Characterization of piezoelectric material for micro thermal harvesters

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Abstract. This paper presents the first realizations of a novel concept for thermal energy harvesting at micro scale. The devices proposed here are based on a two-step transduction combining thermo-mechanical and piezoelectric conversion. In this contribution, we present for the first time results on micro fabricated structures with integrated piezoelectric layers, focusing mainly on the characterization of the piezoelectric material. The process flow to get a bilayered bistable structure is briefly described, highlighting the way how to control the initial deflection. The characterization of the piezoelectric thin film is presented then. The $e_{31,f}$ coefficient is measured in both sensor and actuator mode and is found to be equal to -0.91 C.m⁻² in both configurations. This value, close to the state-of-the-art, is very promising for the future thermal harvesting applications. Finally the buckling of a structure actuated by a voltage was observed and the corresponding displacement measured by laser interferometry.

1. Introduction

These last years have seen the development of many harvesting systems using all kind of surrounding energies to create electrical energy in order to power autonomously wireless sensor networks. The piezoelectric transduction is extensively used to harvest mechanical energy [1, 2]. Regarding thermal energy, a lot of efforts have been done in the conception and optimization of thermoelectric generators based on the Seebeck effect. In this paper are presented the first tiny devices combining both piezoelectric transduction and thermal harvesting. They represent an alternative to the use of thermoelectric materials to harvest thermal energy at microscopic scale using only CMOS standard processes for their fabrication. Indeed the thermoelectric generators need a disproportional heat sink to maintain a temperature gradient across the material, which is limiting the downscaling of the devices, and the thermoelectric materials with the best efficiency are not CMOS compatible.

The working principle of the structures presented here has already been presented [3] at macroscopic scale. A bilayer bridge, initially curved downward, is put in contact with a hot source. The two layers of the structure have very different thermal expansion coefficients (CTE). As a consequence, huge thermal stresses are created when it is heated up. To release these stresses the structure buckles and becomes curved upward. Not anymore in contact with the hot source, the bridge is cooling down, and for the same reasons huge thermal stresses are generated, that lead to the inverse buckling of the structure. A thermal cycle with regular oscillations is then installed. The innovative idea of these microscopic devices is that the piezoelectric element, instead of being an external
commercial buzzer that is impacted at every buckling by the structure, is directly integrated in the
device. Indeed one of the two layers composing the bridge is a piezoelectric material. In this way, the
piezoelectric transduction is converting the whole displacements of the structure in electrical charges
and no more mechanical energy is lost during the impact on a buzzer. In this contribution the
piezoelectric film will be fully characterized in sensor mode as well as in actuator mode on cantilever
test structures, and the first buckling movement observed on the bridge structures is presented.

2. Description of the structures
The structures as shown in Figure 1 were fabricated. A first layer of 200nm of aluminium nitride
(AlN) was deposited by reactive, pulsed, direct current magnetron sputtering on a silicon wafer with
1μm thick thermal silicon oxide on both sides. Then 100nm of platinum (Pt) was sputtered and
patterned by dry etching to create the bottom electrodes of the devices (Figure 2). The active
piezoelectric layer of AlN is sputtered on top of the patterned Pt electrodes, followed by one layer of
aluminium (Al) which has a huge CTE (24 10⁻⁶ K⁻¹) compared to the CTE of AlN (4,5 10⁻⁶ K⁻¹).

![Figure 1. Scheme of a rectangular structure](image1)

![Figure 2. SEM picture of a 300μm by 100μm plate (dashed line: bottom Pt electrode)](image2)

Rectangular structures with different length to width ratio were fabricated, for instance 400μm by
400μm or 2000μm by 200μm in order to see the influence of this ratio on the buckling temperature.
The design of the electrodes is realized in such a way to have two bottom Pt electrodes and one top,
floating electrode in Al. In this way, the piezoelectric charges are collected both at the anchors where
the stresses are higher and at the centre of the plate where the displacements are higher. The charges
should not be compensated between the two electrodes, because the plate will always have a different
sign of curvature at its centre and its anchors.

The initial curvature of the structures is obtained by tuning the deposition parameters of the
different layers to adjust the residual stress. During the sputtering of the AlN layers, as explained in
[4], it is possible to adjust the power density applied on the substrate to modify the number of collision
and by consequence the stress induced in the thin film. The major drawback of tuning this parameter is
that when the power density is reduced to decrease the stress in the film, the (100) crystalline
orientation of the film is reduced. As a high quality for the AlN bottom layer is not required, the stress
in this seed layer can be tuned. By adjusting the deposition temperature of the Al, the stress in the
active AlN layer and in the Al layer can compensate. The Figure 3 illustrates a 400μm by 400μm
device, with a maximum curvature at the centre of 4.5μm.
The curvature is an important parameter to tune the buckling temperature of the device, which increased directly with the deflection. Nevertheless this temperature is limited by the low Al melting point.

3. Characterization of the piezoelectric film

Before any experiment of harvesting, one has to be sure that the piezoelectric film is of good quality in order to have a high charge yield. Two different methods of characterization have been tested on test cantilever structures described in [5]. The cantilever has the full wafer thickness and the same stack as the rectangular structures presented in the former paragraph. The cantilever has standard dimensions (15mm by 1.5mm) as well as the top electrode, which defines the actuation/sensor area (3mm by 1mm).

