Design and Fabrication of a MEMS Thermal Actuator for 3D Optical Switching Applications

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Abstract-**This paper presents a novel thermally-actuated vertical micromirror for optical communications. Fabricated in a standard surface micromachining process, this micromirror can achieve low insertion loss (< 1 dB) and is capable of operating at CMOS-compatible voltage levels. It has a measured maximum power consumption of only 50-mW and a switching speed in the order of 16 ms with 5-V drive.**

I. Introduction

As modern communication systems continue to push data transmission rates deeper into the multigigabit per second range, there is a great interest for developing an all-optical switching solution to replace the existing electronic systems that require optical-to-electronic and electronic-to-optical conversion. Microelectromechanical systems (MEMS) are considered the most promising technology for optical communications including switches, filters, modulators, etc. [1]. A number of MEMS optical switches have been previously developed and documented [2-4]. Most approaches have focused on the use of electrostatic or electromagnetic actuators due to superior switching speeds, however they suffer from requiring significantly large voltage levels (up to 100-V or more) [3, 4]. Also, power consumption is one of the factors that severely limit the practical realization of multi-port configurations. As an alternative to electrostatic and electromagnetic optical switches, this paper presents a novel micromirror based on thermal actuation. The main advantages of thermal actuators are that they exhibit larger displacements and forces than electrostatic actuators and that their thermal expansion is linearly related to the applied heat. Heat is generated in accordance with the Lenz-Joule law by applying an electric current that flows through the device.

II. Device Configuration

As there are great demands for simplified device structures and low cost fabrication technologies, a fairly simple microactuator that only requires two masks for manufacturing was designed as shown in Figure 1. The device consists of a single-layer polysilicon structure anchored to the substrate at two different points and covered with a highly-reflective gold-coating film. The tip of the actuator forms a square micromirror plate. The actuating principle is based on differential thermal expansion of the two materials. When a voltage is applied between the anchor pads, electrical current flows through the device structure thereby increasing its temperature; the asymmetrical thermal expansion between the two adjacent material layers will cause the tip of the actuator to deflect downward to the substrate. The thermal analysis and mechanical deflection of the actuator was estimated based on some of the methods comprehensively elaborated in [5, 6]. The three-dimensional heat transfer problem is described by the so called heat diffusion equation in (1):

$$\nabla^2 T + \frac{\dot{q}}{k} = \frac{1}{\alpha}\frac{\partial T}{\partial t} \qquad (1)$$

where $\nabla^2 T = \frac{\partial^2 T}{\partial x^2} + \frac{\partial^2 T}{\partial y^2} + \frac{\partial^2 T}{\partial z^2}$ and $\alpha = \frac{k}{\rho c}$. T is the temperature distribution, α is the thermal diffusivity, k is the thermal conductivity of the material, ρ represents the density, c is the specific heat capacity, and $\dot{q}$ accounts for a volumetric heat release that is determined by the electrical current density distribution. Considering that the length of the actuator is much larger than the size of its cross section, the electrothermal analysis is generally treated as a one-dimensional problem. The main heat dissipation mechanisms are convective heat transfer from the top surface and heat conduction from the bottom surface through the air to the substrate. The contribution of radiative heat transfer may also be neglected due to its minimal contribution at the working temperatures. To validate the design, the micromirror was simulated using finite element modeling (FEM) with the commercial software ANSYSTM. The material properties and parameters used for simulations are given in Table I.

TABLE I
MATERIAL PROPERTIES

Material property	Polysilicon	Gold
Thermal conductivity of polysilicon (W m^{-1} K^{-1})	148	310
Thermal expansion (K^{-1})	4.7x10^{-6}	14.2x10^{-6}
Specific heat capacity (J kg^{-1} K^{-1})	1x10^{2}	1.29x10^{2}
Density (kg/m^{3})	2.2x10^{3}	19.32 x10^{3}
Resistance (ohm/sq)	20	0.06

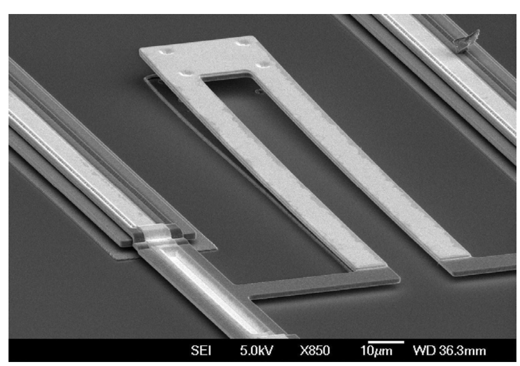

Fig. 1. SEM micrograph of the fabricated micromirror.

