THERMOELECTRIC MEMS GENERATORS AS A POWER SUPPLY FOR A BODY AREA NETWORK

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ABSTRACT

Miniaturized and cost-effective thermoelectric generators (TEGs) scavenging energy from environment could potentially provide power autonomy to consumer electronic products operating at low power. For example, TEGs mounted in a wristwatch have been used to generate electricity from human heat [1].

The key point of IMEC's research in this field [2] is the realization of a body area network, consisting of a set of wireless sensors/actuators, able to provide health, sports, comfort, and safety monitoring functions to the user. The development of miniature energy scavengers built on MEMS technology is a primary goal of the ongoing research, as this will make the network truly power autonomous.

In this paper, the modeling and a novel design of MEMS TEGs especially conceived for human body applications are described. The design is built on the basis of a thermal model of the device, which includes the human body as one of its important elements. For this purpose, the research on human body thermal features is performed. The TEG prototype made with commercial thermopiles is tested with power conditioning electronics and a wireless module mounted on a watchstrap.

HUMAN BODY AS A HEAT SOURCE FOR A THERMOELECTRIC GENERATOR

The modeling of a thermoelectric generator on a human body as well as on the skin of any other warm-blooded animal requires knowledge of the body properties as a heat generator for the small-size objects placed in contact with the skin. The research dedicated to this particular task has been performed on 158 volunteers using large-scale thermoelectric generators assembled for the only purposes of investigating the heat flows through the human skin, thermal management in/on the body and accompanying physiological and psychological problems related to the using of the heat-absorbing device on the skin. The first-generation thermopile converters represent a 3-layer stack of classical BiTe thermopiles supplied with a conventional multi-fin radiator of $3.3\times4.6\times5$ cm^3 or $1.6\times3.6\times3.8$ cm^3 size, Fig. 1.

The statistics on obtained heat flows is illustrated in Fig. 2. The volunteers were asked to attach the device according to their preference, and to take any pose in a chair at the desktop PC appropriate for them during a half-hour experiment. Fig. 3 shows psychological a wrist with a watchstrap and located at the place of a watch. We can see that physiologically there are no reasons for any of two groups to like or dislike the device, because the heat flow and the skin temperatures are very similar.

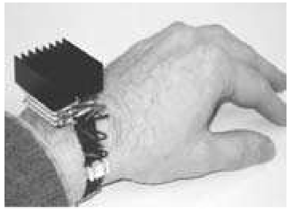

Fig. 1. First-generation TEGs supplied with a watchstrap and used for the study of thermal features of human body.

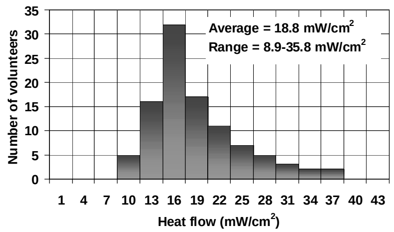

Fig. 2. Heat flow measured on a wrist (at a watch place) of 100 volunteers at an average room temperature of 22.3°C. The average skin temperature is 30.0°C.

At normal laboratory conditions (almost still air if an air conditioning isn't taken into consideration), the heat flow from the body is limited by the physical activity of the person, by air humidity and by the cloth worn because the latter may decrease the overall heat dissipation from the body skin by several tens percent. However, a large fraction of the heat generated in the body goes through the lungs (both, evaporation and heating the air we breath) and through the sweating.

In case of forced air convection, which could mean walking, presence of wind or working fan in the room, the heat flow through the skin may significantly deviate from the conditions of natural convection. The same situation occurs when the device attached to the skin has a developed surface, so that the surface of the contact with the air exceeds the surface of the skin covered by the device; see e.g. the example in Fig. 1. Such way of decreasing the interface resistance between the device

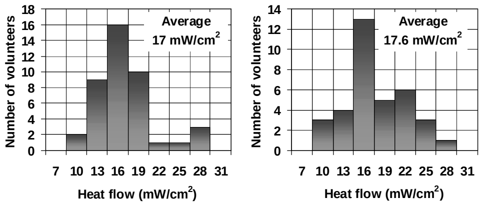

Fig. 3. Psychological reaction on new object on the wrist which is supposed to take heat from the body. The diagrams show the heat flow distribution for (a) 45.5% volunteers saying that the device is acceptable and (b) 54.5% claiming that it is too cold. Note: the average T_{skin} under the hot plate is 30.1ºC for (a) and 30ºC for (b).

skin. Therefore, it's not surprising that the generators with a radiator demonstrated up to 7 times larger heat flow than it occurs on the skin in natural conditions, without the device.

