Processing and Characterization of Piezoelectric Materials into MicroElectroMechanical Systems

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***Abstract*—The Pb(Zr, Ti)O_3 (PZT) based micro electro mechanical systems are presented. Piezoelectric effect, basic piezoelectric equations are explained. Lost silicon mold process for PZT microstructures, PZT thin film deposition, and PZT based piezoelectric micromachined switch device are discussed.**

***Index Terms*—PZT, Piezoelectric, MEMS, Micromachine.**

I. INTRODUCTION

THE past decade has seen the rapid growth of MicroElectroMechanical Systems (MEMS) as an important area of technology. Unique capabilities can be achieved by such integration to realize devices at very small scales such as sensors, actuators, power producing devices, chemical reactors and biomedical devices. [1]

Lead zirconate titanate ($Pb(Zr_xTi_{1-x})O_3$, PZT) is a ceramic material with superior piezoelectric properties that has found widespread applications in sensors, transducers, actuators, and electronic components. Exploiting the actuation method of piezoelectric effect is expected to lead to a substantial improvement in MEMS device performance.[2] In the following, a PZT microstructure processing method and applications of PZT thin film in micromachined switch will be introduced.

II. PIEZOELECTRIC EFFECT AND BASIC PIEZOELECTRIC EQUATIONS

When a mechanical force is applied, a piezoelectric material generates an electrical voltage, by the phenomenon called the direct piezoelectric effect. Conversely, when an electric field is applied, such a material induces mechanical stresses or strains, by the phenomenon called the converse piezoelectric effect.

$$\varepsilon = dE + S^E\sigma \tag{1}$$

$$D = d\sigma + \varepsilon^\sigma E \tag{2}$$

Basic piezoelectric equations are given above, where ε is the strain, d is piezoelectric constant, E is electric field, S^E is compliance, σ is stress, D is electric displacement, and ε^σ is dielectric constant.

III. LOST SILICON MOLD PROCESS FOR PZT CERAMIC MICROSTRUCTURES

In particular, when a pulsed electric field is applied, the piezoelectric material vibrates correspondingly and gives out an ultrasound beam at the same frequency; similarly, when an ultrasound wave arrives, the piezoelectric material responds and transforms the ultrasound into a corresponding electrical signal. By taking advantage of these effects, piezoelectric transducers have been developed for medical imaging. High performance transducers necessitate the fabrication of fine-scale high-aspect-ratio (height-to-width ratio) PZT rod arrays. Here, we report a new lost Si mold process for fabrication of PZT microrods.

A. Lost Si Mold Process

The lost Si mold process is schematically shown in Figure 1.

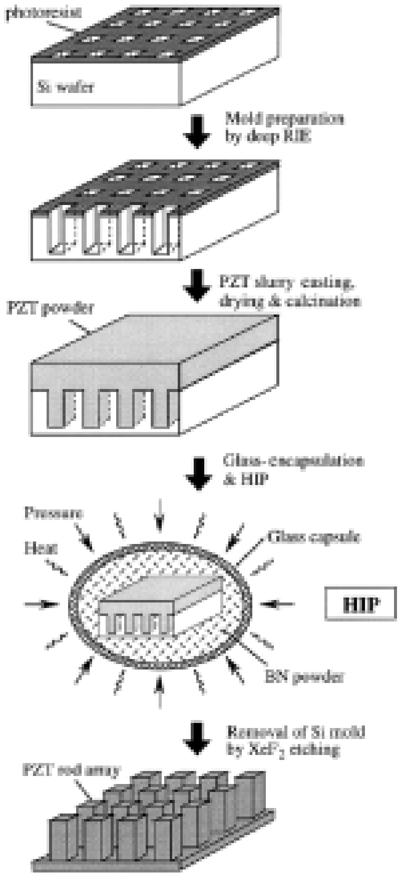

Fig. 1. Lost Si mold process

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First, photoresist windows are formed on Si wafer by using conventional photolithography technique; then, the sample is subjected to deep reactive ion etching (RIE) to form a set of deep vertical holes; after that, the remaining photoresist is dissolved away and a Si mold is obtained. The PZT slurry is cast into the Si mold with the help of ultrasonic agitation, then dried and calcined. The PZT-infiltrated mold is embedded into boron nitride (BN) powder, cold isostatic pressing (CIP) is performed at 100 MPa. The sample is then inserted into a Pyrex glass tube and sintered under isostatic pressures with argon (Ar) gas as a pressure transmitting medium. Peak values of the pressure and temperature are 200 MPa and 1100°C. Finally the PZT structure is released by removing the Si mold using xenon difluoride (XeF2) gas etching. [3,4]

B. *Results of the process*

The obtained PZT rods were 7 μm square in cross section with a 12 μm period (Figure 2). The resulting aspect ratio was more than 12.

