Small-size BiTe Thermopiles and a Thermoelectric Generator for Wearable Sensor Nodes

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Abstract

A wearable wireless sensor is fabricated for measuring the power generated by an embedded wrist thermoelectric generator in real life at different ambient conditions. Small thermopiles with a state-of-the-art aspect ratio of 8.9 of the BiTe thermoelectric legs with a lateral size of 0.15 mm have been fabricated in an industrial process. Composing the thermopiles into four stages gives an effective aspect ratio of 35, which allows thermal matching of the thermoelectric generator with human body and the ambient air. The generator is functional at lowest temperature difference of 3 °C between the skin and still air. As measured on a volunteer, variations of the skin temperature and occasional fluctuations of the ambient temperature allow at least part-time power production at any ambient temperatures. The load of the generator is a battery-less electronic module with variable duty cycle, which is set for pulse radio transmissions of the measured data. Its variable power consumption is dynamically tuned to the power produced.

Introduction

Miniaturizing the thermopiles used for energy scavenging is important for making compact thermoelectric generators (TEGs) functioning at very small temperature differences. This is especially related to wearable devices, which should be personally accepted by their users. Most of the world efforts are concentrated at developing film technologies, however, the progress in commercial fabrication process may also satisfy the needs of energy scavenging. The reasons for that are good thermoelectric quality of the material used in the industrial process and ongoing worldwide developments of low-voltage electronics, which will allow conversion of, e.g., 0.1–0.2 V output of a TEG. Thermal matching of a TEG to the environment [1] allows wearable watch-size TEGs with commercial thermopiles providing functioning of the sensor nodes up to 26–28 °C [2]. The question arises: can they power such devices at higher ambient temperatures and where is the temperature limit?

In order to answer this question a wearable self-powered sensor has been made in 2007 for the only purpose: to measure the power produced by the embedded TEG in real life at different ambient temperatures. This paper discusses all aspects of design and fabrication of the energy scavenger, the device itself and the obtained results.

Fabrication of miniature thermopiles

The design of thermoelectric module is traditional one, i.e. multi-stage thermopiles are needed like in case of Peltier coolers. This allows the demonstration of capabilities of high-Z BiTe for energy scavenging on human skin. According to thermal optimization of the TEG in condition of limited size of the energy scavenger, a lateral size of thermoelectric legs much less than 0.2 mm should be provided. As far as the minimal equivalent length of a thermopile leg required was 5 mm, the only reliable solution was to divide it into several stages thereby making the thermopiles much more stable mechanically. Each of the stages has been composed of 195 thermocouples with the leg dimensions of 1.25 mm × 0.14 mm × 0.14 mm, i.e., with an aspect ratio of 8.9. Extruded rods of BiTe were used for making the legs. Electrical discharge machining provided accuracy of fabrication of +0.00/-0.02 mm, so that the lateral dimension of the legs is 0.15–0.13 mm. The ends of legs have been coated with nickel and pre-tinned. A pattern of thin film copper interconnects has been provided on ceramic plates, which are 0.5 mm-thick on outer sides of a 4-stage assemblies, and 0.25 mm-thick in between the stages. In a stage, thermopiles are connected thermally in parallel and electrically in series to each other. As has been found, soldering of two ceramic plates to the legs at once is preferable because of fragility of BiTe, which becomes critical at small dimensions. For successfully assembling the thermopiles, the accuracy of both mechanical holders and the procedure has been improved in three times. The thermopiles are soldered to each other into four stage assemblies providing an effective length of thermocouples of 5 mm and an equivalent aspect ratio of 35. The dimensions of the assembly are 6.7 mm × 8.0 mm × 8.2 mm.

