow and solid fingers. This difference is a key parameter in the lowering down process later.

The first DRIE etching was conducted with an anisotropic Surface Technology Systems (STS) inductively coupled plasma (ICP) system. This is an anisotropic silicon etching process realized by alternating polymer passivation and etching from the bottom to deepen the trenches vertically. By balancing the etching and deposition in the cyclic way, an accurate control of the anisotropy was obtained. The processing gas was the mixture of C₄F₈, SF₆, and O₂, where C₄F₈ served as the passivation precursor, while SF₆ and O₂ served as the etching gases. The silicon etch rate was about 1.0–1.3 μm/min for 2.0–3.0 μm wide silicon trenches. The etching selectivity between silicon and oxide was more than 80, which implies that the oxide hard mask layer on top of the solid comb fingers was consumed little in this trench etching process step. Thus, the difference between the hollow comb fingers and solid comb fingers on the thickness of the hard mask layers was increased further. The targeted depth of the first trench is \( d₁ \) [see Fig. 4(b)] and the detailed process conditions are listed in Table I as well for comparison with the first and the second trench etch. By using isotropic silicon etching with reaction gas of XeF₂ in the same STS system with the process conditions called prerelease etching, was then carried out with the STS system for depth \( d₂ \) [see Fig. 4(e)]. The etching gases used were same as those for the first trench etching, while the gas flow rate, supplied power, and the process cyclic time were adjusted to fasten the silicon etching. The etch rate at this step could be 2.0–3.0 μm/min for 2.0–3.0 μm wide trenches. The detailed process conditions are listed in Table I, all the exposed silicon was etched. Both the upper and lower comb fingers were fully released from the substrate with various depths, as shown in Fig. 4(f). An asymmetric comb-drive was obtained when the spacer oxide and residual hard mask were removed. The upper short hollow fingers and the lower high solid fingers were achieved with the same top surface. The oxide trimming in Fig. 4(b) is not required for asymmetric comb-drive fabrication because it is not necessary to lower down the solid fingers. However, the double photomask patterning is necessary to realize the two sets of comb fingers with different depths.

### B. Symmetric vertical comb-drive

To realize the symmetric and staggered vertical comb structures, the following processes were developed to lower
down the solid comb fingers. As illustrated by Fig. 4(g), the spacer oxide on the sidewall of the released beams was stripped by isotropic oxide etch in Applied Materials Sub-Atmospheric CVD (SACVD) using $\text{C}_2\text{F}_6$ and $\text{O}_2$ as etching gases at the flow rates of 600 and 700 sccm, respectively, under the process power of 500 W. A fresh protection spacer oxide layer was redeposited using similar processes, as illustrated in Fig. 4(d). However, the bottoms of the silicon comb fingers were covered by oxide [see Fig. 4(h)]. This redeposition is necessary for the lowering down etching process, because the spacer oxide on the sidewall was attacked somewhere during the previous etching processes and there was spacer oxide layer hanging beneath the released silicon beams, as shown in Fig. 4(f), which interfered with the subsequent processes by scattering the incident ions. Meanwhile, the height of the upper fingers can be guaranteed in the subsequent processes as the beam bottom was covered by a new oxide layer. The blank oxide etching in Applied Materials P5000 etcher was employed again to clear the hard mask layer on the top of the solid comb fingers while keeping the hollow comb fingers still being covered by oxide layer [see Fig. 4(h)]. This is due to the difference in the thickness of the hard mask, which was achieved at the step shown in Fig. 4(b) and in the following etching steps. A combined anisotropic and isotropic silicon etching was then adapted to lower down the solid comb fingers, as shown in Fig. 4(i). The anisotropic etching used the same conditions as the first trench etching and the isotropic etching used $\text{SF}_6$ and $\text{O}_2$ as etching gas that are listed in Table II. Finally, isotropic oxide etching was performed to strip spacer oxide on the sidewall and bottom of comb fingers [see Fig. 4(j)].

