PIEZOELECTRICALLY ACTUATED MICROCANTILEVER FOR ACTUATED MIRROR ARRAY APPLICATION

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ABSTRACT

For a projection display application, we have developed a piezoelectrically actuated array of cantilevers whose facets can accurately be controlled for a desired gray level. A 40x40 cantilever array with a pixel size of 100x100 μm^2 has been fabricated, and a piezoelectric ZnO thin film (in spite of its relatively low d_{31}) is successfully used to produce 0.116°/V vertical deflection of the cantilever. In the fabrication processing, we have discovered that many materials have their unique critical HF concentration below which there is no etching by vapor HF, and successfully used vapor HF to release cantilevers with a very high yield and a processing simplicity.

INTRODUCTION

In the digital mirror array [1] and the grating light valves [2] for a projection display application, individual mirror elements are deformed or tilted electrostatically. The control of mirror positions in those devices is basically bistable in that the mirror elements are tilted or deformed into either one of two stable positions. Consequently, the gray scale control inherently requires high speed digital circuitry. Moreover, since the mirror elements are constantly banged into the substrate during the operations, long-term reliability may suffer due to in-operation stiction.

On the other hand, a piezoelectric actuation of mirror elements allows us to have linear control of the mirror tilting, and the gray scale control becomes very simple. Also, the mirror elements formed by surface micromachining never have to touch the substrate during operation, and the in-operation stiction is not a concern. We have fabricated an array of piezoelectrically actuated cantilevers for a projection display system illustrated in Fig. 1. In the system, the piezoelectrically actuated cantilevers are individually tilted for an image formation through a light modulation technique shown in Fig. 2.

With bulk piezo-ceramics (PLZT), a 200 x 400 array of mirror elements was demonstrated to show high light throughput efficiency [3].

A ferroelectric PZT film has large piezoelectric constant (e.g., d_{31}), and can advantageously be used to actuate microstructures. However, PZT thin film lacks a track record up to now. While sputter deposition of PZT requires very tight process control for repeatable quality of PZT films, sol-gel PZT typically has large residual stress. In contrast, a piezoelectric ZnO thin film has been extensively used in commercial SAW filters for TV's IF filters (tens of million

devices per year), and has been proven to be reliable and reproducible (i.e., the ZnO properties are well controlled).

Figure 1. Conceptual picture of the projection display system using the piezoelectrically actuated mirror array.

Figure 2. The light modulation technique with a knife-edge filter.

Moreover, ZnO film (deposited by a rf magnetron sputtering) has been demonstrated to be compatible with a CMOS processing [4]. Though ZnO has relatively low piezoelectric constants, there are many actuator applications whose specifications can be met by ZnO film. After a careful calculation, we concluded that it is feasible to meet the specifications for an actuated mirror array application with ZnO film, and have successfully fabricated working arrays (40 x 40) of ZnO-actuated micro-cantilevers.

THEORY AND DESIGN

For a multi-layer cantilever actuated by a piezoelectric film, the neutral plane is typically designed to be at the bottom plane of the piezoelectric film in order to induce maximum bending stress in the piezoelectric film. For a large deflection, the cantilever should be designed as thin as

possible. Consequently, we first set the thickness of each layer to its minimum thickness limited by a processing. Then, based on the thickness of each layer, we calculate the thickness of ZnO to make the neutral plane of the cantilever coincide with the bottom surface of the ZnO layer. The cross section of our cantilever viewed from the free end is shown in Fig. 3. The requirement that the net axial force on the neutral plane be zero gives the following equation:

$$P = \sum \Delta P_i = \sum \frac{E_i y_i \Delta A_i}{R} = 0 \quad (1)$$

Figure 3. The cross-sectional view of a typical cantilever employed in our mirror array.

where E_i , R , and ΔA_i are the elastic modulus of a layer i , the bending curvature and the cross section area of a layer i , respectively. For the multi-layer beam in Fig. 3, we can derive the following equation for the ZnO thickness (t_{ZnO}):

$$at_{ZnO}^2 + bt_{ZnO} + c = 0, \quad (2)$$

where

$$\begin{aligned} a &= E_{ZnO} W_{ZnO} \\ b &= 2E_{Al} W_{Alt} t_{Alt} \\ c &= E_{Al} W_{Alt} t_{Alt}^2 - E_{SOG} W_{SOG} t_{SOG}^2 \\ &\quad - E_{Al} W_{Alb} [(t_{Alb} + t_{SOG})^2 - t_{SOG}^2] - E_{SiN} W_{SiN} \\ &\quad \times [(t_{Alb} + t_{SOG} + t_{SiN})^2 - (t_{Alb} + t_{SOG})^2] \end{aligned} \quad (3)$$

where W_i , and t_i are the width and the thickness of a layer i , respectively.

Figure 4. (a) A segment of the cantilever along the length direction is shown to produce a piezoelectric strain under an applied voltage. The shown strain is for the case where the layers are not attached to each other. (b) The piezoelectric strain for the real case (where all the layers are attached to each other) can be equivalently modeled using forces applied to the layers as shown.

