ABSTRACT
Vertically supported, comb-shape microresonators with the feasibility of actuation in two perpendicular directions have been demonstrated. The microstructure is made of 2-µm thick polysilicon by a standard surface micromachining process and is vertically lifted and fixed with the assistance of locking springs and micro hinges. With DC bias voltage of 10V and AC driving voltage of 10V, peak-to-peak, under atmospheric pressure, the resonator vibrates in parallel to the comb finger direction at 7.75kHz with measured amplitude of 3.3µm and quality factor of 67. When actuated in the direction normal to the surface of comb finger, the resonator vibrates at 2kHz with vibration amplitudes of 11.2µm and 10.5µm, respectively for the two opposite, comb-shape microstructures. The potential applications of these vertically supported microresonators are in the areas of MOEMS (Micro-opto-electro-mechanical Systems) devices such as optical systems on a chip.

INTRODUCTION
The great potential for MEMS devices is the possibility to integrate a complicated system in a single chip [1]. For example, in the filed of MOEMS, researchers have focused on combining basic optical components such as Fresnel lens [2], grating [3], etc. on a chip. One critical constraint is the difficulty in building up three-dimensional microsystems because most microfabrication technologies are two-dimensional. The introduction of micro hinge structure [4] has helped the construction of surface-micromachined microstructures to the vertical, third dimension. As a result, laterally driven comb actuators moving in parallel on the substrate have been demonstrated to generate out-of-plane motion [5]. Bulk-micromachined vertical comb drive resonators [6] have been used to generate motions perpendicular to the substrate. Several critical issues have hindered the progress of the three-dimensional architecture, including the difficulty in lifting up the devices from the original surface-micromachined positions; the alignment accuracy of micro components to avoid performance degradation; and the interconnections for the lifted microstructures.

Vertically supported microresonators presented in this work address two critical issues in three-dimensional microsystems of critical alignment and reliable mechanical and electrical interconnection by innovative mechanical design features. Furthermore, the actuation of resonators in two perpendicular directions has been demonstrated.

THEORY AND DESIGN
Figure 1 shows the potential optical system on a chip based on the vertically supported microresonators. The first comb resonator could have an optical component such as a lens while the second comb resonator is used as the stationary structure to provide electrostatic excitation. In order to build this three-dimensional optical microsystem, one can start with the standard surface-micromachining process. Figure 2 (a) shows the schematic diagram of the vertically supported lateral microresonator sitting on the substrate before being lifted up. The movable (first) and stationary (second) comb structures are constraint on the substrate by the mechanical hinge structures. The left and right manipulation plates are designed for lifting comb structures to the vertical position by using the mechanical micromanipulator under a probe station. In Figure 2(b), both comb structures are lifted vertically and fixed by the locking springs as shown in Fig.3. These springs are designed to play two important roles at the same time: 1) to supply adequate mechanical force on the hinge to assure good electrical contact between the ground plane and the vertically supported microstructures, and 2) to maintain the designed gap between the two sets of comb fingers after they are raised vertically to avoid electrical short. Mechanical springs (Fig. 3a) with the extrusion design are deformed after the lift process as shown in Fig. 3(b) to provide 1) good electrical contact, 2) mechanical stability, and 3) balanced gaps between the two comb sets.
The equation of motion of the vertical supported resonator in the x direction is derived as follows:

\[ m \frac{d^2x}{dt^2} + c \frac{dx}{dt} + kx = f_0 \sin \omega t \]  
\[ f_0 = n \frac{eq}{d} V_a V_d \]

where \( m \), \( c \), \( k \), \( x \), \( f_0 \), \( \omega \), \( t \), \( n \), \( q \), \( V_d \), and \( V_a \) are the mass of the movable plate including the movable comb structure, damping coefficient, stiffness of the two springs, displacement in the x direction as defined in Fig. 2(b), dynamic electrostatic force amplitude, angular frequency, time, the number of finger on the comb structure, the permittivity of the air, thinness of the suspended structure, DC bias voltage, and driving voltage, respectively. From Eq. (1), the resonant frequency is obtained:

\[ f_r = \frac{1}{2\pi} \sqrt{\frac{k}{m}} \]  

Table 1 summaries the designed vertically supported lateral microresonator.

