MEMS based non-rotatory circumferential scanning optical probe for endoscopic optical coherence tomography

Yingshun Xu\textsuperscript{a,b}\textsuperscript{*}, Janak Singh\textsuperscript{b}, Teo Hui Siang Jason\textsuperscript{b}, Kotlanka Ramakrishna\textsuperscript{b}, C. S. Premchandran\textsuperscript{b}, Chen Wei Sheng Kelvin\textsuperscript{b}, Chuah Tong Kuan\textsuperscript{c,b}, Nanguang Chen\textsuperscript{a}, Malini C. Olivo\textsuperscript{d} and Colin J.R. Sheppard\textsuperscript{a}

\textsuperscript{a} Division of Bioengineering, National University of Singapore, 7 Engineering Drive 1, Singapore 117574; 
\textsuperscript{b} Institute of Microelectronics, 11 Science Park Road, Singapore 117685; 
\textsuperscript{c} Division of Bioengineering, Nanyang Technological University, 70 Nanyang Avenue 1, Singapore 637457; 
\textsuperscript{d} National Cancer Center, 11 Hospital Drive, Singapore 169610.

ABSTRACT

In this paper, we present a non-rotatory circumferential scanning optical probe integrated with a MEMS scanner for in vivo endoscopic optical coherence tomography (OCT). OCT is an emerging optical imaging technique that allows high resolution cross-sectional imaging of tissue microstructure. To extend its usage to endoscopic applications, a miniaturized optical probe based on Microelectromechanical Systems (MEMS) fabrication techniques is currently desired. A 3D electrothermally actuated micromirror realized using micromachining single crystal silicon (SCS) process highlights its very large angular deflection, about 45 degree, with low driving voltage for safety consideration. The micromirror is integrated with a GRIN lens into a waterproof package which is compatible with requirements for minimally invasive endoscopic procedures. To implement circumferential scanning substantially for diagnosis on certain pathological conditions, such as Barret’s esophagus, the micromirror is mounted on 90 degree to optical axis of GRIN lens. 4 Bimorph actuators that are connected to the mirror on one end via supporting beams and springs are selected in this micromirror design. When actuators of the micromirror are driven by 4 channels of sinusoidal waveforms with 90 degree phase differences, beam focused by a GRIN is redirected out of the endoscope by 45 degree tilting mirror plate and achieve circumferential scanning pattern. This novel driving method making full use of very large angular deflection capability of our micromirror is totally different from previously developed or developing micromotor-like rotatory MEMS device for circumferential scanning.

Keywords: Micromirror, Optical coherence tomography, Endoscopy, MEMS

1. INTRODUCTION

Optical coherence tomography (OCT) is an emerging optical imaging modality since its first invention in 1991 [1]. After a period of rapid developments in recent years, OCT has successfully evolved from the time domain systems [2-4], Fourier/spectral domain systems [5-9] to currently dominating swept-source based systems [10-14] for fast data acquisition rate up to several hundred thousands A-lines per second, which has demonstrated the capability of providing real time high resolution cross-sectional images of a wide range of multi-layer tissues, such as retina, skin and mucosa in human body.

\textsuperscript{*} Further author information:
Mr. Yingshun Xu: E-mail: g0500123@nus.edu.sg, Tel: +65 81271322
Dr. Janak Singh: E-mail: janak@ime.a-star.edu.sg, Tel: +65 67705909
Dr. Nanguang Chen: E-mail: biecng@nus.edu.sg, Tel: +65 65164401
Endoscopic application of OCT and the idea of “optical biopsy” were firstly introduced nearly ten years ago [15, 16] and the most important task for scientists and engineers to implement OCT-based endoscopes is how to miniaturize OCT probe and steer the near infrared light beam for scanning and collecting reflected signals from tissue sample in high efficiency. Historically, early stage endeavors on miniature OCT probe implementations were mainly focusing on developments of manipulating single mode fibers for scanning usage. Single mode fibers for near infrared light transmission used in OCT systems is ideally suitable for this kind of purpose. To achieve side-view scanning, the general design of such a kind of probe consists of a mirror or a micro prism mounted at the distal end of single mode fiber to deflect the focused beam from the optical fiber tip out of a window on the side of the probe. External rotational mechanism, such as a motor, for circumferential scanning [17, 18] or a linear translation stage for transverse scanning [19] were connected to drive the single mode fiber but scanning speed was limited to a few Hz.

