Thermoelectric Converters of Human Warmth for Self-Powered Wireless Sensor Nodes

Vladimir Leonov, Tom Torfs, Paolo Fiorini, and Chris Van Hoof

***Abstract*—Solar cells are the most commonly used devices in customer products to achieve power autonomy. This paper discusses a complementary approach to provide power autonomy to devices on a human body, i.e., thermoelectric conversion of human heat. In indoor applications, thermoelectric converters on the skin can provide more power per square centimeter than solar cells, particularly in adverse illumination conditions. Moreover, they work day and night. The first sensor nodes powered by human heat have been demonstrated and tested on people in 2004–2005. They used the state-of-the-art 100-μW watch-size thermoelectric wrist generators fabricated at IMEC and based on custom-design small-size BiTe thermopiles. The sensor node is completed with a power conditioning module, a microcontroller, and a wireless transceiver mounted on a watchstrap.**

***Index Terms*—Bismuth telluride, body-area network, energy scavenger, thermoelectric generator (TEG), thermopile, wireless sensor.**

I. Introduction

SMALL and cost-effective thermoelectric generators scavenging energy from the environment could potentially provide power autonomy to miniaturized and/or wearable electronic products operating at very low power. In industrial environments and in automotive applications, such compact, reliable self-powered devices with sensors, wireless link, and virtually infinite lifetime could replace sensors of today that feature huge amounts of corroding wires that will otherwise completely enmesh cars and buildings in near future. They could be used for unattended sensors placed in critical or even hazardous areas inside buildings, on/in certain pipelines, in mines, inside aircrafts, ships and cars, i.e., in the locations, where there is no (or not enough) light for solar cells. They may potentially impact fire detection, homeland security, as well as many other aspects of human life.

Human beings and, more generally speaking, warmblooded animals (e.g., dangerous and endangered animals, cattle, and pets), can also be a heat source for the devices attached to their skin. A thermoelectric generator (TEG) mounted in a wristwatch has been already used to power a watch using wasted human heat [1]. This is the only known practical application of the TEGs on a human body.

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The key target of IMEC's research in the field of self-powered devices is the realization of a body area network, consisting of a set of wireless sensors and actuators, able to provide health, sports, comfort, and safety monitoring functions to the user [2], [3]. The development of energy scavengers is one of the keystones of the ongoing research at IMEC [4], as this would make the body-area sensor network self-powered and cost-effective. Similar wireless sensors and generators could be used for tracking animal and bird migration and for monitoring their health.

Fabricated TEGs using a MEMS technology could potentially offer much better performance/cost ratio than BiTe thermopiles available on the market and move self-powered devices and systems into mass production. The technology development of MEMS TEGs is ongoing at IMEC. However, at least for the next several years, the classical thermopiles will remain more powerful than their small MEMS counterparts. Then, if the cost factor is not dominant, commercial thermopiles can be used to build sensor systems and body-area network [2], [3] powered by human heat. Taking this point into account, commercial BiTe thermopiles have been utilized in this work to build the first self-powered sensor nodes. The analysis of the performance characteristics of low-power commercial electronic components suggested that a 1.5 V output and a 50–100 μW power are reasonable targets for a TEG to provide power autonomy to the duty-cycled sensors, the accompanying electronic module, and the transceiver. This power requirement is much harder to reach than the one requested by state-of-the-art applications. For comparison, only 1 μW is required to drive an electronic watch [1]. Therefore, the design of TEG on a people's skin performed in this work started with its thorough modeling. To the best of our belief, this is the first research where a sensor node self-powered by human body is demonstrated.

The success of this work is affected to a large extent by the investigation of the features of a human body using a small-size TEG attached to the skin. Some relevant results of this research are briefly discussed in this paper as well.

II. General Consideration of a TEG on Humans

The commercial thermopiles are well suited for industrial applications, where large heated surfaces and large thermal gradients are available. At a few-degree temperature difference and at low thermal conductivity of the heat source and the heat sink, which is the case of, e.g., application on man, the effectiveness of the thermoelectric conversion dramatically decreases and useful generators become too bulky. The main reason for their bulkiness is not the need to obtain more power, but the fact that at least 1 V is necessary to efficiently power the electronics.

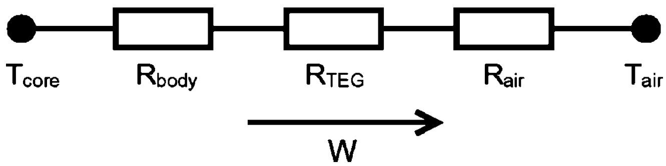

Fig. 1. Simple thermal circuit representing a TEG on the skin. The heat flow W takes place in between the body with a core temperature and the ambient air with lower temperature through three thermal resistors representing the body, the TEG, and the surrounding air.

The voltage V generated by one thermocouple on a matched load is

$$V = (S_p - S_n)\Delta T/2 \quad (1)$$

where S_p and S_n are Seebeck coefficients of p- and n-type legs, and ΔT is the temperature difference between the hot and cold thermocouple junctions. Assuming that the temperature difference of 1 °C is feasible, and that the material of a thermocouple is bismuth telluride with a Seebeck coefficient of ± 0.2 mV/°C, one could obtain a 0.2 mV generated by one thermocouple using (1). Therefore, the total number of thermocouples in the TEG must be 5×10^3 for a 1 V output.