It is known from medical researches that about 80% of the energy spent on physical activity turns into the waste heat. Therefore, the common mistake is to expect the obligatory rise of the heat flow through the skin if the person under test makes physical exercises. For example, our experiment has shown increase of the local heat flow through the generator by 60% when the person is walking. However, this effect isn't attributed to the heat dissipation in the body, but mostly to more efficient performance of the radiator, which during walking works in forced convection conditions. The other experiment, where the person was cycling at the air temperature of 16ºC, has shown 20%-drop of the heat flow starting 3 min of cycling that is explained by the cooling of whole arm by the wind.

The place of attachment of the device to the body plays an important role for the magnitude of the heat flow if the latter is not limited with the heat sink from the generator into the air. First of all, the body has non-uniform temperature distribution not only due to the cloth covering most of the body surface, but also due to the fact that body itself has non-uniform surface temperature due to its anatomy and a cardiovascular system, Fig. 4. The latter resembles the industrial heat-recuperation systems: in general, arteries and veins go close to each other allowing regulation of the heat flow reaching the end of the arteries/arterioles. The presence of arteries is the physical reason for additional variation of the human body properties from place to place, i.e. (i) the heat flow density on the skin and (ii) the thermal resistance of the body between its inner part and the skin surface, where the generator is attached. Fig. 5 illustrates the heat flow obtainable on two different places on the wrist: the curve (1) is obtained on the place where the watch is worn, let us call it a watch place, while significantly better heat flow (2) has been observed on the other side of the wrist, where the only watchstrap usually is. The exact location artery. Actually two main arteries pass through the wrist; the second one is ulnar artery. However, there are also the anterior interosseous branch of ulnar artery and several smaller interconnecting arteries. The arteries bring the wasted heat to the wrist, and its dissipation is reflected in Fig. 4 as more heated areas, which uncover the hidden arteries and bunches of arterioles and capillaries. To the moment, the radial artery is used in our generators as the proper place for a thermoelectric generator because in experiments it gave larger heat flow density through the attached generator.

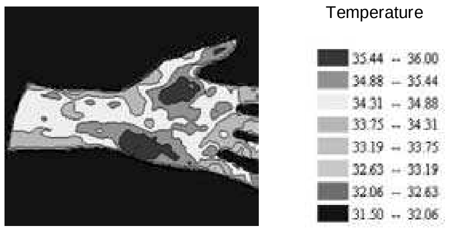

Fig. 4. Infrared image (palmar view) of the hand and wrist taken with 8 – 12 μm infrared camera.

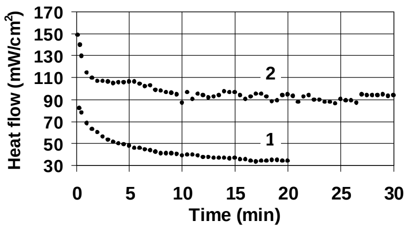

Fig. 5. Heat flow through the TEG at a thermal resistance of 50 cm^2K/W between the skin and the room-temperature heat sink. The heat flow is limited by the body properties on a watch place (1), therefore, it is significantly less than on the radial artery (2).

DESIGN OF THE THERMOELECTRIC GENERATOR

The modeling and designing of a MEMS-based thermoelectric generator is built around the measured human body features that accounted in the model of the generator as a serial variable equivalent thermal resistor. Its average experimental value obtained in laboratory conditions, still air and sitting volunteers is about 300 cm^2K/W on the watch place, including interface thermal resistance between the skin and the hot plate of generator. This thermal resistance drops to 60-90 cm^2K/W on the radial artery, at the point of crossing the watchstrap line.

