Butterfly micro bilayer thermal energy harvester geometry with improved performances

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Abstract. This paper reports the recent progress of a new technology to scavenge thermal energy, implying a double-step transduction through thermal buckling of a bilayer aluminum nitride / aluminum bridge and piezoelectric transduction. A completely new scavenger design is presented, improving greatly its final performance. The butterfly shape reduces the overall device mechanical rigidity, which leads to a decrease of buckling temperatures compared to previously studied rectangular plates. In a first time we compared performances of rectangular and butterfly plates with an equal thickness of Al and AlN. In a second time, with a thicker Al layer than AlN layer, we will study only butterfly structure in terms of output power and buckling temperatures, and compare it to the previous stack.

1. Introduction
The interest in thermal energy harvesters has grown steadily in the past few years [1, 2]. Indeed thermal gradients are present in every environment, from large building facades to small electronic circuits. Harvesters based on Seebeck thermoelectric materials are the most commonly used devices to scavenge thermal energy. A lot of efforts have been invested in order to downscale them, and also to propose alternative ways to harvest thermal gradients at micro scale [3]. We previously presented an original way of harvesting thermal gradients by combining in a two-step transduction both thermal buckling and piezoelectricity [4, 5]. The harvesters are fabricated using standard CMOS processes.

The working principle of the device is based on a two-step transduction. A bilayer plate, initially curved downward (by the effect of residual stresses from fabrication), is put in contact with a hot source. The difference in thermal expansion coefficient of the two layer materials, aluminum (Al) and aluminum nitride (AlN) generates huge thermal stresses in the films that are leading to a mechanical instability called buckling. The plate is inverting suddenly its curvature from a downward to an upward position. The large deformations occurring during buckling are converted into usable electric charges by the piezoelectric AlN layer. By changing the sign of curvature, the plate is not anymore in contact with the hot source. It begins to cool down by natural convection and for the same reasons as before, the change in temperature in the plate is generating thermal stresses that are leading to the inverse buckling of the harvester. In the same time, it goes back in contact with the hot source. Then
we can have regular oscillations of the device with regular electrical peaks at each snap up and down of the plate. The harvested signal could be used later on by some low power-consuming device.

The previously studied harvesters were rectangular, doubly clamped bilayer plates, with equal thickness of AlN and Al layers. This kind of structure was very rigid, especially if width and length of the plate are comparable, so the buckling temperatures were relatively high (over 100°C). Moreover, the neutral plane was situated near the middle of the piezoelectric layer, which was not favorable. In this contribution we will present the advantage of butterfly design compared to rectangular one in terms of buckling temperatures and output power for the equal AlN/Al thickness stack. Then we will present the performances of butterfly structure having a thicker Al layer than AlN layer, and compare its performances to the previous stack.

2. Butterfly structure improvements

The structure previously presented were rectangular plates, clamped on the short sides and free on the long sides. Their fabrication process is described in details in [6]. They were composed of 200nm of AlN seedlayer, 100nm of bottom Pt electrodes and 0.5µm of AlN and 0.5µm of Al as the two active layers with respectively 4.5×10⁻⁶K⁻¹ and 24×10⁻⁶K⁻¹ thermal expansion coefficients. A harvester of this type measuring 1400µm long by 700µm wide could scavenge an output energy density of 230pJ.mm⁻³ with a thermal hysteresis (temperature difference between snap up and down) of 30°C, and a relatively high snap up temperature of 114°C.

The values of thermal hysteresis as well as snap up temperature are not compatible with a future application as thermal switch, which requires a more reduced thermal hysteresis for a better detection of the threshold temperature, or with harvesting applications under 100°C. The rectangular shape of the bridge shows also an aging issue at the anchor, where the stresses are maximized. In order to solve these two issues, we designed a new shape of harvester. It is based on the fact that tapered beam shape, largely studied for piezoelectric energy harvesting [7, 8], is homogenizing the stress along the length generated during vibrations. So we designed a bridge having a butterfly shape as shown in Figure 1. The central, squared part is measuring 400µm, the total length of the device is 1400µm (as the rectangular plate studied before) and the clamped side is measuring 1400µm. This shape decreases the overall mechanical rigidity of the device and also decreases the stress at the clamps.

![Figure 1. SEM pictures of a rectangular structure and butterfly harvester, with in inset the cross-section of the bilayer bridges. The bottom Pt electrodes are indicated with dashed lines.](image)

We tested the butterfly structure with the same procedure as rectangular plate: the whole wafer is put on a hotplate where the temperature is ramped until reaching the structure snap up. The bottom Pt electrode and top Al electrode are connected to an instrumentation amplifier with a load resistance of
1MΩ (which is not optimized). Then the hotplate is switched off and cooled down until reaching the snap down temperature of the butterfly harvester. Both electrical output signals are shown in Figure 2 (a). Two peaks are observed for each snap and are of opposite sign.