In standard thermoelectric modules offered by different companies, one thermocouple usually occupies 7 mm^2 or more. There are two reasons for this relatively large size: 1) these modules are mainly used as thermoelectric coolers, where low electrical resistance is an important factor and 2) the fragility of bismuth telluride, which limits further miniaturizing. Only a few commercial products feature thermocouples occupying a smaller area, down to about 1 mm^2. Nevertheless, some custom designs of thermoelectric modules for cooling small electronic and optoelectronic components are more compact, and the area per thermocouple is about 0.5 mm^2. The total TEG area for 5×10^3 thermocouples is then 2.5 cm × 10 cm. Therefore, a TEG placed on the wrist might be incorporated into a 2–3 cm-wide band.

Above consideration would be correct if the temperature difference of 1 °C could be feasible across the thermopile on human skin. However, the practical situation is much worse even when the ambient temperature is well below the deep body temperature. Let us represent the system formed by a human body, the TEG on the skin, and the ambient air as a thermal circuit made of three related thermal resistances through which the heat flow W arising from the metabolic activity passes (Fig. 1). According to medical researches (see, e.g., [5]), the heat flow from a resting person is, on average, about 6 mW/cm^2 at 28°C. It may reach about 10 mW/cm^2 from the forearm at 22°C. However, on hands it has a maximum at about 28 °C. The most difficult element to model is the local thermal resistance of the body. According to [5], the internal thermal conductance of the body, which is the reciprocal of its thermal resistance is a complex function of position and temperature. For example, the thermal resistance measured on the hand increases by about 7.5 times if the ambient temperature drops from 32 °C to 20 °C. For calculations, we can assume a thermal resistance of about 500 cm^2 K/W on the distal forearm at 28°C (using average internal thermal conductance between the values for the hand and the forearm reported in [5]).

An approximate value of the thermal resistance of commercial thermopiles can be easily calculated from their particular geometry and thermal conductivity of bismuth telluride. For example, values around 50 cm^2 K/W are quite usual for commercial thermopiles.

The surrounding air represents the largest obstacle for the heat dissipation. Indeed, representing the distal forearm as a horizontal cylinder of 5 cm in diameter at a temperature of 33 °C placed in a quiescent air, the calculated thermal resistance of the air is 1030 cm^2 K/W according to heat transfer through convection and radiation [6].

The heat flow can then be calculated using

$$W = (T_{\rm core} - T_{\rm air})/(R_{\rm body} + R_{\rm TEG} + R_{\rm air}). \quad (2)$$

Substituting the above numerical values for three resistors (Fig. 1) into (2) at both the fixed $\mathrm{T_{core}} = 37.5$ °C and $\mathrm{T_{air}} =$ 28 °C, gives a heat flow of 5.9 mW/cm^2 through the TEG as compared with the open skin surface (i.e., at $\mathrm{R_{TEG}} = 0$) of 6.2 mW/cm^2. The product of the heat flow by the thermal resistance of the thermopile gives real thermal gradient on the latter, i.e., $\Delta\mathrm{T_{tp}} = 0.3$ °C instead of 1 °C as initially assumed. Therefore, in order to reach the required 1 V at an ambient temperature of 28 °C, the thermopile size must be increased to 8.3 cm × 10 cm, so it becomes too bulky for application on human wrist. The corresponding number of thermocouples required increases to 1.7×10^4. The alternative approach is to make a low voltage input electronic cascade and a boosting circuit as it was done in [1] for 0.15 V generated by the thermopile. However, this approach is not practical because it requires a lower voltage ASIC. Taking this into account together with comparatively low expected efficiency of possible voltage up-conversion, the design of the TEG in this work has been optimized to the standard requirement for an autonomous device of 0.7-1 V minimum.

III. Key Aspects of Designing the TEG

As shown in the previous section, the TEG on a human skin generating 1 V is possible, but it turns out to be too large even if the commercial thermopiles with the smallest lateral size of legs are used. The electrothermal analogy used in physics and engineering for modeling heat transfer using electrical circuits [(2) and Fig. 1] suggest improving the thermal gradient on a thermopile by increasing its thermal resistance as compared with the ones of the body and of the air. Thus, the ratio $\mathrm{R_{TEG}}/(\mathrm{R_{body}} + \mathrm{R_{air}})$ must be maximized resulting in a reduced size of the TEG at the same generated voltage. The most logical way to increase the thermal resistance of the TEG is to decrease the cross section of the thermocouple leg t^2, where t is its lateral size. The resulting thermal and electrical resistance would rise proportionally to t^{-2}. However, industrial technology of BiTe thermopiles is near to its miniaturization limits, so it is not possible to decrease the lateral size of thermocouple legs without decreasing their length. The remaining possibility is to shrink the thermopile size in all three dimensions: each thermopile leg scaled down by a factor of 2 would have shown doubled thermal and electrical resistance.

Following this approach for miniaturization, small-size thermopiles have been fabricated at Seiko for powering a watch using the human heat [1]. As a state-of-the-art, the thermocouple leg had a lateral size of 80 μm that allowed density of 1300 thermocouples per square centimeter of the chip. Both values are not yet reached in commercial thermopiles. However, we have to underline that only 0.15 V (recalculated from [1] to a matched load) have been obtained in the Seiko TEGs having a watch body as a radiator, i.e., a watch-size generator, therefore, for a 1 V output, the generator size would still remain too large.

