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Realization of a wearable miniaturized thermoelectric generator for human body applications

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ABSTRACT

This paper presents the realization of a full-fledged wearable miniaturized thermoelectric generator (TEG) specifically engineered for human body applications. It is based on a surface micromachined poly-SiGe thermopile. In view of the adverse thermal environment on human body, special attention is paid to the optimal design for the individual thermocouple, for the thermopile featured with a rim structure standing out of Si substrate, and for the wearable TEG. Fabricated by using surface micromachining technology, each thermopile chip contains 2350 or 4700 thermocouples connected thermally in parallel and electrically in series. The effectiveness of the targeted design is validated by both simulation and experiments. To facilitate further packaging, the thermopile chip is flip-chip bonded to a Si chip coated with a thin layer of BCB. Such a bonded thermopile chip delivers an open-circuit output voltage of 12.5 V/(K cm^2) and an output power of 0.026 μW/(K^2 cm^2) on a matched external load. Towards the making of a full-fledged wearable TEG, the bonded thermopile chip is manually assembled with other specially designed components. Being worn on human body, the wearable TEG delivers an open-circuit output voltage of about 0.15 V and an output power of about 0.3 nW on a matched external load. Further improvement in the output performance can be achieved by optimizing material properties, applying metal-to-metal bonding and fabricating thermocouple microstructures on high topography.

1. Introduction

Recent technological advances in integrated circuits, physical sensing and wireless communication have paved the way for the deployment of wearable wireless body area networks (Wireless BAN or WBAN), an enabling technology for continuous health monitoring [1]. A typical wireless body area network is composed of a number of miniature, lightweight, low-power sensing devices, management electronics and wireless transceivers. As an indispensible part of the system, the power supply for these components should be small-sized, lightweight, environment-friendly and everlasting as well. In this context, the traditional batteries and the recent miniaturized fuel cells, both non-rechargeable and rechargeable, are less advantageous than the energy harvesters, especially in terms of effective lifetime and autonomy.

Energy harvesters, also known as energy scavengers, usually capture and convert ambient energy from different forms, such as thermal energy, kinetic energy and electromagnetic energy, into electrical energy [2]. Taking advantage of the Seebeck effect, the thermoelectric generator (TEG) as a type of energy harvester can deliver an electrical output power by converting a heat stream flowing therethrough. Amid the evolution of micromachining technology, a variety of miniaturized TEGs have been made from bismuth telluride (BiTe) compounds, polycrystalline silicon germanium (poly-SiGe) or metals [3–8]. Although ideally BiTe superlattice structures offer a large space for further improvement of the overall thermoelectric properties, characterized by the figure-of-merit *ZT*, the material properties of BiTe compounds practically used in recent miniaturized devices are merely on par with those of poly-SiGe [3–6,9]. Due to the lack of established thin film micromachining technology for BiTe compounds, most of the BiTe-based TEGs are characterized by large dimensions of the individual thermocouple, a relatively small total number of integrated thermocouples and eventually a minimal output voltage [3–6]. Meanwhile, poly-SiGe has been investigated for thermoelectric applications as well due to the wide availability of its thin film processing technology [7,10]. In contrast with BiTe-based TEGs, poly-SiGe based ones normally contain a larger number of individual thermocouples, leading to a higher output voltage under the same temperature difference [7]. However, the much smaller contact area of the poly-SiGe thermocouples gives rise to a more pronounced issue of contact resistance with metal interconnect and consequently a much larger internal electrical resistance.

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Moreover, due to the employment of thin film fabrication technology, the height of poly-SiGe thermocouple legs is usually limited, resulting in a minimal thermal resistance.

An adequately large thermal resistance of each thermocouple is crucial to the proper operation of TEG on human body, because of the limited overall temperature difference from human body to the ambient on one hand and the large thermal resistances of human body and the ambient on the other hand. As opposed to the laboratory experimental environment, where a temperature difference can be artificially enforced on the TEG, a TEG being deployed on human body can utilize only a small fraction of an overall temperature difference of 10–15 K. Hence, the output performance of the traditional TEGs, when deployed on human body, is estimated to be inadequate to fulfill the requirements brought by the wireless body area network.

In an attempt to improve TEG output performance, a poly-SiGe based micromachined thermopile has been designed specifically for human body application [11]. Aimed at increasing the thermal resistance of the TEG with regard to human body and the ambient, several measures are taken in the device design for both the individual thermocouple and the whole thermopile. The effectiveness of these measures is validated with modeling and then proved with experimental results obtained on fabricated devices. The output performance of the TEG can be further pushed up by packaging and assembly. In this work, the thermopile chip is first flip-chip bonded to another Si chip of similar size. Thermal measurement under a fixed temperature difference is carried out on the bonded chip with a specially designed experimental set-up. Then the bonded chip is mounted in between a metal plate and a custom designed pin-featured metal radiator. Other accessories, such as wire connection, a wristwatch strap and a shock protection grid, are also mounted. The resulted full-fledged TEG delivers an open-circuit output voltage of about 150 mV on human body at regular office conditions. The output power of this TEG can be improved considerably by further optimizing the material properties of poly-SiGe. The whole development work, including design, modeling, fabrication, measurement and packaging, is described, the final conclusion is drawn and the future work is suggested.

