CONCEPTION OF AN INTERDIGITATED ELECTRODES BASED CANTILEVER FOR PIEZOELECTRIC ENERGY HARVESTING

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Abstract: This paper reports on conception, simulation, and fabrication of a lead zirconate titanate (PZT) MEMS cantilevers for piezoelectric energy harvesting (EH). We investigate the advantages of interdigitated electrode configurations (IDE) with respect to parallel-plate electrodes (PPE) in terms of output voltage and output power from the constitutive equations of piezoelectricity. Finite element modeling was carried for the case of a *pull-and-release* mode: PZT IDE structures turn out to be the better candidates for piezoelectric EH. We report about the thin-film deposition of PZT on insulating substrates which yield an effective piezoelectric coefficient $e_{IDE}=7C/m^2$. A microfabrication route for IDE piezoMEMS energy harvester is outlined.

Keywords: piezoelectric cantilever, energy harvesting, interdigitated electrodes, PZT thin film.

INTRODUCTION

Piezoelectric energy conversion seems to be more suitable for implementation on the MEMS scale than electromagnetic and electrostatic conversion. Indeed, micro coils are difficult to fabricate with micro machining techniques, and risk to have too high electrical resistances, and electrostatic converters need a bias voltage in order to operate. In contrast, piezoelectrics do not need such a bias voltage, as the active material has a spontaneous polarization.

One popular piezoMEMS structure for energy harvesting (EH) is the cantilever combined with an inertial mass for operating at resonance. The limit of this approach is the narrow excitation frequency range, which drastically reduces the vibrations to be harvested. To overcome this limit, a *pull-and-release* operating mode has been proposed by Rastegar et al. [1].

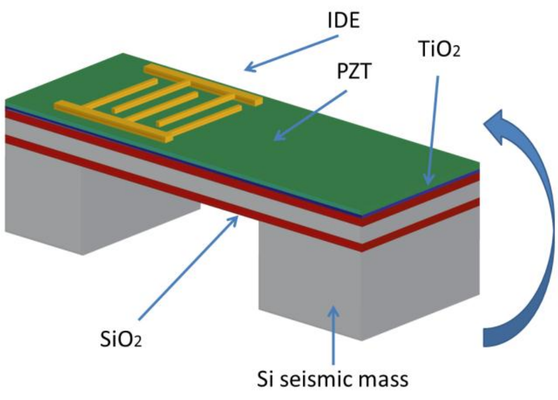

Fig. 1: IDE piezoelectric cantilever. It can be operated in the inertial or in the deflection-coupling modes.

In this kind of devices one side of the cantilever is clamped while the other is deformed by an external source of motion and then left free to oscillate (see Fig. 1). In this way we are able to decouple the frequency of operation from the frequency of the excitation.

Among the most interesting piezoelectric materials in the MEMS field we can cite AlN, and the lead zirconate titanate $Pb(Ti_x,Zr_{1-x})O_3$. While AlN thin film deposition is mastered today on an industrial level, PZT thin film processing is still at the development stage, and intensively investigated for its remarkable piezoelectric coefficients.

The cantilever EH outputs an AC signal, which needs to be rectified since the very majority of micro- and nano-electronic devices are DC powered. The diode bias threshold (which is around 0.2V for a Schottky diode) is therefore one of the most important parameters to take into account: too low output voltages will lead to inefficient conversion. This is the case of parallel-plate configuration of PZT: its remarkably high dielectric permittivity results in a very low voltage for a given film deformation compared to AlN structures.

Interdigitated electrode configuration allows for decoupling the electrode gap from the film thickness (as shown in Fig. 2): we are then able to decrease arbitrarily the capacitance and therefore to increase the output voltage (within the possibilities of poling). Moreover, this system exploits mostly the e_{33} coefficient, which for PZT is about twice as large as e_{31}. This is the reason why it is not casual that one of the first MEMS realization of a PZT-based energy harvester [2] was realized with interdigitated electrodes.

In this paper we will therefore compare PPE and IDE structures from the constitutive equations of the piezoelectricity point of view and by means of a finite element modeling (FEM) analysis. The critical aspect of the PZT thin film deposition on insulating substrates has been investigated and the cantilever micro fabrication route is sketched.