The second feasible way to increase the ratio $\mathrm{R_{TEG}}/(\mathrm{R_{body}} + \mathrm{R_{air}})$ is to compose a multistage thermopile. The obvious drawback to this approach is the resulting thickness of the TEG. In our development, we have supposed that a watch thickness could be a good reference for the maximal possible thickness of a wrist TEG for convenience of the user. As a watch is accepted by most of the people, the same should happen with a TEG if it gets similar appearance and is worn in the same place. (As a "side" effect, few microwatts could be painlessly offered in the future by a TEG to a digital watch on/near the generator.)

The third complementary way is to decrease the denominator of the above ratio. The thermal resistance of the ambient air can be decreased through the use of radiators. The outer surface of a device may serve as a radiator like it was in the watch, however, for more effective heat exchange, a radiator with, e.g., fins or pins can be provided. In this case, the contact surface to the air exceeds the area of the skin occupied by the device, thereby virtually decreasing the thermal resistance of the air per square centimeter of skin and increasing the heat flow through the TEG according to (2).

The thermal resistance of the body can be significantly decreased by placing the TEGs in the locations on the skin, where the largest heat flows are available. However, to the best of our belief, there are no detailed publications on spatial distribution of heat flow on the human body. This topic has been taken up during this work.

The local thermal resistance of the distal forearm has been measured on 77 subjects (sitting quietly in between their usual daily activity) in laboratory conditions, still air, and at an average room temperature of 22.7 °C. Its average value is 440 cm^2 K/W on the outer side of distal forearm, including interface thermal resistance between the skin and the generator attached with a wrist strap. (The whole range of the measured values on the distal forearm including interface thermal resistance, however, extends to 930 cm^2 K/W.) According to the measurement results, the local thermal resistance of the distal forearm reaches its minimum of 90–130 cm^2 K/W on the radial artery, at the point of crossing the watchstrap line. This should not be surprising because the cardiovascular system very much resembles the industrial heat recuperation systems, where the heated liquid is constantly pumped through the pipes maintaining the temperature of the hot side of the heat exchanger. So, putting the TEG near the artery with heated blood decreases the thickness of the tissue in between it and the device. Moreover, the muscles that account for about 40% of the body weight are

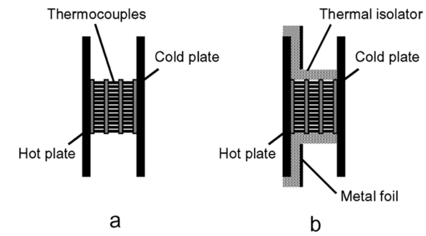

Fig. 2. TEG for on-body use. Three thermopile stages are shown, but the number of stages is variable. (a) Simplest device for operation in preferable vertical orientation (as shown) of the cold plate (radiator); (b) The device with nanoporous isolation.

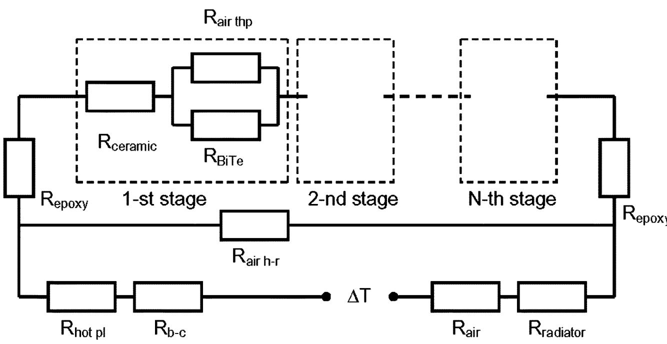

Fig. 3. Thermal circuit used for modeling the TEG. The number of stages is variable, but four stages are used in the final device.

the main mean of the physical thermal isolation of a human being, but these are minimized in between the skin and the radial artery in the chosen location. The distance from the skin to the radial artery in a distal forearm is only a few millimeters, therefore, as have been found in this work, a much larger heat flow (up to 90 mW/cm^2 measured on 1.6 cm $\times$ 1.6 cm area) is locally available without discomfort to the user. The countercurrent heat exchange (because the veins are usually in close proximity to the arteries), however, decreases this value if the heat flow is measured on a larger area.

By implementing the improvements discussed above into a practical design of a TEG, we have arrived at the schematic shown in Fig. 2. The thermal circuit in our model of the TEG is shown in Fig. 3, where the thermal resistance of the TEG is replaced with N block units for N thermopiles stages. Each stage is represented with a thermal resistor $\mathrm{R_{ceramic}}$ for two ceramic plates connected in a series to two parallel resistors, $\mathrm{R_{BiTe}}$ for the thermopile legs, and $\mathrm{R_{air\ thp}}$ representing the air inside the thermopile. All stages have a common parasitic thermal shunt through the thermal resistance of the air $\mathrm{R_{h-r}}$ in between the hot plate and the radiator. The other thermal resistors are in a series to the resistance of the thermopile assembly. These are thermal resistances of the body and the contact to the hot plate, $\mathrm{R_{b-c}}$, of the hot plate, $\mathrm{R_{hot\ pl}}$, of two epoxy layers $\mathrm{R_{epoxy}}$, of the radiator $\mathrm{R_{radiator}}$, and of the ambient air, $\mathrm{R_{air}}$. For the following calculation, it was assumed that the length of the thermopile leg is limited only by the thickness of the device, but not limited technologically. The total thermal resistance of the resistor network shown in Fig. 3, according to (2), determines the heat flow from the body. The body limit of the heat flow at a temperature of 22 °C, as has been measured in [4], is situated well above the

