Thermoelectric Generators on Living Beings

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Abstract

Unobtrusive scavenging of the heat dissipated by living beings through using thermoelectric generators (TEGs) on their skin is discussed in general. Targeting at such application of TEGs on man the measured relevant thermal features of human beings are reported next. As pointed out in the paper, the specific matching conditions of a TEG with the ambient should be satisfied to reach effective performances of such devices. In this work, the design rules are proposed for wearable TEGs to make them efficient and compact. In 2004–2006, three versions of TEGs have been fabricated, tested on people, and their performance characteristics are shown. In parallel, three versions of wearable wireless sensor nodes have been fabricated for demonstration purposes and extensively tested including the first medical device, a battery-less wireless pulse oximeter. The fabrication cost of wearable TEGs can be reduced using modern technologies. One of these, a microelectronic technology, is discussed which can offer micromachined thermopiles for energy scavenging capable to surpass the best commercial thermopiles, e.g., like the ones used in this work, on both performance and cost.

Introduction

Temperature differences available in nature and in/on artificial objects (machinery, buildings, transport, pipelines) can be used to power autonomous devices. This paper discusses thermoelectric converters on living beings in general and gives an overview of first completed wireless devices fully powered by human heat. The driver of the research is not the need to generate electricity itself, but a wish to eliminate, where possible, a primary battery from autonomous wireless devices located in places where sunlight is not available and therefore solar cells cannot be used easily. In some autonomous devices a capacitor or a supercapacitor can be used as a temporarily energy storage buffer for duty-cycled electronics thereby eliminating the need even for rechargeable battery. The developed TEGs and systems are supposed to be used, in first turn, in a human body area network (BAN) being under development at the Holst Centre [1]. However, the basic principles discussed next are applicable to the other possible thermoelectric energy scavengers, i.e., not only on warm-blooded living beings.

Important aspects of designing energy scavengers

Let us imagine that someone placed a thermopile on a surface of the hot (or cold) object. A large part of the temperature difference observed in between such object and the air can be obtained on the thermopile under the condition that the thermal resistance of thermopile is not much less than the one of the ambient air. A “bad” heat source itself may show high thermal resistance as well. As examples, it can be a wall of a building, the surface of plastic pipeline, or the skin of warm-blooded animal. Then, the thermal resistance of the thermopile should also exceed the one of the heat source. However, too high thermal resistance of the thermopile would decrease the heat flow through it and therefore the generated power would decrease, too. More specifically, to make an energy-scavenging thermoelectric generator maximally efficient, the conditions of its thermal matching with the ambient which is the heat source and the heat sink must be satisfied [2].

TEGs on a living being should be comfortable for their wearer. This in particular means the heat flow through the TEGs and therefore through the skin of animals or man must be limited in order not to decrease the skin temperature below the comfortable one. In case of human beings, the skin temperature of about 30–35 °C is comfortable. It can be different in case of animals, and especially birds, which usually feature higher skin temperature, while abrupt nocturnal temperature drop is observed in birds. While air temperature decreases below 20–25 °C, heat transfer into the air from the trunk, head and proximal parts of extremities rapidly increases causing unpleasant lowering the skin temperature. Consequently, to keep the comfort, the heat flow through the TEG must be decreased together with decreasing air temperature, e.g., using a piece of clothing worn on top of it and desirable improvement of the performance of scavengers at increasing temperature difference cannot be obtained.

The size of energy scavengers is an important factor for moving them into mass production. At a size of autonomous device like, e.g., the one of a matchbox, first, there is enough space for a competitive large-size battery so that there could be no need in a scavenger, and, second, the application area would dramatically narrow because most of applications call for smaller devices. This is certainly related to small-size customer products as well as to the devices for security and homeland protection, which should be well hidden. In industry, however, big devices, e.g., bigger than a matchbox, could be acceptable if they offer more power and therefore more functionalities and longer range radio transmission.