Wrist thermoelectric generator

The watch-size thermoelectric generator for outdoor use fabricated in 2005 [2], has been thermally matched to the ambience [1], however, the indoor version of the device has been somewhat thermally mismatched [2] in order to get the required performances. The improved thermopiles described in previous section allowed designing the thermally matched compact TEG for indoor use, moreover, the TEG voltage is improved allowing higher ambient temperatures while the size of the device has decreased by 25 %. The TEG, Fig. 2,

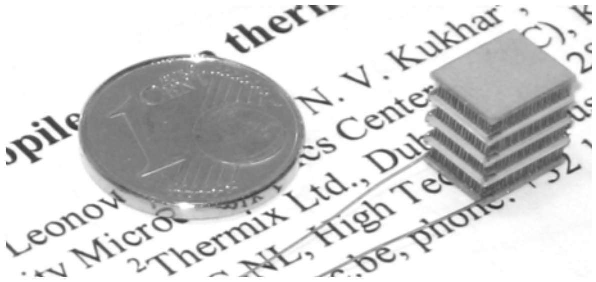

Figure 1. Four-stage thermopile assembly.

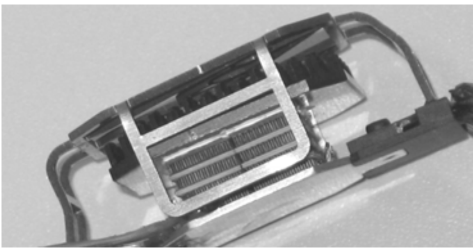

Figure 2. Wearable thermoelectric generator (side view).

has a pin-featured radiator with a size of 8.5 cm^2. The hot plate provides 5–6 cm^2 area of the contact to the skin, depending on a person. The touch- and shock-protection grid above the radiator is a necessary element of the design because of fragility of the thermopiles. The device can be worn either in location of a watch or on the radial artery; the latter is preferable for better performance, while the former is more convenient for the user. The performance characteristics of the TEG have been measured on a wrist with no protection grid in a laboratory in a still air. Depending on orientation of the TEG, the voltage and power vary. The TEG performance has been studied with no radiator and after gluing the radiator, Fig. 3. Five spatial orientations of the TEG have been investigated with the TEG on the radial artery: A–D are measured at horizontal position of the forearm, and E is a hand down. The orientation D is not common, it is like catching a raindrop with a hand. The orientation E is typical, but in such case people usually walk, so that forced air convection improves the produced power at least in two times. Therefore, we consider the positions A–C as adequate to describe the typical indoor situations of active, relaxing or sleeping person. The average power production with the radiator over A–C positions is 182 µW. One may conclude, that the position B reflects an average power production. It is also clear that despite the fact that the radiator used in the device is not much larger than the thermopile unit, it improves the power by a coefficient of 3 on average, Fig. 4. The corresponding rise of the voltage is 70 %. The most dramatic change was observed in case D, where the power has increased in more than 6 times.

Because the radiator is larger than the hot plate used, the average power generation at 24 °C corresponds to more than 21 µW per square centimeter of the radiator. It would further increase to over 25 µW/cm^2 at 22 °C and to about 30 µW/cm^2 if a ZT of one is provided. Therefore, we may state that the TEG works at the theoretical level of power production obtainable on man, which is about 30 µW/cm^2 at a ZT of one [1, 2]. Of course, further increasing the height of the pins of the radiator could improve this value a little, but the device would be too bulky and therefore impractical.

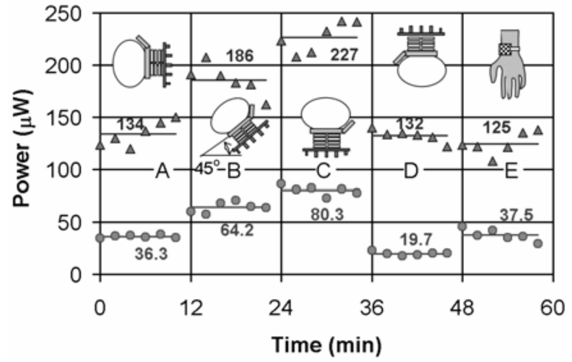

Figure 3. Power produced by the TEG at its different spatial orientations with no radiator (circles) and with the radiator (triangles). Measured in still air at 24 °C on an office worker after several hours of typical daily activity.