INTERDIGITATED ELECTRODES

Some prediction about the relative performance of the IDE and PPE structures can be outlined from a theoretical point of view; which can be derived simply applying the piezoelectric constitutive equations, using the appropriate boundary conditions for the region between the electrode fingers where the polarization is assumed to be in the film plane. The inhomogeneous situation below the electrode fingers is thus neglected.

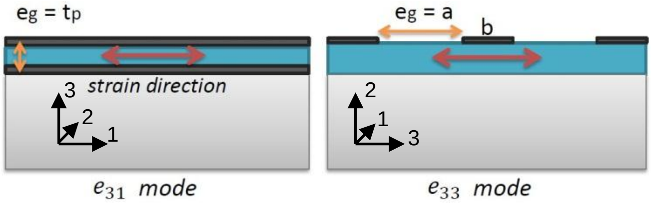

Fig. 2: PPE and IDE operating modes.

With the standard right-handed axis convention with the 3 axis parallel to the polarization vector (see Fig. 2), the constitutive equations can be written in this form in the short-circuit case for IDE structures:

$$\begin{aligned} D_3 &= e_{31}(\xi_1+\xi_2)+e_{33}\xi_3 \\ T_1 &= c_{11}^E\xi_1+c_{12}^E\xi_2+c_{13}^E\xi_3 \\ T_2 &= c_{12}^E\xi_1+c_{11}^E\xi_2+c_{13}^E\xi_3=0 \\ T_3 &= c_{13}^E\,(\xi_1+\xi_2)+c_{33}^E\xi_3 \end{aligned} \tag{1}$$

where D_3 is the electric displacement field component along the 3 axis, ξ_i and T_i are strain and stress components, respectively. e_{ij} and c_{kl}^E are the piezoelectric coefficients and stiffness constants at constant electric field. A thin-film system is free to move in the direction perpendicular to the plane ($T_2 = 0$) and is clamped on the substrate, therefore we can write:

$$\xi_1 = -\upsilon\,\xi_3 \tag{2}$$

where υ is the Poisson's ratio of the substrate along the strain direction. Combining all the equations together we can write the following relationship between D_3 and ξ_3 by introducing the effective coefficient e_{IDE} as follows:

$$\begin{aligned} D_3 &= e_{IDE}\,\xi_3; \\ e_{IDE} &= \left\{e_{31}\left[\upsilon\left(\frac{c_{12}^E}{c_{11}^E}-1\right)-\frac{c_{13}^E}{c_{11}^E}\right]+e_{33}\right\} \end{aligned} \tag{3}$$

In a similar fashion we can derive the same expression for the open-circuit case. In that case we will deal with h_{IDE} effective coefficient which adopts this expression:

$$\begin{aligned} E_3 &= -h_{IDE}\,\xi_3; \\ h_{IDE} &= \left\{h_{31}\left[\upsilon\left(\frac{c_{12}^D}{c_{11}^D}-1\right)-\frac{c_{13}^D}{c_{11}^D}\right]+h_{33}\right\} \end{aligned} \tag{4}$$

where h_{ij} are the piezoelectric coefficients and c_{kl}^D are the stiffness constants at constant charge.

Constitutive equations for the parallel-plate case have been applied elsewhere [3]. It is worth to remind that the axis convention here is different and therefore different is the implementation of the thin-film boundary conditions. Following the same procedure as above one obtains:

$$\begin{aligned} D_3 &= e_{PPE}\,\xi_1; \\ e_{PPE} &= (1-\upsilon)\left[e_{31}-e_{33}\,\frac{c_{13}^E}{c_{33}^E}\right] \end{aligned} \tag{5}$$

$$\begin{aligned} E_3 &= -h_{PPE}\,\xi_1; \\ h_{PPE} &= (1-\upsilon)\left[h_{31}-h_{33}\,\frac{c_{13}^D}{c_{33}^D}\right] \end{aligned} \tag{6}$$