In case of small-size wireless devices on human body, at usually small temperature difference between the skin and ambient air accomplished by high thermal resistance of the body, a specific design of a TEG is required to obtain sufficient power, i.e., tens or hundreds microwatts depending on particular application. Certain locations for wearable devices are preferable where the thermal resistance of the heat source is decreased, i.e., in close proximity either to arteries or to core organs (e.g., the brain). In the latter case, care has to be taken, especially in case of babies and animals (i.e., those who do not complain), that their core is not occasionally overcooled in cold weather. A radiator on outer side of a TEG helps to provide its thermal matching. A multi-stage arrangement of commercial thermopiles or a spacer, separating top and bottom of the TEG, (in case of micromachined thermopiles in it) are useful for two main reasons: these allow thermal matching of a TEG and improve the Rayleigh/Reynolds numbers on the radiator by moving it out of the body-induced convection layer (where possible). All above aspects are actually the rules of designing compact, effective and unobtrusive wearable TEGs.

Human beings as the heat source for TEGs

Small wrist devices are the most convenient for users because they resemble a watch, however, the nighttime power generation can be interrupted, e.g., by putting the hand under a blanket or under a pillow while sleeping. It is obvious that on a sleeping person the head is the only body part, which could provide continuous performance. In cold weather, the heat flow in extremities is restrained by the body thermoregulation, but in the trunk and in the head it is not so well-controlled and rapidly rises while the air temperature falls. Consequently, the heat flow from the head reaches high values, and the TEG on it, especially if supplied with a radiator, may cause overcooling of the brain, which is dangerous for a living being. Therefore, depending on particular application, proper and safe location of the device on living being is required. The knowledge of its body properties is also very important for designing the TEG and for its thermal matching with the ambient.

The skin temperature is nonuniform: in the head and in the trunk of a person it is 33–36 °C, while in extremities, at near-basal metabolic rate, the skin temperature frequently decreases below 30–25 °C even at comfortable indoor temperatures. At air temperature exceeding 25 °C, the skin temperature in arms and legs usually approaches the one in the head. Below 20–25 °C, however, a vasoconstriction and minimized cutaneous blood flow cause essential lowering of skin temperature in extremities.

Fig. 1 depicts variations of skin temperature in persons sitting after several hours of typical daily activity in the office or at home, with a metabolic rate of about 1.2–1.3 met on average, versus air temperature. Three curves show skin temperature in the wrist, i.e., over the radial and ulnar arteries, and on outer side of the wrist. The other curves are for the tips of little fingers (left and right averaged) and the geometric center of the forehead. People wear a shirt and trousers.

For modeling of TEGs on living beings, a local thermal resistance of the body has been introduced recently [3, 4] which denotes the effective thermal resistance observed in between the core organs featuring core temperature and the chosen location on skin. Earlier, in [5], an equivalent thermal resistance, i.e., the one in between the TEG and arterial blood under the device has been used instead, but the temperature of arterial blood in extremities is much more unstable reference point. In the middle of the forearm of a

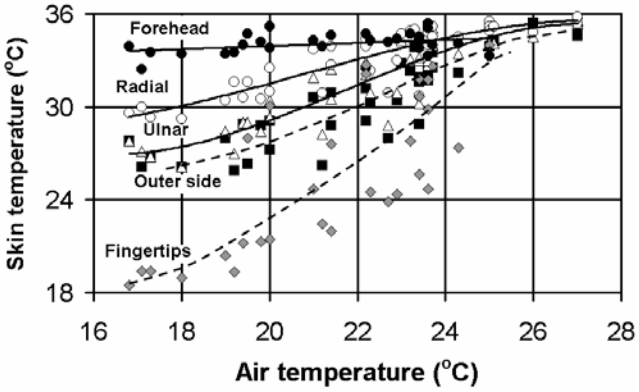

Figure 1. Dependence of skin temperature in human wrist, forehead and tip of small fingers on air temperature.

resting person, basing on results of [6], the blood temperature T_b in the radial artery can be approximated as $T_b = 0.65\ T_{air} + 21$ °C within the 10–22 °C air temperature range. The temperature of the blood further decreases when it reaches the wrist, in particular, due to countercurrent heat exchange with the veins, and, furthermore, it is strongly dependent on personal physical activity.

