A NOVEL FABRICATION METHOD OF A VERTICAL COMB DRIVE USING A SINGLE SOI WAFER FOR OPTICAL MEMS APPLICATIONS

Ki-Hun Jeong and Luke P. Lee
Berkeley Sensor & Actuator Center, Departments of Bioengineering
University of California at Berkeley, CA 94720-1774, USA
Tel.: (510) 642-5855, Fax: (510) 642-5835, e-mail: lplee@socrates.berkeley.edu

ABSTRACT

A novel method for fabricating a self-aligned electrostatic vertical comb drive using a single layer of a SOI wafer is introduced. The fixed combs are anchored to bimorph cantilevers made of two materials with dissimilar thermal coefficient of expansion, i.e., silicon dioxide and single crystal silicon. The cantilever, which provides the vertical offset between fixed comb and movable comb, is deflected by residual stress during cooling down from oxidation temperature to room temperature. In piston motion, the vertical amplitude at the resonant frequency of 3.5 kHz was 30 μm. In torsional motion, the angle of optical deflection at the resonance of 830 Hz was changed by 6.5°. The measured resonant frequencies correspond to the results from a finite element analysis within 10%. This vertical comb drive is useful for optical and biophotonic MEMS requiring out-of-plane torsional or piston motion.

INTRODUCTION

An optical MEMS device capable of out-of-plane torsional or piston motion is a key element in high speed and high resolution optical scanning or switching applications. This kind of device is also essential for the focal length control of a microlens in a 3D raster scanning module for micro confocal imaging array [1]. In particular, a micro optical component on a vertical comb drive, using silicon on insulator (SOI) technology and deep reactive ion etching (DRIE) can be modulated with large deflection at relatively low, precise control, and fast scanning speed over the full range of the out-of-plane motion. However, the fabrication of vertical combs with a single wafer is considered as a challenging task, because conventional microfabrication methods basically define planar geometry.

Many efforts have been made to fabricate vertical comb drives from the flat and smooth surface of a SOI wafer. A vertical comb drive on two layers of single crystal silicon was first demonstrated by a bond-and-etchback process with a buried oxide pattern between two layers of single crystal silicon [2]. However, it requires not only two wafers, but also the critical alignment between upper comb and lower comb to generate the symmetric electrostatic field. In order to operate a vertical comb drive with high electrostatic actuation in low operating voltages, the gap between vertical combs can be minimized by incorporating a self-aligned method. A self-aligned vertical comb drive was demonstrated with a 3-step etch process with a single mask that defines both the top and bottom comb teeth arrays [3]. Both previous methods have been modified with a multi-level beam SOI-MEMS process, which can provide pre-engagement between self-aligned vertical combs and bi-directional motion [4]. Another simple self-aligned fabrication of vertical comb drive was demonstrated by using the reflow of photoresist [5]. The vertical offset mechanism of this method is based on the reflow of photoresist pattern for mechanical coupling a mirror with comb drive.

In this paper, the fabrication and characterizations of a self-aligned vertical comb drive using a single layer of a SOI wafer are described.

OPERATION AND DESIGN

The mechanism of vertical offset between fixed comb and movable comb is based on residual stress. As
illustrated in Fig.1, the fixed combs are anchored to bimorph cantilevers made of two materials with dissimilar thermal coefficient of expansion (TCE), i.e., silicon dioxide and single crystal silicon as shown in Fig. 1. The deflection of a cantilever, providing the vertical offset between fixed comb and movable comb, is caused by residual stress generated within TCE mismatch layers during cooling down from oxidation temperature to room temperature. The vertical comb drive consists of one movable comb above two anchored combs on either side as shown in Fig. 2(a). The movable comb structure incorporates a micromirror, pinhole, microlens holder, or diffraction grating as shown in Fig. 2(c) and (d).

The device consists of three electrodes connected to each comb structure. It can be operated in torsional or piston motion by generating the electrostatic force between the upper movable comb and one lower fixed comb ($V_1$ and $V_{GND}$) or between the upper movable comb and two lower fixed combs ($V_1$, $V_2$ and $V_{GND}$).

The design of this self-aligned vertical comb requires the estimation of the deflection of a bimorph cantilever, which provides the initial engagement between a movable comb and fixed combs. Even though the residual stress arises from either intrinsically or extrinsically stress-causing factors, the deflection was calculated using the analysis presented in previous work, under the assumption that TCE mismatch is the dominant contributor to the deflection of the bimorph cantilever, especially made of single crystal silicon and silicon dioxide with the small thickness ratio [6].

**FABRICATION**

The microfabrication procedure is described in Fig. 3. The vertical comb drive was fabricated on a SOI wafer using three masks to define a comb drive, a bimorph cantilever, and an optical window. In the first step, a 2.3 $\mu$m thick oxide is thermally grown in steam at 1150 °C on a SOI wafer that has 10 $\mu$m thick top silicon, 1 $\mu$m thick buried oxide, and 500 $\mu$m thick silicon substrate. The temperature and thickness of the thermal oxidation are key design parameters since they govern the offset between the self-aligned vertical combs. A 0.7 $\mu$m thick LPCVD polysilicon deposited on the thermal oxide layer was defined by the first mask and then etched by reactive ion etching (Step 1). The patterned polysilicon layer protects the oxide on bimorph cantilevers during a final HF release.

