A 3mm Endoscopic Probe with Integrated MEMS Micromirror for Optical Coherence Tomography Bioimaging

X. J. Mu\textsuperscript{a,b}, G. Y. Zhou\textsuperscript{a,*}, H. H. Feng\textsuperscript{b}, Y. S. Xu\textsuperscript{b}, A. B. Yu\textsuperscript{b}, C. W. Tan\textsuperscript{b}, K. W. S. Chen\textsuperscript{b}, J. Xie\textsuperscript{b}, F. S. Chau\textsuperscript{a}

\textsuperscript{a} Department of Mechanical Engineering, National University of Singapore, 9 Engineering Drive 1, 117576, Singapore
\textsuperscript{b} Institute of Microelectronics, A*STAR (Agency for Science, Technology and Research), 11 Science Park Road, Singapore Science Park II, 117685, Singapore

Abstract

A 3mm diameter endoscopic probe for Optical Coherence Tomography (OCT) has been developed. It consists of a 1mm diameter micromirror, a silicon optical bench (SiOB), a gradient refractive index (GRIN) lens and a single mode optical fiber. The optical probe is enclosed within a biocompatible, transparent and waterproof polycarbonate tube for in vivo diagnostic applications. The two-axis scanning micromirror is driven by electrothermal actuators with a voltage less than 2V for a mechanical deflection of up to 11°. By integrating the MEMS micromirror with a commercial Optical Coherence Tomography system and miniaturized probe, high resolution 2-D/3-D in vivo and in situ images and excellent optical sectioning for imaging multilayer microstructures of internal organs can be realized. The capability of the system is demonstrated by obtaining a 2-D image of an onion.

© 2010 Published by Elsevier Ltd. Open access under CC BY-NC-ND license.

Keywords: OCT probe; Micromirror; SiOB

1. Introduction

Over the years, MEMS has been playing a increasingly significant role in the development of OCT probes, in which post-objective distal scanning MEMS devices are integrated, thus enabling high speed three-dimensional imaging. A variety of MEMS devices based on electrothermal [1,2], electrostatic [3,4], magnetic [5] and pneumatic [6] actuation mechanisms have been demonstrated in various endoscopic OCT applications. The main challenge is the miniaturization of the optics and scanners in the sample arm of the OCT system as there is a trade-off between the size of probe and the quality of OCT images. This paper presents the design and development of a MEMS OCT probe with a smaller diameter (3mm) which is integrated with a relatively large mirror plate (1mm) micromirror compared with a previous design [7]. Besides the main advantageous characteristics of the mirror of a low drive voltage, large mechanical deflection and high fill factor as mentioned in the ref [7], the large mirror plate improves the signal to noise ratio (SNR) of OCT signals. The capability of the system is developed demonstrated by obtaining a preliminary 2-D image of a sample objects, namely an onion.

* Corresponding author. Tel.: +65-96705863; fax: +65-67791459.
E-mail address: mpezgy@nus.edu.sg
2. Device design

The endoscopic probe is designed to meet the needs of in-vivo imaging applications for tubular internal organs. It consists of a novel 3-layer Silicon Optical Bench (SiOB) integrated with a MEMS micromirror standing at the distal of the SiOB, a 1mm diameter gradient refractive index (GRIN) lens connected with a single mode fiber (SMF) for light transmission and a biocompatible waterproof transparent injection micro-molded polycarbonate polymer housing for enclosing all the inner components, as shown in Fig. 1.

![Fig. 1: (a) Schematic 3D model of the OCT probe; (b) Completed probe in a bio-compatible housing](image)

Fig. 2 shows 2-D layout of the micromirror, which is based on electrothermal actuation mechanism and 3D gimbal-less architecture. The thermal actuators are formed from a 2µm-thick silicon cantilever as the base and a 1µm-thick aluminium (Al) heater patterned on it. The resistance of the heater is designed to be around 40Ω. Finite element simulations were conducted using ConventorWare 2006 to predict the performance and understand the behaviour of the two-axis gimbal-less micromirror under various temperature loads. The results typical one is shown in Fig. 2 indicated that the mirror plate can achieve a maximum deflection of 10 degrees.