One can notice in Fig. 1 that the variation of skin temperature on the outer side of distal forearm (the location, where a watch is usually worn) is maximal among the three shown locations over the wrist thereby reflecting larger variations in thermal resistance of the forearm in between arteries and the skin in the specified point. The thermal resistance in extremities can reach very large values, especially in cold weather, and can significantly exceed the thermal resistance of the ambient air. The dependence of the heat flow in the arm, hand and head is illustrated with Fig. 2 as measured in [7] in a still air. In the same plot, the data on a heat flow obtained in experiments with water immersion of the forearm [8] are recalculated to air temperature. This dependence allowed us extracting the thermal resistance of the entire forearm, which is also plotted in Fig. 2.

Some experimental data on the thermal properties of distal forearm of human beings while serving as a heat source for a small-size TEG have been already published [3–5]. In a watch location, a thermal resistance of 440 cm^{2}K/W on average is measured at 22.7 °C (including skin-to-TEG interface thermal resistance), which is two times less than

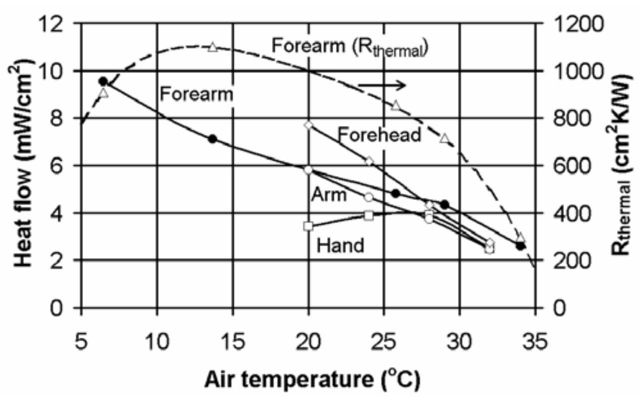

Figure 2. Dependence of heat flow in humans [7, 8], and of the forearm thermal resistance on air temperature.

the thermal resistance of the forearm depicted in Fig. 2. It further decreases to approximately 150–250 cm^{2}K/W under a device positioned exactly on the radial artery, depending on the heat flow and ambient temperature.

The TEG on the skin featuring a radiator changes not only the heat flow, but also the thermal resistance of the body and the skin temperature thereby complicating its designing. Therefore, even the knowledge of open skin temperature and of the related thermal resistance of the body and the heat flow do not represent the input data enough for thermal modeling of a TEG.

The measurement of the heat flow from the open skin surface in the forehead has been performed using thermopiles with no radiator. In this experiment at 21.5 °C, a heat flow of 9.5 mW/cm^2 and a thermal resistance of the forehead of 380 cm^{2}K/W (±5%) have been recorded.

The thermal resistance of the forehead has also been measured with a TEG supplied with a fin radiator of 1.6 cm×1.6 cm×3.8 cm size, Fig. 3. The values measured in this work on a forehead of an office worker are 227 cm^{2}K/W at an air temperature of 21.5 °C, and 156 cm^{2}K/W at 24.7 °C, assuming a daytime deep brain temperature of 37.5 °C. This thermal resistance is measured on a circular area of 4 cm^2 of the forehead at a heat flow of 29 and 22.5 mW/cm^2, respectively. It is important to mention that the skin temperature under the TEG at 21.5 °C has decreased by 3.8 °C from the open skin temperature of 34.7 °C after attaching the TEG. Comparing the thermal resistance at 21.5 °C obtained with and with no radiator, one may notice decreasing of the thermal resistance of the forehead by a coefficient of about 1.7 due to the radiator.

Despite the fact that thermal features of human body have already been extensively studied in medical experiments, the researches have been performed either at the level of a body, its compartments, or at the level of its parts like hands, head, extremities, etc. Therefore, it should not be surprising that the thermoregulation response to increased heat flow observed in medical researches has not been registered in our work with a small-size device on human skin, which drained large heat flow, but on a few square centimeter area only thereby not affecting the overall heat loss.

