第 13 卷　第 5 期
2005 年 10 月
光学 精密工程
Optics and Precision Engineering
Vol. 13　No. 5
Oct. 2005

Article ID　1004-924X(2005)05-0542-06

Magnetic-fluid microelectromechanical light modulator

SEO Jong-wook[1], WANG Xi-jun[2]

(1. *School of Electronic and Electrical Engineering*, *Hongik University*, 72-1,
Sangsu-dong, *Mapo-gu*, *Seoul* 121-791, *Rep. Korea*;
2. *Changchun Institute of Optics*, *Fine Mechanics and Physics*,
Chinese Academy of Sciences, *Changchun* 130033, *China*)

Abstract: A new microfluidic microelectromechanical light modulator using a magnetic fluid is introduced. The optical reflection from the device is modulated by applying an electric current into an electrode, which is enclosed by ferromagnetic thin films as in an inductive head for a magnetic data storage device. The magnetic field produced by the current exerts a magnetic force on the magnetic fluid and drives the fluid to cover the cell surface. The surface tension of the fluid provides a restoring force when the field is reduced. The actuation of the fluid is completed in about 12 ms for both thin-to-thick and thick-to-thin fluid film switchings by magnetic forces and surface tension forces, respectively. It was observed that the switching speed was almost independent of the driving current, and no considerable thermal effect were observed when driven by a current up to 100 mA.

Key words: MEMS; microfluidic; magnetic fluid; light modulator; display; flat-panel display

1　Introduction

During the last few decades, a variety of techniques to implement microelectro mechanical systems (MEMS)-based optical modulators has been explored[1-3]. The micromirror technologies are the most prominent examples of the success stories in the optical MEMS area. The micromirror devices have demonstrated great performance particularly in the projection display areas[2-3]. Despite the great potential for commercial applications, the micromirror devices have a clear drawback in the flat-panel display (FPD) applications. If an FPD is the best fit by a direct-view panel, it can be noticed that the silicon-based MEMS has an insurmountable limit in implementing large size flat display panel due to some of its inherent drawbacks such as structural complexity and poor device scalability. It is very hard to obtain a high level of uniformity across a large panel due to the complexity in process, and it is also very hard to have the pixel size scale with the panel size.

Meanwhile, microfluidic MEMS has also expanded its technical horizon into the area of micromachines for optical applications. Although most of the research effort has been focused on the mechanical, biological, and chemical applications, continuous efforts have been made to explore new areas in optical devices, particularly for display applications[4]. However, most of the ideas reported to date show limited feasibility for FPD devices partly because surface tension dominating the microworld is unfamiliar to manage and require large power consumption[5].

Received date: 2005-03-16; **Revised date**: 2005-06-27.

However, microfluidic MEMS has unparalleled potential advantages for FPD applications over silicon-based technologies. Since no solid-state driven parts are required, manufacturing process could be simplified even for the handling of large substrates.

It is known that magnetic fluid is a suitable candidate material to implement an optical device to modulate light intensity[6]. Magnetic fluid (MF) in the form of a thin film can be used to control the light transmission through the fluid by modulating its thickness[7]. The brightness of a cell will be determined by the thickness of the fluid film, and the thickness can be modulated by applying a magnetic field in the fluid. Moreover, it is possible to keep the magnetic fluid to maintain its thickness profile-consequently, the device brightness-by storing the field pattern in a ferromagnetic medium as in magnetic data storage devices. In this paper, we introduce a new MF-base light modulator suited for the implementation of a direct-view FPD panel by forming a two-dimensional array. The design, fabrication, and experimental results of the device's and its optical performance are presented.