As illustrated in Fig. 4, calculation of the deflection and tip displacement of ZnO-actuated cantilever can be treated as a pure bending with the momentum M^* and moment of inertia I^* [5]. The force densities (P in N/m^2) must satisfy the following equations:

$$\begin{aligned} P_1 &= \frac{d_{31} E E_{SiN} (S_2^* + S_3^*)}{S_1^* + S_2^* + S_3^*} \\ P_2 &= P_3 = \frac{d_{31} E E_{SiN} S_1^*}{S_1^* + S_2^* + S_3^*} \end{aligned} \quad (4)$$

where E is an applied electric field across ZnO film; and S_1^* , S_2^* and S_3^* are the effective cross-section areas defined by:

$$\begin{cases} S_1^* = n_1 W_{Alt} t_{Alt} \\ S_2^* = n_2 W_{ZnO} t_{ZnO} \\ S_3^* = n_1 W_{Alb} t_{Alb} + n_3 W_{SOG} t_{SOG} + W_{SiN} t_{SiN} \end{cases} \quad (5)$$

$$\text{with } n_1 = \frac{E_{Al}}{E_{SiN}}, n_2 = \frac{E_{ZnO}}{E_{SiN}} \text{ and } n_3 = \frac{E_{SOG}}{E_{SiN}}.$$

Thus, M^* and I^* can be obtained by following equations:

$$\begin{aligned} M^* &= \frac{P_1}{2} n_2 W_{ZnO} t_{ZnO}^2 + \frac{P_2}{2} \{ n_3 W_{SOG} t_{SOG}^2 \\ &\quad + n_1 W_{Alb} [(t_{Alb} + t_{SOG})^2 - t_{SOG}^2] \\ &\quad + W_{SiN} [(t_{Alb} + t_{SiN} + t_{SOG})^2 - (t_{Alb} + t_{SOG})^2] \\ &\quad - n_1 W_{Alt} [(t_{Alt} + t_{ZnO})^2 - t_{ZnO}^2] \} \end{aligned} \quad (6)$$

$$\begin{aligned} I^* &= \frac{1}{3} \{ n_2 W_{ZnO} t_{ZnO}^3 + n_1 W_{Alt} [(t_{Alt} + t_{ZnO})^3 - t_{ZnO}^3] \\ &\quad + n_3 W_{SOG} t_{SOG}^3 + n_1 W_{Alb} [(t_{SOG} + t_{Alb})^3 - t_{SOG}^3] \\ &\quad + W_{SiN} [(t_{Alb} + t_{SiN} + t_{SOG})^3 - (t_{SOG} + t_{Alb})^3] \} \end{aligned} \quad (7)$$

But the deflection curvature of the cantilever bending ($1/R$) is

$$\frac{1}{R} = \frac{M^*}{E_{SiN} I^*} \quad (8)$$

For a cantilever array shown in Fig. 8, the cantilever deflection angle θ and the tip displacement Δy are:

$$\begin{cases} \theta = \frac{L_1}{R} \\ \Delta y = R(1 - \cos \theta) + (L - L_1) \sin \theta \end{cases} \quad (9)$$

where L and L_1 are the whole cantilever length and the portion of L that is covered by the ZnO, respectively.

For a cantilever with $L = 150 \mu m$ and $L_1 = 70 \mu m$, the deflection θ and the tip displacement Δy are calculated to be $0.06^\circ/V$ and $0.12 \mu m/V$, respectively.

The fundamental resonant frequency of the cantilever can be estimated by the following equation:

$$f_r = \frac{1.875^2}{2\pi l^2} \sqrt{\left(\frac{EI}{\rho A}\right)_{eff}} \quad (10)$$

where l , E , I , ρ and A are the length, the elastic modulus, the moment of inertia, the density and the cross-section area of composite cantilever, respectively. We typically design f_r to be about 150 kHz, much higher than the operation frequency.

DEVICE FABRICATION

A 40x40 array of ZnO actuated cantilevers (shown in Figs. 6 and 7) is fabricated on a silicon wafer with the fabrication steps illustrated in Fig. 5. The following is a brief description of the 7-mask process. After depositing Si_3N_4 for an electrical isolation, a doped LPCVD polysilicon is deposited and patterned for connecting bottom electrodes. A sacrificial layer of Spin-On-Glass (SOG) is then spin-coated and cured in two steps (at 400 °C for 20 min. and then 850 °C for one hour). Two types of SOG (SOG311 and SOG511 from Accuglass) are used as sacrificial layers for the thicknesses of 0.5 μm and 1 μm . After patterning the SOG for the anchor area, a cantilever supporting layer of 1300 Å thick low stress LPCVD Si_xN_y is deposited. After patterning the silicon nitride with an RIE for an electrical feedthrough window, a 1000 Å thick Al film is deposited by evaporation for the bottom electrode. Additional layer of 3000 Å thick Al is deposited for a step coverage. After spin coating a 1800 Å thick SOG (SOG111) for an electrical isolation, 4500 Å thick ZnO film is sputter-deposited. In a certain HF concentration, the lateral etch of ZnO by vapor HF is very slow, and the SOG111 can be patterned by vapor HF using the same photolithography that is used to pattern the ZnO so that we save one photolithographic step. Finally 800 Å thick Al is evaporated, and used as the top electrode, the reflective surface and the etch mask during the etch channel formation and removal of the sacrificial layer. The perspective view of the cantilever element is shown in Fig. 8.