Recently, many MEMS scanners based on various actuating mechanisms, such as electrothermal [20], electrostatic [21, 22] and magnetic [23] actuation, were developed for distal scanning probes of endoscopic OCT application. Most of MEMS based optical probes can only perform transverse scanning for 2D or 3D image acquisition. Several medical conditions, such as esophageal tumors usually leading to dysphasia and other symptoms, are diagnosed by optical biopsy and circumferential cross-sectional scanning is required. So far only a scratch drive array (SDA) based rotating micromirror [24] and some MEMS motor designs for 360 degree circumferential scanning were reported for such a kind of application. However tradeoffs between overall size and rotating speed of devices were unavoidable. Since the feasibility of 3D scanning micromirror and the SiOB (silicon optical bench) assembly for endoscopic OCT optical probe [25] has been shown, we further explore a large angular deflection 3D scanning micromirror for a novel design of MEMS based non-rotatory circumferential scanning optical probe, which is presented in this article.

2. **3D SCANNING MICROMIRROR**

3D scanning micromirror was initially aiming to offer fast switching in optical communication networks applications with a chip dimension of 2.5 mm x 2.5 mm and the mirror plate diameter of 400 µm [20]. Maximal angular deflection of 3D micromirror is 10° under less than 2V driving voltage. We used this device to study feasibility of integrating scanning micromirror device and obtaining OCT cross-sectional images. Some preliminary results have been reported recently [25]. Further improvements for following aims have been performed by theoretical studies and implemented by modified Silicon-on-Insulator (SOI) fabrication process:

1). Reduces overall size meanwhile remains or increases the fill-in factor of micromirror chips;
2). Increases angular deflection of micromirrors.

A straightforward solution to two aforementioned aims is to use curved biomorph actuators instead of straight actuators. Current improved micromirrors, as a result of this improvement, have a chip dimension of 1.5mm x 1.5mm with a mirror plate having up to 500um diameter and 1mm x 1mm with a mirror plate having up to 400um diameter. Maximal angular deflection of 16° was experimentally achieved by new designs.

### 2.1 Analytical model of electrothermal actuators

Two common materials, silicon and aluminum, are selected for bimorph electrothermal actuators based on bimetallic effect. General theory of bending of bimetallic composite submitted to a uniform heating described by S. Timoshenko in 1925 [26] is given as,

\[
\frac{1}{\rho} = \frac{6\Delta \alpha \Delta T (1 + m)^2}{h \left(3(1 + m)^2 + (1 + mn) \left(m^2 + \frac{1}{mn}\right)\right)} \quad (1)
\]

, where

1/ \( \rho \) = Curvature of biomaterial beam due to bending;

m = the thickness ratio of biomaterial structure;
\( n \) = the elastic moduli ratio of biomaterial structure;

\( h \) = total thickness of biomaterial structure.

\[ \Delta a \] = the difference of coefficient of thermal extension (CTE),

\[ \Delta T \] = isothermal temperature change throughout biomaterial structure.

A 2000 angstrom silicon dioxide thin film serving as electrical isolator between 2um silicon substrate and 1um aluminum heater was ignored for simplification in our model by using Timoshenko’s equation.

<table>
<thead>
<tr>
<th>Materials</th>
<th>Coefficient of thermal expansion ([10^{-6}/K])</th>
<th>Elastic moduli ([10^{11}/N/m^2])</th>
<th>Density ([\text{kg/m}^3])</th>
<th>Thermal conductivity ([\text{W/m/K}])</th>
</tr>
</thead>
<tbody>
<tr>
<td>Al</td>
<td>23.0</td>
<td>0.69</td>
<td>2702</td>
<td>237</td>
</tr>
<tr>
<td>Si</td>
<td>2.6</td>
<td>1.62</td>
<td>2328</td>
<td>150</td>
</tr>
<tr>
<td>Si dioxide</td>
<td>0.4</td>
<td>0.74</td>
<td>2200</td>
<td>1.04</td>
</tr>
</tbody>
</table>

Table 1. Physical data of some materials of interest for the fabrication of bimorph electrothermal actuators.