Design of a wearable thermoelectric generator

The general design of TEGs for using on living beings and in the other energy scavenging applications for powering autonomous devices is shown in Fig. 4. As has

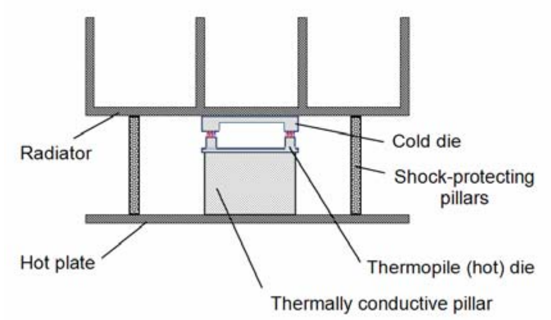

Figure 4. Design of a thermoelectric generator with the micromachined thermopile on a rim.

been shown above, the radiator not only decreases the thermal resistance of the air, but, in addition, it decreases the local thermal resistance of the body under the TEG enhancing the heat flow and allowing better power generation. Even in smallest watch-size wrist generators with comparatively small and thin radiators, the produced power increases, on average, at least in three times due to the radiator.

The TEG shown in Fig. 4, if positioned on a vertical part of the body, allows the air jet of free convection induced by the body pass freely through the TEG in between the hot plate and the radiator thereby the radiator is moved out of the convection layer and the heat transfer from it to the air improves. In case of commercial thermopiles, the thermally conductive pillar and the thermopile dies are replaced with multi-stage thermopiles keeping the distance in between the hot plate and the radiator large enough for passing air jet.

Wearable TEGs and a sensor of 2004

The first wearable thermoelectric generators serving as power supplies for wireless sensor nodes on a wrist have been fabricated in 2004, Fig. 5 [1]. At 22 °C, they produced a power of 100 μW transferred into the electronic module of a sensor node. This power represented the only 40% of the power generated by the TEG because of low efficiency of the voltage up-converter. The latter was a necessary circuit component because the output voltage from the TEG fluctuated within the 0.7–1.5 V range, while the electronic board was operated from 2–2.6 V [9]. However, the power generated at daytime was enough for powering the electronics and a few-meter range radio for transmitting several measured parameters to a nearby PC every 15 s.

The 4-stage thermopiles offered moderate thermal matching of the TEG to the ambient, because the design optimization was a trade off between the thermal efficiency,

Figure 3. TEGs for measuring the heat flows on the skin.

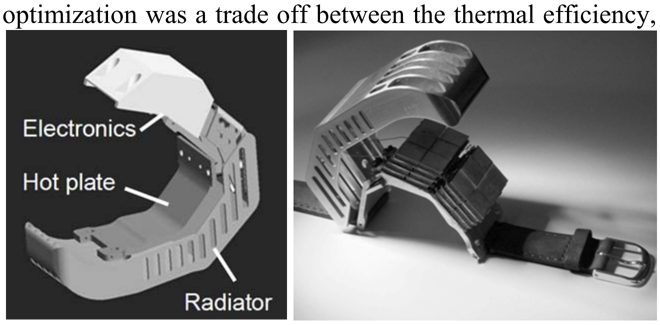

Figure 5. First body-powered thermoelectric generator.

size of the TEG and the cost of thermopiles. For thermal matching of the thermopile with the both air and human wrist, a large hot plate curved according to average profile of the human wrist and a large radiator with fins and slits have been designed, Fig. 5. The pictures of the device and some additional information on the sensor node powered by the TEG can be found in [9, 10].