The benchmarking of different systems for energy harvesting applications is done through the comparison of the output power for a given input for unit volume. For this reason, in order to compare the potentialities of both IDE and PPE systems we define the figure of merit for energy harvesting (FOM) as the product between the effective coefficients e_{ij} and h_{ij}, which has indeed the units of energy per unit volume for a given strain. For a more fair comparison between PPE and IDE structures one has to consider that the equations above applies only when the strain is parallel to the polarization vector, i.e. between the electrodes, which have anyhow a finite width. Calling a the electrode gap and b the electrode width we can correct the FOM by the geometrical factor $a/(a+b)$ which takes into account the fact that not the whole volume of IDE structures can be exploited. We are now ready to compare:

$$\frac{FOM_{IDE}}{FOM_{PPE}} = \frac{e_{IDE}\cdot h_{IDE}}{e_{PPE}\cdot h_{PPE}}\cdot\frac{a}{a+b} = 2.12\cdot\frac{a}{a+b} \tag{7}$$

The 2.12 factor has been obtained by inserting the piezoelectric and stiffness constant reported in the literature for bulk PZT-5H and assuming the polarization lying along the (100) direction of a silicon wafer substrate. For a b/a ratio which goes from 2 to 10 we expect therefore an energy harvesting performance from 1.4 to 2 times better for IDE structures respect to PPE ones. As a matter of principle switching from PPE to IDE structures will then allow us to increase the output voltage and gain in the same time in terms of output power.

It is moreover clear that from both output voltage and figure of merit points of view the larger the electrode gap, the higher the performances. This is in practice limited by the ferroelectricity of PZT: we are indeed forced to pole the material through the same electrodes that we use for EH. With larger electrodes gap larger voltages are needed to achieve a given poling field: we may reach the discharge threshold with unsatisfactory poling fields.

FINITE ELEMENT MODELING

The dynamics of a piezoelectric cantilever-based energy harvester can be solved by coupling the Euler-Bernoulli beam theory, the constitutive equations of the piezoelectricity and the Ohm's law in the simplest case of a resistor connected through the electrodes. Erturk and Inman [4] went through the analytical solution of the equation system for a PPE structure submitted to a harmonic excitation. Adapting these equations to the IDE case submitted to a pull-and-release excitation is not straightforward.

We therefore compare the behavior of AlN PPE structures together with PZT IDE and PZT PPE devices to obtain guidelines for the design of the cantilevers with a finite element method analysis, which has been performed through the commercial software Comsol Multiphysics®.

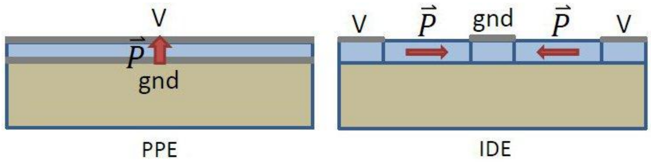

Fig. 3: FEM material polarization setup.

If for PPE structures we can assume the polarization lying perfectly perpendicularly to the film plane, the piezoelectric properties of IDE structures can be as a first approximation modeled as follows: in-plane polarization between the electrodes and decoupled dielectric behavior under them (see Fig. 3).

Here we report the results of a 2D FEM dynamic analysis of a cantilever based energy harvester composed by a silicon cantilever *1mm* long and *5μm* thick, with a tungsten seismic mass of *0.1x0.5mm* attached to its tip. A *2μm* thick piezoelectric layer has been clamped on the top of the silicon cantilever up to the zone corresponding to the seismic mass. Charges are then calculated for a *1mm* deep cantilever. The left end of the cantilever is mechanically clamped. One of the two groups of electrodes for IDE structures has been grounded as well as the bottom electrode of the PPE ones, which is at the interface between the cantilever and the piezoelectric layer.

The dynamic analysis is performed as follows: with a simple resistor connected between the electrodes the tip of the cantilever is bent until the stress in the piezoelectric layer reaches *200MPa*. We took this value as safe threshold to avoid film delamination in operating conditions. The cantilever tip is then release and free to move: tip displacement, stored elastic energy, voltage across the electrodes and current flowing through the resistor have been recorded as a function of the time. The motion of the cantilever results in a damped oscillation, the damping being due to piezoelectric power harvesting.