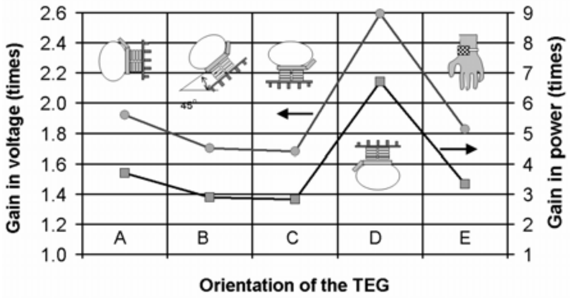

Figure 4. Gain in voltage and power produced by the TEG if the radiator is attached to the thermopiles. Calculated using the data shown in Fig. 3.

Wearable wireless sensor

Despite the fact that performance characteristics of wearable TEGs at different air temperatures have been already measured in our previous researches [2, 3], it was not clear what could be the power generation in a real life, especially, in the range of high ambient temperatures above 25–30 °C. This is, in particular, because the TEGs of 2004-2006 did not provide enough voltage to power electronics at such high temperatures.

In order to constantly monitor the generated power, the charge storage element, a battery or a supercapacitor, must always be maintained below reaching the limit of their storage capacity, otherwise, the charge transfer from the TEG stops. The idea was to use variable data transmission rate as the regulator of power consumption. Actually, this is a nice example of the devices of tomorrow, wherein this feature will be undoubtedly implemented. The TEG was targeted at high ambient temperatures and, therefore, at small temperature differences between the human skin and air. Therefore, a small supercapacitor has been chosen as the charge storage element like it has been done recently [4, 5] instead of a battery [2] because it allows direct charging at lower input voltages.

The power conditioning circuit is shown in Fig. 5. The supercapacitor serves as a short-time energy buffer and provides a steady DC load to the TEG despite the highly variable current consumption by the electronic module in

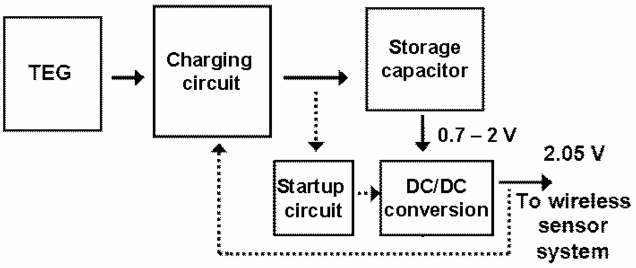

Figure 5. Block diagram of the power conditioning circuit.

condition of pulse radio transmissions. A small rechargeable NiMH battery can be used instead for applications where the system needs to keep operating for longer times under a lack of input power from the TEG. The capacitor (or battery) is charged through an ultra-low-loss rectifier circuit based on a MOSFET [4].

A commercial DC/DC converter (MAX1723) combined with a high-Q inductor steps up the voltage to 2.05 V with an excellent efficiency of 80 % at 100 µW, and at additional quiescent power of about 15 µW. Essential for proper operation is the start-up circuit [4]. It implements an ultra-low-voltage comparator that keeps the DC/DC converter in shutdown regime until a threshold voltage of 1.2–1.3 V is reached. Once started, the DC/DC converter keeps operating until the input voltage drops below approximately 0.5 V. The comparator is implemented as a temperature-compensated bipolar transistor circuit and functions correctly starting at 0 V supply voltage.

The core of the wireless sensor module is IMEC's low power wireless and processing platform of 14 mm × 14 mm size, Fig. 6. It consists of two layers: a wireless layer with a low power 2.4 GHz radio (Nordic nRF2401) with coplanar folded dipole antenna, and a processing layer with a low power microcontroller (TI MSP430). The third, carrier layer implements in this case the power conditioning circuit described above, as well as thermistor circuits in order to accurately measure skin and air temperatures.

The software periodically measures the following parameters and transmits them wirelessly to a nearby receiver: the input voltage and current from the TEG (together this gives the input power from the generator), battery/capacitor voltage, output voltage from DC/DC converter, skin temperature and air temperature, and the current measurement/transmission interval. The latter is an essential parameter because it determines the duty cycle and therefore the average power consumption of the load. The software implements a control algorithm that regulates this interval in order to keep the generator input voltage within a defined range between 0.8 V and 1.0 V. This has two major advantages: (1) the generator is always supplied with a near-matched load, which leads to maximum power being extracted, and (2) under conditions, where insufficient power is being generated (e.g., the person just moved from a cold area to a warm area), the duty cycle is temporarily reduced to very low values, which allows the system to continue working at dramatically decreased power consumption.

