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A theoretical and experimental comparison of 3-3 and 3-1 mode piezoelectric microelectromechanical systems (MEMS)

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ABSTRACT

Two piezoelectric transducer modes applied in microelectromechanical systems are (i) the 3-1 mode with parallel electrodes perpendicular to a vertical polarization vector, and (ii) the 3-3 mode which uses interdigitated (IDT) electrodes to realize an in-plane polarization vector. This study compares the two configurations by deriving a Norton equivalent representation of each approach – including expressions for output charge and device capacitance. The model is verified using a microfabricated device comprised of multiple epitaxial silicon beams with sol–gel deposited lead zirconate titanate at the surface. The beams have identical dimensions and are attached to a common moving element at their tips. The only difference between beams is electrode configuration – enabling a direct comparison. Capacitance and charge measurements verify the presented theory with high accuracy. The Norton equivalent representation is general and enables comparison of any figure of merit, including electromechanical coupling coefficient and signal-to-noise ratio. With respect to coupling coefficient, the experimentally validated theory in this work suggests that 3-3 mode IDT-electrode configurations offer the potential for modest improvements compared against 3-1 mode devices (less than 2×), and the only geometrical parameter affecting this ratio is the fill factor of the IDT electrode.

1. Introduction

Two common modes of piezoelectric transduction applied in microelectromechanical-systems (MEMS) are the 3-1 and 3-3 modes. Fig. 1(a) provides an example schematic of each in which a piezoelectric material resides above a passive bending structure. In Fig. 1(b), horizontal strain in the film creates an electrical field in the vertical direction. In a sensor configuration, the electric potential resulting from the electric field may be read across the metallic electrodes which run parallel to the film as depicted in Fig. 1(b), or alternatively, charge shuffling between the electrodes may be measured in a short-circuit measurement configuration. Fig. 1(c) presents an example of a 3-3 mode device, in which case a set of interdigitated (IDT) electrodes may be used to directly measure the in-plane horizontal strain. As noted in Fig. 1(c), the direction of the polarization vector alternates between each IDT cell. This alternating polarity can only be accomplished with ferroelectric materials, which are poled after deposition. For non-ferroelectric materials such as AlN, crystal direction is aligned during deposition.

IDT electrodes patterned on top of piezoelectric layers have been used for surface acoustic-wave generation for many years [1]. 3-3 extension mode (i.e., non-bending mode) configurations have also been realized using IDT electrodes patterned on both sides of piezoelectric wafers, thereby realizing a wafer-level version of a piezoelectric "stack" [2,3]. Use of IDTs in "bender" applications as summarized in Fig. 1(c) has also been demonstrated. Bending or "bender" configurations refer to those in which the S_{beam} strain labeled in Fig. 1 results from bending as opposed to net extension of the beam or plate. Kugel et al. [4] modeled and compared 3-3 mode benders using IDTs against more traditional 3-1 mode benders. An experimental comparison of several different bender configurations followed in [5], with emphasis placed on a force-generation figure of merit. With respect to bending applications, 3-1 mode devices are historically more common in MEMS and have been used in many applications including accelerometers [6,7], microphones [8,9], atomic force probes [10,11], and energy harvesters [12,13]. Bernstein et al. [14] used 3-3 mode bending in an immersion ultrasonic transducer application. An IDT electrode was patterned above a sol–gel deposited lead-zirconate-titanate (PZT) layer residing on a passive polyimide diaphragm. The use of IDT 3-3 mode in this application enabled the capacitance of the sensors to be tailored by the spacing between electrodes, rather than relying on the

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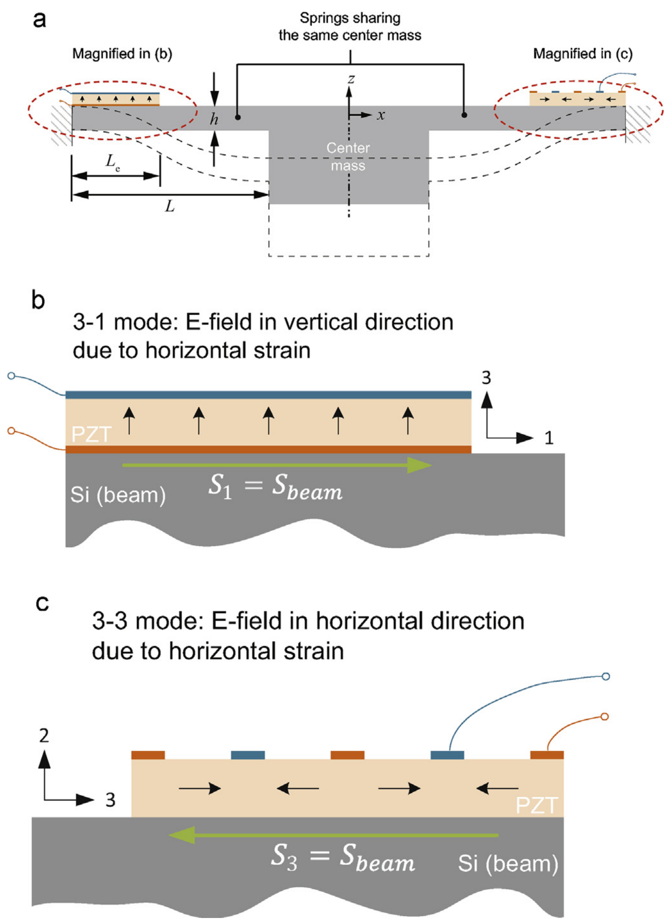