2. Design

2.1. Equivalent circuit model of a TEG deployed on human body

A typical TEG is made up of a number of thermocouples, which are connected electrically in series and thermally in parallel, sandwiched between a bottom chip and a top chip, as schematically shown in Fig. 1.

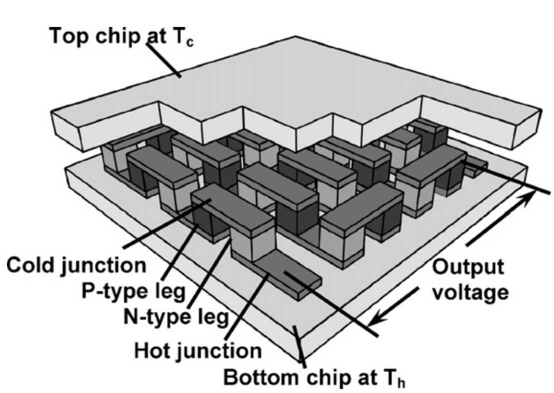

Fig. 1. Schematic configuration of a typical TEG which is made up of a number of thermocouples connected electrically in series and thermally in parallel. The thermocouples are sandwiched between a bottom chip and a top chip.

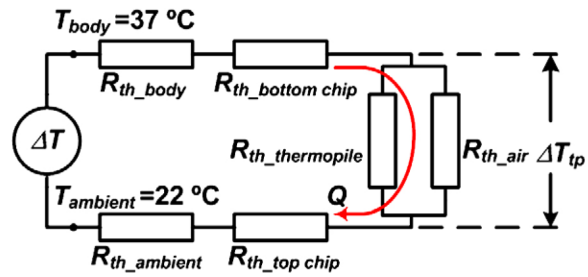

Fig. 2. Equivalent circuit model of a typical TEG deployed on human body.

When there is a temperature difference ΔT_{tp} between the thermocouple junctions, an output voltage V is delivered between the two terminals due to the Seebeck effect:

$$V = n \cdot (\alpha_p - \alpha_n) \cdot \Delta T_{\mathrm{tp}} \tag{1}$$

where n is the total number of thermocouples, α_p and α_n are the Seebeck coefficients for p-type and n-type material, respectively. The output power P is dependent on both the TEG electrical resistance R_{TEG} and the electrical resistance of the external load R_L:

$$P = \frac{V^2}{(R_{TEG} + R_L)^2} \cdot R_L = \frac{n^2 \cdot (\alpha_p - \alpha_n)^2 \cdot \Delta T_{\mathrm{tp}}^2}{(R_{TEG} + R_L)^2} \cdot R_L. \tag{2}$$

On a matched external load, the optimal power output P_o is obtained as

$$P_o = \frac{V^2}{4R_{TEG}} = \frac{n^2 \cdot (\alpha_p - \alpha_n)^2 \cdot \Delta T_{\mathrm{tp}}^2}{4R_{TEG}}. \tag{3}$$

Such a TEG being worn on human body can be analyzed by using the equivalent circuit model illustrated in Fig. 2.

As depicted in Fig. 2, the TEG is connected thermally in series with human body and the ambient. Because of the low thermal conductivity of human skin (namely dermal layer, fatty layer and visceral layer), it constitutes a large thermal resistor in this equivalent circuit [12]. The thermal resistance of the ambient is also large owing to the normally inefficient heat dissipation on the small chip area under a limited temperature difference. In contrast, the thermal resistance of a micromachined TEG is minimal for two reasons. Firstly, each individual thermocouple has a thermal resistance not large enough for applications on human body. This is due to the short thermocouple height, limited by the inability of contact photolithography to resolve fine patterns on a high topography. Secondly, the fact that all the thermocouples are arranged thermally in parallel makes the total thermal resistance even smaller. Consequently, a large portion of the overall temperature difference drops on both human body and the ambient while only a small fraction drops between the junctions of the thermocouples.

As a result of this hostile thermal environment, the design of the TEG in this work is specifically aimed at increasing its thermal resistance. The reduction of the thermal resistances of other components is achieved mainly through proper packaging and smart assembly for the TEG.

2.2. Design of an individual micromachined thermocouple

An individual thermocouple is designed in such a way that its thermal resistance is maximized. As schematically shown in Fig. 3, each thermocouple is composed of p-type and n-type thermocouple legs interconnected by aluminum pads at two junctions (denoted as “A” and “B” in Fig. 3). In this design, several measures have been adopted to maximize the thermal resistance of the thermocouple microstructure. Firstly, a 2.5-μm-deep trench