Effect of Geometric and Material Nonlinearities on the Dynamic Behaviour of PMUTs

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Summary. The general architecture of most piezoelectric MEMS tranducers involves less than a micron thick piezoelectric film which leads to very high operating electric fields even at nominal input voltages. Hence the operation of these transducers is limited by geometory and material induced nonlinearities. In this work we present the non-linear dynamical effects induced by high electric field operation on the vibrational behaviour of Piezoelectric Micromachined Ultrasound Tranducers (PMUTs). We categorize these nonlinear effects into geometrical type and material type based on their source. The geometrical nonlinearities are found to induce duffing oscillator type behaviour which has been expalined theoretically using Von-Karman plate model for multilayerd circular plate under piezoelectric loading.

Introduction and Background

This work explores nonlinear vibrations of Piezoelectric Micromachined Ultrasonic Transducers (PMUTs). While the electrostatic softening induced nonlinearities in capacitive type MUTs have been explored extensively, nonlinear vibrations and the limitations imposed by such nonlinearities on the operation of piezoelectrically driven unimorph structures such as PMUTs are not well understood yet [1][2][4]. The transduction pressure generated by a PMUT is limited by the maximum actuation voltage and hence either by the coercive electric field or the geometrical nonlinearities [2][3]. Understanding the limitations imposed by these nonlinearities will help in development of better designed transducers that can generate higher acoustic pressures by reliable operation in nonlinear regime or by avoiding the nonlinearity imposed constraints.

Device Architecture

Our PMUT device is essentially a multilayer clamped circular plate of 1 mm diameter and 1.6 µm thickness. The various layers involved in the stack are SiO_2 (300 nm), Pt/Ti (100 nm), PZT (1µm) and Au (150 nm) from bottom to top (refer to figures 1(a) and 1(b)). The structure is found to carry an overall 130 N/m mean residual tension due to residual stresses in various thin films of the material stack thus leading to a dominantly membrane type behavior. Fabrication steps followed to obtain these structures involve deposition of various layers on a silicon wafer followed by top side lithography, top side electrode deposition using sputtering, backside alignment and lithography, RIE etching, and Deep Reactive Ion etching for suspending the membranes. For obtaining the optimal deflection sensitivity the top electrode is patterned such that it covers only 65% of the suspended membrane size. Application of sinusoidal voltage between the Au top electrode and Pt bottom electrode leads to an alternating bending moment at the edge of the top electrode which in turn leads to out-of-plane vibrations of the multilayered structure.

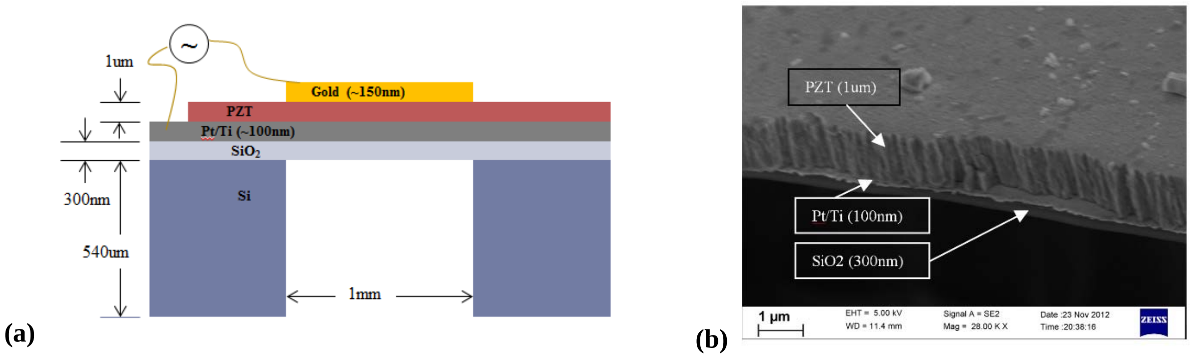

Figure 1: Structure of the PMUT: (a) Schematic cross-section showing the thicknes and size of various layors of the suspended unimproph, (b) SEM micrograph of the cross section of the PMUT membrane after DRIE release.

Experimental and Theoretical Observations

The in-air vibrational characteristics of the PMUT have been captured using a Laser Doppler Vibrometer (LDV). The first natural frequency is found to be approximately 75 kHz and it has been found to match closely with the expected theoretical value. The steady state vibrational behavior of the PMUT has been studied using peak hold method wherein the input actuation frequency is swept very slowly in a 10 kHz band centered at 75 kHz and steady state vibration amplitudes are captured at very small frequency differences across the band.

