Energy Harvesting for Self-Powered Wearable Devices

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Chapter 2
Energy Harvesting for Self-Powered Wearable Devices

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2.1 Introduction to Energy Harvesting in Wearable Systems

Personalized sensor networks optionally should include wearable sensors or a body area network (BAN) wirelessly connected to a home computer or a remote computer through long-distance devices, such as a personal digital assistant or a mobile phone. While long-distance data transmission can typically be performed only by using the batteries as a power supply, the sensors with a short-distance wireless link can be powered autonomously. The idea of a self-powered device is not new and is actually known for centuries. The earliest example of self-powered wearable device is the self-winding watch invented in about 1770. However, typically not much energy is harvested in a small device, so that use of a battery, primary or rechargeable, is beneficial from practical point of view.

There are worldwide efforts ongoing on development of microgenerators that should eliminate the necessity of wiring and batteries in autonomous and stand-alone devices or in devices that are difficult to access. Energy harvesters are being developed for the same purpose. An energy harvester (also called an energy scavenger) is a relatively small power generator that does not require fossil fuel. Instead, it uses energy available in the ambient, such as an electromagnetic energy, vibrations, a wind, a water flow, and a thermal energy. These sources are the same as those used in power plants or power generators such as the ones for powering houses in remote locations, light towers, spacecrafts, and on transport (except those based on fossil fuels). An energy harvester is typically several-to-one centimeter-size power microplant that converts into electricity any primary energy that is available in the ambient. The reason to call them "harvesters" or "scavengers" is the new application area: they are used for powering small devices, such as sensors or sensor nodes. This way of powering them eliminates the need for cost-ineffective work, such as wiring or either

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recharging or replacing batteries. An energy harvester could also be combined with a battery and serve a complementary source of power to improve energy autonomy of a device at limited size of the battery.

Three kinds of energy sources can be used for harvesting in wearable devices. These are the mechanical energy of people's own moving or accelerations on transport, an electromagnetic energy that is mainly light energy, and the heat flow caused by the difference in temperature between the human body and the ambient. There is a difference between truly unobtrusive energy harvesters such as photovoltaic (PV) cells and effort-driven micropower generators. The typical example for the latter is a flashlight that is to be shaken or pre-powered by using the embedded dynamo. A power of the order of Watts can be obtained in such effort-driven microgenerators. However, this way of powering BAN or wearable sensors should be rejected because of additional care required from the patient's side. The worst-case scenario for energy harvesting is a patient who stays in his/her own bed. Then, there is practically no mechanical energy to harvest. The light intensity at home is low. The heat flow minimizes because of a blanket and low metabolic rate, especially, in elderly people. Therefore, only a part of the head and, sometimes, wrists of the person is the only relatively small zone where the energy harvester of thermal or light energy can be located on such patients. The available power is low, too, because the illumination level indoors is low and the heat transfer from the person is determined by natural convection around the head. Nevertheless, even in such case, powering of, e.g., a health-monitoring sensor by using energy harvesters is feasible.

Preventive healthcare is considered as a way to potentially decrease the cost of healthcare, which is steadily on an upward trend. One of the strategies is to shift the health monitoring and management outside the expensive medical centers to family doctors and even to home. For example, the monitoring of chronic diseases while providing real-time data from and to the patient wherever he/she is and at any moment may offer significant potential for both cost reduction at the stage of monitoring and for making curative medicine cost-effective. Wireless healthcare systems, which could be an important component of so-called e-health or eHealth grids, are expected to focus on preventive care and effective provision of continuous treatment to patients, especially those living in remote locations and to elderly people. Real-time monitoring of patient's vital signs and patient-level health data requires use of wearable sensors and mobile devices. It would be good if such devices were small, unobtrusive, and maintenance-free for their entire service life.

2.2 Principles of Energy Harvesting by Using Human Body Heat

Warmblooded animals, or homeotherms, including humans constantly generate heat as a useful side effect of metabolism. However, only a part of this heat is dissipated into the ambient as a heat flow and infrared radiation, the rest of it is rejected in a form of water vapor. Furthermore, only a small fraction of the heat flow can be used in a compact, wearer's friendly and unobtrusive energy scavenger. For example, nobody would like to wear a device on his or her face. Therefore, the heat flow from the face cannot be used. The heat flow can be converted into electricity by using a thermoelectric generator (TEG), the heart of which is a thermopile. It is known from the thermodynamics that the heat flow observed on human skin cannot be effectively converted into electricity, although a human being generates more than 100 W of heat on average. Assuming that about 1–2% of this heat can be used, an electrical power of the order of milliwatts can be obtained using a person as a heat generator. If we recall that watches consume about 1,000 times less power, it is fairly good power.

The human body is not a perfect heat supply for a wearable TEG. The body has high thermal resistance; therefore, the heat flow is quite limited. This is explained by the fact that warmblooded animals have reached in the process of evolution a very effective thermal management. In particular, this includes a very high thermal resistance of the body at ambient temperatures below 20–25°C, especially, if the skin temperature decreases below the sensation of thermal comfort (Monteith and Mount 1974). At typical indoor conditions, the heat flow in a person depends on the location on the body and mainly stays within the 1–10 mW/cm^2. The forehead produces larger heat flow than the area covered by the clothes. Because of thermal insulation due to clothes, not much heat is dissipated from the skin and only about 3–6 mW/cm^2 is observed indoors, on average. Depending on the physical activity of a person, the heat dissipation in extremities "switched" either on or off. This is to preserve the temperature of the body core at low metabolic rate, and to dissipate the excess heat when body temperature rises due to increased physical activity.

The ambient air has a high thermal resistance, too. Indoors, it can be evaluated by using natural heat convection theory. The TEG placed at the interface between the objects with high thermal resistance, i.e., the body and air, must also have relatively high thermal resistance. This can be explained by using electro-thermal analogy, i.e., when voltage, current, and resistance are replaced with temperature difference, ΔT, heat flow, W, and thermal resistance, respectively. The corresponding thermal circuit is shown in Fig. 2.1 for the two cases: (1) a naked human being with no device, and (2) with a TEG on the skin. The human body as a heat generator and the

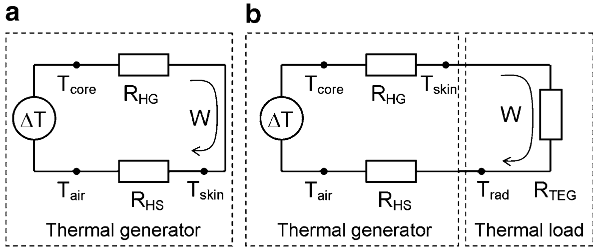

Fig. 2.1 Equivalent thermal circuits of: (**a**) a short-circuit natural thermal generator, and (**b**) the same generator with a thermal load. A relatively small surface of the skin, e.g., several square centimeters, is considered in both cases for the sake of simplicity

ambient air as a heat sink represent natural thermal generator that is shunted on the skin, i.e., at the interface between the body and air (Fig. 2.1a). If a TEG is placed on the skin (Fig. 2.1b), the device behaves as a thermal load of the thermal generator.