The thermopile was supposed to be manufactured at IMEC p-line with a minimal feature size of 1 μm. The self-supported thermocouples standing on the bottom hot-formed on the top cold-plate chip. Two chips form a sandwich with thermopile in between. The optimizations performed on such generator design have lead to the necessity of multi-fold decreasing of the parasitic heat exchange between hot and cold plates, the problem which had no solution until now.

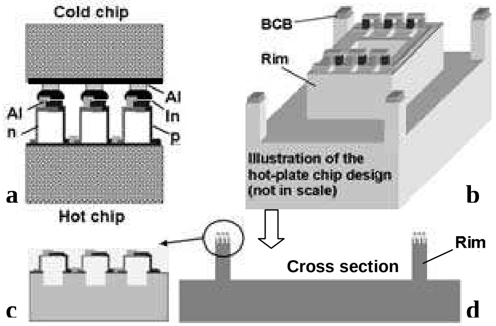

Fig. 6. Design of the poly-SiGe thermopile sandwich.

The solution has been found in making a rim in the both top and bottom silicon chips, Fig. 6, b. The thermopile and the heat spreading structure (bumps) are to be made on top of the rim. Additional spacers will be used above the thermopile sandwich for further decreasing the influence of the parasitic heat flow inside the device on its performance. The first demonstration micromachined TEGs at the size of the embodiment of $3\times3\times1$ cm^3 and the height of the thermocouples of 2.5 μm, are expected to demonstrate 1 – 1.5 V and 1 – 2 μW on a human body.

Depending on material used and the chosen place on the skin, the limits for the performance characteristics vary. Calculations show that inside the buildings, at 22ºC, BiTe may offer up to 30 μW per 1 cm^2 of skin, Fig. 7, while less expensive and more extensively developed poly-SiGe may provide up to 4.5 μW/cm^2. It is important to notice that without the use of the rim the generated power would have been more than 100 times less.

TECHNOLOGY FOR POLY-SiGe THERMOPILES

The market requires low-cost thermoelectric generators because the batteries they are supposed to replace are really cheap. The generators must be reliable to function for many years in almost all conditions of exploitation: in this case, it is possible to approach to the energy/cost ratio obtained with the batteries. Due to thermodynamic limitations caused by the very low thermal gradient on the human skin, future thermoelectric generators will become equal in performance to the battery of the same size in about few-to-10 months of their operation on a human body. To the moment, the polycrystalline SiGe is used as a thermoelectric material for making first demonstration chips. Poly-SiGe is

have been already measured [3]. The additional advantage is that the technology for poly-SiGe layers developed at IMEC provides a very low thermal conductivity of only 0.03 W/cm K.

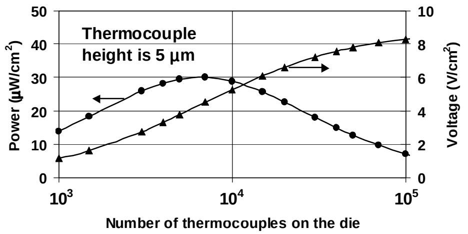

Fig. 7. Calculated power and voltage obtainable on a human body with BiTe TEG of the proposed design occupying 1 cm^2 of the skin with a 5 mm-thick radiator.

A novel element of the thermal design of the TEG is a rim structure, Fig. 6, b and 6, d, fabricated with deep reactive ion etching of Si. The micromachined thermocouples are fabricated on top of the rim and are electrically interconnected in series forming a thermopile. Supplementary 3 μm-deep microcavities made under thermocouples, Fig. 6, c, further decrease the parasitic heat path through the thermal conduction of the air.

A process for the fabrication and assembling the TEG based on SiGe thermopiles has been developed. The process flow starts with etching microcavities under the thermocouples and filling them with SiO_2, Fig. 6, c. It is followed by deposition and patterning the SiO_2 pads on top of the SiO_2-filled microcavities. Then, p- and n-poly-SiGe legs are formed and aluminum interconnections are made on top of hot and cold junctions. The deep ion reactive etch of silicon is then performed to form a rim; at this point all chip surface which isn't covered with the thermocouples or metal lines, is the subject of a deep 0.25 mm-etch. After opening the side of the thermocouples, the sacrificial SiO_2 layers are etched away. The top, a heat spreading chip, represent patterned Al squares covered with indium. The aluminum layer is electrically isolated from silicon with thin Si_3N_4 layer. Upon fabrication of this structure, the top chip is also etched to form a rim of the same height, i.e. 0.25 mm.

