THIN-FILM PZT BASED MONOLITHIC TRANSLATIONAL/TILT MICRO-SCANNER FOR VERTICAL CROSS-SECTIONAL IMAGING WITH DUAL AXES CONFOCAL ENDOMICROSCOPE

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ABSTRACT

A multi-axis micro-scanning mechanism actuated by thin-film PZT is presented for optical cross-sectional imaging in dual axes confocal microscopy. The actuator achieves large translational vertical displacement (200 μm at 18 V_{dc}) by active piezoelectric forcing and large rotational horizontal scanning ($\pm 6^\circ$ mechanical angle at >3 kHz) by resonance of passive oxide cantilevers. Devices are produced from SOI wafers using vertical silicon dioxide barrier trenches for robust encapsulation of structural silicon during XeF₂ release of PZT bending beams. The resulting monolithic micro-scanner is compatible with endoscopic systems for acquiring vertical cross-sectional images from tissue.

INTRODUCTION

Compared to other endomicroscope systems, dual axes confocal microscopy has been shown to perform superior rejection of out-of-focus and scattered light [1], while its high dynamic range allows for deep imaging in tissue with high contrast [2-4]. To take full advantage of the excellent z-axis performance of dual axes confocal microscopy in a miniature 5 mm outer diameter (OD) dual axes architecture, vertical cross-sectional imaging with a MEMS scanner has been proposed in [5]. This requires translating a micro-mirror with large displacement (~ 500 μm) in the into-tissue direction, while also providing rotational, in-plane scanning in at least one axis.

Only a limited number of prior microactuators feature the necessary combination of degrees of freedom desirable for real-time cross-sectional imaging. The majority of existing optical scanning mechanisms provide lateral rotational scanning in one or more axes. Large displacement vertical actuators are less common, though existing large displacement vertical actuators have been demonstrated based on electrothermal, piezoelectric, and electromagnetic transduction, among others. Combined vertical and rotational scanning has previously been achieved in a few instances, including by electrothermal tip-tilt actuators [6] and three-axis electrostatic scanning mirrors (z - θ_x - θ_y) [7]. However, electrostatic axial stroke distance is limited, while electrothermal actuators are restricted in speed by thermal time constants. Lateral/translational piezoelectric actuation has also been implemented [8], but designs to date are limited in z-axis displacement and/or rotational axis scanning speed.

This paper presents a novel, monolithic scanning actuator combining large stroke vertical piezoelectric actuation with high frequency resonant rotational scanning using lead-zirconate-titanate (PZT) thin-films. Thin-film PZT actuators are known to generate fast axial and translational responses [9] and have large force capacity with modest voltage requirements [10]. The actuator in this work produces large static or dynamic z-axis displacement with a serpentine two-beam thin-film PZT vertical actuation structure. At the same time, high-frequency rotational motion can be excited from an inner scanning mirror supported by resonating passive silicon dioxide springs. A sample actuator is shown in Fig. 1 and a schematic view of the actuator structure in Fig. 2. The combined mechanism provides increased displacement range from previous works and higher-frequency

Figure 1: Optical microscope image of translational/tilt micro-scanner with inner resonant spring structure for angular scanning (A), in detail, and symmetric piezoelectric beam bending actuators for vertical translation (B).

Figure 2: Schematic of the translational/tilt micro-scanner showing key components, including mirror platform and PZT actuator locations.

rotation about the in-plane axis, thus directly supporting real-time cross-sectional imaging from dual axes or similar microscopes.

MICRO-SCANNER DESIGN

The translational-tilt micro-scanner is designed to feature vertical and rotational motions through compliant deformation of active and passive thin-film beams at two locations. Vertical motion is generated actively by bending of thin-film PZT unimorphs, arranged in a bend-up/bend-down configuration as in a previous purely vertical bending actuator in [9]. Rotational motion of a central mirror-platform is permitted by passive resonance of inner silicon dioxide beam elements, fabricated from the buried oxide layer of the SOI wafer, and driven by high frequency excitation of that active outer vertical legs.

Figure 3: (a) Material layers in typical thin-film piezoelectric (lead-zirconate-titanate) and electrode stack; (b) Bend-up/bend-down translational vertical motion produced by bending axis manipulation with an additional gold layer.