Figure 5. Fabrication process of the cantilever array (cross-sectional views across A-A' in Fig.6).

Figure 6. Photograph of close-up top view of the piezoelectrically-actuated cantilever array for a projection display. Each pixel occupies 100 x 100 μm^2 area.

Figure 7. Photograph of the part of the fabricated 40 x 40 array of the piezoelectric cantilevers.

Figure 8. Perspective view of the cantilever array.

Vapor HF is used to release the cantilever. We have discovered that many materials have their unique critical HF concentration below which there is no etching by vapor HF. The critical HF concentration varies depending on a type of a material. As we can see in Fig. 9, Al is rarely etched at a sufficiently diluted vapor HF (i.e., 75 ml/min : 6 ml/min of N_2 : HF), while SOG is still highly etched. Thus, with that HF concentration, bare 800Å thick Al can be used as an etch mask during etching SOG to release cantilevers. This discovery has led us to a simpler processing with a higher yield. Specifically the delineation of the top electrode and the etch channel can be performed with one mask: this allows us to save one troublesome step of photoresist strip after the cantilever release. Also we do not have to reserve some margin for protecting Al during cantilever release, and the surface coverage of the reflective surface can be increased.

Figure 9. Etch rates of Al and SOG in vapor HF.

EXPERIMENTAL RESULTS AND DISCUSSION

The tip displacement of cantilever by an electrical input is measured with a laser interferometer. In order to distinguish piezoelectric response from thermal response, an electrical input of an unbiased square wave is applied to the cantilever, and a displacement response of a square-wave form is obtained from 0.1 Hz to as high as 25 kHz. The cantilever tips are observed to deflect about 0.19 $\mu\text{m}/\text{V}$ vertically in piezoelectric response to a 10V_{p-to-p} square wave of 10 Hz. Due to the relative high resistance of each cantilever element (above 100 M Ω), the thermal deflection is about 2 or 3 orders of magnitude smaller than the piezoelectrical response according to our theoretical calculations and experimental measurements. Therefore there is no thermal-enhanced deflection in our cantilevers, unlike those reported earlier [6]. A piezoelectric response of cantilever to a 10V_{zero-to-peak} square wave input at 50Hz is shown in Figure 10.

Figure 10. The cantilever-tip displacement (CH2) for a 50 Hz, 10 V_{zero-to-peak} square wave input (CH1).

Due to the relative narrow air gap underneath the cantilever, the air damping can reduce the vibrational amplitude of the cantilever significantly. For a cantilever with about 1 μm air gap, the vibrational amplitude in the upward direction is observed to be almost twice larger than

that in the downward direction. Indeed the frequency response of the cantilevers is dominated by the air gap distance which is determined by the thickness of the sacrificial layer. Typical frequency responses to a square wave with a 5V amplitude are shown in Figs. 11 and 12 for the cantilevers with the air gap of about 0.5 μm and 1 μm , respectively. If the cantilevers are initially deflected about 30°, the roll-off frequency can be as high as 10 kHz as shown in Fig. 13. Thus, the thickness of the sacrificial layer can be a design parameter to control the response time of the cantilever deflection.

Figure 11. Frequency response of tip displacement of the cantilever with a 0.5 μm high air gap.

Figure 12. Frequency response of tip displacement of the cantilever with a 1 μm high air gap.

Figure 13. Frequency response of tip displacement of the cantilever that is initially bent up about 30°.

Figure 14. The resistance of ZnO and thin SOG on a row of 40 cantilevers as a function of the magnitude of a 8 Hz square wave.

The cantilever has been observed to deflect linearly in the range of 1 - 10 V applied voltage.

The resistivity of ZnO film in the cantilever has been observed to change due to moisture as confirmed by the data shown in Fig. 14. The data marked with (1) in Fig. 14 are for the devices that have gone through the vapor HF release step, and show sharp drops of the ZnO resistance when the magnitude of the electrical input (8 Hz square wave) is higher than 3 V_{peak-to-peak}. With a post-processing baking of the devices at 80 °C for 2 hours, the resistance drop is non existing even with more than 20 V_{p-to-p} input, as can be seen in the data marked (2) in Fig. 14. The devices exposed to ambient moisture for about one week shows their ZnO resistance dropping sharply with 8 V_{p-to-p} input (see (3) in Fig. 15). Unless the ZnO is permanently damaged by too much current, the resistance drops due to moisture can be reversed with baking at 80 °C.

CONCLUSION

We have demonstrated feasibility of piezoelectric ZnO-actuated cantilevers for a projection display application. A complete fabrication processing for the cantilever arrays has successfully been developed, and used to fabricate working arrays of cantilevers (each array consisting of 40 x 40 cantilevers). Relatively large piezoelectric responses with good linearity have been observed.

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