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Flexible bimetal and piezoelectric based thermal to electrical energy converters

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ABSTRACT

A new approach to thermal energy harvesting is presented in this paper. The devices we fabricate are composed of thermal bimetals and piezoelectric membranes. Bimetals that show a snapping behavior when heated are used. When brought to a predetermined temperature, a bimetal snaps abruptly from one position to another. In this step a thermal to mechanical conversion takes place. The provided mechanical energy is then converted into electricity by a piezoelectric membrane. When shocked by the bimetal, the piezoelectric material provides voltage pulses that can be recovered with the help of an energy harvesting circuit. With this approach we have managed to build thin devices that are assembled into matrixes on a flexible substrate, and work at temperatures close to ambient. The key point of their functioning is their intrinsic ability to keep a high temperature gradient when heated and thus work without a heat sink. This is a substantial advantage over the thermal harvesters based on Seebeck effect that need a bulky heat sink for optimal performance. Pulse frequencies of 2.4 Hz have been reached, with an electrical energy per pulse up to 31 μJ. The mechanical energy per cycle delivered by a bimetal is bigger and can reach 770 μJ for a 3 °C temperature difference operation. These results have been obtained while cooling with ambient air, without a heat sink. The main characteristics of our devices and ways to improve the performance are discussed in this paper.

1. Introduction

Heat is one of the most abundant energy sources that can be harvested. All hot objects provide a thermal power that is wasted in the majority of cases. One can think of the heat generated by engines in vehicles, industrial installations or the heat of the human body. The lost heat could be used as a free source of energy to provide power to electronic devices. One of the most interesting applications that can be addressed is wireless sensor nodes. These are low power devices that require energy harvesting in order to be autonomous. Their main application is environment monitoring.

The most common way for harvesting heat is the use of converters based on Seebeck effect, also called thermo electrical generators (TEGs). They are made of solid state materials that have the property of providing a DC voltage when a thermal gradient is applied. The voltage of such a device depends on the Seebeck coefficient, typically in the order of 10^{-4} V/°C for the most common materials [1]. Thus it is necessary to connect several thousand thermoelectric rods in series in order to obtain an output of 1 V, which is a difficult engineering task. A typical thermoelectric generator is made of several thermocouples that are connected thermally in parallel and electrically in series. The materials used have to be good conductors of electricity on one hand and bad conductors of heat on the other hand. Since unbound electrons are good heat conduction media, it is difficult to achieve both properties at the same time. Thus compromises have to be made, and the minimal thermal conductivity that can be reached is that of a glass [2], on the order of 1 W/m/K. This is still 30 times higher than the conductivity of the best insulating materials such as polymer foams (0.03 W/m/K). Therefore, it is difficult to maintain a thermal gradient with a

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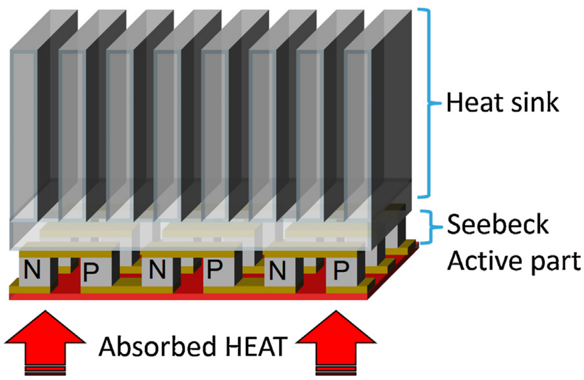

Fig. 1. Thermoelectrical generator with heat sink.

thermoelectric module and in order to manage this, a bulky heat sink is often needed (Fig. 1). As a result, the biggest part of the volume of a Seebeck device is occupied by the sink, which is the electrically passive component.

In order to avoid these drawbacks we propose a new technology, based on a two-step conversion of heat into electricity. The fabricated devices are able to keep a high thermal gradient by their design, due to the efficient thermal management. On one hand these properties open the possibility of addressing use cases with limited space available, such as heat recovery from household appliances. On the other hand, this paves the path to large area applications, since the visual impact of the devices is small and the materials used are cheap and widely available. In other words, the technology described can cover several scales.

2. Working principle

Thermal bimetals are double metal layers fabricated by lamination. One layer has a high coefficient of thermal expansion (CTE) and the other has a low one. The first mentioned layer is also called the active, since it is more sensible to heating and thus generates thermal strain. When heated, a bimetal bends. This is also known as the bimetal effect. It is due to the fact that the active layer tends to expand more than the passive layer when temperature rises. The passive layer is loaded in traction, while the active one is loaded in compression since its expansion is restrained [3].

