Electrical characterization of a buckling thermal energy harvester

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Abstract. This paper presents the electrical characterizations of a novel concept for thermal energy harvesting at micro scale. The devices presented here are based on a two-step transduction combining thermo-mechanical and piezoelectric conversion. The piezoelectric layer is directly integrated into a buckling bilayer plate made of aluminium and aluminium nitride. For the first time, we have characterized the structures electrically and we have investigated their output power during the buckling. Firstly, we have used an insulating tip to make the plate buckle in order to have an estimation of the output power due to piezoelectric contribution only, and to eliminate any pyroelectric contribution that might be present during the thermal actuation. Then, we heated up the structure and we collected the output signal with an instrumentation amplifier in order to measure the voltage generated during the buckling. The output power during the mechanical and the thermal buckling is compared in the paper.

1. Introduction
The development of harvesting systems is growing steadily these last years. They are harvesting all kinds of surrounding energies in order to power autonomous wireless sensor networks. The piezoelectricity is commonly used for mechanical energy harvesting under the form of vibrations (human body movements, household appliances, industrial machines…) \cite{1, 2}. Devices based on the Seebeck effect are the most popular to scavenge thermal energy, and a lot of efforts are made to downscale them \cite{3, 4}. We have originally presented an alternative to thermoelectric materials for micro-scale thermal harvesting applications in \cite{5, 6}. These devices combine piezoelectric transduction and thermal harvesting and are fabricated using CMOS compatible processes. In this work, the devices are characterized electrically and for the first time the output power furnished during the thermal buckling of the bilayer structure is measured.

The working principle of the harvester is based on a two-step transduction. A bilayer plate initially curved downward is put in contact with a hot source. The difference of thermal expansion coefficients (CTE) of the two materials is causing thermal stresses in the films that are leading to a mechanical instability resulting in the buckling. The plate is passing suddenly from a downward to an upward curvature. The large displacements due to the buckling are converted into electric charges by the piezoelectric layer. After the change of curvature, the plate is not anymore in contact with the hot source. It is cooling down by natural convection, and for the same reasons as before, the change in...
temperature of the device is generating thermal stresses that are leading to the inverse buckling of the structure. The curvature being again downward, the plate comes again in contact with the hot point and the thermal cycle is closed. The regular oscillations of the plate are generating electrical peaks that could be considered for powering a low-consumption system.

In this contribution, the output power of the structure is characterized. The buckling is firstly induced mechanically by a tip pushing the curved plate. Such a process helps to distinguish the expected piezoelectric signal from eventual pyroelectric charges due to the change in temperature. Then, the buckling is induced thermally, by putting the device onto a hotplate. The temperatures of snap up and snap down are measured as well as the output power, which will be compared to the one obtained during the mechanical buckling.

2. Mechanical actuation

The structure presented here are composed of a seed layer of AlN 200nm thick, patterned Pt electrodes of 100nm and the two active materials of the bilayer plate: 0,5μm of AlN as the piezoelectric layer and 0,5μm of Al as the metallic layer with high CTE. The layers are deposited by sputtering on a Si (100) wafer with 1μm thermal oxide on both sides. The structures are liberated from the backside by a Bosch process. A top view SEM picture of a 1400μm by 700μm plate is shown in Figure 1 as well as its cross-section in Figure 2. This structure will be characterized this paper. The combination of the 150MPa tensile stress in the top AlN layer, -400MPa compressive stress in the active AlN layer and 230MPa tensile stress in the AlN seed layer result in the initial downward curvature of the structure. The detailed fabrication process is presented in [5].

In order to actuate mechanically the membrane, it was necessary to build a setup (Figure 3 and Figure 4), which is able to reach the backside of the plate, and to give a controlled micrometric displacement. An insulating tip with a diameter of 70μm is then mounted on a piezoelectric multilayer stack, which is able to provide a 30μm displacement at frequencies below 100Hz. Thanks to a camera placed on the front side, we can see the deformation of the plate when the tip enters in a contact. The tip is pushing until the plate buckles. At the beginning, the plate is following the tip displacement. When a critical force applied by the tip is reached, the plate becomes mechanically unstable and snaps up. As the temperature of the plate is the ambient temperature, it has only one stable position, which is the initial position. This means that when it buckles up, it does not reach a more stable position, so the plate returns back in contact with the tip.

