Piezoelectric and electrostatic bimetal-based thermal energy harvesters

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Abstract. This paper reports on innovative thermal energy harvesters (TEH) turning heat fluxes into electricity in a two-step conversion, involving (i) a curved bimetallic strip converting thermal gradients into mechanical oscillations, which are then (ii) converted into electricity by a piezoelectric or an electret-based electrostatic transducer. This work mainly focuses on (i) the optimizations of the piezoelectric devices, (ii) a first demonstration of a Wireless Sensor Node powered by our electrostatic transducers, validating the viability of bimetal-based thermal energy harvesters, and (iii) the possibility of future scaled scavengers by a micrometric silicon approach to improve efficiencies and power densities.

1. Introduction

Thermal energy harvesting is a field of growing interest aimed at turning ambient thermal gradients into electricity to develop fully-autonomous electronic devices, such as wireless sensor networks (WSN). This topic is today dominated by thermoelectric energy harvesters based on bimetallic junctions that generate thermoelectric voltages (Micropelt, Thermolife…).

Bimetal-based thermal energy harvesters (b-TEH), presented in this paper, are an alternative to these devices, employing standard and fully available materials, and compatible with mass production over large areas. The novelty of b-TEH lies in the use of curved bimetallic strips to perform a first thermal-to-mechanical power conversion, turning thermal gradients into mechanical movements. Bimetals are the combination of two metals characterized by different coefficients of thermal expansion (CTE) that are bonded together. This CTE difference makes bimetallic strips thermal actuators, deforming with temperature, and acting as thermo-mechanical converters.

In fact, curved bimetallic strips have long been known as thermal actuators able to quickly switch between two states (snapping and snapping back) according to their temperature and with a hysteresis cycle. Inserted in a cavity with a hot lower plate (T=T_h) and a cold upper plate (T=T_c), curved bimetallic strips become the working substance of a heat engine, kept in an unstable thermodynamic state when exchanging thermal energy either with the hot or the cold source and thus switching constantly. The cycle starts when
the bimetallic strip is in its lower state (figure 1a) and in contact with the lower plate; its temperature increases till reaching its snapping temperature \( T_{sb} \); it suddenly snaps to its upper state, entering in contact with the upper plate (figure 1b) where it is cooled down until reaching its snapping-back temperature \( T_{sb} \) and returning to its lower state. Then, a new cycle restarts, and the thermal gradient is turned into mechanical oscillations. The hysteresis cycle overviewing states and temperatures is presented in figure 1c.

**Figure 1.** Curved bimetallic strip in a cavity subjected to a thermal gradient (a) lower state and (b) upper state; and (c) hysteresis cycle of the bimetallic strip enabling the oscillations

These oscillations can then be converted into electricity by a standard electromechanical converter such as a piezoelectric material, an electrostatic converter or a coil-magnet architecture. We have chosen to focus on the two first ones, converting the shock of the bimetallic strip on the upper plate with a piezoelectric material (section 2) or its movement by an electret-based electrostatic converter (section 3).

2. **Piezoelectric devices**

2.1. **Principle**

The bimetallic strip switching from an unstable equilibrium position to a stable one is followed by a conversion of strain energy into kinetic energy. Our first approach [1] has consisted in harvesting this kinetic energy release into electric energy by making the bimetallic strip shock a piezoelectric oscillator when snapping [2], as shown in figure 2a. In such a structure, the piezoelectric oscillator performs both functions of electro-mechanical transducer and thermal dissipator by enabling the bimetallic strip to cool down and so to snap back. This double function offers the device the advantage of not requiring massive heat sink to maintain its internal thermal gradient (figure 2b) and then to obtain thin prototypes (4mm-thick prototype for a 25mm-long bimetal).

2.2. **Piezoelectric transducer mechanical optimization**

The transducer global efficiency is mainly linked to the quality of the kinetic energy transfer between the bimetallic strip and the transducer, and to the conversion efficiency of the transducer strain energy into electric energy. During this conversion, the energy is either harvested or lost in the clamps. We have focused here on optimizing the piezoelectric transducer to limit the energy losses in the structure.