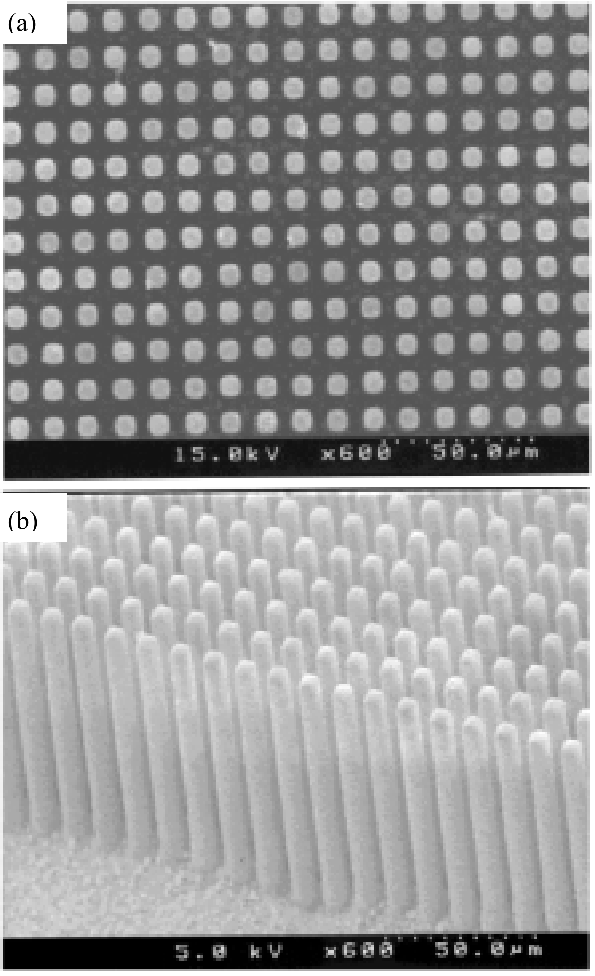

Fig. 2. SEM images of PZT microrod array: (a) top view, (b) side view.

As observed in Figure 2, in contrast to the conventional lost plastic mold technique, a perfect PZTrod array is available by the lost Si mold process without any structure deformation even when the rod width is as fine as 7 μm. [3]

C. *Advantages and Problems*

By taking advantage of the high melting point (1440°C) and high strength of Si, in-mold sintering of PZT structures under high pressures (HIP) has been realized. As a result, the obtained PZT structures can reflect the Si mold configurations exactly. Without pressing, however, it was difficult to fill PZT powder completely into the fine and deep holes even if methods such as vacuum impregnation and ultrasonic agitation were employed. The Si mold process supplies a high design flexibility for the PZT structures. And an additional advantage is that the Si mold can be used as a part of the device. Moreover, in this work, HIP of PZT was successfully conducted at a temperature as low as 800°C for the first time. As a result, the structural bending became almost negligible.

X-ray diffraction (XRD) analyses were performed on the PZT rods. It was shown that perovskite PZT was the major phase, at the same time, certain amounts of undesired pyrochlore-type PZT phase and free lead phase were also observed. Oxygen deficiency may be mainly responsible for the formation of pyrochlore-type PZT phase and lead phase, but it is believed producing the same dense PZT rods at lower temperatures by increasing the HIPing pressures may suppress the formation of undesired phases. [4]

The lost Si mold process has opened up new possibilities for fabricating complex PZT microstructures with fine-scale features, high aspect ratios, and high configuration design flexibility.

IV. PZT BASED PIEZOELECTRIC MICROMACHINED SWITCH

A. *Fabrication Procedure*

A PZT based micromachined switch has been developed with lower actuation voltages and faster switching speeds than electrostatic switches. A schematic representation of the design is shown in Figure 3.

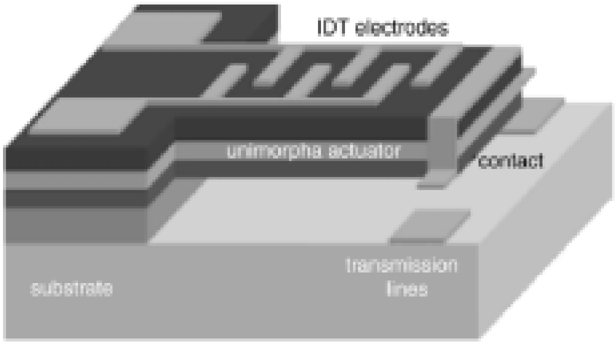

Fig. 3. Schematic illustration of micro-switch

Fabrication begins with an insulating oxidized silicon wafer. A sacrificial polysilicon (2 μm) is deposited by low-pressure chemical vapor deposition methods, and a thin thermal oxide (50 nm) is grown to act as a barrier layer. Low-stress (400 Mpa) silicon nitride (0.5 μm) is deposited as the structural material. A thin silicon oxide (50 nm) is sputter deposited to promote adhesion of the remaining layers with the nitride. A buffer layer of 0.3-μm zirconia and 0.23-μm PZT are spun on using sol-gel techniques. The material stack is then patterned using a combination of ion milling and reactive ion etching. The contact at the end of the cantilever is deposited by sputter deposition and patterned by lift-off. [6]

B. Tests of operation

The PZT thin film was poled and driven with interdigitated (IDT) electrodes to exploit the d_{33} coefficient for switching actuation. Figure 4 shows the switching response to a 1-Hz 0–20V square wave input superimposed on 10V dc. The oscilloscope trace demonstrates that the switch opens and closes concurrently with the applied signal.

