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Influence of secondary converse piezoelectric effect on deflection of fully covered PZT actuators

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ABSTRACT

This paper investigates the influence of secondary converse piezoelectric effect (SCPE) on the deflection of fully covered piezoelectric (PZT) actuators. An analytical model based on the theory of plates and shells as well as a finite element model (FEM) is developed to predict the deflection of the actuator with and without SCPE. Experimental results of the fabricated disc-type and ring-type thick-film PZT actuators agree with both analytical and FEM results. After the influence of SCPE is eliminated, the deflections of disc-type and ring-type actuators with 0.6 electrode radius ratio increase by ∼12.7% and ∼21.2%, respectively. Furthermore, the effects of the electrode size and PZT/Si thickness ratio on SCPE are investigated. The maximum influence of SCPE on deflection can be more than 20% for both types of actuators, which should not be neglected in practical applications.

1. Introduction

Piezoelectric unimorph actuators are commonly used in many engineering applications, such as micropumps [1–3], microspeaker [4], droplet ejector [5], energy harvesting [6], deformable mirror [7] and micro-transformer [8]. A conventional unimorph actuator at centimeter scale is usually fabricated by gluing a piezoelectric disc [9,10] or ring [11,12] to a passive layer, in which the piezoelectric layer (PZT) covers partially (see Fig. 1(a)). To realize the miniaturization and the batch fabrication of the piezoelectric actuators, micro-electromechanical systems (MEMS) technology has been used. The piezoelectric layer can be obtained using sol–gel, sputtering, screen-printing and PZT bonding [13]. It is noted that the PZT thick films in range of 10–100 μm are necessary for many MEMS devices because they can provide large force, high sensitivity, and broad working frequency range compared to thin films. Among these methods, the thickness of the PZT film formed using sol–gel and sputtering methods is usually limited to less than several microns [14]. The PZT thick film with patterns can be formed using screen-printing method easily [15,16]. However, the piezoelectric coefficient is low compared with that of bulk PZT ceramic due to its low sintering temperature and low density. Recently, bonding technologies of bulk PZT film to silicon wafer using an intermediate gold layer [17] or epoxy resin layer [18] have been developed for micro-device applications. Since the patterning of PZT thick film is an uneasy work, the actuator is usually fully covered with PZT film with only the top electrodes patterned (see Fig. 1(b)).

For the fabrication of the MEMS fully covered PZT actuator, the bulk PZT film is recommended to be polarized before device fabrication, which can reduce the polarization stress. For example, it is better to pole the PZT ceramics during the entire bonding process of PZT to Si using a gold layer to improve the bond strength [17]. Additionally, poling a whole PZT film before device fabrication is much easier than poling the fabricated device one by one. As a result of full-wafer poling, the secondary converse piezoelectric effect (SCPE) [19] existing in the actuator affects the actuator performance, which is described as follows: When the actuators, either a disc-type actuator or a ring-type actuator, are bended by being applied a voltage, the bending stress $\boldsymbol{T}$ in the unactuated part PZT induces an electric displacement $\boldsymbol{D}$ due to the piezoelectric effect. The electric displacement $\boldsymbol{D}$ generates an additional electric field $\boldsymbol{E}$. Then the electric field $\boldsymbol{E}$ generates an additional strain $\boldsymbol{S}$ to the original deflection generated by the drive voltage. The total process is $\boldsymbol{T} \rightarrow \boldsymbol{D} \rightarrow \boldsymbol{E} \rightarrow \boldsymbol{S}$. Though the SCPE has been researched theoretically and experimentally for a long time, the influence of the SCPE is rarely considered in practical devices [7,20,21]. This study focuses on the influence of the SCPE on the actuator deflection, based on which, the elimination can be applied to improve the deflection.

Toward this purpose, an analytical model based on the theory of plates and shells as well as a finite element model (FEM) was

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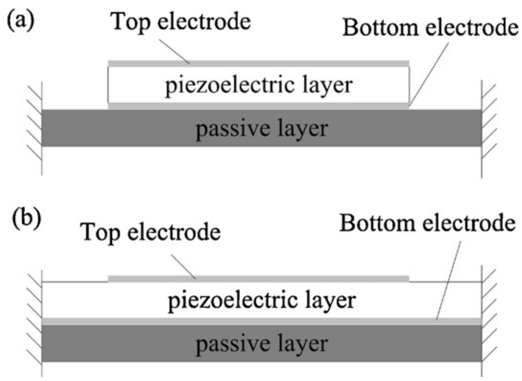

Fig. 1. Schematic drawing of piezoelectric unimorph actuator. (a) Partially covered actuator and (b) fully covered actuator.

developed to predict the deflections of an actuator with and without SCPE. Then the MEMS fully covered PZT actuators with both disc electrode and ring electrode were fabricated. The deflections with or without SCPE were measured and compared with both analytical and FEM results. Furthermore, the effects of the piezoelectric/passive layer thickness ratio and electrode size on SCPE were studied.

2. Method

2.1. Analytical model

The schematic diagrams of typical disc-type and ring-type fully covered piezoelectric unimorph actuators with fixed edge boundary are shown in Fig. 2. The whole PZT is polarized. The bottom electrode has an equal size of the actuator, while the top electrode is patterned to generate a disc electrode or a ring electrode. As shown in the figure, the disc-type actuator deforms concavely by applying a forward voltage; while the ring-type actuator deforms convexly.

