Characterization of PZT thin films for micromotors

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Abstract

Piezoelectric membranes consisting of sputter deposited $PbZr_xTi_{1-x}O_3$ (PZT) films on silicon diaphragms have been investigated for their resonance and piezoelectrical properties, in view of their application as stator of a micromotor. The behavior of resonance frequencies was studied as a function of membrane thickness and dc-bias, in order to derive the total stress in the films and the piezoelectric coupling constant ($d_{31} \approx 40$ pm/V). The latter was also derived from the quasi-static deflections.

1 Introduction

Ultrasonic motors are considered to be superior to other types of micromotors for down scaling [1]. The fabrication technology has to be adapted to the small dimensions, though. One possible approach is a so-called hybrid micromotor, where the stator consists of a piezoelectric thin film on a micro-machined silicon diaphragm. The rotor is fabricated by rather classical means and added in an assembly step.

The first well working PZT ($PbZr_xTi_{1-x}O_3$) thin film micro motor has recently been demonstrated by the authors [2]. The motor was a hybrid type with an elastic fin rotor, proposed by Kurosawa et al.[3,4] for down scaling, and whose micromechanical version was first realized by Racine et al. [5] with ZnO thin films. As expected, the speed of PZT micromotors as compared to ZnO micromotors is 4 to 6 times higher at a given voltage, which roughly corresponds to the ratio of the piezoelectric e_{ij} coefficients. The motor could be operated with voltages as low as 1.0 Vrms, which is sufficiently low for standard battery and IC supply voltages. Yield and reliability of the stator membranes turned out to be quite good and first degradation tests under operating conditions revealed a decrease in amplitude of 5 % in 100 hours [6].

In this work results on the characterization of sputtered thin film PZT actuated stator membranes are reported. For design and simulation of the motor the behavior of the membrane should be predictable. The resonance frequency was therefore measured for different thicknesses of diaphragms. The effect of dc-bias on resonance frequencies and quasi static deflections was studied and the piezoelectric coefficient d_{31} was deduced.

2 Fabrication

The piezoelectric thin film stator was micro machined out of a 3" silicon wafer. Apart from the remaining silicon, the diaphragm consisted of SiO_2, Si_3N_4, and PZT films. The structure was made as simple as possible and is shown schematically in Fig. 1. The electrode below the PZT film (bottom electrode of Pt/Ta) was not structured. Contact pads, conductor lines and top electrodes were patterned from the same aluminum film, deposited directly on the PZT layer. Details of the fabrication have been reported elsewhere [2]. The sputter deposited PZT film of the present study had a composition of 45/55, (100) texture, and was grown on a 30 nm $PbTiO_3$ template at about 600 °C [7].

Three sizes of circular membranes with diameters of 2, 4 and 8 mm have been fabricated. Top electrodes of half the diameter of the membrane allowed excitation of the ground mode B_{00} as well as the B_{10} mode with one circular node.

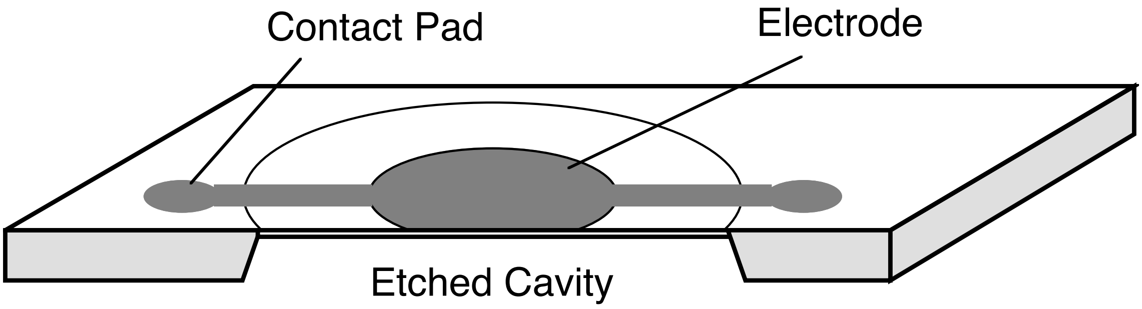

Figure 1. Schematic drawing of the membrane with view onto the top side of the wafer.

3 Characterization

3.1 Resonance frequencies and film stress

The membrane deflections as a function of the excitation frequency have been measured by means of optical interferometry [8]. Resonance amplitudes of up to 1.1µm/V have been found (ground mode (B00) at 53 kHz with a 16 µm thick, 2 mm wide membrane covered with 0.6 µm PZT). The symmetry of the modes has been determined by mapping the nodal lines with quartz powder (Chladni figures). For not too small thicknesses, our membranes are in principle well approximated by the model for thin clamped circular disks, for which exact values of the resonance frequencies are available [9]. In the limit of zero thickness, pure membrane behavior should be observed. Also in this case the resonance frequencies are tabulated [9]. The spectrum of the same 2 mm membrane was measured for different silicon thicknesses. A crossover from membrane to disk behavior has been observed (Fig.2). For curve fitting a first order perturbation calculation (Rayleigh-Ritz method) was applied:

$$\omega_{nk}^2 = \frac{\lambda_{nk}^4}{\mu \cdot a^4} \cdot \left\{ \frac{E_i \cdot h_i^3}{12(1-\nu_i^2)} \right\} + \frac{x_{nk}^2}{\mu \cdot a^2} \cdot S$$