Watch-size TEGs and a wireless sensor of 2005

The lateral leg dimension of the thermopiles fabricated at Thermix, Ukraine, in 2005 has been reduced by 50 %, to 0.21 mm, which allowed excellent thermal matching of the TEGs to the ambient. The proportionally increased thermal resistance of the thermopiles called, according to thermal matching condition, for two times smaller both hot plate and the radiator. Therefore, the TEG dimensions have been halved to the size of a man watch thereby dramatically improving their acceptance by the users, Fig. 6. The watch-size wrist TEGs have been designed for the use at ambient temperatures not exceeding 23 °C and generate a daytime power of 0.2–0.3 mW on average when worn by office workers indoor. This power decreases to about 0.1 mW at night or on resting people, i.e., at low metabolic rate, Fig. 7. Therefore, taking into account adverse illumination conditions at home, on transport and at night, the demonstrated TEGs are much more powerful, on 24-hour average, than the best solar cells because the majority of people spend indoor most of the lifetime. Higher voltage produced by the TEG at about the same output power as it was in TEGs of 2004 allows direct charging of a NiMH cell. However, at least 1.3 V generated by the TEG is required for charging the battery which is not always the case. The modeling, design and performance characteristics of the TEG and the related sensor node are described in [3, 9]. Two versions of the TEG have been fabricated, Fig. 6. For indoor use, a pin-featured radiator provided the satisfactory performance. For outdoor use, with typically more movement, frequent presence of wind and higher metabolic activity, the perforated circular plate is used as a radiator and the number of thermopiles required for the same performance, as well as the size of the TEG, is decreased by 25%. An encapsulation of the thermopiles using a 5-μm thin polyethylene was provided to make the TEG waterproof. Ultra-low-power 300–600 MHz ANS1601 radio transmitter, which operates down to 0.9 V supply with a power efficiency of 12 nJ/bit has been used in the sensor node allowing transmission of the voltage on a battery and of light sensor data every two seconds.

Figure 6. Wrist TEGs fabricated in 2005 for outdoor use (left) and for indoor use (right). The thermopile assembly of outdoor version is shown in the middle.

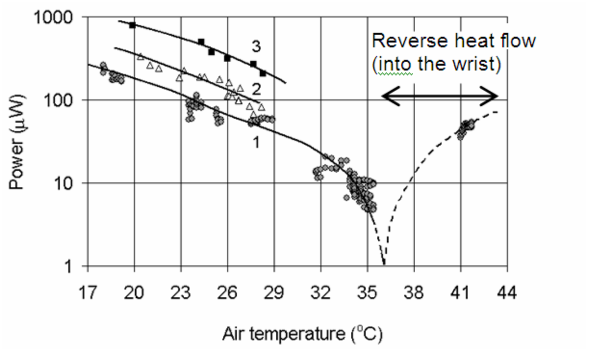

Figure 7. Power produced by indoor TEG version on a resting person (1), after typical activity in the office (2, measured when sitting in a still air), and when walking indoor at a speed of 4 km/hr (3, forced air convection).

Wireless autonomous pulse oximeter of 2006

In 2006, a wireless pulse oximeter has been designed, fabricated and tested on people, Fig. 8 [11, 12]. A TEG similar to the one of 2005 has been used in this device with a minimal power production of about 100 μW. A gold-like coating of the radiator ensured nice appearance of the device, high reflection coefficient in visible region and high emission coefficient in LWIR region. To make the pulse oximeter working in any situations, the charging of a supercapacitor was implemented instead of the battery, so the device is battery-less and operational even at an open circuit voltage of 0.7 V which is the case up to about 29 °C ambient temperature. The device has been designed for ambient temperatures of 22–23 °C. At temperatures of 25–27 °C (at daytime metabolic rate) the power generated becomes less than the power consumed, so that the device switches to a sleeping regime. During sleeping, power consumption is extremely low so the device wakes up again upon collecting enough charge in the supercapacitor, when voltage on it exceeds 1.2 V. The low-power electronics works at a power consumption of 62 μW, i.e., less than 90 μW is required at the input, so the device provides a non-stop operation at standard temperatures maintained in hospital wards and emergency waiting rooms. The disadvantage of energy storage in a supercapacitor is however that only about half of the energy produced over 24 hours is used for the electronics: when the storage supercapacitor is full, there is no power transfer from the

Figure 8. Body-powered pulse oximeter and the application running on a laptop with an update rate of 15 s.

TEG until the next duty-cycled measurement of the oxygen content in a blood is performed.