The thermal circuit of a wearable TEG placed in contact with the skin involves the thermal resistance of the body, R_{HG}, and of the ambient air, R_{HS}. These resistors are connected in series and represent the thermal resistance of the thermal generator. Despite the fact that the air is a heat sink, in terms of thermal circuit, its thermal resistance acts in the same way as the one of the body, i.e., of the heat generator, and must be included into the thermal generator. In other words, the thermal resistance of the body and air is the thermal resistance of the environment surrounding the TEG. The heat flow in the circuit, W, is the ratio of the temperature difference between the deep body temperature, or core temperature, T_{core} and the ambient air with the temperature T_{air} to the thermal resistance of the circuit. The normal core temperature in humans is about 37°C with a day-to-night variation of 0.5–1°C. Animals, in general, have similar core temperatures, but in cattle it is frequently a little higher, up to 39°C. In camels and baby animals, it can further raise up to about 41°C. The highest core temperatures, up to about 45°C, have been registered in small birds. Typically, the bird temperature ranges between 38°C and 42°C. At night, however, birds have the lowest temperature, which is called nocturnal hypothermia. In general, the smaller the animal, the smaller wearable TEG is needed to produce the same power. The smallest TEG is required on a bird because of a high heat transfer coefficient from it during flight (forced air convection), which is good for the bird.

It is obvious from Fig. 2.1b that the available temperature difference $\Delta T = T_{core} - T_{air}$ can never appear on the TEG because of high thermal resistance of the ambient air and, frequently, of the body. The ratio $R_{TEG}/(R_{HG} + R_{HS} + R_{TEG})$ determines the part of available temperature difference to be obtained on a TEG, i.e., $\Delta T_{TEG} = (T_{skin} - T_{rad})$, where T_{rad} is the temperature of the outer surface of the TEG, which is called radiator. The thermal resistors composing the thermal generator are variable and depend on each other, and on the thermal resistance of a TEG. Therefore, T_{skin} and T_{rad} in Fig. 2.1b are not the same as in Fig. 2.1a at the same ambient conditions. The increased thermal resistance of the circuit in Fig. 2.1b due to a thermal load causes also the heat flow W to decrease.

Because of specific conditions of a thermopile application discussed above, there are specific requirements to both the thermopile and the TEG in most of the energy harvesters including wearable devices. First, the optimal thermal resistance of a thermopile, R_{tp}, required for maximum power generation must be equal to:

$$R_{tp} = \frac{R_{pp} R_{TEGopt}}{R_{pp} - R_{TEGopt}}, \tag{2.1}$$

where R_{pp} is the parasitic thermal resistance of a TEG, and R_{TEGopt} is the optimal thermal resistance of a TEG, at which power generation reaches its maximum. The parasitic thermal resistance, R_{pp}, is always observed due to: (1) air inside the TEG, (2) holding mechanical components interconnecting the cold and hot sides of a TEG, i.e., the elements connected thermally in parallel to the thermopile, and (3) a heat exchange due to infrared radiation. The thermal resistor R_{pp} is connected thermally in parallel to the thermopile between its hot and cold junctions. Actually, it may include some thermal resistance associated with parasitic heat transfer from the heat source to the radiator or to the boundary layer through convection and radiation outside the TEG. The optimal thermal resistance of a TEG can be obtained from the equation of its thermal matching with the ambient:

$$R_{TEGopt} = \frac{(R_{HG} + R_{HS})\,R_{em}}{2(R_{HG} + R_{HS}) \; + R_{em}}, \tag{2.2}$$

where R_{HG} is the local thermal resistance of human body between the body core and the chosen location on the skin, R_{HS} is the thermal resistance of a heat sink, i.e., the thermal resistance due to convection and radiation on the outer side of TEG, and R_{em} is the thermal resistance of a TEG which could occur if the TEG would be "empty," namely, with no thermoelectric material in it. Equation (2.2) is a thermal equivalent of electrical matching of a generator with its load. The last requirement is that the thermal insulation factor N, defined as

$$N = R_{em}/(R_{HG} + R_{HS}), \tag{2.3}$$

must preferably be more than one. This ratio depends on the area of radiator, the contact area with the skin, and on the thickness of a TEG. The thinner the TEG, the less power it regrettably produces due to thermal shunting of a thermopile through the air and holding components. The maximum power takes place at the optimal temperature difference between the cold and hot thermopile junctions, ΔT_{tp}. The latter can be expressed as:

$$\Delta T_{tp} = \frac{\Delta T}{2(1 + 1/N)}, \tag{2.4}$$

so that at $N = 1$, only 25% of ΔT can be obtained on the thermopile. If $N \gg 1$, ΔT_{tp} approaches a half of ΔT like in the other reversible heat engines. The thermal conductivity of air is significantly less than that of thermoelectric material and can therefore be neglected. In this case, one can obtain the expression for the power that can be reached in a wearable TEG, P_{max}, as:

$$P_{max} = \frac{Z}{8}\frac{\Delta T}{(R_{HG} + R_{HS})}\Delta T_{tp}, \tag{2.5}$$

where Z is the thermoelectric figure-of-merit.

From (2.1) to (2.5), a compact wearable TEG should be semiempty, where the thermopile must occupy only a minor part of the device volume. The rest must be filled with air or with a material showing thermal conductivity less than the thermal conductivity of air. The radiation heat exchange between the hot and cold components of a TEG must preferably be minimized through the use of materials with low emission coefficient in long-wave infrared spectral region, i.e., metals. The requirement of a "semiempty" TEG offers a good chance to body-powered power converters to be embedded in pieces of clothing. Such low-weight devices could be user-friendly and comfortable while being worn.

2.3 Calculated Characteristics of Wearable TEGs

The factor N, as follows from (2.4) to (2.5), must exceed one for satisfactory power generation. This places a barrier for the minimal thickness of a TEG at a fixed area that it occupies on the human body. The thermal resistance of the thermoelectric material and air between the two plates of a TEG is proportional to the distance between the plates (Fig. 2.2). However, decreasing the thickness of a TEG does not essentially affect the thermal resistance of thermal generator (Fig. 2.1). As a result, e.g., a thermopile weaved in clothes cannot produce satisfactory power levels. This is because N becomes much less than one. Therefore, unacceptably low ΔT_{tp} is developed on the thermopile. It could have a thermal resistance of a few cm^{2}K/W, while for reaching the power maximum it should be hundred times higher.

There are two basic ways to maximize the power. The first way is to make a thin TEG, say, 3-mm-thin, and provide a very good thermal isolation between the plates of the TEG (Fig. 2.2b). This increases numerator of (2.3), the factor N, and the power. The two plates larger than the area occupied by a thermopile are required to