The PMUT starts showing nonlinear behavior when operated above 5 V at its resonance (Figure 2(a)). As the actuation voltage is increased above 5 V, geometrical nonlinearity induced stress stiffening leads to an increase in the resonant frequency. Figure 2(a) also shows the steady state vibrations of the PMUT in response to the forward frequency sweep (increasing from 70 kHz to 80 kHz) and reverse frequency sweep (decreasing from 80 kHz to 70 kHz). For operation at 7V and 8V the *jump* phenomenon is clearly observed during forward and reverse frequency sweeps near 76 kHz and 75.3 kHz respectively. This vibrational behavior is typical of a Duffing type oscillator. The Duffing oscillator model for the PMUT has been obtained analytically by using method of multiple scales to expand Von-Karman plate model of the multilayered pre-stressed PMUT [1]. The model is able to accurately predict the onset of stress-stiffening induced bending in the backbone curve and non-linear deflection amplitudes as shown in figure 2(b).

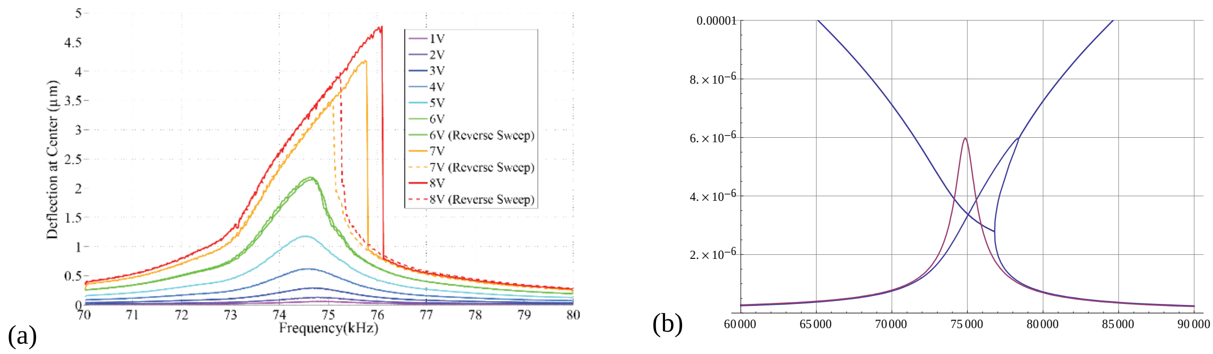

Figure 2: Duffing oscillattor behaviour of a PMUT: (a) Experimentally captured frequency response of the PMUT showing jump phenomenon when actuated at high voltages (above 6V) (b) Analytically obtained solution for the frequency response of a PMUT with and without consideration of geometric non-linearities during large amplitude vibrations.

Another unique observation presented in this work is on the transient behavior of PMUT vibrations in response to electric field with amplitude higher than or very close to the coercive electric field. Unlike the low voltage operation where steady state vibrations are achieved very quickly, large deflections are found to build-up slowly in the PMUT for high voltage operations. As shown in figure (3) these vibrations build up to as high as a center deflection amplitude of 5 µm followed by a sudden reduction by almost an order of magnitude. We believe that this reduction in amplitude of vibration of PMUT membrane is because of piezoelectric fatigue or de-poling in presence of high amplitude alternating electric fields.

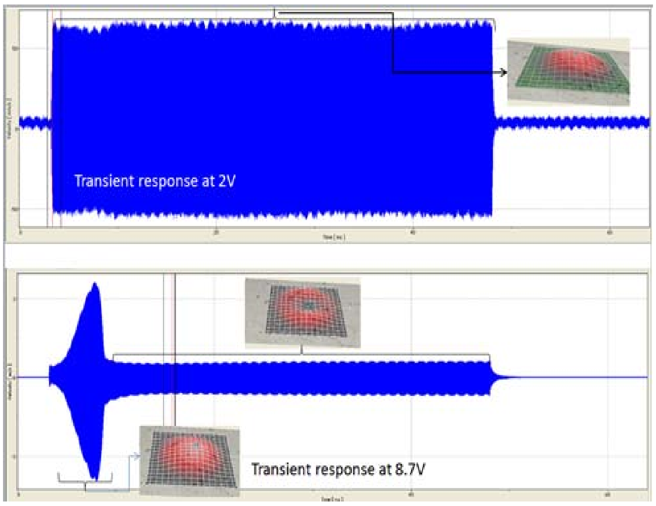

Figure 3: Comparision of transient response of PMUT under low voltage (2V) and high voltage (8.7 V) (close to coercive electric filed) conditions. While low voltage operation quickly acheives steady state vibrations, high voltage operation shows very high deflections followed by a drop due to material non-linearities.

References

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