In order not to destroy thermopile mechanically during assembling the device and further exploitation, a number of thermocouples are left with sacrificial oxide. These thermocouples serve as stoppers when mounting top chip on the bottom one. The assembling of two chips is performed using BCB layer on top of four pillars made on the chip corners, Fig. 6. The assembled thermopile sandwich is supposed to be mounted on a metal hot plate touching the skin and supplied with a watchstrap. The radiators will have different shape (not designed to the moment). The radiator as well as the rest of the device will be protected with a touch- and shock-protecting grid

Fabrication of the poly-SiGe thermopiles is ongoing (See Fig. 8).

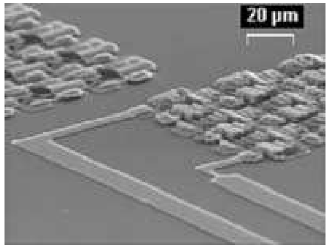

Fig. 8. Detail of the chip containing about 5000 poly-SiGe thermocouples forming a thermopile before etching the rim.

PROTOTYPE OF THE THERMOELECTRIC GENERATOR MADE WITH BiTe THERMOPILES

In order to accelerate fabrication of the prototypes of thermoelectric generator, the classical commercial BiTe thermopiles have been used to make the second-generation thermoelectric bracelet, Fig. 9, a. Each thermopile has a size of $8.2 \times 8.9 \times 2.4$ mm^3 and composed of 128 thermocouples; 48 thermopiles are used in total.

The power conditioning electronics suitable for a TEG operating on human body has been developed. It includes up-conversion and voltage stabilization and has been mounted on the bracelet. The prototype generates in average 100 µW of useful electrical power, stored in 2 NiMH batteries. The prototype has been used to transmit several measured quantities to a PC with a wireless module working at 2.4 GHz. An example of the data transmitted during one day is shown in Fig. 9, b.

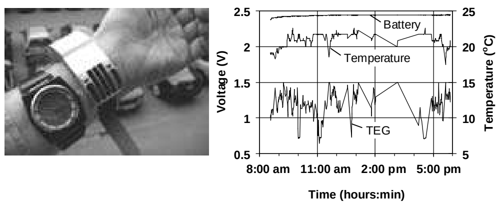

Fig. 9. (a) Photo of the bracelet with TEG, power conditioning electronics and wireless module. For comparison, a watch is shown. (b) The data transmitted from the TEG using wireless module: voltage from the TEG and on the battery, and the sensor chip temperature.

CONCLUSIONS

The features of human body as a heat source for a small-size thermoelectric generator attached to the skin have been investigated. The obtained results have been used in modeling the thermoelectric generators for application on a human body. The modeling has resulted in a new element of the thermal design, i.e. the pillar/rim structure, which allows solving the problem of parasitic heat flows deteriorating performance of a micromachined thermopiles. The model gives all necessary design parameters to obtain the optimal performance of the TEG.

The technology for a poly-SiGe TEG has been developed and, after having completed trial run, the first demonstrator run is currently in the process line. Depending on the final bracelet design, the first MEMS-based TEGs are expected to produce a few-microwatt level of the power on a watch-size surface, however, this is already many thousand times better than the current state of the art on the micromachined TEGs. The cloth-incorporated devices are also being considered as one of possible first demonstrators. After that, step-by-step improvement of the technology should hopefully lead to 4.5-30 µW/cm^2 of generated power as it is obtained from modeling, depending on materials of the thermocouples.

The first demonstration thermoelectric bracelet using commercial BiTe thermopiles has been designed and tested. The average power stored in the battery is about 100 µW allowing transmission of the data from the sensor layer and the generator parameters to a PC using a self-powered wireless module.

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