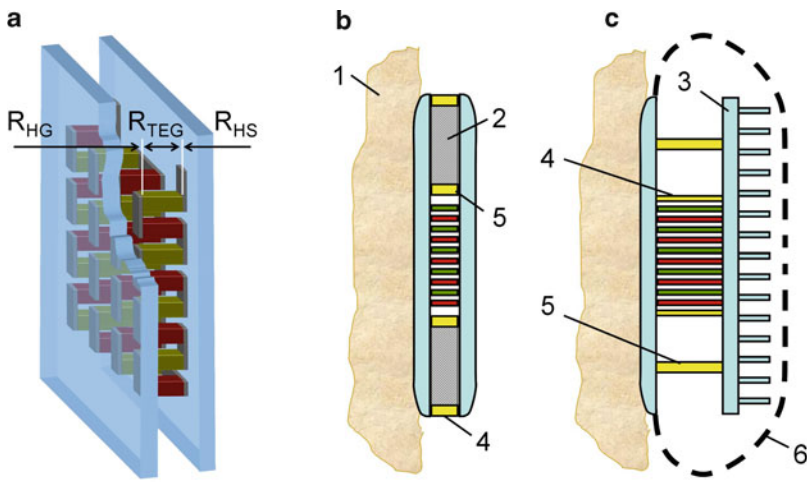

Fig. 2.2 A thermopile between the hot and cold plates of a thermoelectric generator (**a**), and the cross-section of wearable thermoelectric generators: (**b**) a thin TEG on the human skin (1) filled with the material (2) with a thermal conductivity much less than that of air, and (**c**) a thick air-filled TEG with a radiator (3). The other thermally isolating and shock-protecting components are: (4) encapsulation wall, (5) rigid supports such as pillars, and (6) a thermally isolating protection grid that allows air convection and being transparent for infrared radiation

decrease the thermal resistance of the thermal generator (i.e., of the environment) and to get optimal temperature difference on the thermopile. Because of fragility of thermoelectric materials, the device must be enforced by using stiff supports, such as pillars or an encapsulating wall, placed in between the plates. In principle, filling of such a TEG with the material having thermal conductivity less than that of air could be advantageous for further lowering parasitic heat exchange between the plates. The device could be integrated into a piece of clothing. However, such a TEG does not reach the best power that can be obtained on a person because of a low factor N. Furthermore, accounting for technological limitations in industrial fabrication process of thermopiles, only a low voltage, much less than 1 V can be obtained in a compact device. As a result, only several thermoelectric devices connected electrically in series could guarantee an output voltage of the order of 0.5–1 V, which can be effectively used for powering electronic devices. As an alternative, the TEG could be made thicker, e.g., 1–2-cm thick. Despite complications related to integration of such units into clothes, it could reach much higher N, and therefore better power per unit area of the skin. As a result, thicker units would produce higher voltage and it becomes possible to use only one unit for powering a wearable device, of course, if the TEG produces power enough for the particular application.

The second way to maximize power is to decrease the denominator in (2.3), i.e., the thermal resistance of the thermal generator. This can be done by using a fin radiator, or the one with pins. Of course, such radiator consumes some volume of the TEG. The device with a radiator cannot be therefore thin. However, in a TEG that has a thickness of 1–2 cm, the radiator helps to further increase the factor N and the power.

As a numerical example, let us analyze a wearable TEG resembling a big button of 3 cm in diameter. In the calculations, we will vary the thickness of such unit and determine the dependence of maximum power on its thickness. The device resembles the one shown in Fig. 2.2b; however, the empty space between the plates is filled with air, i.e., (2) is air. Two rigid metal plates with a thickness of 1 mm will provide stiffness to the device and good thermal conductance from the human skin to the thermopile and from the latter to the ambient air. The small temperature drop related to limited thermal conductivity of the plate material is neglected. It is assumed that the unit is integrated in a piece of clothing and is located on the chest or arm of the person. We assume that the heat transfer to the ambient is described by natural convection and radiation. The heat transfer correlations are used for a vertical plate with a characteristic length of 30 cm (Incropera and DeWitt 1996) while assuming that the heat transfer from the outer surface of the device is the same as from the clothed human being. The calculations are performed for the distance between the plates from 0.5 to 8 mm, so that the thickness of the TEG varies from 2.5 to 10 mm. The other parameters are: air temperature is 22°C, the deep body temperature of a subject is 37°C, the thermal resistance of the body is 250 cm^2K/W, $Z = 0.003\ K^{-1}$, the supports and encapsulation together have a thermal resistance of 400 K/W per 1 mm distance between the plates, the emission coefficient of the outer surface of the TEG is 90%, no radiation heat transfer between the polished aluminum plates, and no convection inside the TEG, i.e., it is encapsulated.

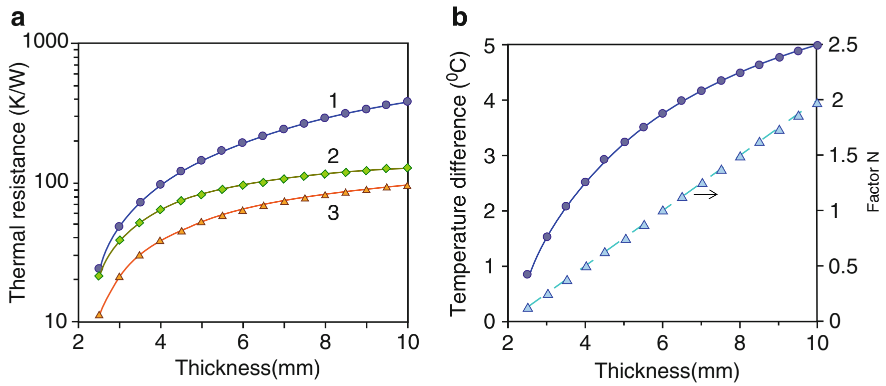

Fig. 2.3 Calculated dependence of thermal characteristics of optimal both the thermoelectric generator and the thermopile on the thickness of a TEG: (**a**) the optimal thermal resistance of an empty TEG (1), of the matched TEG (2) and of the thermopile (3), and (**b**) the temperature difference on a thermopile (1) and the factor N (2)

The results of modeling show that the thermal resistance of an empty TEG that scales linearly with its thickness results in a decreased thermal resistance of the thermally matched TEG if it is thin (Fig. 2.3a). The factor N becomes small and the temperature difference on the thermopile decreases to about 1°C even in the optimized TEG (Fig. 2.3b). At the thickness less than 6 mm, even a half of the theoretical power, (2.5), cannot be reached because $N < 1$.

Ideally, a wearable device and its power supply should be small. Therefore, the power produced per unit volume of a TEG is of primary importance. Under the conditions specified above, it has a maximum in a 4–5-mm-thick device (Fig. 2.4a). The absolute power produced in a thicker device increases (Fig. 2.4b); however, the volume increases more rapidly than the power. Analysis shows that increasing the thickness from 2.5 to 6 mm causes an increase of the power because of increase in numerator of (2.3). In a thicker device, on the contrary, decreasing the denominator of (2.3) could effectively help to further increase the power. Therefore, a second device has been modeled, which resembles the TEG shown in Fig. 2.2c. In the modeled device, there is no protection grid. Then, the only difference with the first modeled device is that a part of its volume is occupied by a radiator. The results of such modeling are shown in Fig. 2.4, too. The radiator size increases up to 40% of the device volume in a 10-mm-thick TEG. It enables keeping the maximum power generation independent of the volume (Fig. 2.4a). Therefore, power generated by such TEG increases linearly at least up to 10-mm thickness.