The damping factor depends on the value of the load resistor. The simulations have been therefore repeated for several resistor values until the highest damping factor has been obtained. Since we focused on the maximum transmitted power from the device to the resistor, as expected the load resistor values matches the module of the output impedance of the analyzed device, i.e: $R = 1/\omega C$, where C is the capacitance and ω the angular frequency of the tip motion.

In the figures 4, 5 and 6 the output power together with the output voltages for the AlN PPE, PZT PPE and PZT IDE ($a=8\mu m$ and $b=2\mu m$) respectively.

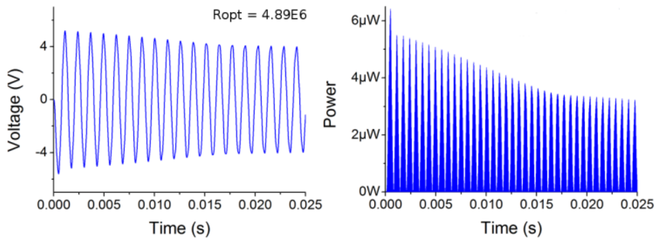

Fig. 4: AlN PPE.

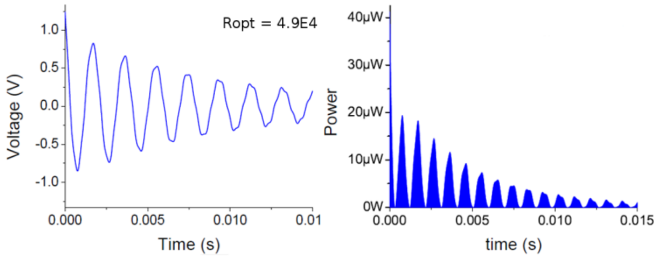

Fig. 5: PZT PPE.

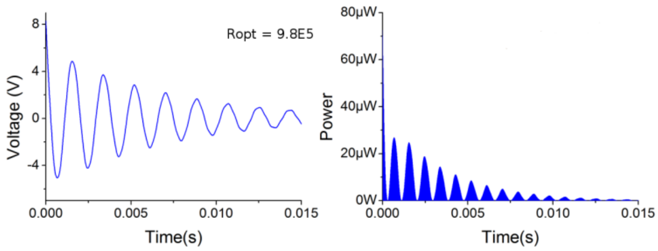

Fig. 6: PZT IDE.

From the comparison of these three different cases we can immediately observe how AlN PPE device shows a very good output voltage (Fig. 4), well above the diode rectification threshold, but the damping coefficient is very low, reflecting the smaller piezoelectric energy conversion. In contrast, the PZT PPE structure (Fig.5) shows good damping (faster energy harvesting), but also a low output voltage, which will turn result in a very inefficient charge collection by the DC circuit. For a *pull-and-release* excitation mode, the faster is the piezoelectric damping, the higher is the output power, since this allows to excite the cantilever with a higher rates. Therefore PZT IDE structures (Fig. 6) are the best candidate for piezoelectric MEMS energy harvesting since not only they show very good output power (about ten times more than the corresponding AlN structures) and high output voltage but also faster harvesting. To highlight the difference in the efficiency between AlN PPE structures and PZT IDE, the decay of the elastic energy stored in the cantilever has been simulated (Fig. 7).

For sake of comparison with other energy harvesters reported in the literature, we can easily estimate the harvested power per unit area or volume. If we arm the cantilever every *5ms* (i.e. after almost all the elastic energy has been harvested) we would achieve $1.2mW/cm^2$ considering the beam area only, or $24mW/cm^3$ considering 20 cantilever levels per *cm*. Of course, the power is in addition limited by the input force of the deflection mechanism.

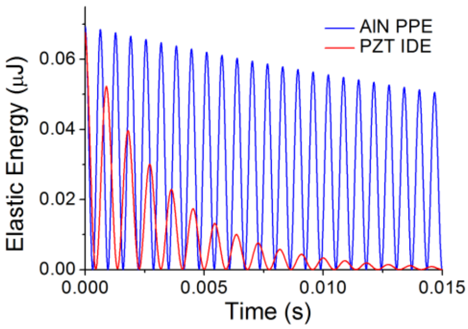

Fig. 7: Comparison between AlN PPE and PZT IDE.