The snap up temperature for one particular structure is 100°C, while snap back occurs at 90°C. The buckling temperature is a bit lower than the rectangular plate, but the great improvement lies in the reduction by three of the thermal hysteresis. The only drawback of the butterfly harvester is its smaller active area compared to rectangular plate, which results in a lower output energy.

3. Non-symmetric stack butterfly structure

Optimizing the thickness ratio between AlN and Al active layers can increase the efficiency of the harvester. Indeed in the previous studied case, the neutral plane was situated near the middle of the active AlN layer (90nm above the mid-thickness). This is not a favorable situation as the stresses at the neutral plane are zero. Moreover the neutral plane being near the mid-thickness of the piezoelectric layer, one part will undergo compressive stress while the other part tensile stress, and the charges generated by the AlN will compensate.

A device with a thicker Al layer present several advantages: it will shift the neutral plane toward the Al layer and the thermal behavior will be enhanced: the thicker Al layer, which has the higher thermal expansion coefficient, acting as a “thermal leader”. With a thicker Al layer we expect also a lower snap up temperature, as it will generate higher thermal stresses. The position of the neutral plane with 1µm of AlN and 2µm of Al is 70nm under the Al layer, which is much more favorable. We will study only butterfly geometry having this non-symmetric stack and compare the results to the same butterfly geometry having symmetric stack.

![Figure 2](image_url)

**Figure 2.** Output voltage during thermal buckling of a butterfly structure with symmetric stack (a) and non-symmetric stack (b)

In a first time, we studied the output signal of the butterfly with the new stack. As before, we put the whole wafer on a hotplate and increased the temperature until reaching the snap up. The output signal is measured through an instrumentation amplifier with a load resistance of 1MΩ. The output voltage is shown in Figure 2 (b). The buckling temperatures are much lower than with symmetric stack, and the thermal hysteresis is still 10°C. But in this case, the structure, when buckling, is oscillating at its natural frequency. Moreover, the output energy is twenty times higher than with symmetric stack.

In a second time, we will study more precisely the harvester behavior during heating up and cooling down. The impedance phase of the device is measured at different temperatures of the hotplate, which can be considered as device temperature, as shown in Figure 3 for the first resonance mode. We can see that during heating, the resonance frequency is decreasing until a threshold
temperature where there is a jump in resonance frequency. This threshold temperature corresponds to the snap up temperature. The resonance frequency is increasing continuously if the temperature is further increased.

![Impedance phase during heating (a) and resonance frequency during heating and cooling (b) of butterfly structure with 1μm of AlN and 2μm of Al.](image)

**Figure 3.** Impedance phase during heating (a) and resonance frequency during heating and cooling (b) of butterfly structure with 1μm of AlN and 2μm of Al.

When the device is cooled down, the resonance frequency is decreasing, and as during heating, a gap in resonance frequency is observed at a specific threshold temperature, lower than the first one, and corresponding to the snap down temperature. This change of resonance frequency is due to the shape change of the structure. Indeed during heating up, the structure is first deforming linearly, until the stress level reaches the buckling limit, where the plate is suddenly changing its curvature to an upward position. The resonance frequency is getting lower during cooling down because the structure being in an upward position, the Al layer can deform more than in the downward position. The measurement of the device impedance constitutes a reliable means to track the structure buckling.

4. Conclusion
This paper presents an innovative structure, butterfly shape for micro thermal energy harvesting. The thermal and electrical performances of this new design are compared to the previous, rectangular harvester. The buckling temperature, and especially the thermal hysteresis are decreased in order to adapt to a future commercial application. In a second time, a different, non-symmetric AlN/Al stack is tested with an improvement of the output energy and a decrease of the buckling temperature. This new design increases up to 20 times the output energy. A new technique in order to track precisely the structure buckling consists in the measurement of the electrical impedance for various temperatures.

References
[1] E. Hourtakis and A. G. Nassiopoulou, *Sensors 2013*, 13, pp. 13596 - 608
[2] A. Moser, M. Erd, M. Kostic, K. Cobry, M. Kroener and P. Woias, *J. Elec. Mat.*, 2012, 41, pp. 1653 – 61
[3] T. Huesgen, J. Ruhhammer, G. Biancuzzi and P. Woias, *J. Micromech. Microeng.*, 2010, 20, pp. 104004 – 13
[4] E. Trioux, S. Monfray, T. Skotnicki, S. Basrour and P. Muralt, *Proc. PowerMEMS 2014*, 557
[5] E. Trioux, L. Rufer, S. Monfray, T. Skotnick, P. Muralt and S. Basrour, *Proc. PowerMEMS 2015*, 660
[6] E. Trioux, S. Monfray, T. Skotnick, P. Muralt and S. Basrour, *IEEE Sensors'14*, pp. 2171 – 74, Valencia, Spain
[7] D. Benaschi, L. Moro, S. Zelenika and E. Brusa, *Microsyst. Technol.*, 2010, 16, pp. 657 – 68
[8] M. Defosseux, M. Allain and S. Basrour, *Proc. PowerMEMS 2010*, pp. 339 – 46