Microelectronics Journal 45 (2014) 554–558

Contents lists available at ScienceDirect

Microelectronics Journal

journal homepage: www.elsevier.com/locate/mejo

# A disruptive technology for thermal to electrical energy conversion

O. Puscasu [a,b,c,*], S. Monfray [a], C. Maître [a], P.J. Cottinet [b], D. Rapisarda [c], G. Savelli [c], F. Gaillard [c], G. Ricotti [d], P. Ancey [a], F. Boeuf [a], D. Guyomar [b], T. Skotnicki [a]

[a] STMicroelectronics (Crolles 2) SAS, 850 rue Jean Monnet, 38926 Crolles Cedex, France
[b] LGEF, INSA Lyon, 8 Rue de la Physique, 69621 Villeurbanne Cedex, France
[c] CEA Liten, 17 rue des Martyrs, 38054 Grenoble Cedex 9, France
[d] STMicroelectronics, 20010 Cornaredo, Milan, Italy

ARTICLE INFO

*Article history:*
Received 30 November 2012
Received in revised form
25 October 2013
Accepted 16 December 2013
Available online 1 February 2014

*Keywords:*
Bimetal
Piezoelectric
Thermal to electrical conversion
Scaling laws
Power gain

ABSTRACT

A disruptive approach to thermal energy harvesting is presented. The new technique can be used for powering ultra-low power electronics. We propose a two-step conversion of heat into electricity: thermal to mechanical accomplished with thermal bimetals and mechanical to electrical accomplished with piezoelectrics. Devices can work in a wide range of temperatures: from $-40$ °C to 300 °C and the available mechanical power density is in the order of 1 mW/cm$^2$. The first electrical results and the first prototype built on a flexible substrate are presented in this work. We evidenced that one of the keys to improve the generated power density is downscaling of individual devices. To demonstrate this point, laws modeling downscaling have been established and show that the miniaturization of the devices by a factor $k$ increases the generated power density by the same factor, due to the higher heat transfer rate. The path followed in order to establish the laws is given in this paper.

## 1. Introduction

Heat is one of the most abundant energy sources that can be converted into electricity in order to power circuits. Significant efforts have been made in order to harvest heat through the development of thermoelectric generators (TEGs), based on the Seebeck effect [1]. They require rare materials containing bismuth telluride (Tellurium has almost the same abundance as Platinum, and is one of the most rare solid elements on Earth), or complex nanostructures in order to provide useful levels of power at temperatures close to ambient. These materials exhibit relatively high thermal conductivities at room temperature resulting in the need for a heat sink in order to insure thermal resistance matching between the modules and their environment (Fig. 1). This condition is necessary for an adequate thermal gradient for module functioning, especially when natural convection cooling is used. The lack of a heat sink in the latter situation can result in a power drop of one or several orders of magnitude.

In typical use cases a harvesting device uses free available energy in order to power ultra-low power devices that provide useful functions. Wireless sensors can be given as an example. These are devices that monitor the environment by measuring parameters of interest (temperature, humidity, presence of chemical elements). The gathered information is subsequently transmitted by radio emission, therefore avoiding the need for wires.

The power level needed by a wireless sensor depends on the functions it insures. Applications like temperature sensing can be addressed with 10 μW of electrical power. Since the one of the desired characteristics for wireless sensors is reduced size the harvesting devices powering them up should be as small as possible. In the case of state of the art Seebeck devices the heat sink takes the biggest part of the volume, making them inconvenient for use in applications requiring inconspicuous modules.

An innovative way of harvesting, that allows avoiding the above mentioned difficulties, is presented in this work. It enables the fabrication of thin modules that work without a heat sink at temperatures close to ambient. The key point of the integration of this technology is the ability to keep an important gradient on a device body by intelligent control over the thermal flow (Fig. 2). The working principle as well as the first experimental results with the innovative devices are presented in the following section. The scaling laws showing the potential of the technology are given subsequently in Sections 3 and 4.

## 2. Working principle and first results

An elementary device of our technology is based on a thermal bimetal that snaps when it is being heated and then cooled down. A thermal bimetal is a double layer consisting of a material of high

---

* Corresponding author at: STMicroelectronics, Process Integration, 850 rue Jean Monnet, 38926 Crolles, France. Tel.: +33 649 895 395.
*E-mail addresses:* onoriu.puscasu@st.com, onoriu.puscasu@insa-lyon.fr (O. Puscasu).

0026-2692/$ - see front matter © 2014 Elsevier Ltd. All rights reserved.
http://dx.doi.org/10.1016/j.mejo.2013.12.003

coefficient of thermal expansion (CTE $> 10 \times 10^{-6}\,\mathrm{K}^{-1}$) and a material of low CTE ($\approx 1 \times 10^{-6}\,\mathrm{K}^{-1}$). It is necessary to give the layer a concave shape in order to make it snap, that is to move quickly from one stable position to another under the effect of rising or decreasing temperature [2]. Such a bimetal snaps while reaching a predefined temperature, programmable by engineering. This temperature can range between negative values, as low as −40 °C, up to high temperatures, exceeding 300 °C. If the bimetal is cooled down, mechanical instability will be created and it will snap again so as to reach its initial shape. The snap back temperature is also programmable by design. The difference between the two snap temperatures, further called hysteresis of the bimetal, can be as small as 2 °C. Greater values of 15 °C or higher have also been obtained. They depend on the geometric distortion applied to the center of the bimetal.