One should not expect linear increase of the power in devices thicker than 1 cm. Actually, in such devices, the other effects that have been neglected in the above modeling start to be important. Application of the radiator results in local increase of the heat flow in humans. The larger the radiator, the larger is the heat flow and the lower is the skin temperature under the TEG. The radiator temperature decreases below the temperature of the outer surface of a clothed person. Therefore, the heat transfer becomes less effective than it was assumed in the model. We can

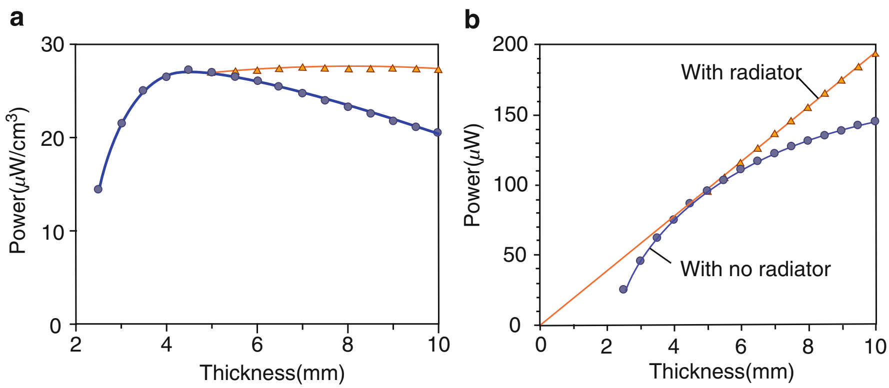

Fig. 2.4 Calculated dependence of the power on a thickness of an optimal TEG with no radiator (*circles*) (Fig. 2.2b), and with the radiator of an optimal size (*triangles*) (Fig. 2.2c): (**a**) power per unit volume, (**b**) power produced in a TEG of 3 cm in diameter. A *dashed line* in (**b**) is the guide for an eye

conclude from Fig. 2.4 that an optimized small wearable TEG can produce about 25 μW/cm^2 and about 25 μW/cm^3 indoors, i.e., with no wind, no sunlight, no pieces of clothing worn on top of the TEG, and in the location on the human body, where the thermal resistance of the latter is 250 cm^{2}K/W.

The measured performance characteristics of wearable TEGs are close to their theoretical analysis performed in this section. However, if the TEG is located on an open skin surface, the radiator temperature is significantly less than the skin temperature. Consequently, the power per unit volume decreases as compared with calculations performed in this section due to higher temperature of the convection layer formed around the human body. Based on both theoretical and practical results (still to be discussed below), we conclude that a correctly designed unobtrusive TEG in the right location on the human body can produce approximately 10–30 μW/cm^2 of electrical power in moderate climate, on 24-h average. The produced power depends on the thickness of a TEG and its size: the thicker the TEG, the better is power generation while the larger the TEG, the less power per unit area is produced. It also very much depends on the location on the human being therefore the latter requires particular attention.

2.4 Human Body as a Heat Source for a Wearable Thermoelectric Power Supply

Medical studies of the properties of a human being, in particular, of heat flows and its thermal conductance are typically performed on the whole human body or on its parts such as the head, arm, hand or trunk (Hardy et al. 1970; Itoh et al. 1972). Furthermore, they are mainly conducted on naked skin surface. Clothes change the overall heat flow from the human body and its pattern. Clothes have a tremendous effect on the heat transfer from the body at ambient temperatures less than 25–28°C. All three main channels of heat rejection, namely, convection, radiation, and evaporation from the skin surface are affected by clothes. The lower the ambient temperature, the larger is the percentage of heat dissipated from open skin, i.e., from the face. The trunk has much more stable temperature at different ambient conditions (temperature, wind, and sunlight) than the head and extremities. This is because people choose appropriate clothes depending on the weather conditions. However, even indoors, at typical temperatures of 20–25°C, certain variations of the skin temperature are observed on the scale of centimeters. An example of the temperature map of the wrist and hand is shown in Fig. 2.5a. The temperature profile around the wrist is shown in Fig. 2.5b as measured at two indoor ambient temperatures. The temperature reaches maximum close to the radial and ulnar arteries. Local heat flows also change from place to place. If a TEG is attached to the body, especially the one with a radiator, the heat flow depends not only on the skin temperature, but also on the local thermal resistance of the human body. The latter is defined as a thermal resistance between the body core and the chosen location on the skin.

As an example, the skin temperature has been measured in the middle of the forehead before attaching a TEG and under attached TEG. At 21.5°C, a heat flow of 9.5 mW/cm^2 and a thermal resistance of 380 cm^{2}K/W have been measured by using a thermopile with a thermal resistance of 50 cm^{2}K/W attached to the forehead. A skin temperature of 34.7°C has been measured, but a deep brain temperature of 37.5°C has been assumed to obtain the thermal resistance. Then, a TEG with a fin radiator of 1.6 cm × 1.6 cm × 3.8 cm size has been attached on the same place. The contact area between the TEG and the skin was 4 cm^2. The heat flow has increased to 22.5 mW/cm^2, the thermal resistance of the forehead has decreased to 227 cm^{2}K/W, and the skin temperature under the TEG dropped to 30.9°C.

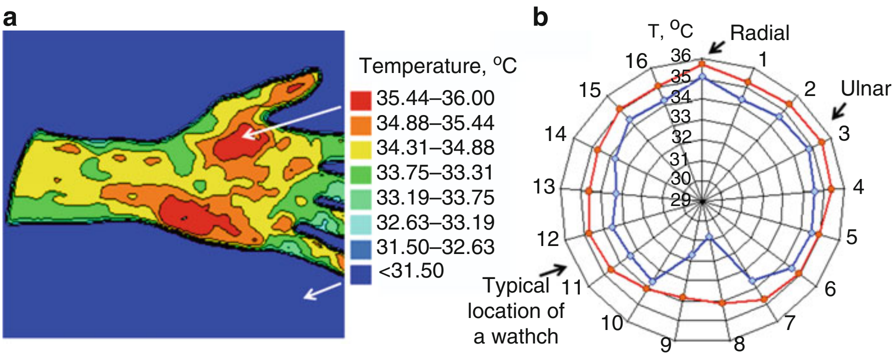

Fig. 2.5 (**a**) Temperature map of the hand (palmar view). The infrared image is taken with calibrated radiometric camera within the 8–12 μm spectral range. (**b**) Temperature profiles around the wrist with a circumference of 17 cm at two ambient temperatures, 27°C (*circles*) and 22.3°C (*diamonds*), measured indoors

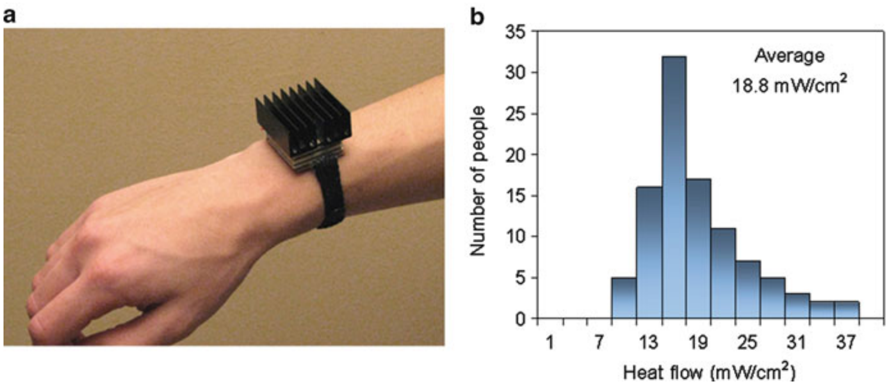

Fig. 2.6 (**a**) Thermoelectric generator on the wrist and (**b**) the heat flow through the TEG per square centimeter of the skin measured indoors on the wrist of 100 people sitting still at a mean room temperature of 22.3°C

The increase of heat flow due to radiator has caused a decrease in the thermal resistance of the forehead by a factor of 1.7.