For use in cross-sectional imaging in endoscopic microscopy, critical attributes of a translational-tilt scanner are range-of-motion and frequency of scanning. Fast-axis motion, in this case from the passive resonant angular vibration, should occur at frequencies of several kilohertz, with scan angles on the order of 5 to 10°, while slow-axis motion should occur at DC to 100 Hz, with at least 5 Hz bandwidth required to avoid motion artifacts. Between 200 and 500 μm of displacement are required to fully support dual axes confocal penetration depth, depending on the setting.

Vertical (slow-axis) displacement and scanning speed can be estimated from the vertical stiffness of the piezoelectric leg structures. Each of these leg structures consists of a thin-film composite consisting of thin-film PZT, metal electrodes, and a base silicon dioxide layer, as shown in Fig. 3(a). The natural bending direction of the PZT beams is upward, due to the presence of the underlying silicon dioxide layer, but a thick gold film is added to portions of each beam to provide translation rather than rotation at the tip of the beam, as shown in Fig. 3(b). Net vertical stiffness in the first (vertical) axis, k_1 , can be estimated as:

$$k_1 = \frac{4k_{v,F}}{N_{beam}} \quad (1)$$

where

$$k_{v,F} = \left(\frac{L_{Au}^3}{3(EI)_1 + 3(EI)_{ox}} + \frac{(L_{beam} - L_{Au})^3}{3(EI)_2 + 3(EI)_{ox}} \right)^{-1} \quad (2)$$

with N_{beam} the number of folded piezoelectric beams in each of the four legs supporting the stage, L_{Au} the length of the portion of the beam covered with gold (bend-down) and L_{beam} is the total beam length. Three bending moduli are relevant, the composite moduli with and without the gold layer, $(EI)_1$ and $(EI)_2$, and that of the buried oxide layer under the beams, $(EI)_{ox}$, left behind by the fabrication process. The effect of the buried oxide as a parallel spring is simplified into the denominators of (2). Note also that $k_{v,F}$ in (2) represents the equivalent stiffness of the single vertical actuator, marked by the dash-line box in figure 2, obtained from a displacement-force relation.

The natural frequency of the system for vertical translation may then be estimated according to

$$f_n = \frac{\omega_n}{2\pi} = \frac{1}{2\pi} \sqrt{\frac{4k_{v,F}}{m_{total} N_{Beam}}} \quad (3)$$

where m_{total} is the total mass of the inner stage and scanning mirror.

Static displacement of the translational stage may be estimated from the internal moments generated by the bend-up and bend-down actuator sections,

$$z = N_{beam} \left(\frac{(M_1 + M_L)L_{Au}^2}{2(EI)_1 + 2(EI)_{ox}} + \frac{(M_2 - M_L)(L_{beam} - L_{Au})^2}{2(EI)_2 + 2(EI)_{ox}} \right) \quad (4)$$

where M_L is a reaction moment maintaining angular compatibility between bend-up and bend-down segments of the leg,

$$M_L = \frac{M_{act,1}L_{Au}((EI)_2 + (EI)_{ox}) - M_{act,2}(L_{beam} - L_{Au})((EI)_1 + (EI)_{ox})}{L_{Au}((EI)_2 + (EI)_{ox}) + (L_{beam} - L_{Au})((EI)_1 + (EI)_{ox})} \quad (5)$$

Fast-axis rotation in the current scanner design is generated from resonance of a central mirror platform supported by passive silicon dioxide cantilever beams. A low-voltage, high-frequency AC signal is added to the low-frequency voltage controlling vertical translation. This excites resonance of the inner mirror platform, leading to substantial rotational scan angles. However, it would likewise be possible to use thin-film PZT bending beams for active rotational scanning, and comparative performance is estimated in this section.

One advantage of a passive rotational scanner is simplified multi-axis scanner design. The use of a single voltage input to generate both vertical and rotational motions simplifies wiring in compact imaging instruments, and eliminates the need for additional interconnects from the fixed exterior frame of the device to the moving vertical stage, which would reduce vertical scanning range. This is the primary driver behind passive resonant design in the current micro-scanner for dual axes endomicroscopy. Nonetheless, it is useful to compare performance of the passive versus active rotational scanning. To model passive resonant behavior, first the resonant frequency of the inner mirror platform, f_{inner} , can be estimated from the cantilever beams modeled as an additional mass-spring damper system,

$$f_{inner} \approx \frac{1}{2\pi} \sqrt{N_{ox} \frac{3(EI)_{inner}}{L_{ox}^3 m_{inner}}} = \frac{1}{2\pi} \sqrt{\frac{k_2}{m_{inner}}} \quad (6)$$

where N_{ox} is the number of parallel inner silicon dioxide cantilevers, $(EI)_{inner}$ is the composite modulus and area moment of inertia of those cantilevers, L_{ox} is the cantilever length, m_{inner} is the mass of the central mirror platform, and k_2 is the net effective inner beam array stiffness.