The resulting system shows very robust operation in different weather and physical activity of the person. The transmitted parameters allow properly characterization of the environmental conditions and TEG behavior at these different conditions. Fig. 7 shows the completed system.

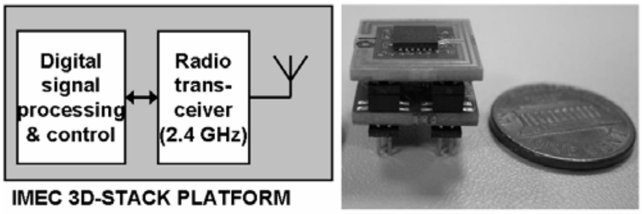

Figure 6. 3D-stack wireless processing platform (left) and prototype implementation with connectors (right).

Figure 7. Wireless sensor for tracking the power produced on humans: the TEG (left) and electronic module (right).

Performance characteristics of the device

The performance of the TEG has been tested in a real life in hot weather conditions of St. Louis MO (a city, 38° N, June), and Costa Blanca, Spain (a resort, 37° N, August), where daytime temperatures reached 30–35 °C. The data transmission rate automatically varied depending on the voltage on the supercapacitor, Fig. 8. In most of the situations, varying the transmission rate within the 1-to-10 s in between the transmissions was enough to keep the system within the 0.8–1.1 V range.

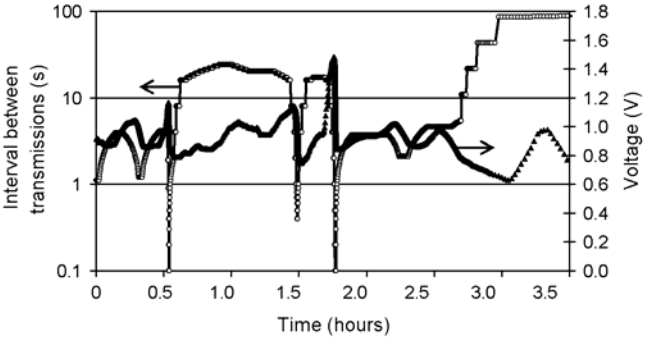

Figure 8. The example of variations in transmission rate (circles) depending on the voltage on the supercapacitor.

In a steady state, which is rarely in a real life, the TEG produces expected power, Fig. 9. The generator supplies the power enough for the electronics at lowest temperature difference of 3 °C between the skin and the still air at relatively low metabolic rates of 1–1.2 met on average. Fig. 10 illustrates moving of a person from the 21 °C room into the 30 °C air outdoor. In few tens of minutes after that, the skin temperature rises by 2 °C due to thermoregulation. During the transition, the power increases, so that in cases when the skin temperature at these moments has only 0.5–1 °C temperature difference with the air, the generation

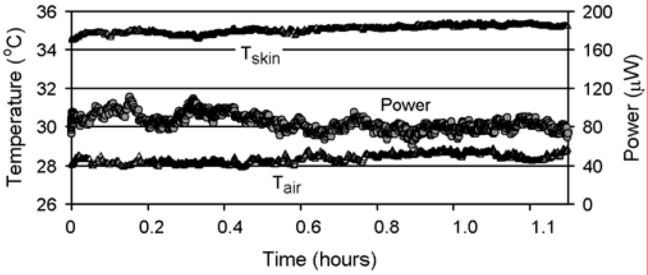

Figure 9. Power generation in steady conditions.

usually does not stop. Such peaks of the power generation caused by joined effects of the device–wrist heat capacity, the thermoregulation mechanisms and the variable heat transfer from the radiator occur all the time and are the main reasons for a hysteresis observed in power-temperature dependences, Fig. 11, a. The statistical results obtained are shown in Fig. 11, b. Important is that the average power production is not zeroed at a zero temperature difference, on the other hand, the amount of experimental points within the 33–35 °C range is comparatively small and the average is considered as an estimate. Stable average power observed within the 23–27 °C range is caused by the body thermoregulation.