The thermal resistance of the wrist under a large-size TEG with a fin radiator of 1.6 cm × 3.6 cm × 3.8 cm size (Fig. 2.6a) has been measured in the distal forearm of students at 22.7°C. In the typical location of a watch, its average value measured on 77 volunteers sitting still for several tens of minutes is 440 cm^2K/W. The volunteers have been asked to attach the TEG to the wrist with tightness according to their preferences. Therefore, the contact area of the hot plate of a TEG with the skin varied a little in uncontrollable way. Therefore, the statistical data presented below in Fig. 2.6b account for the user-related tightness, which is useful for designing TEGs. The heat flow through a TEG was 200 mW, on average; however, it depended on the skin temperature. The latter measured on 77 persons shows variations within the 27.5–32.5°C range with 30°C on average. The mean heat flow varied with the skin temperature from 15 to 24 mW/cm^2. However, the standard deviation, σ, due to difference between subjects was large, with a σ/mean of 17%. Therefore, the corresponding thermal resistance largely varied. In 90% of studied subjects, the thermal resistance of the body combined with the skin-to-TEG interface contact resistance was within the 200–650 cm^2K/W range.

To understand importance of the thermal resistance of the body for designing a TEG, we divide the thermal resistance into two components. The first one, $R_{c\text{-}r}$, denotes the thermal resistance between the body core and the arterial blood in the wrist. The second component, $R_{r\text{-TEG}}$, denotes the thermal resistance between the arterial blood and the hot plate of the TEG. At a blood temperature of 35.8°C, on estimate, the $R_{c\text{-}r}$ and $R_{r\text{-TEG}}$ can be evaluated, assuming a core temperature of 37°C (Fig. 2.7a). As one can see, only $R_{r\text{-TEG}}$ strongly depends on the skin temperature. Therefore, within the measured range for skin temperatures, the thermal resistance in the wrist observed between arteries and the skin dominates over the vasomotor

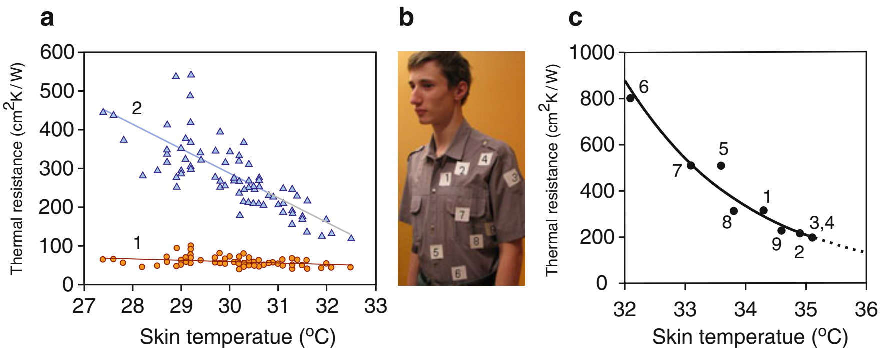

Fig. 2.7 (**a**) Estimated thermal resistance per square centimeter of the skin measured at 22.7 ± 0.5°C on the wrist of 77 people under the attached TEG: (1) is the thermal resistance between the body core and arterial blood in the wrist, (2) is the thermal resistance between the arterial blood and TEG. (**b**) Nine locations, where the thermal resistance of the human being has been measured, and (**c**) is the thermal resistance of the human body at 23°C depending on its location on the trunk

response, thermal resistance of the cardiovascular system, and interface contact resistance between the skin and the TEG.

Two experiments have been conducted to demonstrate the importance of accounting for the thermal resistance of the body. In the first one, its comparative measurements have been performed in three locations: on the forehead, on the wrist (on the radial artery), and on the chest, left side, on lowest ribs. A TEG with a size of 3 cm × 4 cm × 0.65 cm and with a thermal resistance of 580 cm^{2}K/W has been used in this experiment. The heat flow at 22.8°C was the same, however the skin temperature was different, from 33.8°C in the wrist to 35.8°C in the forehead. The corresponding thermal resistance of the body varied from one location to another by a factor of three. The same TEG has also been integrated sequentially in nine locations in a shirt (Fig. 2.7b). The corresponding thermal resistance shows large variations (Fig. 2.7c). Therefore, the power generation varies within a factor of three over the nine measured locations.

In the second experiment, the ability of the human being to provide large heat flow has been studied. A thermopile with a thermal resistance of 50 cm^{2}K/W has been attached to the wrist in two locations, namely, on the radial artery and in the typical location of a watch. A large piece of aluminum maintained at room temperature has been provided on the outer side of the thermopile and served as almost perfect heat sink. The experiment shows that, on the radial artery, a heat flow of 90 mW/cm^2 exceeds by a factor of three the heat flow that the human being can provide in the location of a watch. However, in indoor applications, the heat flow exceeding 15–30 mW/cm^2, depending on the location of a TEG, causes sensation of cold. Therefore, an acceptable heat flow of 10–20 mW/cm^2 through a wearable TEG supplied with a radiator seems the maximum indoors.

In cold environment, certain zones of the human body allow larger heat flow with no sensation of cold. As measured outdoors on the neck, near an artery, the maximum heat flow of 60 mW/cm^2 was acceptable at air temperature of 0°C. At a temperature of –4°C, a heat flow of 70 mW/cm^2 was still quite comfortable on the front side of the leg, about 25 cm above the knee of a person wearing jeans. The maximum comfortable heat flow of 100–130 mW/cm^2 has been registered on the radial artery in the wrist, at air temperatures of –4°C to +2.3°C. Therefore, the TEG with a thickness of 3 cm unobtrusively produced in this location a power of 1–1.4 mW/cm^2 on a walking person.

2.5 TEGs in Wearable Devices

The first wearable TEG serving as a power supply for a simple wireless sensor worn on a wrist has been fabricated in 2004 (Fig. 2.8a, b). At 22°C, it produces a power of 100 μW transferred into the electronic module of a sensor node. This is the only 40% of the generated power because of low efficiency of the voltage up-converter. The latter is a necessary circuit component because the output voltage from the TEG fluctuates indoors within the 0.7–1.5 V range. At 0.7 V output, the power is not enough for the sensor, while at 1.5 V, too much power is produced. Therefore, at the system level, a short-or long-term power reserve must be provided in the form of rechargeable battery or a supercapacitor to avoid power

Fig. 2.8 (**a**) The first wrist TEG: (1) is the electronics module, (2) is a hot plate, and (3) is a radiator. (**b**) A similar TEG worn next to a watch. (**c**) A TEG with a pin-featured radiator. (**d**) A waterproof TEG for outdoor use. (**e**) A TEG in the wireless sensor for measuring the power generated by people in real life. (**f**) The power produced by the device shown in (**c**) in the office on a sitting (*circles*) and walking (*triangles*) person

shortages. By using such energy storage element, the power gained by a TEG on occasional basis can be uniformly redistributed and consumed at near-constant rate over a long period of time. In the first wireless sensor, the electronic board was powered by two NiMH cells (2.4 V). The power generated at daytime was enough for powering the electronics and a 2.4 GHz radio, and for transmitting several measured parameters to a nearby PC every 15 s.