### Table 1. Calculated parameters of the microactuator

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
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<tbody>
<tr>
<td>( m )</td>
<td>4.36x10^{-10} kg</td>
</tr>
<tr>
<td>( k )</td>
<td>1.0N/m</td>
</tr>
<tr>
<td>( f_r )</td>
<td>7.6kHz</td>
</tr>
</tbody>
</table>

Based on Young's modulus of 110GPa for polysilicon.

![Fig. 3. Design of the locking spring in generating the mechanical force to lock the microstructure as well as providing electrical contacts for the vertically supported structures.](image)

**FABRICATION**

The vertically supported comb resonators have been fabricated by the standard surface micromachining process [4,7]. Figure 4 shows the SEM photograph of one released microresonator where the size of the movable plate is 400\( \mu \)m x 400\( \mu \)m and it is connected to the supporting beam structure via two springs. The stationary comb structure at the right hand side is attached to the right manipulation plate. Etching holes are designed on any structure with big areas for the fast release etching process and hinges are designed to assist lifting structures vertically. Figure 5 depicts the SEM photograph of the lifted resonator. The micro hinges and locking springs helped positioning and interconnecting the microstructures. The lower left part of the Fig.5 shows the enlarged SEM photograph of a deflected locking spring (Fig. 3(b)) and a hinge. Figure 6 is the top view SEM photograph showing that good alignment of two comb structures was achieved.
Fig. 4. SEM photograph of a vertically supported microresonator by surface micromachining before the microstructures are lifted vertically.

Fig. 5. SEM photograph of the microresonator after being lifted from the substrate by using a probe: vertical structures are electrically connected to the contact pads by micro hinges and locking springs.

Fig. 6. Top view of the lifted resonator structure in Fig. 5 showing good alignment is achieved.

(a) Before vibrating

(b) After vibrating

Fig. 7. Optical photographs showing the movement right at the intersection of the two comb structures: (a) without excitation and (b) with excitation. The resonator is actuated by AC voltage of $10V_{pp}$ and DC voltage of 10V at the resonant frequency of 7.75kHz.

Fig. 8. Frequency response: the vibration amplitudes are optically measured under AC driving voltage of $10V_{pp}$ and DC bias voltage of 10V; the resonant frequency is 7.75kHz and quality factor is estimated as 67.

RESULTS AND DISCUSSIONS

The comb resonator was optically observed to resonate under atmospheric pressure with the AC driving voltage, $V_{ac}$, of 10Volts, peak-to-peak and DC bias voltage, $V_d$, of 10Volts as shown in Fig. 2(b) was applied. Figures 7 (a) and (b) are optical photographs taken from slightly inclined resonator to show the movable and stationary comb structures from the top, without excitation and with excitation in motion, respectively. The frequency response is recorded in Figure 8 when the vibration amplitudes are optically measured. It is found that the resonant frequency of the vertically supported microresonator is at 7.75kHz and the quality factor is estimated as 67. Furthermore, the vibration amplitude is 3.3$\mu$m at resonance.
CONCLUSIONS

We have successfully demonstrated a new class of vertically supported comb resonators that actuate in two perpendicular directions depending on the excitation frequencies. The prototype microresonator is designed and fabricated by using the surface micromachining technology and experimental results shows that the resonant frequency is at 7.75kHz with a quality factor of 67 in the direction parallel to the comb finger under a DC bias voltage of 10V and AC driving voltage of 10Vpp. The resonance in the direction normal to the surface of the comb finger has been observed. The vibration amplitude has been measured as 11.2µm for the movable comb structure and 10.5µm for the originally designed, stationary comb structure. As such, these microresonators might find potential applications in the area of MEMS or MOEMS including optical systems on a chip.

REFERENCES