3.1. Actuator mode

The test cantilever is first tested in actuator mode. The structure is clamped mechanically and a laser interferometer is focused on its free end to measure the displacements. A voltage is applied between the bottom and the top electrode. From the displacements measured at the free end, the stress induced in the piezoelectric film can be calculated as follow:

$$\sigma_1 = \frac{Y_{\text{sub}}}{3(1-\nu_{\text{sub}})b_f} \left[ b_f + (1-b_f)(1-\nu_{\text{sub}}) \right] \frac{w(x_2)}{x_f(2x_2-x_1)} \frac{t_{\text{sub}}^2}{t_p}$$

where $Y_{\text{sub}}$ is the Young modulus of the substrate, $\nu_{\text{sub}}$ its Poisson ratio, $b_f$ is the ratio between the cantilever width and the electrode width, $x_j$ is the length of the electrode and $x_2$ the measurement point of the interferometer, $t_{\text{sub}}$ the thickness of the substrate and $t_p$ the thickness of the piezoelectric layer, $w(x_2)$ the displacement along z-direction of the point $x_2$.

The stresses $\sigma_1$ generated in the x-direction by the actuation voltage are directly proportional to the piezoelectric coefficient $e_{31,f}$ according to this equation:

$$\sigma_1 = -e_{31,f} E_f$$

The Figure 4 shows the $e_{31,f}$ coefficient obtained for two different cantilevers, one being oriented along the (110) direction of the Si substrate, the other one along the (100) direction. The value for the Young modulus and the Poisson ratio were taken in [6]. The $e_{31,f}$ coefficients in both cases, respectively -1.042 C.m⁻² and -0.919 C.m⁻² are comparable, they present only 10% difference.
Figure 4. a) Evolution of the stress with the electric field across a 1 μm thick AlN layer for a cantilever, oriented along the (110) direction of the Si substrate

Figure 4. b) Evolution of the stress with the electric field across a 1 μm thick AlN layer for a cantilever, oriented along the (100) direction of the Si substrate

These results are the first indication that the film is of high piezoelectric quality. Indeed the state of the art for the $e_{31,f}$ coefficient obtained with the same geometry of cantilever is -1.05 C.m⁻², with a top electrode that was not patterned by dry etching but deposited by lift-off technique. The underneath piezoelectric layer is not damaged by the dry etching plasma; its quality is higher then.

3.2. Sensor mode

The cantilever test structures are then tested in sensor mode. The sample is put in the same conditions as before: it is clamped and two probes are contacting the top and bottom electrodes. An alumina tip is put in contact with the sample at a distance $x_2$ from the clamp. The tip displacement is controlled by a piezoelectric actuator to furnish exactly 4.5 μm of displacement at a frequency of 110 Hz.

The charges are collected by a charge amplifier and registered on an oscilloscope. Using the same technique as in [3], the strain corresponding to this displacement was found to be $2.4 \times 10^{-5}$, and the $e_{31,f}$ value was -0.89 C.m⁻² for a sample oriented along the (110) direction. By changing the charge amplifier by a instrumentation amplifier, one can measure directly the voltage generated by the displacement of the free end of the cantilever, and get the $h_{31,f}$ coefficient, which was $-4.1 \times 10^9$ V.m⁻¹.

For energy harvesting systems one can use the following figure of merit (FOM) as described in [4]. For these samples the FOM was of 3.2 GJ.m⁻³, which is not as good as non-patterned AlN film (around 11 GJ.m⁻³) and PZT thin films (18 GJ.m⁻³).

This difference could one more time be explained by the micromachining of the top electrode, which can damage the underlying piezoelectric layer.

4. First buckling in actuator mode

In this section, the buckling of a rectangular device of 1400 μm long by 700 μm width is presented. A voltage is applied between the two Pt bottom electrodes to actuate the structure. The displacement is measured with the same laser interferometer setup used to characterize the piezoelectric film on the cantilever.
Figure 5. Displacement and buckling of a 1400μm by 700μm bridge when applying an actuation voltage

The device presented here is 1400μm long by 700μm wide, and had an initial deflection of 6μm downward. A slight movement in the direction of the curvature can be observed at low voltage, but suddenly at 170V, the plate change curvature and a huge displacement of 5μm is measured. The applied voltage necessary to cause buckling is high due to non-optimized structures. Indeed devices with higher initial curvature are stiffer and would present a higher buckling voltage. Also, as the device has a high output impedance, an impedance matching circuit can be designed in order to decrease considerably the applied voltage.

5. Conclusion
In this paper the first structures presenting a novel concept of thermal energy harvesting at microscale are presented. After a brief description of the working principle as well as the fabrication process, the characterization of the piezoelectric film is detailed. Two kinds of test were performed in order to measure the performance of the thin film both in sensor and actuator mode. The film quality was found to be good, the $e_{31,f}$ coefficients were between -1.04 C.m$^{-2}$ in actuator mode and -0.92 C.m$^{-2}$ in sensor mode, which hits well the literature values for AlN thin films. On the other hand, its quality is not optimal because of the fabrication process of the top electrode, which is dry etched. This process and especially the plasma used to etch Al ($Cl_2$ and $BCl_3$) is damaging the AlN layer underneath. Finally an actuation voltage is applied to one rectangular structure until it buckles. A displacement of 5μm is achieved. The challenge now is to cause the buckling thermally, by local heating. One way to do it could be to apply a current through the continuous platinum path and heat the device by Joule effect, or to use a powerful laser and to focus it on the Al layer.

6. References
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