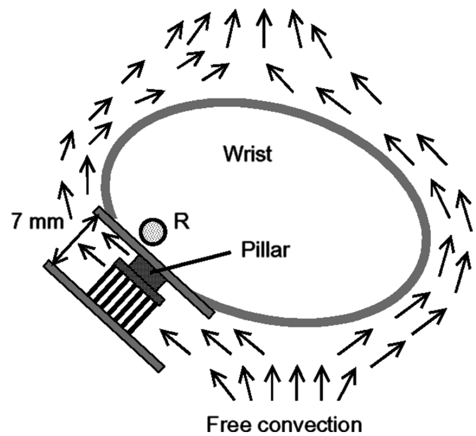

Fig. 4. Schematic of the thermopile on a wrist and its orientation used in calculation of Fig. 5. A pillar with variable height maintains the 7 mm distance between the plates, while the length of thermocouple leg changes. Radial artery is marked with "R."

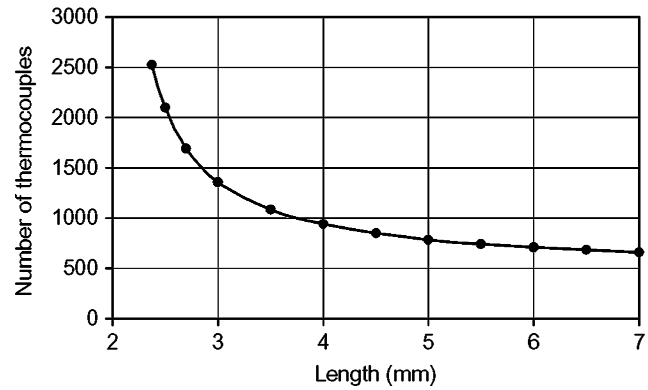

Fig. 5. Dependence of the number of thermocouples on their length needed to satisfy the requirement of 1 V on a matched load. Calculated for a wrist TEG in quiescent air at 22 °C. The drawing of the device and its orientation is shown in Fig. 4.

practically obtainable heat flow for on-body TEG of a watch size and does not affect the results obtained below.

To minimize the TEG size, it is assumed that the thermocouple legs have the smallest lateral size available on the market, i.e., 210 μm. (This limit has been reached in the frame of this work together with Thermix, Ukraine, and was not available on the market before.) For modeling, we assume that the "hot" plate touching the skin and the cold plate functioning as a flat radiator have a thickness of 1 mm and a square shape of 3 cm $\times$ 3 cm. The distance in between the hot and cold plates is fixed at 7 mm (Fig. 4) so that the total thickness of the device becomes 9 mm. A pillar of material with high thermal conductivity is supposed to be placed under the thermopile to maintain the distance between the plates according to [7], while changing the length of the thermopile legs. The cold plate is thereby moved 7 mm away from the hot plate, where the temperature of the air jet of the free convection from the wrist decreases to about 20% of the temperature difference in between the skin temperature and the temperature of ambient air. (This value is for the case illustrated by Fig. 4.) By doing so, the Rayleigh number of the convection on the radiator is decoupled from the one on the wrist and the resulting heat exchange improves making the local heat flow through the TEG (with low thermal resistance) larger than it could occur on the skin at other equal conditions. In contrast, complete filling of the volume in between the plates with, e.g., a nanoporous material would cause the air jet to flow around the device thereby significantly decreasing the Rayleigh number to the value equal or less than the one on the skin.

Idealizing the case, all thermal joints and material of the plates and of the pillar are assumed thermally perfect with no thermal resistance, i.e., that there are no temperature drops on them. For simplicity, the possible heat exchange to/from the legs emerged into the air jet heated by the distal forearm is not accounted for. The calculation is performed for 22 °C, still air and the spatial configuration on a wearer shown in Fig. 4. The inclination of 45 ° is not the best for the performance of a radiator, but reflects a medium case between the best and worst possible conditions of operation: the wrist orientation is not fixed. The calculation of the voltage and the power on a matched load gives an idea of how many thermocouples are necessary to reach 1 V output, depending on the length of the thermocouple legs (Fig. 5). One can see that the number of thermocouples rapidly increases at the lengths below 3–4 mm and results in completely filling the device with thermocouple legs at about 2.4 mm. It turns out it is not possible to reach the 1 V output on the matched load at 22 °C for shorter legs, so the device must grow in size. However, even these 2.4 mm-leg thermopiles at the specified lateral size are not available on the market. The logical solution then is to compose a multistage thermopile from the stages with shorter legs that could be found on the market. The drawbacks of this approach are the reduced total length of the legs in between the hot and cold plates (because of some space consumed by the plates of the separate stages) and the larger cost (more thermopiles are required).