The fabrication process of the micromirror was mainly carried out on the basis of the silicon-on-insulator (SOI) MEMS process that has been reported previously [7]. As shown in Fig. 3, a series of CMOS-compatible processes (a)-(d) and MEMS processes (e)-(i) followed by a device release process were sequentially carried out. Since most steps of the fabrication process have been clearly described step by step in [8], only differences in and modifications of the fabrication process in this study will be mentioned in the following sections.

The CMOS-compatible process started with an 8-in, 4µm-thick device layer and a 725µm-thick handle layer SOI p-type wafer, as shown in Fig. 3(a). The silicon backbones of bimorph actuators and flexural springs are selectively thinned down to approximately 2µm by using the deep reactive-ion etching (DRIE) process while the thickness of the mirror plate located at the centre remained at 4µm (Fig. 3(b)). In Figs. 3(c) and (d), 2000A silicon dioxide is deposited as an electrical isolation layer within its actuators. One micrometer thick Al layer is used as the heater and one layer of the bimorph microstructure and 2µm silicon used as the other layer. In addition, 5000A silicon dioxide is formed as the hard mask for its actuators and springs.

![Fig. 3: SOI micromirror fabrication process flow;](image)

In order to enhance the reflectivity of the mirror surface, in this study, it is coated with a 300A Cr /500A Au. A 500A Cr /1µm is coated to the pad by using low-stress electronic beam evaporation after the thickness of the wafer had been reduced to 450µm via backside grinding and polishing, (in Fig. 3(e)). The resulting radius of curvature of the mirror plate is experimentally found to be 45mm. Subsequently the frontside 2µm silicon Reactive-ion etching is
stopped at the 1µm buried oxide layer, as shown in Fig. 3(f). The cavity on the backside for release is opened by DRIE as shown in Fig. 3(g).

In the device release process, a 1µm-thick silicon oxide layer is deposited on the backside to help the fragile silicon membrane survive the following releasing process, (Fig. 3(h)). The wafer is then proceeded to mechanical dicing with a 100µm-thick SU-8 layer coated on the front side of the wafer as a protective layer. After mechanical dicing, the SU-8 layers on diced chips are cleaned by an SU-8 wet clean process. Diced chips are individually attached onto a support wafer and fixed by polyimide tapes. Finally, the 2µm oxide membrane is etched off using a plasma oxide etch process to release all moveable parts of the micromirror, as shown in Fig. 3(i).

In the work presented in this paper, a unique 3-layer SiOB integrated with a large mirror plate (1 mm) diameter has been developed, as shown in Fig. 4. The large mirror plate, shown in Fig. 4(a), provides the chip high fill factor. The SiOB consists of lower substrate, middle substrate and upper substrate. The lower substrate, shown in Fig. 4(b), has five Cr/Au metal lines deposited to create the electrical contact between the micromirror and the external drive circuit with the assistance of microsoldering technology. The vertical sidewall trench formed by DRIE is also oriented at 45° to the optical axis, e.g. the axis of the SiOB, so that the incident beam is optically deflected by 90°. The micro solder balls shown in Fig. 4(c) are utilized to realize the electrical contact between the pads on the micromirror and the five metal lines on the lower substrate, while the comb isolator is helpful for avoiding short circuits between among solder balls. The relative positions of the mirror and SiOB are shown in Fig. 4(d). Figures 4(e) and (f) show the assembly of the customized GRIN lens (GRINTECH, Germany) and SiOB in the upper substrate, housing the GRIN lens and a single mode fiber (SMF) together with a glass spacer for accurate positioning. Thus, the optical axis of the GRIN lens assembly is precisely aligned with the centre of the mirror plate.

3. Device characteristics

Characterization of the two-axis micromirror, i.e. the voltage-mechanical deflection relationship, frequency response and the curvature of the mirror plate were carried out. A precision semiconductor parameter analyzer (4156C, Agilent Technologies, USA) is used for the measurements. The maximum measured mechanical deflection of 11° was obtained at an operating voltage of 1.3V, as shown in Fig. 5(a). In order to measure the frequency response, a unipolar 1.2V peak-to-peak sinusoidal signal was applied to one bimorph actuator of the micromirror. The -3dB cut-off frequency was obtained as 60Hz, after the driving frequency was scanned from 1 to 300Hz (Fig. 5(b)). The radius of curvature of the mirror plate was measured to be about 45mm, as shown in Fig. 6. An optical surface profiler (Wyko DMEMS NT 3300, Veeco Instruments Inc., USA) was used for this test.

