Optical Materials 56 (2016) 110–115

Contents lists available at ScienceDirect

Optical Materials

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

Design and performance benchmark of various architectures of a piezoelectric bimetallic strip heat engine

J. Boughaleb [a,b,c,*], A. Arnaud [a,d,e], S. Monfray [a], P.J. Cottinet [b], S. Quenard [c], 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] G2Elab, Univ. Grenoble Alpes, F38000 Grenoble, France
[e] CNRS, Univ. Grenoble Alpes, F38000 Grenoble, France

ARTICLE INFO

Article history:
Received 31 October 2015
Received in revised form 8 January 2016
Accepted 9 January 2016
Available online 12 January 2016

Keywords:
Energy harvesting
Bimetallic strip heat engine
Piezoelectric membrane
Configurations benchmark

ABSTRACT

This paper deals with an investigation of a thermal energy harvester based on the coupling of a piezoelectric membrane and a bimetallic strip heat engine. The general working principle of the device consists of a double conversion mechanism: the thermal energy is first converted into mechanical energy by means of a bimetallic strip, then the mechanical energy is converted into electricity with a piezoelectric membrane. This paper deals with the study and optimization of the harvester's design. First, the piezoelectric membrane configuration is studied to find the most efficient way to convert mechanical energy into electricity. A benchmark of various piezoelectric materials is then presented to point out the most efficient materials. Finally, our study focuses on the bimetallic strip's properties: the effect of its dimensions of its thermal hysteresis on the harvester's performances are studied and compared. Thanks to these different steps, we were able to point out the best configuration to convert efficiently thermal heat flux into electricity.

1. Introduction

Wireless sensor networks have known an important development these last years thanks to the reduction in size and in the power consumptions of the CMOS circuitry. The aim of such intelligent networks is to replace long transmission distances with thousands of low cost and low power wireless devices. Intelligent environments are consequently created and allow the monitoring of numerous quantities in environments usually run on batteries. Batteries have many drawbacks related to their wiring, their short lifetime and their elevated costs which do not make them the most adapted solution for powering autonomous node networks: in fact, replacing thousands of batteries every year in areas difficult to access could sometimes be impractical. To make wireless sensor nodes become autonomous and self-sufficient all over their lifetime, many energy harvesting devices have been developed. The goal is to scavenge the available energies in the environment of the nodes and to convert it into usable electrical power. Resources like mechanical vibrations are harvested thanks to piezoelectric materials as reported in Refs. [1,2], solar energy using photovoltaic modules as seen in Ref. [3] and heat flows using thermoelectric structures in Ref. [4] or pyroelectric materials as shown in Refs. [5,6]. In the thermal field, thermoelectric generators based on the Seebeck effect are the most used because of their efficiency. They use solid-state materials exhibiting high electrical conductivities but also high thermal conductivities in the same time. This property makes very difficult to maintain a significant temperature difference across the generator especially when the operating temperature is close to the ambient temperature. This leads to the use of heat sinks and thus raises the issue of compactness of the device as the heat sink represents the main part of the harvester as reported in Ref. [7].

To avoid the drawbacks related to thermoelectric generators, thin and compact devices capable of harvesting heat flows each time a thermal gradient is available, including those close to ambient temperature, without any heat sink, have been developed and reported in Refs. [8–11]. They convert wasted heat into electrical energy by means of thermo-mechanically bistable bimetallic strips and piezoelectric membranes.

---

* Corresponding author at: STMicroelectronics (Crolles 2) SAS, 850 Rue Jean Monnet, 38926 Crolles Cedex, France.

E-mail address: jihane.boughaleb@st.com (J. Boughaleb).

http://dx.doi.org/10.1016/j.optmat.2016.01.019
0925-3467/© 2016 Elsevier B.V. All rights reserved.

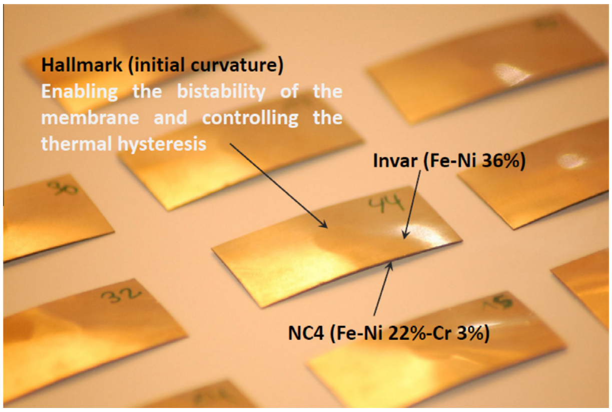

Fig. 1. Shape of the bimetal with its hallmark.

This paper presents an optimization work of a piezoelectric bimetallic strip heat engine in order to find the most efficient harvester's design. The first part of this article is devoted to the explanation of the device's working principle. In the second part, the main guidelines to find the most efficient design are exposed and experimentally tested and validated. The last part is about the interpretation and discussions of the previous experiments.