Micromachined thermopiles for energy scavengers

As shown in previous sections, wireless devices fully powered by living being are realistic. However, their high fabrication cost, which is determined by the cost of thermopiles, disturbs to mass production of such devices. Cost-effective solutions for TEGs based on microelectronic technology are in development at the Holst Centre and IMEC since 2004. The proposed solutions are based on the fact that a 1 mm^2 die with a micromachined thermopile may provide the same power and larger voltage than the TEGs described above [5]. According to the performed modeling, the MEMS thermopile should be fabricated on a tall, e.g. 0.25 mm-tall, micromachined pillar or a rim. In addition, it must be placed in contact to a several millimeter-tall pillar below or above the thermopile in order to keep large distance in between the hot plate and the radiator, Fig. 4. This design of the TEG allows decoupling of the thermal resistance of the air inside the TEG from the thermocouple height, which is few micrometers in a micromachined thermopile. As comes out of modeling of the TEGs and statistically supported by performance of fabricated devices, an average power production on human beings at 22 °C that can be obtained in a 1–1.5 cm thick TEG is 0.03 mW/cm^2 in case of BiTe. This limit, however, can be reached only in certain locations on the body and decreases in case of thinner devices.

Two parallel developments are being carried out in the area of micromachined thermopiles. The first one is a technology development of polycrystalline SiGe MEMS thermopiles, the second research is targeted at several different ways of deposition and patterning of thin and thick films of BiTe. The poly-SiGe is chosen for demonstration of feasibility of micromachined thermopiles because the

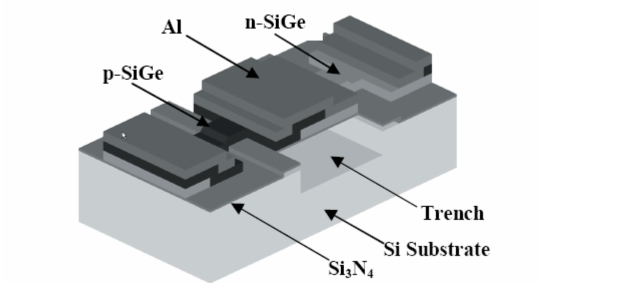

Figure 9. Schematic of poly-SiGe thermocouple with a 0.5 µm-high step and 2.5 µm-deep trench.

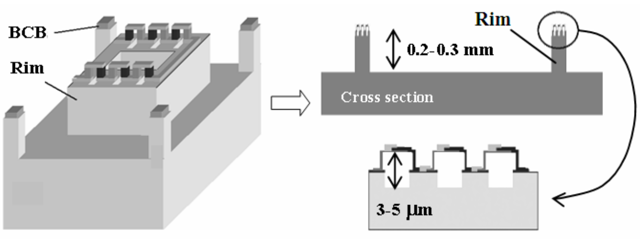

Figure 10. Schematic of a micromachined thermopile on a micromachined rim as proposed in [5].

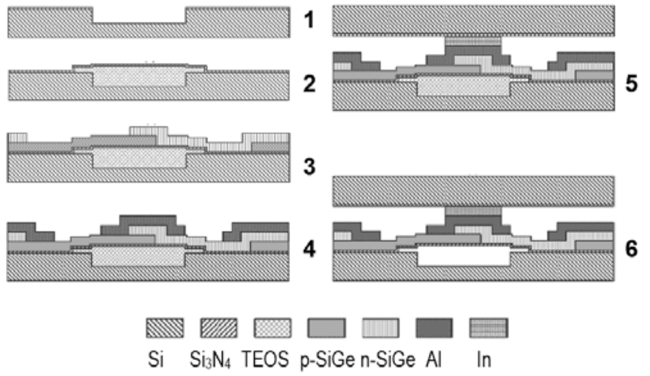

Figure 11. Key process steps for fabrication of poly-SiGe thermopiles and assembling the thermopile micro-sandwich.