IV. Design of the Thermoelectric Generator

According to the results obtained above, the only feasible solution to the problem is to make a multistage thermopile. The device used for the modeling is shown in Fig. 2. It contains 158 thermocouples per stage. The lateral size of the legs is 0.21 mm and the length is 1.27 mm. The thermopile size is 6.7 mm $\times$ 8.4 mm $\times$ 1.8 mm. Using such "bricks," the thermopile block can be built with a different number of columns. Up to four stages can be placed into the 7 mm gap in between aluminum hot and cold plates. This allowed variation of the thermal resistance of the TEG in a way is similar to the one described in the previous section. The input fixed parameters are the core temperature and the ambient temperature; the other parameters are variable. In this section, we present as an example the results obtained for 22 °C and free convection. To get reliable average performance characteristics on a sitting person during the daytime activity, the inclination of the TEG on a wrist is set to 45°. The materials used for the modeling and implemented later in the practical devices are: aluminum type 6063-T4 for the hot and cold plates, 96% alumina ceramic for thermopile plates, and the heat sink compound with thermal conductivity of 3 W/cm K for assembling the device. The inner surfaces of the hot and cold plates are supposed to be polished to minimize top–bottom radiative heat exchange in the TEG on

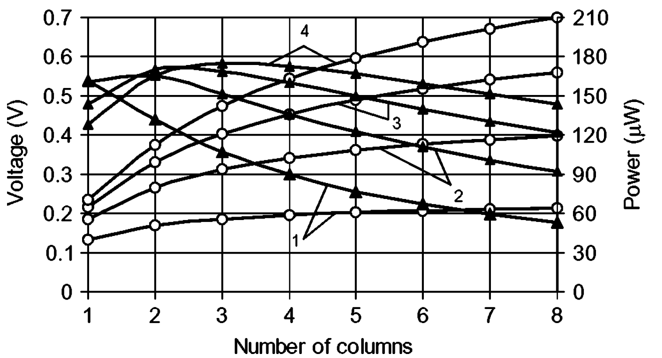

Fig. 6. Dependence of the output voltage (circles) and the power transferred into the matched load (triangles) on the quantity of thermopiles in the TEG and their arrangement, i.e., on the number of stages (marked with numbers 1–4) and columns. Calculated for a wrist TEG in quiescent air at 22 °C.

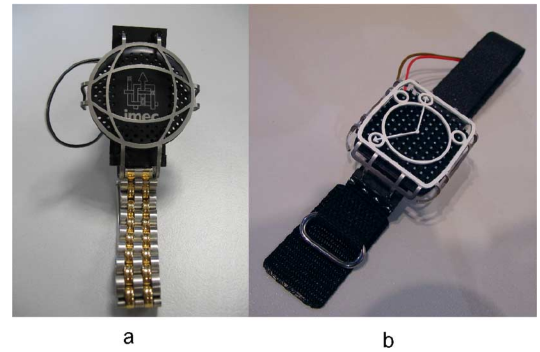

Fig. 7. Thermoelectric generators. (a) Waterproof version "Mini-Matrix 2R" containing 24 thermopiles. (b) "Five to seven" design containing 32 thermopiles and a pin radiator. The metal touch-and-shock protecting grids above the TEG do not touch the radiator.

the plate area outside the thermopiles. The outer surface of the radiator, on contrast, must have a coating with high emission coefficient in the LWIR region for enhancing the radiation exchange with the environment.

The modeling is performed in the following way. It starts with the assumption of a reasonable temperature drop from the radiator to the ambient air. Then, the heat transfer to air through free convection and radiation is calculated resulting in a first-approximation thermal resistance of the air. The thermal resistances of the thermopiles, of the air inside them and in the cavity in between the hot and cold plates are calculated giving the thermal resistance of the device. The last component of the thermal circuit is the thermal resistance of the body. The reasonable value of 150–500 cm^2 K/W can be used depending on the intended location of the device on a wrist (where the smallest value is for the radial artery). Then, using (2), we obtain the first-iteration heat flow through the device. Having this heat flow, the temperatures on all parts of the TEG are obtained. Then, several iterations are performed recalculating the heat transfer from the radiator, the heat exchange in the device, and the resulting heat flow. Further iterations give more exact temperatures on all device components and in the air. Some modeling results are presented next. In Fig. 6, the voltage on the matched load and the related transferred power are shown for the different number of thermopile stages and columns. Accounting for the cost factor in applications, the maximal number of thermopiles used in the modeling does not exceed 32.

As one can see in Fig. 6, the required voltage of 1 V cannot be obtained at the specified conditions. Therefore, two types of the TEGs have been fabricated. The first one is the TEG with six thermopile columns and flat radiator [Fig. 7(a)] for outdoor use. It works on a moving person, when the heat exchange significantly improves, in presence of wind or in still air, but at lower ambient temperatures.

To make the TEG work indoors and on a sitting person (with no forced air convection), the devices with a larger radiator of about 38 mm × 34 mm featured with small pins have been fabricated [Fig. 7(b)] called "five-to-seven" design according to the appearance of the protection grid. In addition, eight thermopile columns have been used instead of six. As it is clear from Fig. 6, the generated power slightly decreases, however, the voltage increases by about 10%. The resulting parameters in the same conditions as above are: 0.93 V and 250 μW on a matched load. Therefore, using mismatching of the load when connecting the TEG to electronics, the voltage of 1.2–1.3 V can be obtained at 22 °C for further use to charge a battery, however, with an unavoidable loss in usable power. The lower voltage of a 0.9 V on a matched load can, in principle, be up-converted, but the loss would be similar. The larger radiator has lower thermal resistance of 54 K/W than the flat one used before (Fig. 6), and therefore according to the modeling must increase the heat flow from the body to 120 mW. The hot plate of the TEG has a size of about 6 cm^2, therefore, a heat flow of 20 mW/cm^2 must be transferred to it from the radial artery at 22 °C and still air. With the pin radiator, the thickness of the device increases to 12 mm (without the protection grid which occupies 2.5 mm more), however, this is still similar to a typical thickness of a watch.