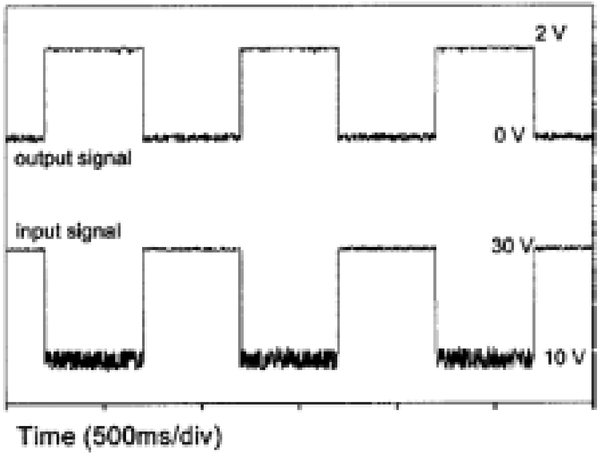

Fig. 4. Switching response (top) to a 1 Hz 20 V square wave (bottom).

Further tests were conducted to observe the switching behavior when actuated by short pulses. A 30-V 4-µs pulse and a 50-V 4-µs pulse were used as input signals, and the response results are given in Figure 5.

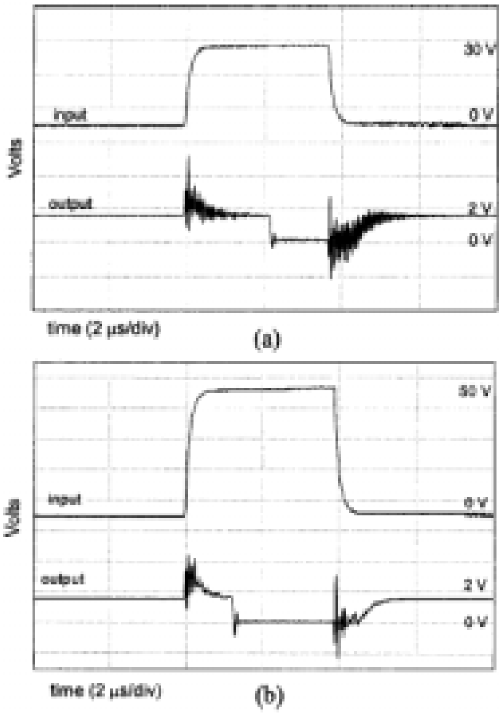

Fig. 5. Switching response to (a) 30-V and (b) 50-V 2-µs pulse.

As can be seen, the switching on time is decreased from 2.5 to about 1.5 µs, while the switching off time remains constant. Preliminary results have demonstrated that signals up to 100 MHz can be switched, with approximately 30 dB of isolation between the on and off states.

C. Discussion

A one-degree-of-freedom dynamic model is set for this system, The equation of motion is given as:

$$F = m\frac{d^2z}{dt^2} + b\frac{dz}{dt} + kz \tag{3}$$

where k is the spring constant of the cantilever, All forms of damping have been ignored, b=0. With the tip displacement and velocity set to zero as initial conditions, the particular solution is given as:

$$z(t) = z_0 - z_0\cos(\omega_n t) \tag{4}$$

The time required to close the gap(δ) between the contact and the transmission lines can be obtained from Eq.(4):

$$\tau_{on} = \frac{1}{2\pi f_0}\cos^{-1}(1-\frac{\delta}{z_0}) \tag{5}$$

The calculated τ_{on}=3.3µs for this device, which is comparable to the measured value. [5] Since z_0 is proportional to the driving voltage, the larger the driving voltage, the shorter τ_{on}, which is consistent with experiments. The turn-off time, however, is solely determined by the gap spacing and the natural frequency.

V. CONCLUSION

Piezoelectric materials have been successfully applied in a variety of MEMS applications. The development of fabrication methods such as PZT structural micromachining, low-stress silicon nitride deposition, and solution deposition of piezoelectric thin films has been essential. The MEMS applications described here compare favorably with other MEMS approaches based on commonly used electrostatic actuation. The continued promise for piezoelectric MEMS is attractive.

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