As λ and x coefficients the unperturbed values have been taken, except for λ_{00}, which had to be slightly increased by 3%, accounting probably for inaccurate geometry. The elastic energy term in the brackets {} and the mass density µ are the exact values [11] for the three layer situation Si - (SiO_2, Si_3N_4, Pt) - PZT. S is the sum of the products of film stress times film thickness. The curve fit yielded an average film stress of 80 MPa (tensile), which is a rather low value.

3.2 Resonance frequency shift

When a dc field parallel to the polarisation is added to the ac field, the resonance frequency is shifted to higher frequencies. The piezoelectric stress, which is tensile in this case, adds to the stretching forces of the film stresses. For antiparallel fields (smaller than the coercive field) the resonance frequency decreases. Due to the hysteresis of polarization a "butterfly" figure is obtained (see fig. 3). The stress in the membrane plane (x,y) for a clamped film in x and y directions, and free in z direction, is obtained as:

$$\sigma_x(E_3) = \sigma_y(E_3) = -\tilde{e}_{31} \cdot E_3$$

$$\tilde{e}_{31} = \frac{d_{31}}{s_{11}^E + s_{12}^E} = \left(e_{31} + \frac{s_{13}^E \cdot e_{33}}{{}_{11}^E + s_{12}^E} \right)$$

(s: elastic compliance, E_3: electric field). Note that the effective coefficient is larger than e_{31}, because of the anisotropic clamping situation (on the other hand, the effective d_{33} is smaller [12]). The potential energy for a stretched circular membrane has been calculated for the exact deflection functions of the circular disk and added to the disk energy as a first order perturbation term (Rayleigh-Ritz method). Since our electrode has only half of the circumference of the membrane, only half of the piezoelectric stretching force adds to the film stretching forces.

As a result, d_{31} values of -55 pm/V (13 µm) and -45 pm/V (22 µm) have been obtained (taking bulk values for the elastic constants). This is about 50 % of the bulk ceramic value (undoped PZT). Fig. 3 shows that the best operating conditions are between -8 to +2 V, where d_{31} is nearly constant.

3.3 Static deflections

The deflection at quasi static frequencies also allows to calculate the piezoelectric coefficient. The bending moments

$$M_x = M_y = M = \sigma(E_3) \cdot t_p \cdot \frac{h}{2}$$

(t_p: thickness of piezoelectric film, h: thickness of silicon) bend the membrane at the site of the electrode. The problem is best solved by the so called energy method, i.e. by minimizing the potential energy with suitable test functions [10]. The energy consists of tree parts: U_{el} is the elastic energy due to the bending of the disk, U_M is the work done by the piezoelectric moment M, and U_S is the stretching energy due to the (tensile) film stresses.

$$U_{el} = \frac{1}{2} D \int_0^a 2\pi r dr \times$$

$$\left[\left(\frac{d^2 w}{dr^2} + \frac{1}{r}\frac{dw}{dr} \right) - 2(1-\nu)\frac{1}{r}\frac{dw}{dr}\frac{d^2 w}{dr^2} \right]$$

$$D = \frac{E \cdot h^3}{12(1-\nu^2)}$$

$$U_M = \frac{1}{2} M \int_0^{a/2} 2\pi r dr \cdot \left(\frac{d^2 w}{dr^2} + \frac{1}{r}\frac{dw}{dr} \right)$$

$$U_S = \frac{1}{2} S \int_0^a 2\pi r dr \cdot \left(\frac{dw}{dr} \right)^2 , \quad S = \sigma_f \cdot t_f$$

(E and ν: elastic modulus and Poisson ratio of silicon 100, σ_f and t_f: average film stress and total film thickness.) The following function was taken as test function:

$$w(r) = \begin{cases} \gamma \cdot \left(2\ln 2 \cdot a^2 - 3 \cdot r^2 \right) & , r \le \frac{a}{2} \\ \gamma (r^2 - a^2 - 2 \cdot a^2 \cdot \ln(r/a)) & , r \ge \frac{a}{2} \end{cases}$$

The two parts obey the differential equation for disks with zero lateral forces ($\Delta\Delta w = 0$), have a constant Δw, and have the right boundary conditions for clamping at r = a. The minimum condition $dU/d\gamma = 0$ yields the optimal value for γ:

$$\gamma = \frac{1.5 \cdot M}{2.55 * a^2 * S + 48 \cdot D}$$

The deflections of a 13 µm membrane with known stress (S = 120 N/m) have been measured at 1 kHz as a function of the applied dc bias voltage (s. fig.4). Figure 4 can be considered as a differential d_{31} loop. Values for d_{31} of 41 pm/V in saturation, and 35 pm/V at zero field with negative poling were obtained. These values are thus within 20 % of the results obtained with the resonance frequency shift method. Without considering the stress of the films, a value of 33 instead of 41 pm/V is obtained. A larger membrane with 4 mm diameter and 20 µm thickness, with the same sputtered film, was also evaluated . The poled film yielded a d_{31} of 40 pm/V at zero field.