The process is different from the other fabrication techniques of high aspect ratio silicon structure in several aspects. First, the deep trench etching was divided into two
steps to allow the variation in the height of the two sets of the comb fingers. Second, the hard mask layer was partially etched before the second silicon DRIE to obtain hard masks with different thicknesses for hollow and solid comb fingers. Finally, the solid comb fingers were lowered down by trimming away the top hard mask layer and further etching down the silicon beams by employing the combination of anisotropic and isotropic etchings.

C. Vertical comb-drive

The fabricated vertical comb-drive is shown in Fig. 5, where the upper hollow comb fingers and the lower solid comb fingers can be observed. The size of the actuator is approximately 1.5 mm × 0.6 mm. The cross-sectional view of the symmetric vertical comb-drive is shown in Fig. 6, where the widths of hollow fingers and solid fingers are 4.0 μm (width of the frame is 1.5 μm) and 2.0 μm, respectively. The height of the fingers is 10.0 ± 1.0 μm when the etching depths of the first DRIE \( d_1 \) and second DRIE \( d_2 \) are 15.0 μm. The lateral gap between the two sets of fingers is 2.5 μm without any misalignment, and the vertical offset between the upper and lower fingers is \( -2.6 \) μm which can be tailored by adjusting the process conditions as shown in Fig. 7. A positive vertical gap between upper and lower comb fingers of \(+3.2\) μm is shown in Fig. 7(a) and a \(0.0\) μm offset is indicated by Fig. 7(b), where the sidewall spacer oxide in white color remains before the oxide stripping.

The designed and fabricated dimensions of the three vertical comb-drives are listed and compared in Table III. All three different designs have solid comb fingers with a width of \(2.0\) μm. The width of the hollow finger is \(4.0\) μm for the first design, \(5.5\) μm for the second design, and \(6.5\) μm for the third design. Planar gaps for the three designs are \(2.5, 2.0\) and \(2.5\) μm, respectively. The vertical offset varies from positive to zero and to negative. The height of the comb fingers is greater than \(10.0\) μm and the aspect ratio of the comb fingers is greater than \(4.0\), and can be further increased to \(15.0\) by increasing the trench depth. However, there are some difficulties with the sidewall PECVD oxide coverage, unless a better conformal coverage process, such as thermal oxidation or low-pressure CVD oxide deposition, is utilized.

The unique hollow comb finger structure is investigated particularly. The cross-sectional scanning electron microscope (SEM) micrographs of the vertical comb structures with hollow fingers in various widths are shown in Fig. 8, where the width of the solid comb fingers is \(2.0\) μm and the lateral gap is \(2.5\) μm. The widths of the hollow fingers are designed to be \(3.0, 4.0,\) and \(4.5\) μm, respectively. These three different designs were fabricated using the same process conditions, and the targeted heights of the hollow fingers and solid fingers are \(10.0\) μm. The fabricated hollow fingers are narrowed to a certain extent with a negative profile, limiting the depth and aspect ratio. The lower solid beams are narrowed to \(1.9\) μm, resulting in a wider lateral gap. The fabricated widths of the \(3.0\) μm wide hollow fingers \((1.0\) μm wide frame and \(1.0\) μm wide trench) are \(2.80\) μm on top, \(2.6\) μm at middle, and \(2.39\) μm at bottom, as shown in Fig. 8(a). This beam narrowing is due mainly to the undercutting during the deep trench etching. These phenomena are also observed in Figs. 8(b) and 8(c), where the widths of the hollow fingers at the middle part decrease from \(4.0\) to \(3.7\) μm and

<table>
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<tr>
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<td>Height of hollow finger beam</td>
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Fig. 8. SEM micrographs of various vertical comb structure: (a) \(3.0\) μm wide hollow beam with two \(1.0\) μm frame beams and \(1.0\) μm inner trench, (b) \(4.0\) μm wide hollow beam with two \(1.5\) μm frame beams and \(1.0\) μm inner trench, and (c) \(4.5\) μm wide hollow beam with two \(1.5\) μm frame beams and \(1.5\) μm inner trench.
from 4.5 to 4.1 µm, respectively. The heights of the hollow fingers and solid fingers are within the range of 10.0±1.0 µm.