After selection of materials combination, only the thickness ratio, \( n \), is left as the only variable. Fig.1 shows the prediction of the deflection as a function of \( n \) for the Al-Si combination. It is evident from Fig.1 that the optimized thickness ratio was found around 0.7. But there is no great difference in the curvature with the thickness ratio ranging from 0.5 to 1. Using thickness of silicon substrate = 2 um, the optimized thickness ratio we selected for current improved micromirrors is 0.5 and corresponding thickness of aluminum heater is 1 um.

2.2 Finite element analysis (FEA)

FEA modeling and simulations were carried out using Coventorware 2006 to understand the behavior of the flexural springs and overall functioning of the 3D micromirror under certain temperature loads. Geometrical and temperature load parameters were used to understand the effect of different layouts with a variation of springs and actuators. It was found that the largest angular deflection of micromirrors in simulation was archived by longer curved actuators and the length and shape of springs had no obvious effects on maximal angular deflection. Therefore an optimum length with trade-off between flexibility and strength was required. Full micromirror model for Coventorware FEA analysis and simulation results are shown in Fig.2. Typical parameters for the two bimorph materials (aluminum and silicon) have been shown in Table 1. From Fig.2(c), springs connecting actuators and mirror plate perform not only mechanical deformation cushioning but also thermal isolators to prohibit heat flow from freely propagating from one heated actuator via spring-mirror plate-spring to other three cold actuators. High thermal resistance of flexural springs was formed by springs’ tiny diameter of 2um.
2.3 Fabrication process

Fabrication process designed for micromirror fabrication is outlined in Fig. 3. SCS silicon is selected to be the primary structure material for all the components in the device.

Fabrication process started from a SOI wafer with 1um thickness buried oxide layer and 2 or 4 um thickness top SCS layer. The following steps have a slight difference according to which kind of SOI is chosen for fabrication. The top SCS layer is used to form both lower substrate in bimorph actuators and the rigid mirror membrane. Two methods are used to balance stresses induced by front side high reflectivity Cr-Au thin film deposition for larger curvature, e.g. better flatness. One is that micromirror is to be formed in thick silicon. Another method is using backside Cr-Au thin film deposition. Al-Si thin-film cantilevers formed by metal deposition and backside DRIE process provide 3D scanning capability. Due to no substrate or other microstructures directly above or below the mirror membrane, therefore large angular deflection of 3D micromirror is allowed.
2.4 Characterization of micromirrors

The following Fig. 4 shows structures of a fabricated 3D micromirror chip after releasing the gold mirror plate, actuators and springs.

Experiments were conducted to characterize the 3D scanning mirror. A Precision Semiconductor Parameter Analyzer (Agilent 4156C) is used to plot the voltage and current relationship on the actuators in Fig. 5 (a). The maximal current before the actuator breakdown is 0.24mA. The angle of deflection and temperature at different voltage input was also measured and shown in Fig. 5 (b). Temperature and, more importantly, the angle of deflection of the actuator are not very responsive to voltage input of less than 0.7V. However, when input goes beyond this voltage input, both parameters vary linearly with voltage. To overcome this initial no-linearity, an offset voltage can be introduced. When input voltage exceeds 1.5V, the actuator will break down due to excess bending.
Fig. 5. (a) Measured electrical current with respect to delivered driving voltage; (b) Measured deflection / temperature with respect to delivered driving voltage. Temperature variations of a bimorph actuator were measured by an IR camera.

3. OPTICAL PROBE ASSEMBLY ON SILICON OPTICAL BENCH (SIOB)

Miniaturizing the overall dimension of optical probes to meet the requirements for endoscopic imaging is a challenge for the packaging of the probe. The optical components and the mirror need to be packaged in a miniaturized format and at the same time the packaging material must be transparent to near infrared light. Previously, assembly and housing for OCT optical probes with a diameter of about 5mm were realized by using an acrylic sheath package with wire bonding connections for electrical power delivery [21] and a machined aluminum package with tiny screw sets for alignment [22]. However, some important endoscopic imaging applications, such as intravascular imaging for atherosclerosis, need smaller size optical probes. Therefore a silicon optical bench (SiOB) was designed and fabricated to assemble the fiber, GRIN lens and a 3D micromirror, which has been shown in Fig.6.

![Diagrams of Current vs Voltage and Deflection/Temp vs Voltage](image)

Fig. 6. Demonstration of optical probe assembly based on SiOB.

