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# Electromechanical performance of piezoelectric scanning mirrors for medical endoscopy

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ABSTRACT

The electromechanical performance of piezoelectric scanning mirrors for endoscopy imaging is presented. The devices are supported by a single actuating cantilever to achieve a high fill factor, the ratio of mirror area to the combined mirror and actuator area. The largest fill factor devices (74%) achieved 10° mechanical scan range at ±10 V with a 300 μm long cantilever. The largest angular displacement of 30° mechanical scan range was obtained with a 500 μm long cantilever device with a 63% fill factor driven at 40 $V_{pp}$. A systematic investigation of device performance (displacement and speed) as a function of fabrication and operational parameters including the stress balance in the cantilever revealed unexpectedly large displacements with lack of inversion at the coercive field. An interpretation of the results is presented based on piezoelectric film domain orientation and clamping with supporting piezoelectric film characterization measurements.



## 1. Introduction

A variety of optical imaging techniques are being investigated for optical biopsy applications with the goal of non-invasive rapid identification of precancerous and cancerous growth in the epithelial layer of tissue. These techniques include multiphoton fluorescence, confocal microendoscopy and optical coherence tomography (OCT) [1,2]. Clinical implementation of these techniques in a endoscope generally requires some form of laser beam scanning, which has been demonstrated with MEMS mirrors at the distal end of the probe (e.g. confocal [3]), multiphoton [4], OCT [5]) or fiber scanning approaches (multiphoton [6], OCT [7]).

Among MEMS mirrors, electrostatically actuated devices offer high speed, but provide limited mechanical scanning range at non-resonance (typically 2–3°) and have a large actuator footprint [3,4,8]. Electrothermal mirrors have been extensively investigated in both single bender [9] and 2D scanning configurations [10,11] and achieve large scanning angles (up to ±30°) at low driving voltages at the expense of high driving current, the requirement for thermal isolation of the actuator, and often a poor temporal response.

The fabrication and characterization of piezoelectric cantilevered mirrors designed by our group for endoscopic forward looking OCT was described recently [12]. These actuated mirrors feature a large fill factor (mirror/(mirror + actuator) areas) because, unlike two-axis configurations, the mirror is supported on only one side. The fabrication approach improved on previously reported piezoelectric devices [13,14] by separately defining the actuator arm and optical mirror thickness: a 12 μm mirror thickness provided flatness for optical performance while a thin short actuator arm enabled a large scanning range under sub-resonant conditions. A similar fabrication approach was later used by others to demonstrate a two-dimensional rastering piezomirror [15,16]. This device enables both bending and torsional actuation modes, however it achieves adequate scanning range only at resonance frequency operation. Operation in sub-resonance regime is highly desirable for exploiting piezomirrors in endoscopic biomedical applications, where a low (tens of Hz), arbitrary scanning speed is convenient to optimize signal-to-noise with suitable integration times. The first generation piezoelectric mirror devices met the designed scanning range of ±6° (equivalent to ±12° optical) providing for an adequately sized image (~1 mm). The mirror operated in sub-resonance condition with a stable low frequency response and resonance frequency in the hundreds of Hz.

The aim of this paper is to explore the performance limits of the devices and to establish the trade-offs between scanning range, speed and driving conditions. In piezoelectric cantilevers the scanning range linearly increases with the cantilever length; however, increased length negatively impacts the time response of the device and the fill factor. A systematic investigation of the performance (displacement and speed) as a function of several fabrication and operational parameters including the effect of stress balance in the cantilever, dc offset in the driving voltage and piezoelectric

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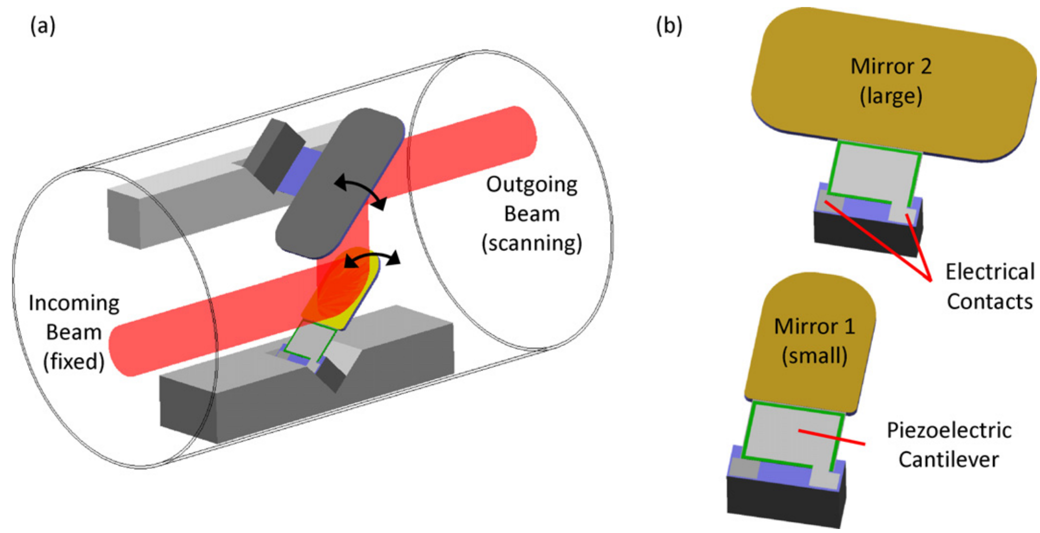