V. Power Generation on a Wrist Indoor and Outdoor

The generators have been intensively tested to obtain experimental data on indoor power generation, which are depicted in Figs. 8 and 9 for the TEG of Fig. 7(b). We may see that for the usual daily activity (accompanied by the related metabolism), the generator produces the calculated voltage and power (curve 2). However, prolonged sitting without any activity may cause shifting the performance characteristics to curve 1. Depending on the type of energy storage, i.e., a capacitor for a short-term storage or a battery, the limits of the average 24-hour energy production vary. In the former case, the electronics powered by the TEG must rely on the lowest curve, i.e., must not consume more than 100 μW at 22 °C. In the latter case, however, the average energy production approaches or even exceeds the 250 μW level calculated in the previous section. It must be clear that much higher power levels are usually obtained when the person walks or if there is an external airflow, e.g., wind. As a rule of thumb, at 22 °C, the TEG produces, on average, 300 μW on a sitting person at daytime activity; this power halves for a person sitting for a very long time with no activity, but doubles when he/she walks, curve 3. The same results are applicable to the outdoor application. The only reason for testing the TEGs indoors was the uncontrollable wind outdoor. Therefore, the outdoor performance is usually much better than indoor thanks to the wind

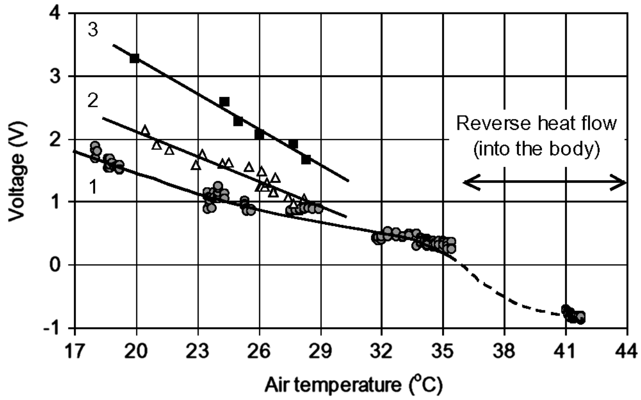

Fig. 8. Open-circuit voltage generated by "five to seven" TEG indoor. (1) Measurements on the person quietly sitting for very long time (hours) with no intermediate activity. (2) Person performs usual activity (walking in between offices, working on PC, etc.) in between the measurements, however, at least 5–10 min before the measurements, all activity is interrupted. (3) Person walks indoor at about 4 km/hr. The lines are the guides for the eye.

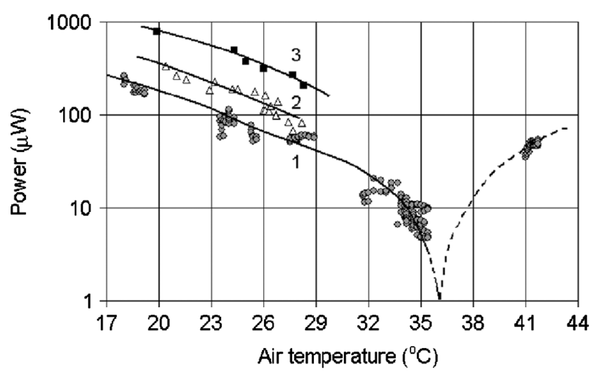

Fig. 9. Power on the matched load of 3.3 k Ω generated by "five to seven" TEG in a still air. The description of the curves is in Fig. 8. The lines are the guides for the eye.

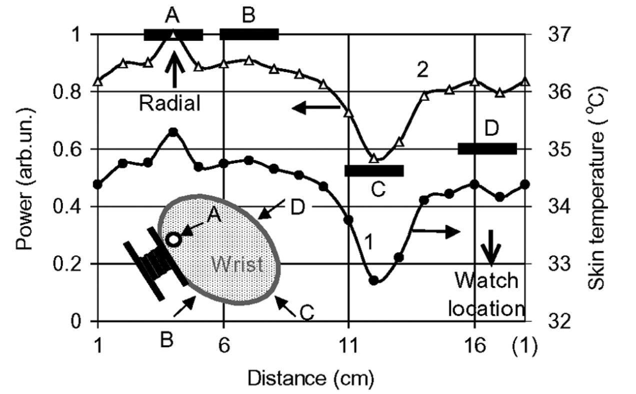

Fig. 10. Temperature on open skin surface around the distal forearm measured using a thermocouple thermometer averaged over 12 measurements at 23 °–27 °C with an average of 25.2°C (1), the calculated power if the open skin temperature is used as a reference (2) and the power measured in four locations on a wrist (four measurement points marked with characters). In inset, the fixed spatial orientation of the TEG and four tested locations A, B, C, and D are shown, while the wrist has been rotated in between the measurement points.