FABRICATION

The fabrication process used to produce prototype thin-film PZT micro-scanner in this paper has been presented in detail in [11], with key features highlighted in this section. The process provides two key features for the two-axis micro-scanner: a robust encapsulation strategy that protects silicon structures supported by thin-film PZT actuator, and process compatibility with backside patterning and thus multi-level fabrication of a full-wafer-thickness

fixed frame and silicon features from a silicon-on-insulator (SOI) device layer integrated with the PZT thin film.

The process begins with a silicon-on-insulator (SOI) wafer with a 30 μm thick device layer, 2 μm thick buried oxide layer, and 500 μm thick handle layer. 3 μm wide trenches are etched to the buried silicon dioxide layer along the sidewalls of bulk-micro machined silicon structures, such as silicon connectors between two PZT unimorphs in a serpentine vertical actuator pair. Pre-furnace-cleaned trenches are then filled with silicon dioxide by low pressure chemical vapor deposition (LPCVD). Since keyholes are formed in the oxide-filled trenches, the top oxide is removed by either chemical mechanical polishing (CMP) or reactive ion-etching (RIE), and the upper part of the trench is etched by short RIE to open the keyholes. The LPCVD process is repeated to fill in the opened trenches. Several iterations of LPCVD and polishing may diminish the size of keyholes but it is difficult to eliminate them entirely. Eventually, planarization of the surface of refilled oxide trenches is followed by additional silicon dioxide deposition by plasma-enhanced chemical vapor deposition (PECVD) to reach a minimum target base oxide thickness of 2000 $\text{\AA}$.

After SOI wafers have been processed, PZT and electrode layers were deposited and patterned at the U.S. Army Research Laboratory (Adelphi, MD) and Radiant Technologies, Inc. (Albuquerque, NM). The resulting metal stack consists of a platinum bottom electrode, PZT film, and platinum top electrode. Two argon milling steps for the top electrode and PZT layers, and a wet etch for contact vias to the bottom electrode are next performed. Then a 1 μm -thick Ti/Au layer is deposited on top of the PZT actuator surface where desired by a lift-off process. Next, the silicon microstructure in the top device layer is patterned and micro-machined by deep reactive ion-etching (DRIE).

To begin device release, oven-baked photoresist is used to protect the microstructure of the top device layer, and the backside of the SOI wafer is patterned to open the area underneath the central mirror-stage. Backside patterning and etching also provide the open area for XeF_2 to etch the underneath silicon layer of the actuator. During the XeF_2 under-etching process of thin-film PZT actuator and silicon microstructure layer, a uniform undercut length of the PZT/Au unimorph actuator structure is obtained thanks to the oxide barrier trenches. Figure 4 shows a scanning electron microscopic image of a sample vertical actuator at the connection of the two beams, including the encapsulated silicon connector between the beams and buried oxide as it extends from underneath the beam structure.

Figure 4: Detail of thin-film PZT unimorphs forming legs of a translational-tilt micro-scanner, showing clearly defined silicon rigid structures between thin-film composite beams produced through the silicon encapsulation process.

Figure 5: Translational displacement of the central stage platform under various static voltages (solid:model; dash:experiment).

RESULTS

Micro-scanner translational and angular displacements were measured experimentally using a Keyence laser displacement sensor and Polytec Laser Doppler Vibrometer (LDV). Static displacement of the central platform of the actuator at various applied voltages is shown in Fig. 4. As can be seen, actuator displacement exceeds 200 μm at less than 20 V. Once the effective electroactive piezoelectric coefficient of the thin-film PZT is known from independent experiments [11], the model presented in (1)-(5) predicts large displacement frequency reasonably well, but shows much greater nonlinearity at low voltages, possibly due to non-ideal asymmetry of individual legs, especially at heights where stage position is nearly equal to the height of the surrounding frame. Dynamic testing of stage displacement shows the resonant frequency of the stage for vertical translation to be approximately 150 Hz, although a tilting mode of the outer portion of the platform at lower frequencies limits low-frequency scanning bandwidth in practical usage to between 0 and

Figure 6: Experimentally measured resonant peaks of inner-axis rotational motion at 5 V and 7 V dc bias, with 2 Vpp ac excitation show large scanning angles at certain stage positions, but substantial variability in behavior depending on stage height. Disturbance of outer frame vertical height is negligible.