**Figure 2.** (a) Piezoelectric device principle. (b) Thermal optimization of the device. (c) Output signal of the transducer. (d) Detail of the signal after a bimetallic strip snap

This optimization has led to the design of a new transducer that minimizes the stress exercised on the oscillator clamp and so to the diffusion of energy into the Teflon cavity, and increases the efficiency of the piezoelectric conversion. This geometry has enabled to raise the harvested energy to 24.6 µJ per snap (vs.
1.8\mu J with the conventional devices). This approach is currently under investigation to power a Wireless Sensor Node.

3. Electrostatic devices

Electrostatic-based electrostatic converters are built on a capacitive architecture made of two plates separated by an air gap and polarized by an electret (figure 3a) [3]. The electret is a permanently charged dielectric that induces charges on the two plates, with \( Q_i = Q_1 + Q_2 \), where \( Q_i \) and \( Q_1 \) and \( Q_2 \) are respectively, the charges on the electret, the lower electrode and the upper electrode; its equivalent electric model is presented in figure 3b. A relative movement between the two plates induces a new repartition of charges between the two electrodes, converting the mechanical movement into electric charges that are collected by a load (R).

![Figure 3](image_url)

**Figure 3.** (a) Electret-based converter, (b) equivalent electric model of the electret-based converter, be-TEH in (c) its lower state and (d) its upper plate.

The above-mentioned bimetal-based heat engine can be easily combined with an electret-based converter (thereby becoming a bimetal-and-electret-based TEH [be-TEH]) by adding an electret on the upper plate and by connecting a load between the upper plate and the bimetal strip, turning the bimetallic strip's oscillations into electricity. First proofs of concept have already been presented in [4], but the devices required forced convection to work. Therefore, in order to increase the thermal gradient between the upper and the lower plates, so as to ensure the bimetallic strip's oscillations without forced convection, a heat sink and a localized hot point have been added (figures 3c and 3d).

Prototypes have been manufactured from B72M (CTE=26.4\times10^{-6})/Invar(CTE=2\times10^{-6}) curved bimetallic strips measuring 1cm\times2cm\times115\mu m, characterized by \( (T_s, T_a) = (47^\circ C, 43^\circ C) \). The electret is made of a 25\mu m-thick FEP Teflon layer charged by a corona discharge at 500V and directly glued on the heat sink. The device (figure 4a) is set on a hot source at 70\degree C and, as expected, the bimetallic strip oscillates without forced convection, turning the thermal gradient into electricity. The output power is in the 5\mu W range and the snapping frequency is about 2Hz (figure 4b).

As the energy harvester's output voltage is not compatible with standard electronic circuits, a power management circuit implementing SECE (Synchronous Electric Charge Extraction [5]) and withstanding devices in parallel has been manufactured (figure 4c). Ten bimetallic strips have been connected to this power management circuit to power a wireless sensor node consuming 80\mu J per emission every 40 seconds (figure 4d), definitely validating the suitability of be-TEH to power WSN from ambient thermal energy [6].

![Figure 4](image_url)

**Figure 4.** (a) prototype, (b) output voltage (c) power management circuit implementing SECE and (d) WSN supplied by 10 devices in parallel
Nevertheless, at this scale, the capacitance variation between the two equilibrium states is around 50%, limiting the efficiency of the power management circuit due to a large impact of parasitic capacitances: the scaling of the structure down to micrometer scale should enable to increase the capacitance variation and then to reduce the impact of these parasitic capacitances. Moreover, according to Timoshenko’s bimetallic strips modeling [7], and as demonstrated in [8], the bimetallic strips scaling helps achieving higher thermal energy transfer rates, switching speeds, snapping frequencies, and electrets-bimetallic strips capacitance variations, and will result in a global increase of our devices efficiency and power densities.

4. Miniaturization of electrostatic devices

4.1. Bimetallic strips modeling
As demonstrated by Timoshenko in [9], if its initial curvature $\delta_o$ (see figure 1a) exceeds a critical ratio such that $\delta_o > t/\sqrt{3}$ (t: total beam thickness), the bimetallic strip will have a snap action. Otherwise, if it is lower, the snap action disappears and the bimetallic strip only buckles slowly. Thanks to this model, the evolution of snapping and snapping-back temperatures for all the different parameters of the bimetallic strips can be plotted in order to evaluate the best materials couple and the bimetallic strips dimensions. The influence of the initial curvature $\delta_o$ on the stability of a bimetallic strip is shown in figure 5a while figure 5b depicts the sensibility of the snapping temperature to the CTE difference and to the bimetallic strip's length.