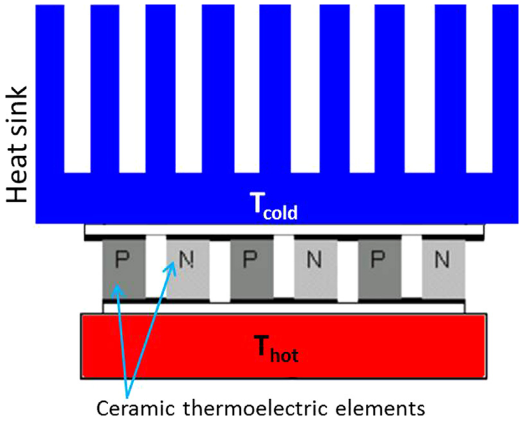

**Fig. 1.** Seebeck module with heat sink.

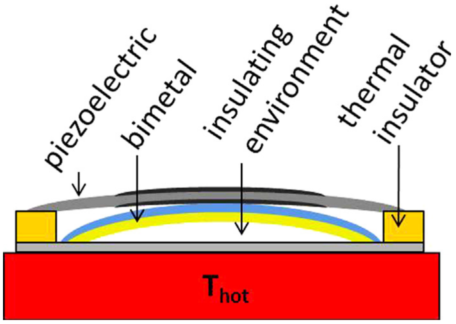

**Fig. 2.** Module with bimetal—no heat sink needed.

Thus, if a bimetal is put between a hot and a cold surface, it snaps upon heating so as to get in contact with the cold side and then snaps back after being cooled as soon as the predefined temperature is reached (Fig. 3). Therefore, an oscillation cycle is created and mechanical power is generated. While moving quickly the bimetal actuates a piezoelectric that generates voltage pulses (Fig. 4). This way a small electrical generator is created. The signal the piezoelectric provides is processed with the help of a power management circuit that insures the storage of the converted energy, as in [3].

One of the first proofs of concept has been done by using a bimetal that snaps up at 122 °C and down at 117 °C with an area of 6.5 cm$^2$, and a 0.3 mm thickness. The bimetal actuated a piezoelectric membrane with a 27 mm diameter attached to a cold surface. The resulting thickness of the bimetal and piezoelectric stack is of a few millimeters. An electrical power of 12 μW has been obtained on a hot plate at 130 °C. At this stage the generated power is sufficient for the needs of a wireless temperature sensor that performs a measurement every few minutes. The bimetal oscillates with a frequency up to 0.5 Hz and develops a kinetic energy about 16 mJ per snap cycle, that is 1.2 mW/cm$^2$ of mechanical power available.

The proof of concept has been done with separate parts with no prototype mounting. The subsequent efforts have been focused on fabrication of prototypes that work with natural convection cooling. As a result, a prototype working on a hot source at 100 °C by being

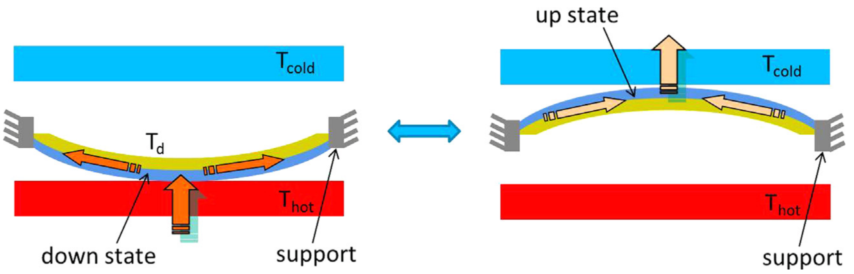

**Fig. 3.** Down and up state of a bimetal.

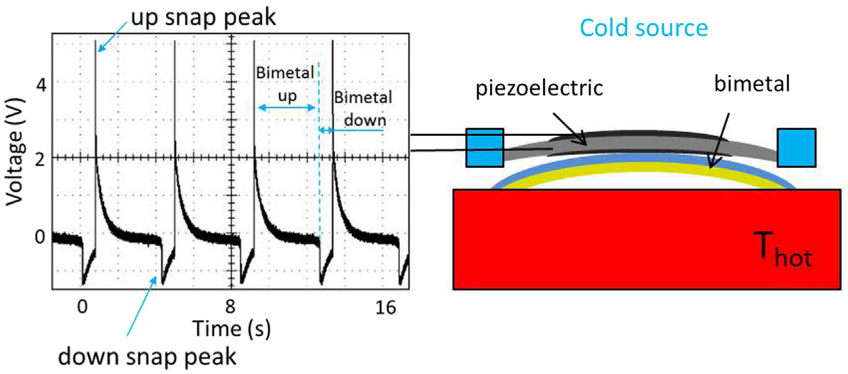

**Fig. 4.** Signal generated by a bimetal and a piezoelectric.