**Fig. 1.** (a) Conceptual schematic of a dual-mirror cascade configuration packaged inside a 2.9 mm inner diameter catheter. (b) Drawings of the two component mirrors.

layer thickness is reported. The electrical reliability of the devices was also improved by implementing a crucial modification of the electrical isolation layer which enables application of larger voltages. Unexpectedly large displacements were observed with lack of inversion at the coercive field. An interpretation of the results is presented based on piezoelectric film domain orientation and clamping, and this model was verified with piezoelectric film characterization measurements.

The overall goal was an optimization of the devices for endoscopic imaging applications which require large scanning angle ($\geq 10^{\circ}$) in sub-resonance condition with as compact an actuator as possible.

## 2. Experimental procedures

### 2.1. Design

The mirrors were designed to provide forward-looking two-dimensional scanning of a 500 μm diameter beam within a 2.9 mm inner diameter catheter in the cascaded configuration shown in Fig. 1. Each mirror is actuated in one dimension by a piezoelectric cantilever extending from one side of the mirror. This actuator configuration provides a large ratio of optical aperture to device size. Mirror sizes were chosen to ensure that the light beam is intercepted by the scanning mirrors at any scan position within a 10° mechanical angle range. The first mirror on the beam path is 600 μm × 840 μm and the second one is 1600 μm × 840 μm. The total die size is approximately 1 mm × 2 mm for the small mirror and 1.6 mm × 2 mm for the large mirror. For convenience, larger dice (5 mm × 5 mm) with two mirrors were used for electromechanical evaluation of devices.

A detailed discussion of the design considerations for the cantilever is found in [12]. Briefly, scanning range is expected to increase with longer cantilever length and smaller PZT thickness. Devices of each mirror size were fabricated with cantilever lengths of 300, 400, and 500 μm. For the 600 μm × 840 μm mirrors, the cantilever width was 600 μm. For the 1600 μm × 840 μm mirrors, the cantilever width ranged from 600 to 1600 μm. PZT thicknesses of 0.64 μm and 0.96 μm were investigated.

### 2.2. Fabrication

Devices were fabricated on 100 mm silicon wafers with 2500–4000 A thermal oxide. The front side process sequence formed the piezoelectric actuator and the reflective mirror. A Ti/Pt layer was deposited by electron beam evaporation. For the piezoelectric layer, $Pb(Zr_{0.53}Ti_{0.47})O_3$ (PZT) was spin-coated from metal organic precursors (as in [17]) in 80 nm layers and annealed at 700 °C for 5 min after every two layers for total thicknesses of 0.64–0.96 μm. The PZT was patterned using a wet etch ($10H_2O$:10HCl:1HF), and the Ti/Pt layer was patterned by argon ion milling to form the bottom electrode. Next, an insulator was deposited to prevent shorting between the top and bottom metal layers. In the previously reported devices [12], PECVD of silicon dioxide was used for this isolation layer; however, it did not provide adequate step coverage at the edge of the PZT and was replaced with spin-coated benzocyclobutene (BCB, CYCLOTENE 4022, Dow Chemical Co.). A photoimageable BCB was used to pattern and remove this layer from both the actuation cantilever and the mirror. The top actuation electrode was deposited by electron beam evaporation of Ti/Au/Ti and patterned with a standard photoresist liftoff process. Silicon nitride was deposited by PECVD in order to alter the stress in the cantilever portion of the device. The thickness of this layer influences the native tilt of the mirrors as discussed in detail in Section 2.3. To form the reflective mirror surface, Ti/Au was deposited and patterned in a photoresist liftoff process followed by conformal vapor deposition of parylene-C over the entire top surface of the wafer to protect the mirror surface during processing of the back sides of the wafers.

A two-step deep reactive ion etch (DRIE) process was used on the backsides of the wafers to completely remove the silicon from

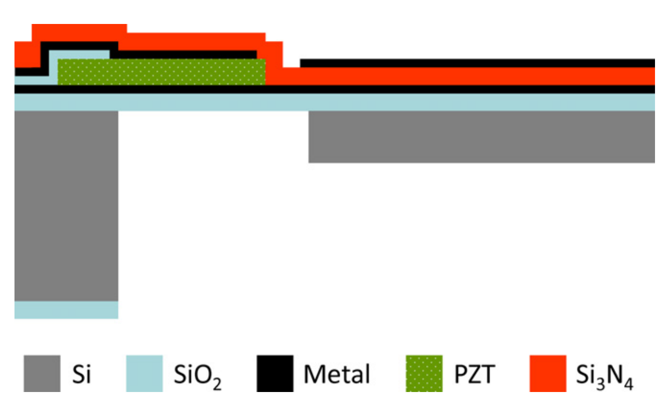


**Fig. 2.** Illustration of the device cross section.