80 Hz. In either event, vertical actuation rate is more than adequate to avoid motion artifacts during endoscopic imaging.

Measurement of inner mirror platform tilt angle indicates large angular displacement, to as much as 5.5° mechanical scanning angle, at as little as 2 Vpp AC excitation of the outer PZT leg structures, as shown in Fig. 6. This angular rotation of the inner mirror platform is accompanied by almost negligible ($<0.1 \mu\text{m}$) displacement of the outer, vertical translating frame due to large frequency separation between the vertical slow axis and inner fast axis resonances. However, there is substantial nonlinear behavior in the inner axis resonance, as the inner resonant frequency was observed to vary between 3 and 3.8 kHz, depending on the DC offset to the piezoelectric actuators (i.e., the height of the mirror platform).

CONCLUSION

Combining active and passive flexural beam structures for vertical and rotational translation of a central mirror platform is shown to provide suitable scanning actuation for cross-sectional imaging in dual axes confocal endomicroscopy. Both large translational vertical displacements and high-frequency resonant tilting actuation are achieved. Limitations of the device include nonlinear behavior of the inner resonance for tilt scanning at different vertical displacements.

REFERENCES

- [1] T.D. Wong, M.J. Mandella, C.H. Contag, and G.S. Kino, "Dual-axis Confocal Imaging for High-Resolution *in vivo* Imaging," *Optical Letters*, 28, 6 (2003).
- [2] J.T.C. Liu, M.J. Mandella, J.M. Crawford, S. Friedland, R. Soetino, C.H. Contag, G.S. Kino, and T.D. Wang, "A Dual Axes Confocal Reflectance Microscope for Distinguishing Colonic Neoplasia," *Journal of Biomedical Optics*, 10 (2006).
- [3] Z. Qiu, Z. Liu, X. Duan, S. Khondee, B. Joshi, M.J. Mandella, K.R. Oldham, K. Kurabayashi, and T.D. Wang, "Targeted Vertical Cross-sectional Imaging with Handheld Near-infrared Dual Axes Confocal Fluorescence Endomicroscope," *Biomedical Optics Express*, 4 (2013).
- [4] Z. Qiu, S. Khondee, X. Duan, H. Li, M.J. Mandella, B.P. Joshi, Q. Zhou, S.R. Owens, K. Kurabayashi, K.R. Oldham, and T.D. Wang, "Vertical Cross-Sectional Imaging of Colonic Dysplasia *in vivo* with Multi-spectral Dual Axes Confocal Endomicroscopy," *Gastroenterology*, 146, 3 (2014).
- [5] W. Piyawattanametha and T.D. Wang, "Miniature Dual Axes Confocal Microscope for Real Time *in vivo* Imaging," *Advances in Solid State Circuit Technologies* (2010).
- [6] L. Wu and H. Xie, "A Large Vertical Displacement Electrothermal Bimorph Microactuator with Very Small Lateral Shift," *Sensors and Actuators A* (2010).
- [7] D. Lee, K. Krishnamoorthy, K. Yu, and O. Solgaard, "Single-Crystalline Silicon Micromirrors Actuated by Self-aligned Vertical Electrostatic Comb Drives with Piston-motion and Rotational Capabilities," *Sensors and Actuators A: Physical*, 114, 2-3 (2004).
- [8] Y. Zhu, W. Liu, W. Liao, H. Xie, "A piezoelectric unimorph actuator based tip-tilt-piston micromirror with high fill factor and small tilt and lateral shift," *Sensors and Actuators A: Physical*, 167, 6 (2011).
- [9] Z. Qiu, J.S. Pulskamp, X. Lin, C.H. Rhee, T.D. Wang, R.G. Polcawich and K.R. Oldham, "Large Displacement Vertical Translational Actuator based on Piezoelectric Thin Films," *Journal of Microelectromechanical Systems*, 20, 7 (2010).
- [10] P. Murali, R.G. Polcawich, and S. Trolier-McKinstry,

"Piezoelectric Thin Films for Sensors," *MRS Bulletin*, 34 (2009).

- [11] C.H. Rhee, J.S. Pulskamp, R.G. Polcawich, and K.R. Oldham, "Multi-degree-of-freedom Thin-film PZT-actuated Microrobotic Leg," *Journal of Microelectromechanical Systems*, 21, 6 (2012).

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