IV. NOTCHING EFFECT AND SILICON RESIDUE EFFECT

Two significant problems arise during the vertical comb-drive fabrication process. First, a notching effect occurs in the etching steps after the prerelease etching. Second, the silicon residue effect happens during the lowering down etching process. The mechanisms for the occurrences and approaches to address these effects will be discussed in this section.

A. Notching effect

A notching effect is the unexpected lateral silicon etching, which damages the microstructures and degrades the performance of the comb-drive actuator. The mechanism of the notching effect varies in different processes. For example, it occurs at the interface of silicon and buried oxide due to charging on the insulator layer when the process is carried out on a SOI wafer. In this study, the lower part of the solid silicon fingers was seriously damaged by the lateral notching as observed from Fig. 9, due to the reaction between the silicon beam and the etching gas. This particular notching occurs after the prerelease etching [Fig. 4(e)] and the undercut release etching [Fig. 4(f)], where the position is just below the bottom of the upper fingers at the depth of $d_1$ from the top surface. The worst case, as shown in Fig. 9(b), is that the fingers are completely broken after the lowering down etching process [Fig. 4(i)]. Hence, the height of the lower fingers is constrained to a very small value by this notching effect, and it is impossible to achieve symmetric staggered comb-drive. The mechanisms for the notching effect in this process are analyzed in order to solve this problem.

The notching effect has a strong relation with the aspect ratio of the silicon structure as shown in Fig. 10. When the etched trench was fixed at 30.0 µm in depth, with exactly the same process conditions, the notching effect was most prevalent on silicon beams with 2.0 µm lateral gap [see Fig. 10(a)]. The beams were better with 2.5 µm trench [see Fig. 10(b)] and showed little damage with 3.0 µm trench [see Fig. 10(c)].

The process condition, in particular the prerelease etching, also plays an important role in influencing the notching effect. A vertical comb-drive with exactly the same design...
was fabricated with two different prerelease etching conditions. These two conditions result in different oxide consumption rates during the prerelease step, which were about 300 and 100 Å/min, respectively. The notching effect for these two different prerelease etching conditions is shown in Fig. 11. Obviously, notching [see Fig. 11(a)] with a high oxide consumption rate is more apparent than notching [see Fig. 11(b)] with a relative low oxide consumption rate. Clearly, the process with high oxide consumption rate tends to have a more serious notching effect.

The principle of the DRIE based on the Bosch process using the RIE STS ICP system also accounts for the notching effect. This technique consists of a series of alternative etch and passivation cycles with each cycle lasting for a few seconds. The passivation step deposits a polymer layer onto the feature to prevent lateral etching, and the etching step removes the polymer from the bottom of the feature followed by silicon etching. Since the DRIE process starts from the etch cycle on bare silicon surface, the silicon etch rate during the first etch cycle is faster. In addition, the silicon etching rate drops along the etching depth due to the loading effect. Therefore, scallops formed along the trench sidewall are not uniform and the highest peaks always appear near the starting point of the deep etching. However, as described in the process flow, the two sets of comb fingers are obtained after two times of deep etching. The second etching starts from the depth of \( d_1 \). Hence, the scallop peak appears at the joint section, which negatively impacts the spacer oxide coverage at this critical section compared to the other vertical portions. The next prerelease etching, (especially with a high oxide consumption rate) attacks the weak spacer oxide on the trench sidewall and reacts with the silicon, which in turn results in the notching effect. The isotropic releasing gas (XeF\(_2\)) reacts with silicon wherever it makes contact. The silicon fingers are etched laterally when the oxide spacer coverage is poor, and the fingers will break [see Fig. 9(b)] if the isotropic etch is too long. The lowering down etching process is also a contributing factor to the notching effect, which damages the fingers.