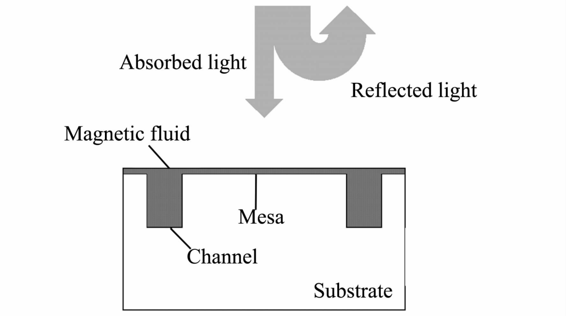
2 Operation principle

The operation of the device relies on the modulation of light reflection from the surface of the light reflective substrate by modulating the thickness of the MF thin film placed on the substrate. The MF thickness is modulated by applying a non-uniform magnetic field[8], which can be produced by passing an electric current through a patterned conductor that is in close contact with the fluid. The magnetic force exerted by that the field drives the fluid into the region of strong field making the place darker. On the other hand, as the magnetic field strength is reduced by lowering the current level, a small amount of the fluid can be sustained by the field making the region brighter. The excess liquid spreads out to the lower-field regions by the action of surface tension force.

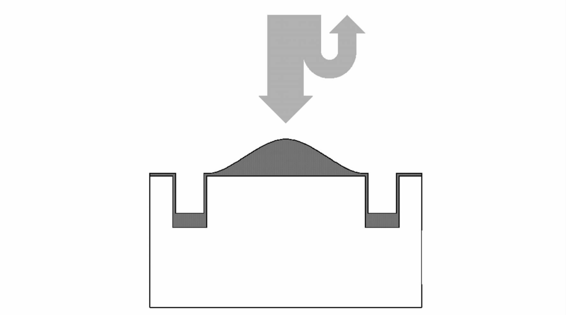
Fig. 1 shows the schematic representation of the device operation. As depicted in the figure, most of the magnetic fluid will stay in the channel around the cell due to the capillarity when no field is applied. Only a thin layer of the liquid will reside on the mesa, and the cell will be at a light state as in Fig. 1(a). On the other hand, upon the creation of magnetic field in the middle of the mesa by applying an electric current, a certain amount of the fluid corresponding to the field strength will be driven from the channel to the mesa making its surface darker as shown in Fig. 1(b).

One of the major concerns in the cell design is to create a strong non-uniform magnetic field in the middle of the mesa using a minimum amount of driving current. Since it is required to drive a large volume of fluid for a high contrast ratio, it is essential to produce a magnetic field as strong as possible. However, the current level to obtain a strong field is to be limited as low as possible to minimize power consumption and thermal effects such as thermocapillary convection and liquid evaporation. The power consumption of the device is mostly due to the Joulean heat generation in the current-carrying conductor, and increases with the current level. In addition, the heat generation in the conductor results in thermocapillary convection by producing a temperature gradient in the liquid film[9]. The thermocapillary convection not only drives magnetic fluid into the opposite direction to the actuation by the magnetic field, but also is hard to control.

A strong non-uniform magnetic field can be created by enclosing the current-carrying electrodes with a thin ferromagnetic film as in a thin-film inductive head for magnetic storage devices as depicted in Fig. 2. Fig. 2(a) shows the top view of the cell where the electrodes with a spiral shape and the magnetic gaps with a rectangular shape can be seen. Fig. 2(b) shows the cross-sectional view of the cell along the cutting line A-A' in Fig. 2(a). Also shown in the figure is the magnified view of the cell cross-section. The magnetic field will be concentrated in the vicinity of the gap, and magnetic fluid will flow toward the gap. The equilibrium shape of the liquid will become approximately identical with one of the field contours[10].



(a) Light state with a thin MF reflecting much of the incoming light.



(b) Dark state with a thick MF absorbing much of the incoming light

Fig. 1 Schematic representation of operation principle.

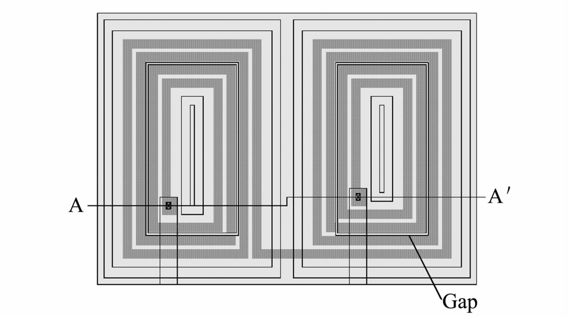


Fig. 2(a) Top view of the device showing the spiral electrode coils and the rectangular magnetic gaps