![Figure 5](image)

**Figure 5.** (a) Stability of Ti-Au bimetallic strips (L=200µm) as a function of the dimensions (thickness and middle deflection). (b) Snapping temperature (for $t=\delta_o\sqrt{3}=0.5µm$) as a function of the bimetallic strip length.

4.2. Micro-bimetallic strips process
As previously explained, the bimetallic strip mechanical instability is mainly linked to the ratio between the thickness of each metal layer and its curvature. The development of a micro-bimetallic strip process based on the use of a resist [10] enables to control this last parameter with a good precision. Figure 6a summarizes the different steps of the bimetallic strips fabrication. The coated resist is first patterned into arrays of rectangles, forming parallelepipeds of resist. Baking the resist at 140°C makes it melt and turns parallelepipeds of resist into rounded shapes for the bimetallic strips. Both metal layers are then deposited on the resist by PVD at 210°C to avoid the metal layers suffering from excessive residual stress and the resist from collapsing. The bimetallic strips are then shaped thanks to lithography and finally released after resist stripping.

![Figure 6](image)

**Figure 6.** Process of fabrication of a Ti-Au bimetallic strip: (1) Resist coating; (2) Resist patterning; (3) Resist baking at 140°C; (4) Au layer PVD at 210°C; (5) Ti layer PVD at 210°C; (6) Bimetallic strip patterning and etching; (7) Resist stripping and bimetallic strips release.
We have already developed the first bimetallic strips with a middle curvature (δ₀) of 8 µm to validate the process feasibility. First characterizations realized on Ti-Cu bimetallic strips have pointed out a problem of copper oxidation, modifying irreversibly the mechanical properties of the bimetallic strips and so preventing them from snapping. Choosing Ti and Au, which have a CTE difference close to the one of Ti-Cu, has enabled to tackle this issue (figures 6 b and c). Next steps will consist in (i) reducing the height of the micro-lenses to lower the snapping and snapping-back temperatures of the bimetallic strips and (ii) in creating the electret needed to harvest thermal energy.

5. Conclusion
Last optimizations and developments realized on piezoelectric and electrostatic prototypes have shown the relevance and the effectiveness of bimetal-based devices as thermal energy harvesters. The modifications performed on the piezoelectric devices have enabled to broaden their operating temperature ranges and their output powers (about 5µW at 0.22Hz). Similar output powers (5µW at 2Hz) have been reached with electret-based prototypes. The power level of ten parallelized electrostatic devices at ambient temperature has enabled to supply a wireless sensor node thanks to our own power management circuits, making b-TEH suitable for wireless sensors applications. Finally, because of their manufacturing easiness and their theoretical efficiency, electret-based energy harvesters at micro-scale are our next step. A new microelectronic process based on Timoshenko’s bimetallic strip modeling has been developed in this perspective.

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References
[1] Puscasu O et al 2012 Proc. Electron Devices Meeting (IEDM), 2012 IEEE (10-13 Dec. 2012) 12.5.1-12.5.4
[2] Gu L, Livermore C 2011 Smart Mater. Struct. 20 045004
[3] Boisseau S et al 2012 Small-Scale Energy Harvesting, ed M. Lallart, Intech, doi:10.5772/51360.
[4] Boisseau S et al 2013 Smart Mater. Struct. 22 025021
[5] Lefeuvre E et al 2005 J. Intell. Mater. Syst. Struct. 16 865
[6] Boisseau S et al Bimetal-and-electret-based thermal energy harvesters – Application to a battery-free Wireless Sensor Node, Submitted to Smart Materials and Structures
[7] Timoshenko S 1925 JOSA 11 233-55
[8] Puscasu O et al 2012 Silicon Nanoelectronics Workshop (SNW), 2012 IEEE (10-11 June 2012) 1
[9] Timoshenko S and Gere J 1961 Theory of elastic stability (New York: McGraw-Hill) 312
[10] Audran S et al 2010 J. Micromech. Microeng. 20 095008