Silicon, a good material for micromachining, is selected as the substrate to create smaller dimension to meet miniaturization. In current design aiming to transverse scanning, a 45 degree angle trench is used to place the micro mirror to achieve larger scanning range. Electrical lines are formed on the optical bench and are connected to silicon...
micro mirror by using micro solder balls. A small diameter GRIN lens with low numerical aperture (NA) has been used to focus the optical beam onto the 3D micromirror.

Fig. 6. (a) SEM graph showing 3 micro solder balls providing electrical connection between SiOB and the 3D micromirror in the old design; (b) Optical microscopic photo of improved 3D micromirror with 5 pads aligned in one side that has been connected to SiOB; (c) Experimental set up for coupling efficiency testing of the optical probe.

KOH wet etching was used to precisely form 45 degree angle trench for containing the 3D micromirror on 8 inch silicon wafers. Dimensions of structures on SiOB were calculated to make sure that the pads on the 3D micromirror can be well aligned to metal lines to electrical connection. The Cr-Au was deposited on the silicon wafer for electrical lines forming by magnetic sputtering method and lithography technique. The distal end of metal lines is formed on the 54.7 degree side
wall of the 45 degree trench and the proximal end is extended to the end of the SiOB to connect to the external voltage source. A customized GRIN lens with spacer and single mode fiber is used and hence there is no need to do align the fiber and lens separately. A UV cure epoxy is used to attach the GRIN lens and the fiber to the bench. Micro solder balls are attached to the mirror device and are subjected to reflow. A micro-operation machine picked the 3D micromirror and attached to the lower silicon substrate. The solder balls on the 3D micromirror got contact with the metal lines on the SiOB. The integrated GRIN lens and fiber attached silicon substrate is sandwich bonded with the mirror attached silicon substrate. The final assembly is encapsulated into a transparent and biocompatible plastic injection molded tube suitable to meet endoscope requirements.

4. LARGE ANGULAR DEFLECTION 3D SCANNING MICROMIRROR

Fundamental motion in circumferential scanning is to deflect a focused beam by 90 degree out of the packaging and then smoothly steer it in 360 degree. Therefore a 3D scanning micromirror is required to have a capability of tilting 45 degree at least. The main improvements on a large angular deflection micromirror to meet that requirement are the modification of bimorph actuators and enhancement of springs. The fabrication process for the new design is basically compatible with current modified SOI fabrication process.

In our previous designs, the mirror plate was pulling down with downward bending heated Al-Si actuators. If this scheme is still used in the new large angular deflection 3D micromirror, a potential drawback is that the surrounding silicon substrate blocks the light reflected by mirror plate. Even though silicon is partially transparent in near infrared wavelength region, unavoidable signal loss is still induced. Therefore, a modified actuator design shown in Fig.7 (a) is proposed with a long beam connecting the actuators and springs. Conversely, in the following new design, motion of the mirror plate has been changed to upward tilting to avoid any light obstruction during circumferential scanning.

In the old design, the angular deflection of mirror plate is dependent of two factors, the vertical displacement on the tip of the actuator and the size of mirror plate. It is obvious that longer actuators have large vertical displacement. Differently, the new upward bending actuator directly provides the bending angle of deflection which has nothing related with the size of mirror plate. Furthermore, an obvious lateral shift occurred in large angular deflection shown as CD vector in Fig.7 (b) is partially buffered by the enhanced spring system. More s-shapes have been added in the enhanced spring system for better mechanical cushioning. In Fig.8, a series of simulation results by Coventorware 2006 shows the circumferential scanning procedure under four channels sinusoidal waveform with a certain phase difference. All curved structures in the layout have been replaced by straight structures to simplify the simulation.

![Fig. 7. (a) Layout of the new large angular deflection 3D micromirror for simulation; (b) Demonstration of large angular deflection of a mirror plate.](image-url)
Fig. 8. (a) Simulated deflection of new large angular deflection 3D micromirror; (b) A sequential series of simulated results shows the circumferential scanning procedure under four channels sinusoidal waveform.
5. CONCLUSION

In this paper, we present a feasibility study to demonstrate usability of 3D scanning micromirror and corresponding SiOB packaging techniques and also a new design of large angular 3D micromirror devices specifically for non-rotatory circumferential scanning optical probe. Based on successfully developments of current 3D scanning micromirrors, the large angular deflection 3D micromirror with modified upward bending actuators and enhanced spring system succeeds in term of the advantages of electrothermal micromirrors: the large mechanical deflection and low driving voltage.

REFERENCES