The output signal is collected by an instrumentation amplifier with a gain of 1. The load resistance placed in parallel to the input of the amplifier is optimized to obtain the maximum output power of the tested plate and it is found to be at 1MΩ (Figure 5). This value is then taken for the following measurements. The same plate is then actuated by the tip in order to cause its buckling. In Figure 6,
the dashed line represents the displacement of the tip. The maximum voltage corresponds to the maximum elongation of the piezoelectric stack while the lower voltage corresponds to its minimum. The positive peak is the piezoelectric signal of the device when it buckles upward and the negative peak the signal when it buckles back downward.

Figure 3. Schematic of the actuation setup

Figure 4. Image of the setup

The instantaneous power of one peak $P_{int}$ is related to its energy $w_{int}$ by the following formula:

$$P_{int} = \frac{1}{\Delta t} \int v_{out}^2/R_{load} \, dt = w_{int}/\Delta t$$

(1)

where $v_{out}$ is the output voltage, $R_{load}$ the load resistance and $\Delta t$ the time period over which the integration is done. The average power generated by the device at a given actuation frequency is calculated by the product of the energy per peak, $W_{int}$, and the actuation frequency. For instance when the plate is actuated at 20Hz, the mean instantaneous power density is of 48nW.cm$^{-2}$, and the corresponding mean energy density per peak is 3.6pJ.cm$^{-2}$. The average power density, 0.7nW.cm$^{-2}$, is then much lower than the instantaneous power density. Increasing the actuation frequency would also increase the average output power density of the structure. Measurements at 30Hz were performed, and with a relatively unchanged instantaneous power density (41nW.cm$^{-2}$), the average power density increased to 1.9nW.cm$^{-2}$.

Figure 5. Output power in function of the load resistance

Figure 6. Mechanical buckling of the plate at 20Hz

3. Thermal actuation

With a mechanical actuation, we have obtained the pure piezoelectric signal as a result of the device buckling. To actuate thermally the plates, we put them on a hotplate and the temperature was slowly
increased. The structure was heated mostly by conduction through the substrate. A thermocouple was measuring the temperature of the surface of the hot plate. The same structure tested before was buckling up at 83°C and buckling down at 62°C. A top view of the structure is shown in inset of the Figure 7 when buckling up (a) and when buckling down (b) which is similar to the initial shape of the device.

![Inset images of the device after buckling up and down](image)

**Figure 7.** Output signal for thermal buckling up at 83°C (a) and thermal buckling down at 62°C (b) with inset images of the device after buckling up and after buckling down respectively.

The corresponding instantaneous power of the buckling up and buckling down peaks is calculated in the same manner as for the mechanical actuation. For the snap up, the device generated 18nW.cm⁻² while for the snap down, the power was 49nW.cm⁻². The peaks are of the opposite sign compared to the mechanical actuation because the positive and negative inputs of the amplifier were inverted. The same value is found for the snap down as for the mechanical actuation, which is what was expected. On the other hand, the instantaneous power during the snap up is much lower than for the mechanical actuation. This can be explained by the pyroelectric charges that are acting against the piezoelectric charges. The average power density is not relevant in this case because of the time necessary for the hot plate cools down to lower the temperature and cause the snap back of the plate. The time between the snap up and down is then very long and does not correspond to the real thermal cycle of the system at which the system is able to work.

4. Conclusion

This paper presents the first electrical characterization of the mechanical and thermal buckling of a micro thermal energy harvester based on a bilayer structure. The instantaneous output power in both cases is measured around 48nW.cm⁻² for the mechanical actuation, value that is confirmed in the snap back of the thermal actuation. The instantaneous power during the thermal snap up is 4 times lower, which might be due to pyroelectric charges that are acting against the piezoelectric signal. Moreover, the thermal hysteresis of the tested device is of 20°C, which is relatively high. We are currently working on different geometries that might reduce this hysteresis to make the system more adapted to future applications.

References

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