If a bimetal membrane is given a specific initial curved shape it snaps when heated (Fig. 2). This means it moves quickly to a stable position from an unstable one, and changes the orientation of its curvature [4–6]. If the bimetal is heated on a hot plate and touches a cold plate while in its upper position, it will cool down and snap back. Thus, an oscillation cycle between a hot and a cold plate will be created (Fig. 3).

The snap temperature of a bimetal depends on its dimensions and the materials used. Its expression for a bimetal strip in a rigid frame is [3]:

$$T_u = \frac{1 + \frac{6f_0^2}{s^2} \cdot \left(\frac{1}{3} - \frac{1}{9}\frac{s^2}{f_0^2} \right)^{3/2}}{\frac{3}{16} \cdot \frac{L^2}{sf_0} \cdot (\alpha_2 - \alpha_1)}$$

with L, s, f_0—length, thickness and initial deflection of the bimetal, α_2, α_1—coefficients of thermal expansion of the active and passive layer, T_0—the reference temperature. The back snap temperature also depends on the geometrical parameters. The difference between forward snap and back snap temperatures is called hysteresis of the bimetal.

Elastic energy builds up inside the bimetal during the heating step. It is released and converted to kinetic energy during snap action. As a result the bimetal shocks on the cold plate at the end of its path. If a piezoelectric membrane is used as a cold plate, it will bend under shock and thus generate voltage. Periodic pulses will appear during the oscillation cycles of the bimetal, and the device will work as an energy harvester [7].

The first prototypes using bimetals and piezoelectrics have been demonstrated on a rigid substrate [8–10]. Also a theoretical analysis has been carried out on the scaling laws of the devices showing the advantages of micro scale fabrication [11]. The mounting of prototypes on a flexible substrate has been done to show the complete features of this technology and is presented in this work.

Bimetal and piezoelectric material association is a way to make two step conversion of heat into electricity. Alternative ways exist and have been studied [10–13]. The association of a bimetal with an electret has been studied so as to have mechanoelectrical conversion based on an electrostatic principle. As opposed to piezoelectric based devices, the latter still need a heat sink in order to work. The advantage they bring for now is a better mechanoelectrical coupling with respect to piezoelectric conversion. The need to work with a heat sink is determined by bimetal engineering, since in order to have a good coupling the bimetal interacting with an electret has to be thin. It turns out that the fabrication of thin bimetals with a small hysteresis is more challenging. Thus, the generated power per unit surface is higher due to the better coupling, but the thickness of the prototypes is bigger, since a heat sink is used. Piezoelectric based devices use thicker bimetals that provide a high energy per snap and allow a small hysteresis. Therefore, it is easier to ensure a good thermal management in comparison to electret based devices, and also to existing Seebeck effect devices.

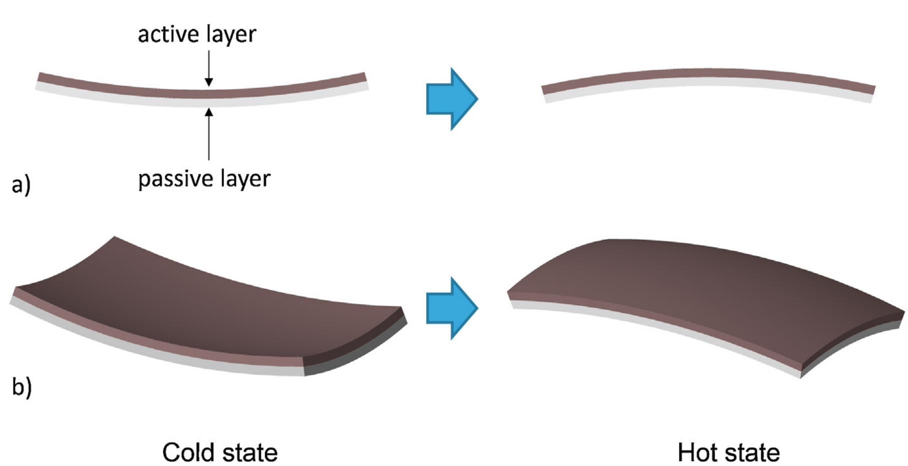

Fig. 2. Snap action of a thermal bimetal: (a) longitudinal cross section; (b) 3D shape.