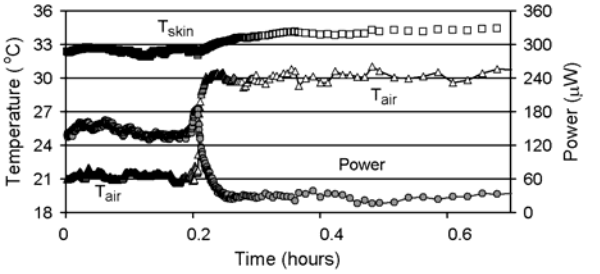

Figure 10. Variations in power generation and skin temperature with the air temperature.

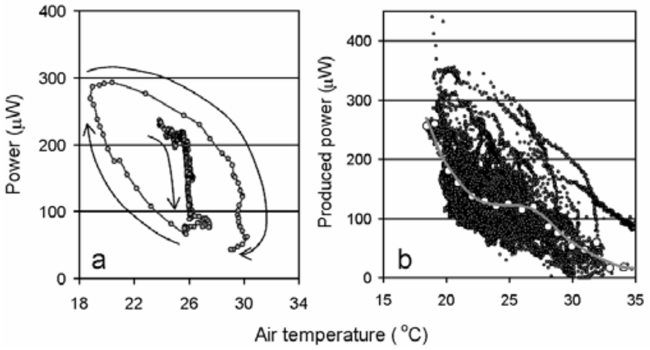

Figure 11. (a) The loops of power generation in a real life. The arrows show the direction of changes. (b) A set of over 32 000 experimental points (small circles), their average (large circles) and the fitting line.

The dependence of the power is shown in Fig. 12 versus temperature difference between the skin and the air. The average power production (linear fit) does not go to zero at zero ΔT, however, there are some cases when the power is not delivered to the supercapacitor at ΔT<5 °C. It occurs when the voltage from the TEG is less than the one on the supercapacitor while walking from outdoor into the air-conditioned building because the temperature of the radiator momentary approaches the air temperature.

Important feature of the TEG is that it operates at all the ambient temperatures. It demonstrates that high temperatures is not an obstacle for the devices self-powered from the body. The developed thermoelectric generator will be used in a personal body area network (BAN) of Holst Centre.

Conclusions

Miniature thermopiles fabricated according to the developed advanced industrial process allow watch-size energy scavengers for wearable devices, which are thermally matched to the ambience. As a result, the TEG can supply the voltage and power to the electronic module of a wireless sensor constantly at air temperatures below 32 °C. Within the 32–36 °C range, however, the power production in a real life does not stop: due to variations in the skin and air temperatures, as well as because of the variable air flow on the TEG (wind, walking), a part-time power generation still takes place. Above 36 °C, the power is expected to increase because of increasing reverse heat flow into the body [2], therefore, we may conclude that the fabricated TEG works at all the ambient temperatures, at least, part-time. The commercial technology is proven to be useful for powering wearable autonomous devices. Because a small rechargeable battery can be easily added to autonomous devices [2] resembling the one developed in this work, such devices can be powered the year round at proper managing of the power consumption.

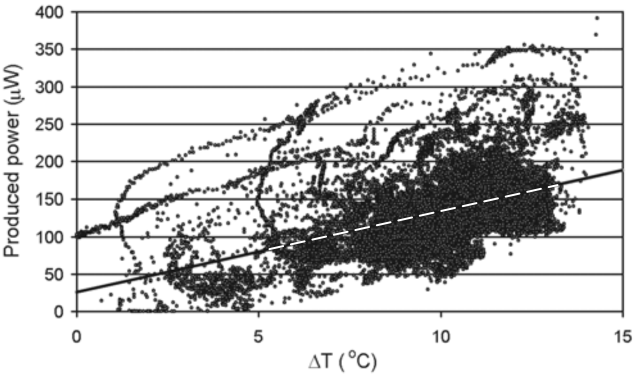

Figure 12. Dependence of the power generation in a real life on temperature difference between the skin and the air.

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