4. OCT imaging experiments

The testing of the assembled SiOB MEMS OCT probe was carried out in conjunction with a commercial swept source OCT system (OCM1300SS, Thorlabs, USA). A schematic diagram of the system is shown in Fig. 7(a) with the swept source OCT system incorporating a high speed frequency swept external cavity laser (SL1325-P16, Thorlabs, USA), which has a full-width at half-maximum (FWHM) bandwidth of 110nm centred at 1325nm and a 16kHz fast frequency sweep rate. The output of the light source is split into the sample arm and reference arm by a broadband 50/50 fiber coupler. The A-line acquisition trigger signal generated by the swept light source was fed to a PCI digitizer (ATS460, AlazarTech, Canada) to initiate data acquisition of the OCT interference fringe signals.
The sample arm of the swept source OCT system includes a microscopy head which was replaced with the assembled SiOB MEMS OCT probe. A photograph of the probe holder and multi-axis sample platform for testing is shown in Fig. 7(b). A SMF of a certain length was inserted into the reference arm to compensate for the optical path length mismatch between the two arms. Sawtooth waveforms were generated by a 12 bit high speed analog output board (PCI 6711, National Instruments, USA) to drive two adjacent actuators of the micromirror for fast raster scan across the sample surface. The peak-to-peak amplitude and frequency of the sawtooth waveform were controlled by the software of the OCT system.

In-Vitro testing on part of onion has been carried out, as shown in Fig. 8(a), in which he assembled OCT probe without its housing is stuck to the probe holder by adhesive tape. Figure.8 (b) shows the 2D cross-sectional image of the onion by using the developed OCT probe compared with that obtained from a commercial microscope head.

5. Conclusion

A two-axis scanning MEMS micromirror based OCT probe has been developed and demonstrated. Due to the large mirror plate and adoption of a new 3-layer substrate design, OCT signals of higher SNR are helping to capture most of the light scattered back from the sample for improved OCT imaging. The small size of 3mm outer diameter of the probe potentially extends its application to intravascular level. The -3dB cut-off frequency obtained is 60Hz which is well above the frequency of 20 Hz, which is compulsory for imaging by our optical probe.

Acknowledgements

This work was supported by the Joint Council Office of A-STAR under Grant Number CCOGA02_002_2008.

References

[1] Y. Pan, H. XIE and G. K. Fedder, Endoscopic optical coherence tomography based on a microelectromechanical mirror, Opt. Lett. 26(2001), 1966.
[2] H. XIE, Y. Pan and G. K. Fedder, Endoscopic optical coherence tomographic imaging with a CMOS-MEMS micromirror, Sensor Actuator A, 103(2003), 237.
[3] J. M. Zara, S. Yazdanfar, K. D. Rao, J. A. Izatt and S. W. Smith, Electrostatic micromachined scanning mirror for optical coherence tomography, Opt. Lett. 28(2003),628.
[4] W. Jung, J. Zhang, L. Wang, Z. Chen, D. McCormick and N. Tien, Three-dimensional endoscopic optical coherence tomography by use of a two-axis microelectromechanical scanning mirror, Appl. Phys. Lett. 88(2006), 163910.
[5] K. H. Kim, B. H. Park, G. N. Maguluri, T. W. Lee, F. J. Rogomentich, M. G. Bancu, B. E. Bouma, J. F. de Boer and J. J. Bernstein, Two-axis magnetically-driven MEMS scanning catheter for endoscopic high-speed optical coherence tomography, Opt. Express, 15(2007), 18130.
[6] K. Aljasem, A. Werber, A. Seifert and H. Zappe, Fiber optic tunable probe for endoscopic optical coherence tomography, J. Opt. A: Pure Appl. Opt. 10(2008), 044012.
[7] Y. Xu, J. Singh, C. S. Premachandran, A. Khairyanto, K. W. S. Chen, N. Chen, C. J. R. Sheppard and M. Olivo, Design and development of a 3D scanning MEMS OCT probe using a novel SiOB package assembly, Journal of Micromechanics and Microengineering, 18 (2008), 125005.
[8] J. Singh, J. H. S. Teo, Y. Xu, C. S. Premachandran, N. Chen, K. Ramakrishna, M. Olivo and C. J. R. Sheppard, A two axes scanning SOI MEMS micromirror for endoscopic bioimaging, Journal of Micromechanics and Microengineering, 18 (2008), 025001.