MICROFABRICATION

IDE structures microfabrication requires the deposition of PZT thin films onto insulating substrates, a topic, which has not been intensively studied in the literature so far. We investigated two deposition routes: gradient-free sol-gel deposition [5] and RF magnetron sputtering from a ceramic 53/47 target. In both cases we employed the same substrate based on silicon wafers: after the growth of *2µm* of SiO_2 by means of wet oxidation, a *15nm* thick TiO_2 chemical barrier layer has been deposited by means of RF sputtering in a Balzers BAS 450 sputtering tool. A *20nm* thick $PbTiO_3$ seed layer is deposited by a sol-gel technique.

Subsequently, *2µm* thick PZT thin films were deposited, either by sol/gel or by sputtering. In Fig. 8 we can appreciate the SEM section of the sputtered film, which has been deposited with a deposition rate of *15nm/min*.

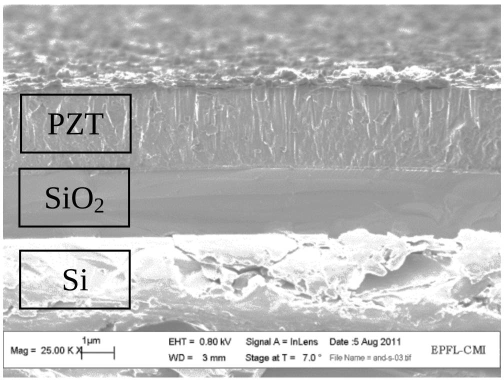

Fig. 8: SEM section of the sputtered PZT film.

The microstructure show quite dense and columnar structure and the XRD pattern shows a mainly (100) oriented perovskite (see Fig. 9). The effective piezoelectric coefficients have been measured through a setup described elsewhere [3], for an $a=4\mu m$ and $b=5\mu m$ pattern, yelding $e_{IDE}=7\ C/m^2$, $h_{IDE}=3.7\cdot10^7 V/m$ and $FOM=2.0\cdot10^8 J/m^3$ after poling for *15mins* at *150°C* with *60V* applied voltage.

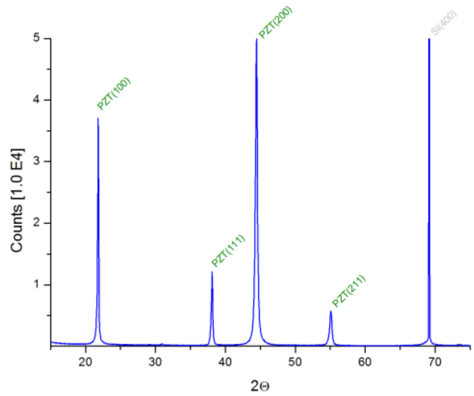

Fig. 9: XRD pattern of the sputtered PZT film.

The microfabrication proceeds then with the patterning of a *100nm* thick Pt IDE structure by a lift-off technique combined with e-beam evaporation. The cantilever structure is then defined through the front-etch of the wafer, which consists in the wet etch of PZT in an aqueous solution composed by 25% HCl and 75% of water and few droplets of HF, followed by reactive ion etching (RIE, Alcatel AMS200) of SiO_2 and Si until reaching the buried oxide. The seismic mass is then defined and the cantilever is released by backside deep RIE.

CONCLUSIONS

Micromachined IDE electrode based cantilevers for piezoelectric energy harvesting were studied both theoretically and experimentally. A figure of merit for comparison has been proposed and calculated for both PPE and IDE structures. The latter yielded higher energy densities and output voltages. These results have been confirmed by FEM analysis of pull-and-release excited cantilevers: IDE PPE structures show output voltages well above the diode bias threshold and much faster harvesting than AlN based devices. PZT thin film deposition onto insulating substrates was achieved with both sol-gel and RF sputtering. The characterization of the real devices is subject of ongoing work.

Acknowledgements

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