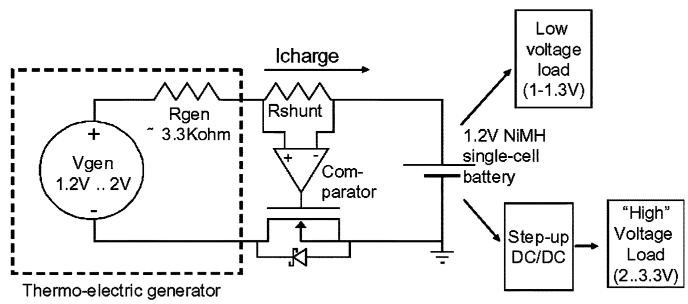

Fig. 11. Power conditioning circuit for the TEG.

and due to the fact that more time is spent on walking, physical activity, etc., thereby creating an air flow onto the radiator. For the TEG shown in Fig. 7(a), the calculated data of Fig. 6 also, in general, coincide with the test results. For this generator, intended for outdoor use, an encapsulation of the thermopiles is performed using a 5 μm-thin polyethylene film making it waterproof.

The advantage of proper positioning of a TEG on a wrist is illustrated in Fig. 10, where the circumference of the wrist (17 cm in this particular case) is stretched over the x axis. The nonuniform temperature distribution over a wrist measured with no device attached reflects the subcutaneous variations of the forearm structure. The areas proximal to radial and ulnar arteries are more heated by incoming blood despite the presence of the veins. The calculated power and the measured power deviate from each other. The reason for that is the different local thermal resistance of the body over the wrist. The "watch" location of the TEG ensures much less power as compared with the location on the arteries. The difference dramatically increases, e.g., at an ambient temperature of 17 °C when accompanied by the effect of "cold hands." In these conditions, the radial artery produces the largest heat flow with the related largest power generated by the TEG. The power produced in the experiment on the ulnar artery was on average only 67% of the one on the radial artery, while on a "watch" location, the generated power was 2.5 times less than on the radial artery.

VI. Prototypes of Self-Powered Sensor Nodes

The practical demonstration of successfully using the power produced by the TEGs has been done at the system level. For this purpose, the electronic circuits have been designed and fabricated. The power generated by the TEG is stored in a single-cell 1.2 V NiMH rechargeable battery (Fig. 11). The input stage contains a rectifier circuit used to prevent the battery from discharging through the generator if the generated voltage would occasionally drop below the battery voltage. A passive rectifier (silicon or Schottky diode) would introduce an unacceptable voltage drop. Instead, an active rectifier circuit is used based on an n-channel FET, which is reverse-connected (so the body diode conducts in the correct direction). A comparator measuring the voltage over a small shunt resistor will fully turn on the FET for positive charge currents, resulting in a very low voltage drop. Reverse currents will be blocked. A Schottky diode is added in parallel to the FET's body diode to lower the startup voltage drop, before the comparator turns on the FET.

This simple circuit has some drawbacks: 1) it will only store charges for generator output voltages greater than 1.2 V–1.3 V, which is normally the case with the watch-size thermoelectric generator with some mismatch of the load and 2) it inherently

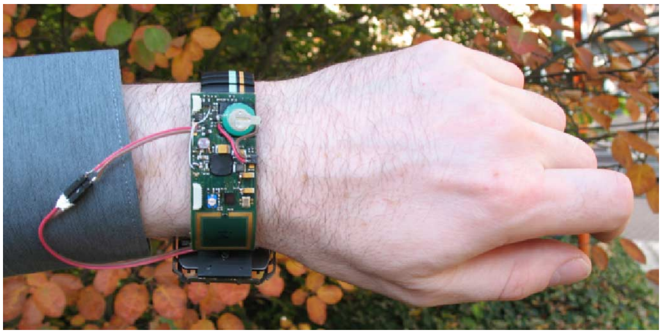

Fig. 12. Prototype flex circuit integrated onto the bracelet of the TEG.

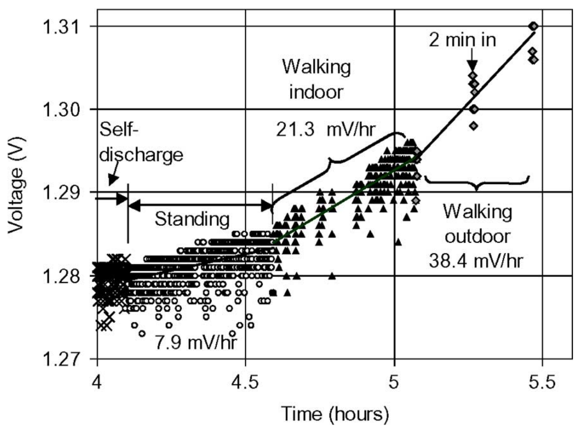

Fig. 13. Voltage on the battery wirelessly transmitted to a PC-station. For the outdoor test (at about 16 °–17 °C temperature and wind estimated to be 5–7 m/s), the person was too far from the station, therefore, the data are transmitted only when the person returned to the station for 2 min in the middle and at the end of the experiment.

presents a somewhat mismatched load to the generator. For example, for a typical open circuit voltage of 1.6 V generated by the TEG, a near-constant voltage load at 1.2 V instead of a matched load at 0.8 V leads to 145 μW of power being delivered into the battery, instead of a theoretically possible 194 μW (i.e., the matching efficiency is 75%). However, the simplicity of the circuit also causes it to be very robust (no startup issues) and consume virtually no static power (the comparator does not need to be fast, so submicroampere quiescent currents can be obtained with off-the-shelf components).