This explanation was verified by the damaged position of the lower fingers. The broken point occurs exactly at the depth of \( d_1 \) from the top. This is the depth of the first deep etching or the starting point of the second deep etching. This implies that the damage occurs at the weak joint. This notching problem was resolved by multiple spacer oxide depositions to obtain better spacer coverage. One method to improve the spacer coverage is to increase the PECVD oxide deposition time, but the top opening will be blocked by the deposited oxide and the weak joint will still not be well covered. On the contrary, multiple deposition and anisotropic oxide etching are more efficient. This is because longer deposition periods assure more conformal coverage on the sidewall, and the top trench opening is assured by the anisotropic oxide etching. For trenches with higher aspect ratios, a slow prerelease condition is recommended to prevent the notching effect. As a result, fingers with adjustable heights can be achieved without the notching problems. The final cross-sectional views of the fingers using the improved process are depicted in Figs. 12(a) and 12(b).

### B. Silicon residue effect

A silicon residue effect arises during the lowering down etching process [Fig. 4(h)]. This phenomenon can be observed in Fig. 13, where the silicon residues remain on top of the solid comb fingers after the lowering down etching process. This is the result of the spacer oxide protection layer and the pure anisotropic process, which is observed to be more serious at the corners. As is widely known, silicon anisotropic deep etching is performed using a mixture of SF\(_6\), C\(_4\)F\(_8\), and O\(_2\), which has a very high etching selectivity between silicon and oxide. Consequently, the protective ox-
ide layer on the solid comb fingers is not removed during the silicon DRIE, and it acts as shadow masks in the subsequent anisotropic silicon etching.

To resolve this problem, a combination of anisotropic and isotropic silicon etching processes was developed, where the former serves to lower down the beam, and the latter to remove the silicon residues clearly. The process conditions for these two kinds of lowering down etching are listed in Table II. The final lowered solid fingers of the vertical comb drive without any silicon residue are shown in Fig. 8.

V. CONCLUSIONS

This article demonstrates the feasibility of a vertical comb-drive actuator on a monolithic silicon substrate with a combination of two uniquely designed photomasks. The first mask defines all the microstructures while the second mask selectively covers only the upper hollow fingers. Multiple DRIE etchings with the association of spacer oxide protection are developed to obtain the asymmetric comb-drive structure. By employing the lowering down etching process, symmetric vertical comb-drive actuator is fabricated. In this process, the notching effect and the silicon residue effect are analyzed. The notching effect results from the two-step deep trench etching, and poor sidewall spacer oxide coverage is addressed by multiple spacer oxide depositions. The silicon residue effect is overcome by employing isotropic and anisotropic etching to lower down the beam. This uniquely designed photomask and dry process have successfully avoided the misalignment, residual stresses, and stiction problems to achieve asymmetric and symmetric staggered comb-drive ac-

Fig. 12. SEM micrographs of the vertical comb structure with modified process: (a) 4.0 μm wide hollow fingers with 2.5 μm planar gap and −2.0 μm offset and (b) 5.5 μm hollow fingers with 2.0 μm planar gap and +3.2 μm offset.

Fig. 13. SEM micrograph of silicon residues on the solid comb after lowering down etching process.
tuators. Three advantages are observed through this study: (1) simple fabrication process without alignment problems, (2) adjustable offset between the upper hollow and lower solid comb fingers, and (3) compatible with the complementary metal-oxide-semiconductor process on a monolithic single-crystal silicon substrate.

Various designs with hollow finger width varied from 3.0 to 7.5 µm and lateral gaps from 2.0 to 3.0 µm are obtained by this fabrication technique. The narrowest hollow comb finger achieved is less than 3.0 µm and it can be reduced further. Positive, zero, and negative vertical offsets are obtained by adjusting the process conditions. The height of the comb fingers is 10.0 µm with an aspect ratio of 4.0, which can be increased further. The vertical comb-drive actuator on the monolithic single-crystal silicon substrate has potential in many applications, such as an optical switch, a scanning micromirror, and accelerometers that require vertical and/or torsional motion.

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