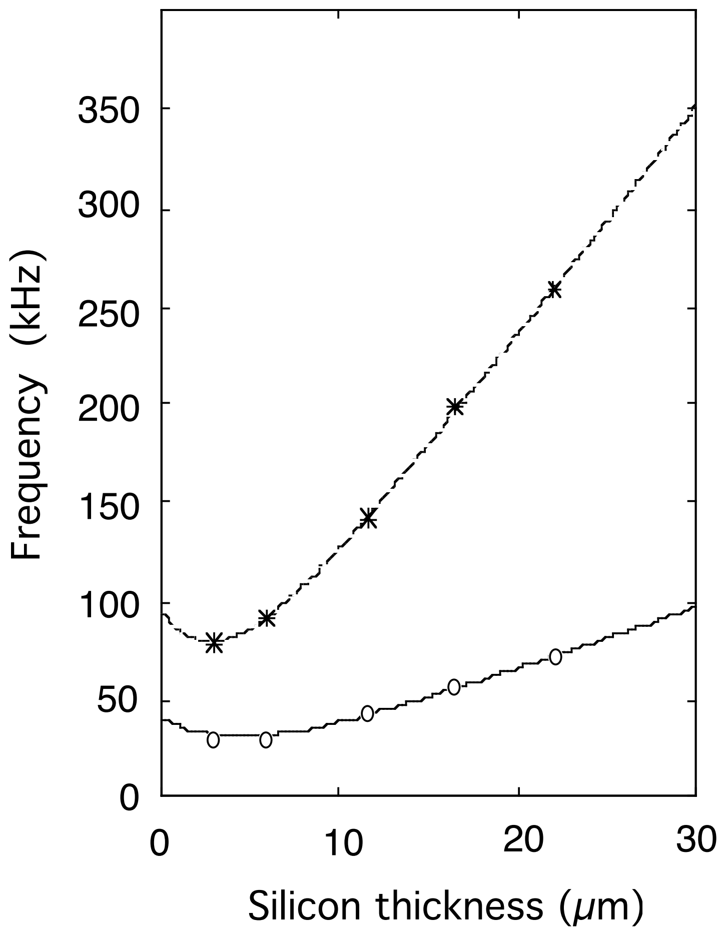

Figure 2. Resonance frequencies as a function of the silicon thickness of 2 mm diameter diaphragms with sputtered PZT films. The curve fit is discussed in the text.

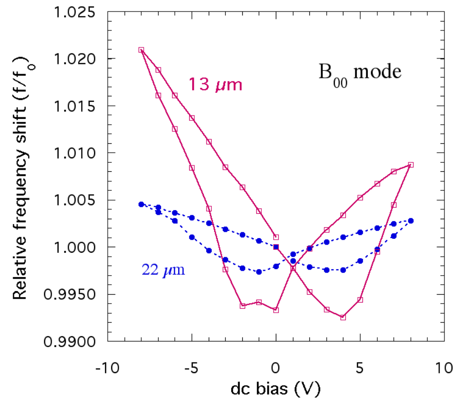

Figure 3. Frequency vs. dc bias loops for two thicknesses of 2 mm diameter diaphragms with sputtered PZT films. Same wafer as for fig. 2.

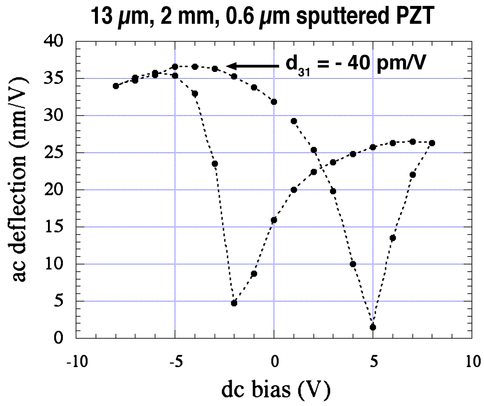

Figure 4. Interferometric measurements of membrane deflections as a function of dc bias. Sample of the same wafer as used for fig. 2.

Figure 3 and 4 illustrate the asymmetry of our PZT films. They exhibit a preferred direction of polarisation, which requires a negative bias to the top electrode for poling. The advantage of an asymmetry is a larger piezoelectric (and pyroelectric) signal at low fields.

4 Conclusions

PZT activated membranes could be characterized with respect to eigen frequencies, film stress, and piezoelectrical coupling strength. The behavior was analyzed by means of simplified calculations. The different experiments show consistent results.

Acknowledgements

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