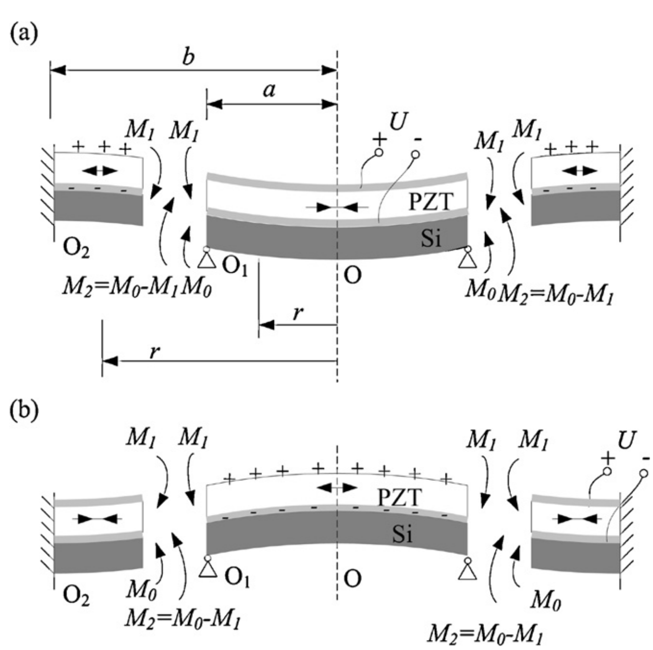

Fig. 2. Deflection of (a) disc-type actuator and (b) ring-type actuator. b, radius of the actuator; a, radius of the top electrode; M_0, moment caused by actuation of PZT; M_1, moment between two parts; M_2, equivalent moment applied on the central part. The arrows in PZT film represent the direction of generated stress. "+" and "−" on PZT surface indicate the generated electric charges.

Some analytical models based on the theory of plates and shells have been developed for disc-type [9] and ring-type [11] partially covered piezoelectric actuators. These models do not need to consider the influence of SCPE due to the patterned PZT layer. We develop this approach to predict the deflections of the fully covered actuator with and without SCPE. This approach makes use of Kirchhoff's assumption for thin plates which requires the radius-to-thickness ratio to be at least 10. Another simplification is to ignore the bonding layer effects on the actuator performance. In a similar research on the partially covered PZT actuator [9], it is found that increasing the bonding layer will reduce the deflection. But this effect is not significant when PZT/passive layer thickness ratio is beyond 0.4. Furthermore, as for disc-type and ring-type actuators presented in this study, the bonding layer thickness is very small. Therefore, it is reasonable to adopt this simplification.

According to the theory of plates and shells, there exists a neutral surface that does not have transverse strain or radial strain. The location of this neutral surface is found to be:

$$h_n = \frac{1}{2}\frac{E_{si}h_{si}^2/(1-\nu_{si}^2) + E_{pzt}(h_{pzt}^2 + 2h_{si}h_{pzt})/(1-\nu_{pzt}^2)}{E_{si}h_{si}/(1-\nu_{si}^2) + E_{pzt}h_{pzt}/(1-\nu_{pzt}^2)}, \quad (1)$$

where E_{pzt}, ν_{pzt} and h_{pzt} are the Young's modulus, the Poisson ratio and the thickness of the PZT layer, respectively. E_{si}, ν_{si} and h_{si} are the Young's modulus, the Poisson ratio and the thickness of the silicon layer, respectively.

The actuator is divided into two parts: the disc part (simply supported at $r=a$) and the ring part (fixed supported at $r=b$). The deflections of these two parts relative to the supporting point O_1 and O_2 are calculated using the following equations, respectively:

$$w_1(r) = \frac{M_0(b^2-a^2)(a^2-r^2)}{4D_e b^2}, \quad (0 \le r \le a), \quad (2)$$

$$w_2(r) = \frac{M_0 a^2[(r^2-b^2) - 2b^2\ln(r/b)]}{4D_e b^2}, \quad (a < r \le b). \quad (3)$$

Here, M_0 is the moment caused by the actuation of the PZT. The moments M_0 of the disc-type actuator and the ring-type actuator are contrary, which can be calculated using the following equations, respectively:

For a disc-type actuator,

$$M_0 = f_1 d_{31} U, \quad (4a)$$

For a ring-type actuator,

$$M_0 = -f_1 d_{31} U, \quad (4b)$$

where $f_1 = \dfrac{D_e/h_{pzt}}{(h/2)(2/h)((1/E_{pzt}h_{pzt}) + (1/E_{si}h_{si}))(D_{pzt}+D_{si})}$.

In Eqs. (2)–(4) a and b are the radius of the top electrode and the actuator, respectively, h is the total thickness of the actuator, D_e is the equivalent flexural stiffness of the actuator, D_{pzt} and D_{si} are the flexural stiffness of PZT and silicon layer, respectively, d_{31} is the transverse piezoelectric coefficient of the PZT film, U is the voltage applied on the PZT.

The deflection profiles without SCPE can be calculated according to Eqs. (2)–(4) for a disc-type actuator and a ring-type actuator. And the total deflection at the central point O of the actuator is:

$$w_o = -\frac{M_0 a^2 \ln(a/b)}{2D_e}. \quad (5)$$

Then the voltage generated on unactuated PZT can be calculated. Since the strain distribution across the thickness