Fig. 1. Schematics of (a) piezoelectric elements on a passive bending structure, (b) 3-1 mode operation, and (c) 3-3 mode operation.

thickness of the piezoelectric film as in the case of 3-1 mode benders. The small capacitance afforded by the 3-3 mode IDT configuration (~0.25 pF) was an advantage for impedance matching the sensor to readout electronics. With respect to MEMS, a second advantage, as cited by Xu et al. [15], is reduction of fabrication steps since depositing and patterning bottom electrodes are not required. In an energy harvesting MEMS application, Jeon et al. [16] used cantilevers with 3-3 mode IDT electrodes and cited an advantage over 3-1 mode benders for the harvesting application: the ability to achieve larger output voltages for overcoming threshold voltages in rectification electronics.

Comparisons between 3-3 mode and 3-1 mode benders have been made, but these have typically focused on a single figure of merit. Several macro-scale (non MEMS) commercial elements were experimentally compared for battery-charging applications [17,18]. More recently in a MEMS energy harvesting application, Kim et al. [19] fabricated 3-3 mode (IDT electroded) and 3-1 mode (parallel electroded) cantilevers of similar size and volume, and compared output power extracted from each beam. Yu et al. [20] and Wang et al. [7] present results from both 3-3 mode and 3-1 mode PZT MEMS accelerometers in two separately published works. A similar fabrication process was used in each case, and it was noted that 3-3 mode IDT configurations have potential to achieve small signal-to-noise ratio (SNR) improvements over 3-1 mode devices of similar size. Mo et al. [21] provide a theoretical comparison between IDT and 3-1 mode devices. The analysis is general and not limited to thin films, and no experimental results are presented.

In this work, the approach to modeling, while still being routed in the fundamental piezoelectric equations, is different than previously presented. Norton equivalent network models of single 3-3 and 3-1 mode cells are presented, and the results are then extended to full-length electrodes using a parallel summation of single-cell equations. The single-cell equations use effective material parameters, which are common in MEMS as typically only effective properties can be measured and extracted from microfabricated structures. Rigorous definition of effective properties in terms of actual material properties is reviewed. Together, the Norton equivalent cell approach combined with the use of effective material parameters keeps the analysis simple and streamlined. Further, an analysis based on a Norton (or Thévenin) equivalent is the most general analysis that can be made, and from there a comparative analysis for any application can be made, including comparison of coupling coefficients, SNR, and actuator strength. In this study, analytical analysis of the IDT cell assumes electric fields exist only in regions between electrodes, are horizontal, and are of constant magnitude through the thickness of the piezoelectric film. The accuracy of these assumptions for various film thicknesses is quantified with finite element analysis (FEA). The assumptions are accurate for cases where films are thin relative to the electrode pitch, as is the case for many MEMS structures.

A case-study device is presented for model verification. The device is a micromachined structure with beams of identical dimensions, identical PZT volume and layer thicknesses, and anchored to the same moving mass. The only difference between the beams is electrode configuration. Charge output and capacitance measurements are made and results agree exceptionally well with theory (within 3% difference). In what follows, theory is first presented, followed by a description of the case-study device and related measurements. With the theory validated, a discussion comparing coupling coefficients and SNR is presented.

2. Theory

Analysis of the 3-3 mode IDT structure may be performed by analyzing a unit cell, and then recognizing that the full electrode set is comprised of many cells electrically connected in parallel. Analysis of the 3-1 mode cell may also be performed on a unit-cell basis in an identical fashion to facilitate a direct comparison against the 3-3 mode case. In the following analysis, subscript IDT denotes the 3-3 mode configuration and subscript PP (for "parallel-plate" electrodes) denotes 3-1 mode device operation. In comparing Fig. 1(b) and (c), it is noted that the numbered coordinate systems are oriented differently. This must be the case to maintain the convention that the 3 axes be aligned with the polarization axis of the material. To facilitate the following comparative analysis, Fig. 1(a) includes a non-numbered coordinate system that is the same for both cases, in which the "x" and "z" axes are parallel and perpendicular to, respectively, the beams. For simplicity of presentation, the following analysis proceeds under the assumption that the horizontal strain in the piezoelectric film (i.e., x-axis strain) is approximately uniform along the vertical axis (i.e., z-axis), as is the case for thin piezoelectric films residing on top of much thicker passive beams, i.e., referring to Fig. 1(b), the S_1 strain within the film has no z-axis dependence. Similarly, referring to Fig. 1(c), the S_3 strain has no z-axis dependence within the film. In the 3-1 mode case, $S_1 = S_{beam}$ and in the 3-3 mode case, $S_3 = S_{beam}$, where S_{beam} is the horizontal strain at the top surface of the beam. It is shown in Section 5 that conclusions from the comparative analysis apply for general film thicknesses, and the more general allowance of z-axis dependent horizontal strain.

2.1. Analysis of IDT unit cell (i.e., 3-3 mode)

A 3-3 mode IDT electrode may be analyzed by considering a unit cell depicted in Fig. 2(a), with critical geometrical parameters