The second 0.5 $\mu$m thick thermal oxide is grown on the polysilicon structure and silicon to serve as a masking layer in defining the structure of comb drives on a top silicon layer as well as to make the backside process easy. The polysilicon thickness is reduced down to 0.2 $\mu$m during oxidation, but does not significantly affect the residual stresses on a bimorph cantilever (Step 2), because the thermal oxide and single crystal silicon of a bimorph cantilever are much thicker. After definition of the oxide on the top silicon, the 500 $\mu$m thick bottom silicon substrate is etched away by deep reactive ion etching to provide an optical window (Step 3). Thereafter, the top silicon structures are etched by DRIE with the previously defined 0.5$\mu$m thick oxide mask (Step 4). In the end, all the grown thermal oxide layers including the exposed buried oxide of the SOI wafer are removed in HF (step 5). The residual stress in the bimorph cantilever results in the vertical offset between movable and fixed combs.
RESULTS AND DISCUSSION

The deflection of a bimorph cantilever and vertical offset was measured with a Wyko NT3300 optical profiler. The depth profile on a part of the device is displayed in the contour plot of Fig.4 (a). No deflection is observed on the movable comb structure. The calculated and measured deflections of the cantilever beam along the AA’ line are plotted in Fig.4 (b). The beam deflection and vertical offset increase along the length of the beam. The measurements were performed for five cantilevers located at different sites over the wafer. At the end of the 680 µm long cantilever, the average maximum deflection is 16.9 µm and the standard deviation is 0.86 µm. The vertical offset between the combs shows 18.3 µm on the first comb, 9.2 µm on the second comb and 3 µm on the third comb as shown in Fig.4 (c). Since single crystal silicon is known as stress free material and thermal oxidation process is well established, the precise control of the deflection of the bimorph cantilever should be possible.

The frequency and phase responses of the vertical comb drive was characterized in both torsional and piston motion with a Polytech laser vibrometer, which has a minimum beam spot size of 3 µm and vertical resolution of 2 nm. The resonant frequencies at each motion were measured by applying 5.5 V dc bias and ac 10 V, as shown in Fig.5. In piston motion, the vertical amplitude is 30 µm at the resonant frequency of 3.5 kHz. In torsional motion, the optical angle of the deflection at the resonance of 830 Hz is up to 6.5°. We also confirmed that the phase angles at both resonances are shifted by 90°. Q-factors are 24.2 in piston motion and 7.6 in torsional motion. Because the mechanical spring in piston motion was designed to have higher stiffness than that in torsional motion, the piston motion resonant frequency is higher. Q-factor also increase with the spring constant provided the damping coefficients are comparable in both motion.

For comparison, the modal analysis was performed by a finite element method using ANSYS ver.5.7. These simulated resonances were at 3388 kHz in piston motion and at 910 Hz in torsional motion, which correspond to the measured results within 10 %.

The dc modulation of the device at resonance is plotted in Fig.6. In a vertical comb drive with a microlens holder, the vertical amplitudes and optical angles of the deflection at resonance under constant ac voltage (10 V) increase linearly with applied dc bias voltages between 3 V to 5.5 V. The resonant transmissibility, defined by the ratio of output amplitude to input DC voltage at resonance, is 4.7663 µm per unit dc bias voltage in piston motion and 0.4467° per unit dc bias voltage in torsional motion.

The pull-in of the device occurs at dc bias 9.5 V in piston motion and 8.5 V in torsional motion. The voltage in torsional motion is smaller, because the electrostatic force is applied to only one side electrode (V1).
The force causes in-plane motion then makes it unstable, while the electrostatic force in piston motion is attracted by both side electrodes \((V_1\) and \(V_2\)). In future design, the moment of inertia relative to the principle axis of torsional motion needs to be minimized in order to increase the stability and optical scanning angle in torsional motion.

**CONCLUSIONS**

A novel fabrication method of self-aligned vertical comb drive has been demonstrated. The vertical offset can be determined by the residual stress in a bimorph cantilever anchoring fixed comb. In piston motion, the vertical amplitude at the resonant frequency of 3.5 kHz was 30 \(\mu\)m. In torsional motion, the angle of optical deflection at the resonance of 830 Hz was changed by 6.5\(^\circ\). The measured resonant frequencies correspond to the results form a finite element analysis within 10\%. In the future, The new design of a mechanical suspension will be optimized to improve the stability of the device and the static DC control, which can compromise with vertical offset variation. This method for fabricating micro optical components with out-of-plane motion on a SOI wafer can provide high speed, precise position control, low cost and high optical performance in optical and biophotonic MEMS applications.

**ACKNOWLEDGEMENT**

This work is fully supported by the BIOFLIPS program from Defense Advanced Research Projects Agency. We would like to thank the staff of the Berkeley Microfabrication Facility for their helpful support and S. Kwon for setting up a laser vibrometer for the device characterization.