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DC Voltage Induced Parametric Potential Energy Modulation in Bistable Piezoelectric MEMS Membranes

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Summary:

This paper explores the potential energy modulation of bistable PiezoMEMS membranes via stress tuning. The static deflection of the membrane is tuned by applying DC voltage, while external air pressure enables load-deflection measurements for the potential energy analysis. The effect of DC on the membrane is closely related to the membrane's stress and its initial static buckling height. Membranes that are already buckled and exhibit bistability demonstrate minimal changes when subjected to DC. In contrast, membranes that are buckled but remain monostable exhibit a significant response to DC.

Keywords: Bistability, Piezo, Membranes, potential energy, parametric.

Motivation and Objective

Bistable PiezoMEMS membranes are attractive for energy-efficient solutions, featuring two stable mechanical states [1,2]. However, the ability to precisely measure and control the potential energy landscape of these structures is a challenge. Hence investigating the influence of external factors like voltage and pressure on these membranes opens a new door for enabling tunable and adaptive bistable PiezoMEMS systems. Understanding how these factors interact with the membranes' properties can provide deeper insights into optimizing device performance and reliability.

The main objective of this research is to find the potential energy landscapes of PiezoMEMS membranes and investigate how their potential can be modulated by tuning the mechanical stress of the membrane by a DC voltage. With this approach, we are trying to establish a parametric correlation between the applied DC voltage and the membrane's potential landscape which helps to provide insights into dynamic stress control of bistable PiezoMEMS membranes. This approach is attractive for stress-modulated applications like varifocal MEMS mirrors [3].

Methodology

The silicon PiezoMEMS bistable membranes with diameters ranging from 600 to 800 µm and a thickness of ~3.43 µm were fabricated according to standard MEMS fabrication processes. The membrane has a stacked structure with a piezoelectric layer sandwiched between top and bottom electrode layers. Aluminum nitride (AlN) serves as piezoelectric layer whose stress is tuned to achieve the compressive stress needed to induce membrane buckling. Air pressure (both positive and negative) is applied as an external force perpendicular to the membrane surface (always from below the membrane) to conduct load-displacement measurements. Simultaneously, a DC voltage is applied to the system. The static deformation of the membrane under varying air pressures and applied voltages is measured with White Light Interferometry (WLI) (see Fig. 1).

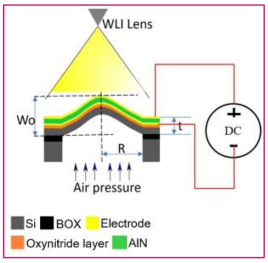

Fig. 1 Schematic of the measurement setup for DC voltage-induced parametric potential energy modulation in bistable piezoelectric MEMS membranes.

The parametrically modulated potential is derived from the load-deflection data corresponding to each applied voltage. To achieve a static buckling height ($w_0 > 0$), the membrane must exhibit compressive residual stress that exceeds its characteristic critical stress σ_c [1] given by eq. (1),

$$\sigma_c = -\frac{4 \cdot E_{eff} \cdot t^2}{3 \cdot R^2 \cdot (1 - \nu_{eff}^2)} \quad (1)$$

where E_{eff} represents the effective biaxial Young's modulus of the membrane, t is the

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membrane thickness, R denotes the membrane radius, and ν_{eff} is the effective Poisson’s ratio.

Results

The stress within the whole wafer varied from the center to the edge of the wafer (see Fig. 2. (left)) resulting in the maximum static buckling height in the edge regions of the wafer ($\sigma_0 \approx 65$ MPa $\approx 3\sigma_c$), while the minimum was observed at the center ($\sigma_0 \approx 20$ MPa $\approx \sigma_c$), (see Fig. 2. (right)), marked as regions A, B, and C.

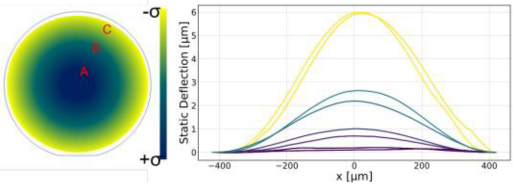

Fig. 2. Typical representation of stress variation in membranes across a wafer (left) and initial static buckling height of membranes with respect to its location on the wafer (right).

Experimental findings have shown that the effect of DC voltage on piezo membranes is strongly correlated with the initial stress and stiffness of the membrane. When DC voltage was applied, membranes in region A, which experienced minimal or no buckling, exhibited a negligible response, even when voltages as high as 60 volts were applied. This suggests that the voltage induced stress is not sufficient to achieve an effective membrane stress above σ_c. On the other hand, membranes in region C, which are highly buckled and exhibit bistability, also demonstrated only small changes in their static deflection (approximately 50 nm for 10 volts). This is because their mechanical stiffness has increased due to the buckling, making it more difficult to further deform the membrane. However, membranes in region B, the intermediate stress region, which are buckled but can remain only in one state, showed significant changes in buckling height when DC voltage was applied, approximately 500 nm for 10 volts (see Fig. 3 (top)). This is because the compressive stress in this region is still moderate, and the mechanical stiffness remains within an optimal range, allowing the voltage induced stress to effectively induce further deformation. These findings also open up new possibilities, where selectively adjusting the stress can transform a monostable membrane into a bistable one or modulate the deflection profile for tunable applications.

The potential energy of these membranes (see Fig. 3) was found from load-displacement measurements by applying air pressure steps *of* 30 mbar*,* generating forces that are orders of magnitude higher than those due to the applied DC voltage. Therefore, the distinct contribution of the DC voltage in the potential curves is "washed out" by the dominant air pressure effect.

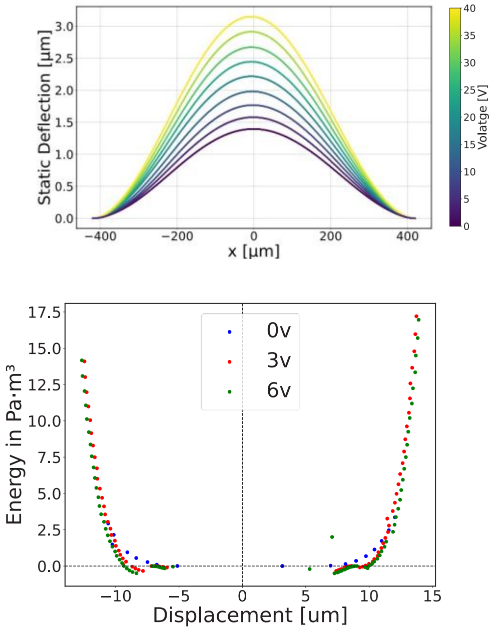

Fig. 3 DC Voltage response of a buckled monostable membrane from region B (top) and potential landscape of a buckled bistable membrane from region C (down).

Even if the membranes exhibited a linear response with DC voltage, under combined loading (air pressure + DC), air pressure induces larger deflections. But, in addition, their effective stiffness values increase and this minimizes the distinct contributions of the DC voltage to deflection and hence, we see minimal or even no changes in the potential profiles under DC voltage. To address this, membranes capable of withstanding higher DC voltages to achieve maximal deflection changes, while employing finer air pressure steps in the range of 1 mbar will help to capture parametric potential modulation accurately.

Acknowledgment

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