The single-cell battery voltage (1-1.3 V) can be used to directly power modern deep-submicron digital and RF circuits. In our sensor module prototype, we have used it to directly power the ANS1601 ultra-low-power 300–600 MHz radio transmitter designed by AnSem, which operates down to 0.9 V supply with a power efficiency of 12 nJ/bit.

Other parts in a wireless sensor module, such as high-performance analog circuitry, generally require higher supply voltages (between 2 V and 3.3 V). To power these circuits, the voltage of a single-cell battery is boosted by a step-up DC/DC converter to the required voltage. This introduces additional loss in efficiency. In our prototypes, we have used the Maxim MAX1722 DC/DC converter because of its low quiescent current of 1.5μA. However, at a 100 μW power level, the typical efficiency of these DC/DC converters is only 65%–70%. While this is a significant loss factor, it is not critical because we are operating the components that require high current directly from the battery voltage without this intermediate DC/DC conversion.

In Fig. 12, a prototype sensor module self-powered by body heat can be seen assembled with the TEG. It has been implemented as a flex circuit mounted on the bracelet of the watch-style thermoelectric generator of "five-to-seven" design. The circuit measures and transmits the battery voltage, the temperature and/or light intensity every 2 s. The average power consumption in such a usage scenario is approximately 50–75 μW. This leads to sustainable energy autonomy, as the TEG delivers 100 μW at 22 °C. This can be seen on a system level in Fig. 13, where the battery is being charged, while the system is operational and transmitting. Depending on the activity of the user (standing still or walking), the slope of the battery charge-up curve differs following the power delivered by the generator.

VII. Conclusion

The first prototypes of the wireless sensor nodes on human beings powered by thermoelectric generators are designed, fabricated, and tested on people. Taking into account a 50–100 μW minimal power requirement for low-power duty-cycled sensor nodes, the TEGs reliably operate at indoor ambient temperatures. The average power generation at daytime of about 250μW corresponds to about 20 μW/cm^2, which is better than solar cells in many indoor situations, especially considering the TEG power is also available at nighttime.

The applications presented in the moment are quite simple (i.e., the temperature, voltage and light intensity transmitted), however, the research is ongoing to demonstrate practically usable devices built on the same principle. The low-power custom-designed ASICs may be, in principle, much more energy efficient than the current electronic boards with commercial components used in our self-powered sensor nodes. This will allow implementation of more complex functionalities in the nodes or increasing their duty cycle. The human body area network of the future will be composed from several sensor node units each more or less resembling the demonstrated sensor nodes. Such units could be located on a head, glasses (for those who wears it), neck, etc., and implemented into a special suit or into a cap, a shirt, or a belt.

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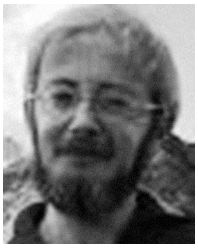
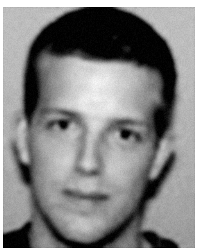


Vladimir Leonov was born in St. Petersburg, Russia, in 1958. He received the Ph.D. degree in optical devices from the State Optical Institute, St. Petersburg, where he worked during 1981–1998 on thermal detectors and arrays, as a Senior Scientist.

From 1998 to 2000, he was with Southern Methodist University, Dallas, TX, where he worked on pyroelectric infrared arrays for Raytheon. From 2000 to 2003, he was a Principal Scientist at XenICs, Leuven, Belgium, and starting in 2003, he has been a Senior Scientist at IMEC, Leuven, Belgium. He has authored about 100 publications including 10 patents. His major interests are concentrated on energy scavengers (power MEMS), electrets and poly-SiGe infrared arrays.



Tom Torfs was born in Lier, Belgium, in 1979. He graduated from KIH De Nayer, Belgium, in 2001

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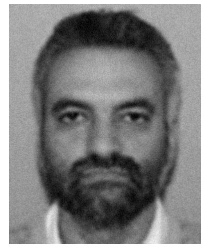
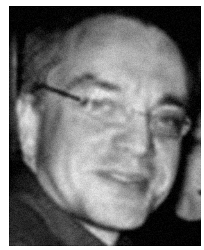


Paolo Fiorini was born in Rome, Italy, in 1953. He received the Ph.D. degree in physics from the University of Rome, Rome in 1977.

He has been active in the field of electrical and optical properties of semiconductors for many years, working at the University of Rome, where he was an Associate Professor of Solid State Physics. In the recent years, he has performed research in the field of microsystems, and he is now leading the research team on power MEMS at the Interuniversity Microelectronics Center (IMEC), Leuven, Belgium.



Chris Van Hoof was born in Antwerp, Belgium, in 1963. He received the Ph.D. degree in electrical engineering from the University of Leuven, Leuven, Belgium, in collaboration with the Interuniversity Microelectronics Center (IMEC), Leuven, in 1992.

His research concentrated on quantum-effect components. He became a Laureate of the Belgian Royal Academy of Sciences based on his postdoctoral research. He became successively head of the detector systems group in 1998, Director of the Microsystems Department in 2002, and Director of the Integrated Systems Department in 2004. He is responsible for the microsystems activities, the RF systems activities, and the above-IC and 3-D integration and packaging activities at IMEC. Since 2000, he has been a Guest Professor at the University of Leuven. He has authored more than 100 publications (80 based on peer review) and he has given 20 invited presentations.