In 2005–2006, watch-size wrist TEGs of three different designs have been fabricated (Fig. 2.8c–e). The power generated in the office on a person sitting still for a while is shown in Fig. 2.8f. At 20–22°C indoors, the TEG produces 200–300 μW at an open-circuit voltage of 2 V. This power decreases to about 100–150 μW at night or on a person resting for a long period of time, i.e., at low metabolic rate. However, it rises in a few minutes of walking indoors to 500–700 μW. This power increase is explained by the forced air convection on a walking person. On the same reason, i.e., because of wind and more physical activities, wearable TEGs work better outdoors. Taking into account adverse illumination conditions at home, on transport and at night, these TEGs are much more powerful, on 24-h average, than the best PV cells because the majority of people spend indoors most of the lifetime. Higher voltage allows direct charging of an NiMH cell. However, at temperatures above 26°C, the TEG is mismatched with the cell and the efficiency of power transfer decreases. Therefore, some wireless sensors have been made with a supercapacitor as the charge storage element instead of a battery because the former can start storing energy at lower voltage. This means that the battery-less device works more efficiently at higher ambient temperatures than the device with a battery.

An example of such sensor node is shown in Fig. 2.8e. The 4-stage thermopiles used in the TEG have an equivalent aspect ratio of thermocouple legs of 35. At a distance of 7 mm between the hot plate and the radiator, this aspect ratio is the optimal one. Therefore, at ambient temperatures within the 20–22°C, the TEG produces more than 25 μW/cm^2, i.e., almost the maximum possible power. In the best orientation of the TEG, namely, facing the radiator down, the power reaches 30 μW/cm^2. The battery-less wireless sensor node has been designed to track the power produced by the human being at high ambient temperatures in real life. To make it functional at such temperatures, the duty cycle for the radio transmission bursts is made variable to prevent power shortages. On the other hand, it allows consumption of all the produced power at typical ambient temperatures, where otherwise the supercapacitor would be saturated and the harvested energy would not be transferred into it. By varying the interval between transmissions from 0.1 to 100 s, the voltage on the charge storage supercapacitor is maintained always near the matching point. The sensor node has been tested up to an ambient temperature of 35°C. The measurement results show that a temperature difference of 2–3°C between the skin and air provides enough power for the sensor. An interesting observation is that due to fluctuations of air and skin temperatures, different activities of a person, and variable both sunlight and wind, a battery-free device is able to work at any ambient temperature, at least, a part of the time. Even at a mean ambient temperature equal to the skin temperature, the average power production is not zero.

It is interesting to compare the performance characteristics of the TEG shown in Fig. 2.8d with the modeling results obtained in Sect. 2.3. This TEG has a distance between the plates of 7 mm, the 0.5-mm-thick hot plate and the 1.5-mm-thick cold plate, so that the TEG has a thickness of 9 mm. According to Fig. 2.4, it can produce up to 20 μW/cm^2. There are some differences between the calculated case and the TEG shown in Fig. 2.8d. First, the TEG has a larger cold plate of 3.4 cm in diameter, but a contact area of about 6 cm^2 between the hot plate and the skin is less than in above calculations. It has also been tested on the wrist therefore the heat transfer coefficient is better than in the modeled device. However, the protection grid adversely affects the power and partially decreases the convective and radiation heat transfer from the TEG. The measurements of the power generation have been performed at ambient temperatures of 23–25°C. The device produces by about 17% less power per unit area than its thicker version shown in Fig. 2.8c. This corresponds to a power of 140 μW, or 15.8 μW/cm^2 at 22°C, a pretty close to the modeled 140 μW (Fig. 2.4). More exact modeling of this device on the wrist performed earlier has predicted 160 μW, or 17.8 μW/cm^2 at 22°C, but with no protection grid.

A TEG similar to the one shown in Fig. 2.8c has been used as an energy supply for the first body-powered medical sensor, namely, a pulse oximeter or SpO_2 sensor. The device noninvasively measures the oxygen content in arterial blood by using a commercially available finger sensor (Fig. 2.9). This battery-free device is fully self-powered at an output update rate every 15 s. Its power consumption in this case is 62 μW, while the TEG typically produces more than 100 μW. About 47% of power is used for the signal processing, 36% is consumed by two LEDs, 12% is used for a quiescent power, and 5% for the radio. The device switches automatically on if there is enough voltage on the supercapacitor. In case of fully discharged supercapacitor, it starts in about 15 min after putting the device on.

The signal processing in the pulse oximeter is performed onboard therefore a minimal power is required for the radio transmission. In case of monitoring biopotential signals, the waveform must be transmitted. In this case, the radio consumes most of the power. To demonstrate the possibility of creation of more complex battery-less wireless devices, a two-channel electroencephalography (EEG) system has been fabricated (Van Bavel et al. 2008). It consumes 0.8 mW

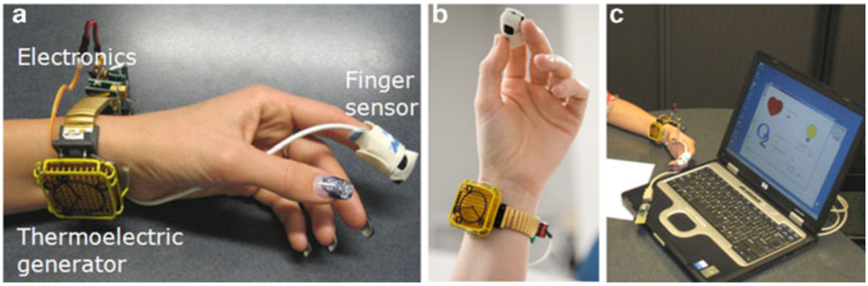

Fig. 2.9 Wireless pulse oximeter (**a**, **b**) and the application running on a laptop (**c**)

Fig. 2.10 Wireless electrocardiography system powered by the body heat: (**a**) and (**b**) show the TEG components in the assembling stage, and (**c**) is a completed device. (1) is a thermopile module, (2) is a hot plate, (3) is a radiator and (4) is the electronics module

therefore the TEG must provide more power at 22°C to make sure that there will be no power shortages at higher ambient temperatures. Taking into account that the limit of the power calculated and measured in TEGs of 1–1.3-cm thick is about 25 μW/cm^2, the device must occupy a relatively large area. Therefore, the TEG has been divided into 10 units. The units are connected to each other in a track resembling those of crawler-type tanks or big bulldozers (Fig. 2.10).

The thickness of radiators has been increased as compared to wrist TEGs to increase the power per unit area of the skin. The TEG has a thickness of 29 mm. The size of a hot plate track is 4 cm × 20 cm with a contact area to the skin of 64 cm^2. The measured power at 22°C is about 2.5 mW, or 30 μW/cm^2. The system has been designed for the indoor use at 21–26°C. At a temperature below 18–19°C, the heat flow through the TEG increases and the device is considered by users as too cold. (At a temperature of 19°C, the power increases to 3.7 mW.) Therefore, to make it acceptable for outdoor use at low ambient temperatures, the heat flow must be decreased, i.e., the radiators must be smaller. As a result, at high ambient temperatures the TEG would not produce enough power and its size would further grow. Therefore, in the TEG acceptable at low ambient temperatures, PV cells could be added. In a device with fixed dimensions, they compensate for a lack of power from the TEG at high temperatures. Furthermore, PV cells are more efficient outdoors and can gain a significant energy to be stored in a battery.

The EEG system, pulse oximeter, and the other sensors described in this section have power consumption less than the power generated by a TEG in the worst application scenario. However, at ambient temperatures of 35–38°C, thermoelectric power minimizes. To provide enough power in such situation, a secondary battery must be provided. As it has been shown, smart power management together with decreased duty cycle and power consumption in case of energy deficit enable body-powered devices in a wide temperature range. If high ambient temperatures are expected for long periods of time for a particular application, it is also beneficial to hybridize a TEG with PV cells.