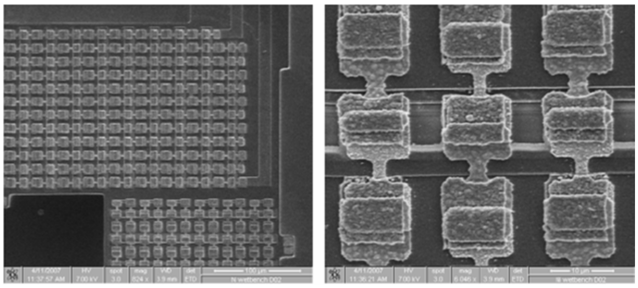

Figure 12. A corner of micromachined poly-SiGe thermopile rim with 4700 thermocouples on top of 0.3 mm-tall Si rim (left) and 3 thermocouples (right) with the central row released and suspended over a trench at 3 µm distance from the substrate [14].

fabrication technologies for this material are well developed and it is extensively used for fabrication of microelectronic and MEMS devices at IMEC. The design of poly-SiGe micromachined thermopile, Figs. 9, 10, has been optimized for using on human beings at 22 °C in a 3 cm × 3 cm-large, 1 cm-thick embodiment shown in Fig. 4.

The fabrication process is shown in Fig. 11, where the steps 1–4 are for a thermopile die, and the steps 5–6 show assembling it with cold die and the release step [13].

The pictures of first poly-SiGe micromachined thermopiles fabricated in 2007 are shown in Fig. 12 [14]. The squares in Fig. 12, right, define area of hot junctions (top and bottom rows) and the cold ones (central row), while the thermocouple legs are narrow bridges in between these.

A ZT of 0.1 is obtained in n-SiGe legs, while for p-SiGe, the ZT obtained to the moment is 4 times less and still needs to be improved to reach calculated performance in a watch-size TEG embodiment of 1–1.5 µW and 1–1.5 V at 20 °C.

The next step in development of the MEMS thermopiles is based on using projection lithography with large depth of focus to fabricate thermopiles with an aspect ratio of 4–5. The proposed design [4] allows reaching the theoretical limits of power production on animals and man. The ASML PAS5500/100 i-line stepper has been recently used for exposure of narrow lines on profiled silicon wafer and the resolution consistent with the calculations has been obtained, Fig. 13 [15].

A parallel development of the film technologies for BiTe thermopiles is ongoing. The first films are being tested at

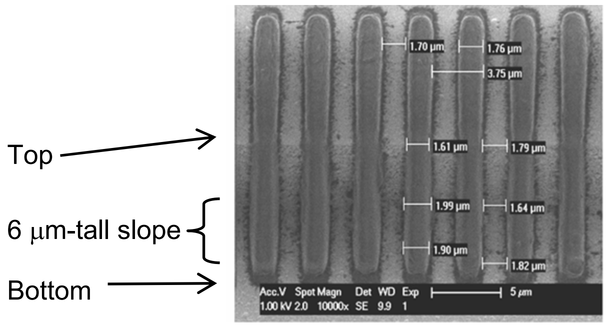

Figure 13. The 1.8 μm-wide lines of a photoresist fabricated over 6 μm topography [15].

IMEC, which have been fabricated in 2007 at the American University in Cairo, Egypt.

Conclusions

An infinite plurality of wireless autonomous smart sensors is foreseen to appear in mass production in coming decades. Powering of these devices in outdoor applications will be provided with solar cells, while for indoor devices and in many technical applications, where vibrations and wasted heat flows are available, this task will be solved using other energy scavengers.

As shown in this work, TEGs on living beings provide enough power for practical applications, moreover, they outperform solar cells on human beings. At a ZT of 1 and a temperature of 22 °C, the power obtainable in unobtrusive device on a human body is limited to 1–2 mW, while for big animals, e.g., a cattle, it can reach several milliwatts safely for the wearers. Thermoelectric energy scavengers, however, will be competitive with the batteries only at dramatically reduced fabrication cost. An enormous market for miniature thermopiles for energy scavenging is already open and calls for cost-effective solutions, therefore to enter this new market of autonomous devices, thermoelectric industry must be reoriented at using thin- and thick-film technologies, e.g. like the microelectronic technology discussed in this work.

The current researches Holst Centre and IMEC are conducting towards effective miniature thermopiles based on microelectronic technologies, new thermopile technologies and designs, more complex wearable devices, implantable devices, body area network as well as devices and systems for transport and industrial applications.

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