III. FABRICATION AND EXPERIMENTS

The proposed MEMS micromirror was fabricated using the standard Multi-User MEMS process (MUMPs) and released using HF etchant without the need for auxiliary micro-assembling techniques. The length of the bimorph actuator is 185-µm, the lateral suspension flexures are 50-µm long, and the width and thickness of the beams are 10-µm and 1.5-µm respectively. The micromirror plate measures 35-µm by 25-µm. The effect of residual stress due to peel forces and thermal expansion mismatch that curls up the tip of the actuator was considered when designing the micromirror. In this case, residual stress helps to increase the height of the micromirror to 5-µm from the substrate as can be appreciated in Figure 2. Figure 3 shows the displacement as a function of the applied voltage. It can be seen that the actuator displays excellent linearity with respect to the control voltage, this feature permits 3D (analog) operation useful for large multi-port crossconnect switches and servo-scanning optical applications. Measured power consumption ranges from 10 to 50 mW for input voltages within 1 to 5-V and switching speed is 16 ms. Figure 4 presents a microphotograph of the mirror in the instant in which is reflecting a beam of light.

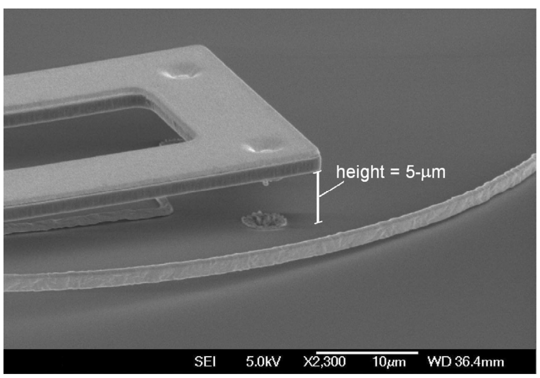

Fig. 2. SEM micrograph showing the height of the tip.

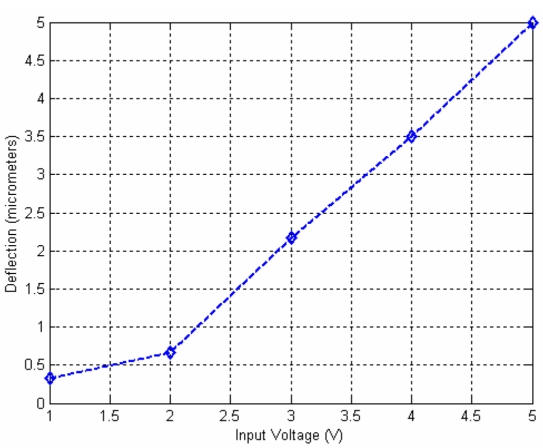

Fig. 3. Displacement of the actuator as a function of voltage.

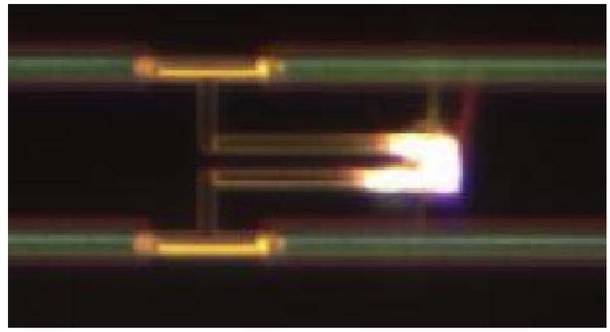

Fig. 4. Microphotograph of the optical switch operation.

IV. CONCLUSIONS

A simple thermally-actuated micromirror that can be implemented in a standard fabrication process without the need for the use of exotic or composite materials has been demonstrated. Due to the low operating voltages and fabrication requirements, the device is fully compatible with CMOS circuit technology that permits the integration of micro-optics and electronic components in a single microsystem, eliminating the need for complex control wiring and further reducing cost and volume. The actuator exhibits high-linearity operating from 1-V up to 5-V. Maximum vertical displacement is 5-µm and measured dynamic response achieves 16 ms switching times.

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REFERENCES

[1] P. De Dobbelaere et al., "Digital MEMS for optical switching", *IEEE Communications Magazine*, Vol. 40, Issue 3, pp. 88 – 95, Mar 2002.
[2] L. Hsiao-Wen, et al., "Low-loss 1x2 MEMS optical switch with three degrees-of-freedom actuation", *2003 IEEE/LEOS International Conference on Optical MEMS*, pp. 131 – 132, Aug. 2003.
[3] R. Guerre, F. Fahrni, and P. Renaud, "Fast 10□s microelectromechanical optical switch inside a planar hollow waveguide (PHW)", *Journal of Lightwave Technology*, Vol. 24, Issue 3, pp. 1486 – 1498, March 2006.
[4] 4. V. Milanović, "Multilevel Beam SOI-MEMS for Optical Applications", *Proc. Int. Conf. on Electronics, Circuits, and Systems*, pp. 281-285, Sep 2002.
[5] 5. B.C. Read, V.M. Bright, and J.H. Comtois, "Mechanical and optical characteristics of thermal microactuators fabricated in a CMOS process", *Proc. SPIE 2642*, pp. 22–32, 1995.
[6] 6. N.D. Mankame and G.K. Ananthasuresh, "Comprehensive thermal modeling and characterization of an electro-thermal-compliant microactuator", *J. Micromech. Microeng.*, vol. 11, pp. 452-62, 2001.