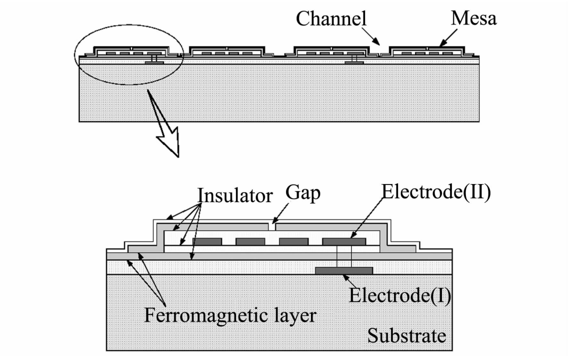


Fig. 2(b) Cross-sectional view of the device with a magnified view showing the vertical layer structure of the device.

3 Experiment and discussions

A device with a structure shown in Fig. 2 was fabricated on an alumina (Al_2O_3) substrate using a process developed for the fabrication of thin-film inductive heads for magnetic data-storage devices. Fabrication starts with the sputter deposition of a base insulator (Al_2O_3; 0.5 μm) followed by the deposition and patterning of metal I (Cu; 2.0 μm), insulator II (Al_2O_3; 0.3 μm), permalloy I (NiFe; 3.5 μm), insulator II (UV-cured PR; 3.5 μm), metal II (Cu; 2.5 μm), insulator III (Al_2O_3; 4.5 μm), permalloy II (NiFe; 3.5 μm), insulator IV (Al_2O_3; 0.5 μm) layers. The copper (Cu) electrodes and the permalloy (NiFe) shield layers were formed using electroplating after photoresist (PR) patterning by photolithography. The insulator layers enclosing the coils were patterned using a UV-cured photoresist. The device was passivated by a thin alumina film (insulator IV) for electrical insulation and surface protection from erosion. Bonding pads using 5.0 μm thick gold (Au) were finally formed for safe wire bonding. Fig. 3(a) and (b) show the cross-sectional and aerial views of the fabricated cell, respectively. The device used in the study consists of 16 turns of coil with a width/gap of 5 μm/2.5 μm and a magnetic gap of 10 μm. A diced sample was mounted on a lead frame, wire-bonded, and applied with magnetic fluid using a plastic blade. A diester-base magnetite (Fe_3O_4) magnetic fluid with a saturation magnetization about 270×10^{-4} T and a specific gravity of 1.1 (@ 25 ℃) was used in the study.

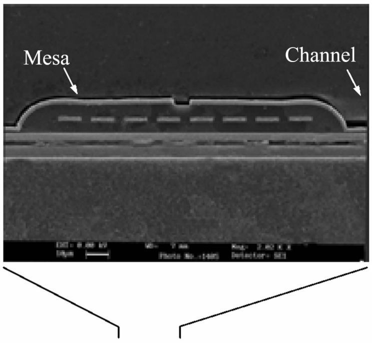


Fig. 3(a) SEM micrograph of the cell cross-section. spiral electrode coil and ferromagnetic thin film enclosing the coil are visible.

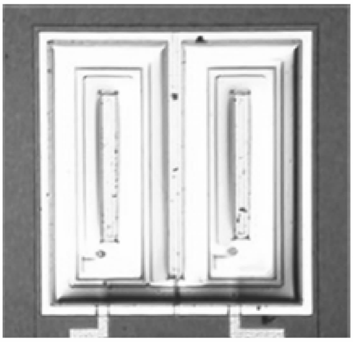
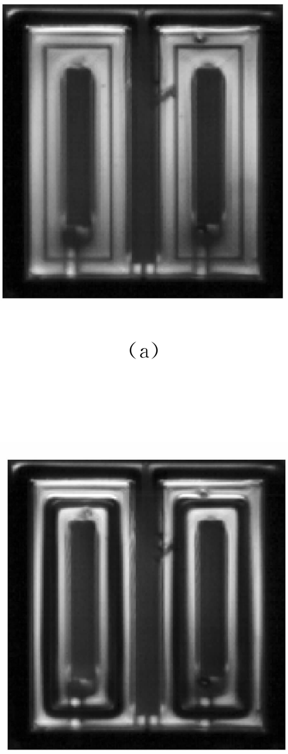