2.6 Hybrid Thermoelectric-Photovoltaic Wearable Energy Harvesters

Hybrid energy scavengers have been fabricated for EEG systems in 2008 primarily to avoid sensation of cold induced by a TEG in cold weather. Figure 2.11a illustrates the principle of hybridization of a TEG and PV cells. The latter are mounted on the outer surface of radiators and serve as their external heat dissipating surface. The TEG and PV cells are connected in two parallel electrical circuits and charge one supercapacitor. Additional power gained by PV cells enables decreasing heat flow through the TEG (and the produced power, too) thereby making it comfortable in harsh weather conditions. One of the systems is shown in Fig. 2.11b.

The hybrid power supply provides more than 1 mW in most of the situations. This is more than enough for the two-channel EEG application consuming 0.8 mW. The absolute and relative input power gained from the thermoelectric and PV power supplies constantly varies, thereby reflecting variations in both the illumination level and the heat transfer from the head. A power of 45 mW was generated by PV cells in direct sunlight (March, Belgium), while a power of 0.2 mW has been measured in the office, far from the window in a cloudy day. The TEG provides much more uniform power output than PV cells because it depends mainly on air temperature and wind speed. At 22°C, indoors, the TEG generates 1.5 mW, while outdoors, at 9.5°C with no wind, the power increases to 5.5 mW. The EEG system is

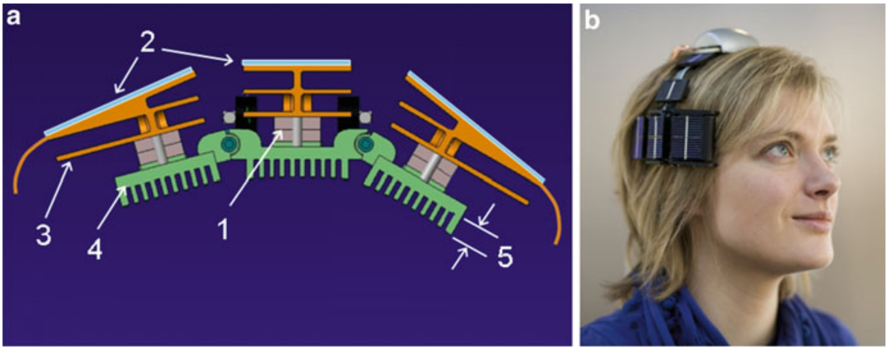

Fig. 2.11 (**a**) Cross-section of the hybrid thermoelectric-photovoltaic generator unit used in an EEG system: (1) is a thermopile, (2) are PV cells, (3) is a radiator, (4) is a hot plate with (5) thermal shunts. (**b**) Two-channel EEG system with a hybrid power supply (reproduced with permission from Van Bavel et al. 2008)

battery-free, so the power exceeding 1 mW is typically wasted. However, using a supercapacitor instead of secondary battery allows demonstration of a nice system feature: in less than 1 min (typically, in 10–30 s) after putting it on, the charge storage supercapacitor is charged from the fully discharged state and the system is self-started by the body heat.

As tested outdoors at a temperature of 7°C, the device is still very comfortable for the user. As a rule of thumb, at 10°C outdoors, PV cells generate eight times more power than the TEG while indoors the latter offers eight times more power than PV cells in the office. By using a two-way power supply that exploits both the heat dissipated from person's temples and ambient light as energy sources, the dimensions and weight of the TEG are reduced. The location on the hair is much more convenient, according to user's responses. In addition, the EEG system works much more reliably at high ambient temperature like 28°C (with available light).

Comparison of a TEG with PV cells of the same area shows that the latter generate much less power on average, because not much light is available indoors, where the authors and the reader of this book are resting at this moment. In addition, the quantum efficiency of high-efficiency PV cells at low illumination rapidly decreases. If high efficiency is obtained in PV cells indoors, they could become competitive to a thin TEG. The power in a TEG scales proportionally to its thickness, at least within the 4–10 mm range. However, as modeled in Sect. 2.3, even in a 4-mm-thin TEG, it can reach 10 $\mu W/cm^2$. This is still much better than the power generated by high-efficiency monocrystalline silicon cells, especially on a 24-h average.

2.7 TEGs in Clothing

A system integrated in a piece of clothing must be thin, lightweight, and should sustain repeated laundry and pressing. Therefore, it must be waterproof, either bendable under load or rigid, and sustain high temperatures. High accelerations in modern washing machines up to about 300 g together with mechanical shocks during use of devices set additional requirements for the mechanical strength and shock protection. Photovoltaic cells are thin and even if enforced with a rigid or a flexible metal plate, have a thickness of about 1 mm. TEGs can also be made flexible, i.e., with thin plates. However, as pointed out in Sect. 2.3, the TEGs must not be thinner than about 2 mm, otherwise, the area occupied by the TEG would dramatically enlarge. The system components must also provide the sweat path from the body to prevent wetting of the skin at high metabolic rate, e.g., during exercise, and in a summer season. At a system level, a part-time use of a piece of clothing suggests that the devices must hibernate during long periods of nonuse and perform auto-start when in use.

To demonstrate the feasibility of such devices, an electrocardiography (ECG) system has been integrated into an office-style shirt in 2009 (Fig. 2.12a). Unlike the EEG and SpO_2 sensors described in previous sections, it is powered by a secondary

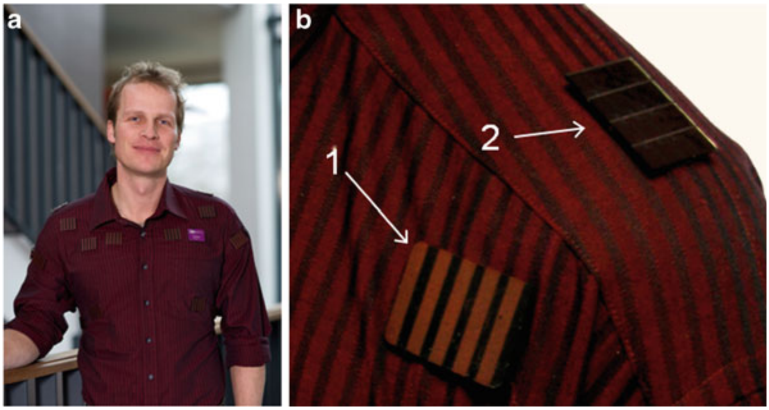

Fig. 2.12 (**a**) Electrocardiography system integrated in a shirt. (**b**) One of thermoelectric modules (1) and the left-side PV cell (2)

battery. The battery is constantly recharged using the wearer's body heat. The power consumption of the energy-efficient ECG system is 0.44–0.5 mW depending on the sample rate. Given the best demonstrated power efficiency of 75% of voltage up-converter, the only 0.6–0.7 mW are required from the TEG. The sample rate is set automatically depending on available power. To be comfortable for the user, the TEG is built on modular approach. Fourteen 6.5-mm-thin TEG modules with outer metal plates of 3 cm × 4 cm size acting as radiators have been integrated into the front side of the shirt (Fig. 2.12b). They occupy less than 1.5% of the total area of the shirt. According to the modeling results (Fig. 2.4a), the TEG modules must produce near-maximum power per unit volume. In the office, the TEG typically provides the power within the 0.8–1 mW range at about 1 V on the matched load during person's usual sedentary activity. On a person walking indoors, the power production increases to 2–3 mW due to forced convection. The radiators of TEG modules have been painted like chameleon into the shirt colors, except one module, which is done to show the module size. The wiring and the other modules of ECG system are located on the inner side of the shirt. Because of high thermal resistance of thermally matched TEG modules, they are never cold. As measured at about 10°C outdoors on a person wearing a thick jacket, the power typically increases a little at low ambient temperatures.