2. Device general working principle

The thermal energy harvester reported in this paper is based on a double steps conversion mechanism of wasted heat flux into usable electricity. This is possible thanks to a bimetallic strip heat engine converting thermal energy into mechanical energy by exploiting the thermo-mechanical bistability of bimetal membranes made of two materials having a mismatch of their coefficients of thermal expansion.

In this article, bimetallic shells made of Invar and NC4 alloy (Invar (Fe–Ni 36%) acting as the low coefficient of thermal expansion coefficient (CTE) layer and NC4 (Fe–Ni 22%–Cr 3%) acting as the high CTE layer) are mounted in the harvester (Fig. 1). The antagonistic effect of the thermal mismatch of the shell's materials and the initial curvature of the membrane are at the origin of the bistable behavior of the shell characterized by a thermal hysteresis, as reported by Wittrick in Ref. [12].

Fig. 2 shows the general scheme of the harvester and shape of the bistable bimetal that snaps up or snaps down each time its temperature reaches the hysteresis temperatures called the snapping temperature T_s and the snapping back one T_{sb}. Arnaud et al. explained in more details the working principle of such heat engines in Refs. [13,14].

To convert the kinetic energy released by the snapping bimetals, the bistable membrane is coupled with a piezoelectric transducer. That way, each time the bimetal snaps up, it impacts the piezoelectric membrane and the piezoelectric transducers oscillates at its resonance frequency. At the opposite, when the bimetal snaps down, it releases the piezoelectric transducer allowing it to vibrate freely. Consequently, during these two phases, the bimetal mechanical energy is converted into electricity.

3. Harvester's design optimization

The conversion mechanism of the harvester is now clarified and the fabrication of the harvester must be presented. To achieve this goal, a study of many configurations is established depending on the bimetals' dimensions, bimetals' thermal hysteresis, on the piezoelectric materials and transducer's positioning. The aim of this design benchmark is to point out the best harvester's structure that ensures an efficient conversion of heat into electricity. First of all, the harvester being a thermal energy scavenger bound to work without any heat sink, it is important to maintain an important thermal gradient across the structure. This is ensured by using a thermally insulating material. Prototypes thus are made of peek substrate with a copper cylinder at its middle to transfer efficiently the heat flux from the hot source to the bimetal at its top. This material allows taking advantage of its high glass transition temperature around 143 °C, as well as its high elastic modulus (3.8 GPa) that enhances the piezoceramic clamping and reduces the mechanical energy losses. For the piezoelectric material choice and the bimetallic strip, many options are possible.

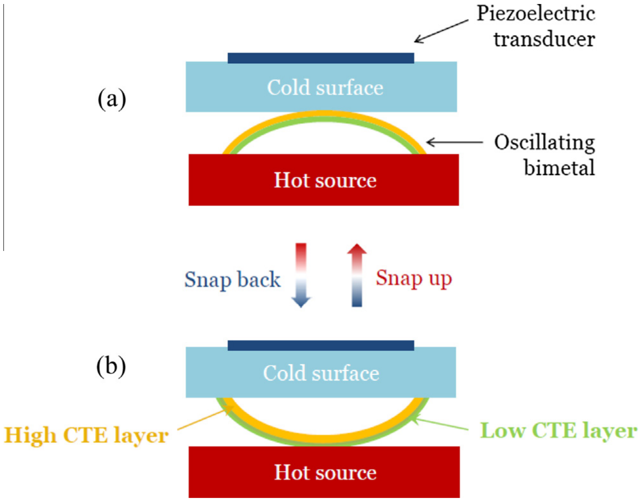

Fig. 2. Scheme of the coupled piezoelectric–bimetal heat engine with (a) the upper and (b) lower states of the bimetal.

3.1. Positioning of the piezoelectric membrane

The piezoelectric membrane insuring the electro-mechanical conversion step is positioned over the bimetal at the top of the device. Consequently, two different configurations are possible: it can either be clamped at one end of the peek substrate as shown in Fig. 3b to be used as cantilever or at the opposite it can be clamped at its two ends as shown in Fig. 3a. Hereafter, these two configurations are studied to know the most powerful one. To extract the electrical power available across the piezoceramic capacitor, the output signal of the piezoelectric membrane is measured over the whole range of the operating temperatures of the device (Fig. 4). This study enables to extract the optimal working temperature at which the output power reaches a maximum value (Fig. 5). This procedure is repeated for each harvester's architecture to compare their performances.

Figs. 4 and 5 represent the results of the harvester with a clamped–clamped piezoelectric membrane. The same work is conducted in the case of a clamped-free membrane. The values of the electrical power are compared in Table 1. This first comparison shows that the double clamped piezoelectric membrane harvests more energy than the clamped-free membrane because the membrane is more stressed in the first harvester's configuration. The mechanical energy delivered by the bimetal is thus more efficiently converted into electrical energy if the piezoelectric beam is clamped at its two ends.

3.2. Optimization of different piezoelectric materials properties

Another key point of our system is the choice of the piezoelectric ceramic to convert the mechanical energy released by the