Fig. 3(b) Photograph of the device aerial view

The device was tested by applying an electric current, which consists of repeating groups of five 100 ms wide rectangular pulses with gradually increasing amplitudes. The operation of the device was investigated by analyzing the images captured with an 8-bit gray scale using a high speed CCD (Charge Coupled Device) camera by translating the local brightness into thickness as will be discussed below. Fig. 4(a) and (b) show the captured images (420 × 480 pixels, frame rate = 250 fps) of the device before and at the end of a 100 mA current pulse, respectively. As shown in the figure, the liquid is driven toward the gap region where the magnetic field is concentrated, and the light reflection from the surface is reduced. No significant thermal effect has been observed under the pulsed operation up to a current level of 100 mA. On the other hand, it was found that thermocapillary convection starts to play a significant role in the fluid actuation and the liquid starts to flow out of the mesa when the current is increased above 100 mA.



(a)

(b)

Fig. 4 Captured images of the cell surface (a) before and (b) at the end of the 100 mA current pulse applied to the coil.

Fig. 5 shows the variation of the surface luminance level along the horizontal center line of the cell upon the application of driving current. It can be seen from the figure that the regions near the magnetic gaps become darker when the current is applied. It is also recognizable that the surface reflectance becomes slightly higher at the mesa edges and the channel regions indicating that the liquid is driven from the regions to the center of the mesa. It can be estimated from the figure that the fluid thickness on the mesa is increased by the liquid actuationwhereas that in the channel is decreased. Considering that the images were captured with a frame rate of 250 fps(each frame is 4 ms apart from the adjacent ones), it was measured that the major portion of the liquid actuationby magnetic forces is completed in a few milliseconds. The returning of the liquid by surface tension forcesfinishes in a few milliseconds as well. It was also found that the transition speed from a dark state to a light stateis almost independent of the magnitude of the driving current, i. e. the initial amount of liquid.

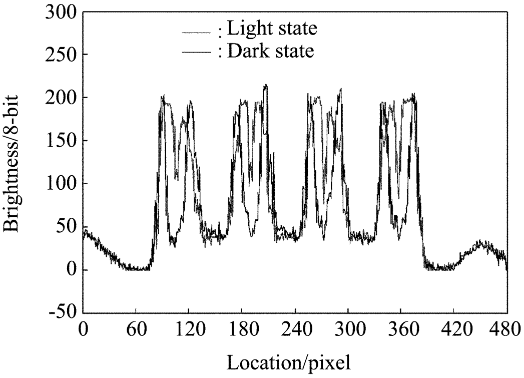


Fig. 5 Cell brightness along the horizontal centerline before and after the application of the current pulse with an amplitude of 100 mA

More liquid moves toward the gap as the current level is increased and the dependence can be visualized by plotting the volume (per unit length) of the actuated fluid versus the applied current as shown in Fig. 6. The figure shows a linear relationship between the volume of the driven liquid and the current above a threshold level as well as a large nonlinearity at the low-current region. Both of the features are favorable for display applications, and the nonlinearity in particular is essential for pixel addressing[11]. The reliability of the magnetic fluid actuation was investigated by observing the variation of the luminance distribution across the cell between the repeating current pulses. It was found that the luminance deviation is very small, and a reliable operation can be achieved and can provide a proper sealing.

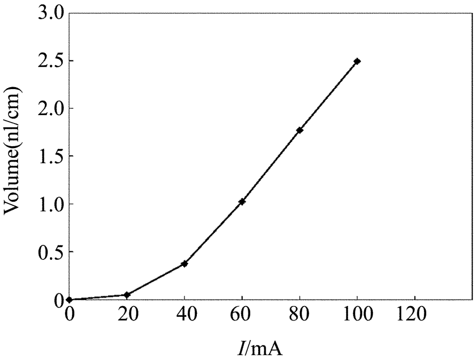


Fig. 6 Volume of the actuated magnetic fluid as a function of current pulse amplitude

4 Conclusions

It has been shown that the actuation of magnetic fluid in the form of a thin film can be performed electrically by applying a moderate level of driving current. The thickness of the fluid was modulated by the magnetic field generated by the current in the vicinity of the magnetic gap at the center of the device mesa. The devices used in the study were fabricated using a process compatible with that for the fabrication of thin film inductive head for magnetic data-storage devices. The actuation of the diester-base magnetite (Fe_3O_4) magnetic fluid with a saturation magnetization about 270×10^{-4} T Gauss was achieved by applying electric current pulses with an amplitude of 100 mA. The resistance heating in the coil does not generate any significant thermal effects if the current level is maintained below 100 mA. The major portion of the fluid actuation was completed in about 12 ms for both the light-to-dark (*i. e.* thin-to-thick fluid film) switching by magnetic forces and the dark-to-light (*i. e.* thick-to-thin fluid film) switching by surface tension forces.

References:

[1] DOBBELAERE P D, FALTA K, FAN L, GLOECKNER S, PATA S. Digital MEMS for optical switching[J]. *IEEE Comm. Mag.*, 2002, 40(3): 88-95.

[2] KESSEL P F V, HORNBECK L J, MEIER R E, DOUGLASS M R. A MEMS-based projection display[J]. *Proc. IEEE*, 1998, 86(8): 1687-1704.

[3] KIM S G, HWANG K H, KIM J S, CHOI Y J, KIM J M. Thin-film micromirror array(TMA) for high luminance and cost-competitive information display systems[J]. *Proc. SPIE, Projection Display V*, 1999, 3634: 207-216.

[4] MAKIHARA M, SATO M, SHIMOKAWA F, NISHIDA Y. Micromechanical optical switches based on thermocapillary integrated in waveguide substrate[J]. *J. Lightwave Technol.*, 1999, 1(17): 14-18.

[5] KIM C J. Micropumping by electrowetting[C]. *Proc. ASME Int. Mechcanical Engineering Congress and Exposition, New York, NY*, 2001: 1-8.

[6] SEO J W, PARK S J. An Experimental study of light modulator using magnetic fluid for display applications[J]. *J. Magn. Magn. Mater.*, 1999, 192: 499-504.

[7] SEO J W, JEON M, PARK S J, LEE H S. An experimental and numerical investigation of flat panel display cell using magnetic fluid[J]. *J. Magn. Magn. Mater.*, 2002, 252: 353-355.

[8] BERKOVSKY B M, MEDVEDEV V F, KRAKOV M S. *Magnetic fluids: engineering applications*[M]. Oxford: Oxford University Press, 1993.

[9] SCHATZ M F, NEITZEL G P. Experiments on thermocapillary instabilities[J]. *Annu. Rev. Fluid Mech.*, 2001, 33: 93-127.

[10] BASHTOVOI V, BERKOVSKI B, BASHTOVOI V. *Magnetic fluids and applications handbook*[M]. Bashtovoi, Ed. NewYork: Begell House, 1996: 395-464.

[11] SOBEL A. *Electro-optical display*[M]. M. A. Karim, Ed. New York: Marcel Dekker, Inc., 1992: 121-185.

Brief professional biography of the author:

SEO Jong-wook received the B. S., M. S., and Ph. D. degrees all in Electrical engineering from Seoul National University, Seoul, Korea, in 1982, from Advanced Institute of Science and Technology(KAIST), Daejeon, Korea, in 1984, and from the University of Illinois at Urbana-Champaign(UIUC), Illinois in 1993, respectively. He worked for Daewoo Telecom to develop fiber-optic telecommunications equipment from 1984 to 1989, and for Daewoo Electronics to develop active-matrix backplanes for actuated mirror array(AMA) devices for display applications from 1994 to 1996. He is an associate professor at the Electronics Engineering Department of Hongik University, Seoul, Korea. His group is concentrating on research areas such as MEMS devices for display applications, OLED display devices and systems, and semiconductor light-emitting devices.