Two charging circuits, one with a TEG, and the other with PV cells are connected to the power management module. Two amorphous silicon solar cells of 2.5 cm × 4 cm size each has been integrated in the shirt on its shoulders. PV cells have been added to the system because if the shirt is not worn for months, the battery can be emptied due to its self-discharge. When the shirt is not used for a long period of time, more than a month, it must be stored in an environment where light is available periodically, e.g., in a wardrobe with windows. The power provided by solar cells is enough to compensate for the self-discharge of the battery and for the standby power. In this way, even after months of non-use, the electronics is maintained in the ready-to-start state, waiting for the moment the shirt is used again. If accidentally the battery is completely discharged, the shirt is still not lost. Its PV cells must be just placed in direct sunlight and charged for several days. By using a wake-up button, the operability of the system can then be verified. Once the battery reaches the minimum working voltage, the up-converter becomes functional and the ECG shirt can be worn again. During its daily use, the produced power typically exceeds the power consumption, so the battery will be fully charged in a course of several days. The system components, i.e., a TEG, PV cells and electronics in a flex circuit, have waterproof encapsulation and sustain machine washing with drying cycle at 1,000 rpm. If the TEG voltage drops to near-zero, which happens when the shirt is taken off, the system switches into a standby regime with 1 μW power consumption. The self-start of the system takes place within a few seconds after touching the skin while the shirt is being put on again.

At a conversion efficiency of 75%, the system functions up to 25–29°C, depending on the activity of the user. The harvesting still takes place up to 31°C during a walk. This does not mean that the system will stop at an ambient temperature of, e.g., 35°C. In such case, the battery will provide the power until the user enters an air-conditioned room. Furthermore, a temperature of 35°C outdoors with a high probability means that there is a plenty of sunlight, so that PV cells instead of a TEG will be the main power supply for a while.

2.8 Development of New Technologies for Wearable Thermopiles

The theory (see Sect. 2.2) does not require large-size thermopiles for the maximum power generation in a wearable TEG. The only requirement for a TEG is that it must have a thermally matched thermopile with high thermal resistance per square centimeter of the skin. However, the power per unit area, at least within the 4–10 mm thickness of a TEG, scales linearly with its thickness (Sect. 2.3). If a small-size thermopile is used in such TEG, the distance between the two plates of a TEG (Fig. 2.2) must be kept the same. The design of a TEG changes a little (Fig. 2.13a), i.e., one or two thermal shunts must interconnect a small-size thermopile with the plates. (A thermal shunt is a thermally conducting element such as a spacer, a fin or a pillar that thermally shunts a part of the environment.) Then, a miniaturized thermopile can produce about the same power in a TEG of a fixed thickness as obtained by using large-size thermopiles purchased on the market. This does not mean that any small-size thermopile is good for wearable devices. Still both the electrical contact resistance and the thermal conductance parallel to the thermopile in a TEG must be minimized because these are parasitic factors that adversely affect its performance characteristics (Sect. 2.2).

The modeling of a thermopile in a wearable TEG shows that due to scaling laws, the smaller the thermopile, the lower aspect ratio is required to provide its thermal matching (Fig. 2.13b). (An aspect ratio is the ratio of the length of thermocouple

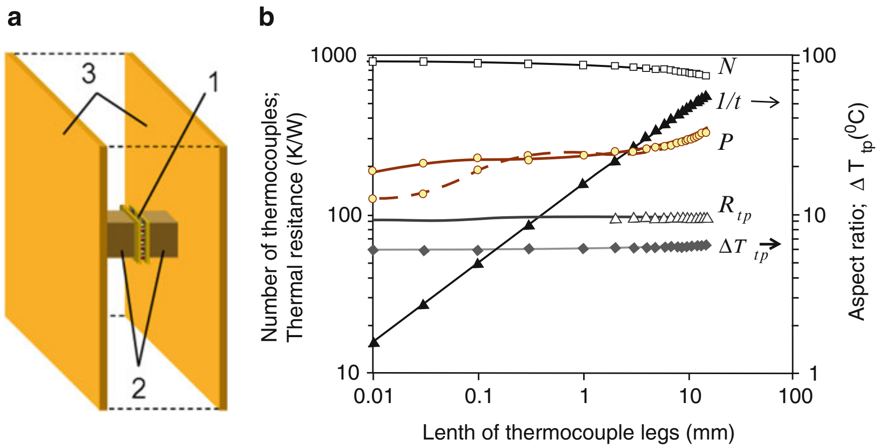

Fig. 2.13 (**a**) Design of a wearable TEG with a small-size thermopile (1) that is thermally connected to the plates (3) by using thermal shunts (2). (**b**) Modeled dependence of optimal parameters of a thermally matched thermopile in a wearable TEG of 3 cm × 3 cm × 1.7 cm size on the length of thermocouple legs: N is the optimal quantity of thermocouples, l/t is an aspect ratio of thermocouple legs, R_{tp} is the thermal resistance of a thermopile, ΔT_{tp} is the temperature difference between hot and cold junctions, and P is the power calculated at a contact resistance of 10 Ω μm^2 (*solid line*) and 100 Ω μm^2 (*dashed line*) between semiconducting legs and metal interconnects

legs, l, to their lateral dimension, t.) Commercially available thermopiles require high aspect ratio. For the device modeled in this section (Fig. 2.13b), it must exceed 20, at $l = 2$ mm, and 50, at $l = 15$ mm. Both values essentially exceed capabilities of industrial technologies. Therefore, the only practical solution has been found to build the TEGs described in this chapter, namely, the use of multistage thermopiles. Decreasing the thermopile size causes proportional decrease of an aspect ratio that is required for the same thermal resistance. As a result, at a length of thermocouple legs of about 10 μm, the optimal aspect ratio decreases to values acceptable in microelectronic and microelectro mechanical systems (MEMS) technologies. At larger dimensions, thick-film and inkjet printing technologies could be used instead in thermopiles fabricated on a polymer tape (Stark 2006) as well as in membrane-based and membrane-less thermopiles (Van Andel et al. 2010).

With microelectronic technologies, the aspect ratio required for 6–15-μm-long thermocouples can be reached using projection lithography because a critical dimension of 1–3 μm is sufficient. One of the possible designs is shown in Fig. 2.14a. A height of 6 μm with inclined thermocouple legs has been already reached in the technological process developed for the polycrystalline SiGe (Fig. 2.14b) (Su et al. 2010). This height corresponds to about 12 μm length of thermocouples. A research is ongoing toward practical demonstration of poly-SiGe thermopiles with high aspect ratio. The required low contact resistance between semiconducting legs and metal interconnects, i.e., less than 100 Ω μm^2 (Fig. 2.13b) seems feasible (Wijngaards and Wolffenbuttel 2005). Alternatively, an on-chip vacuum packaging can enable required performance characteristics even at larger contact resistance

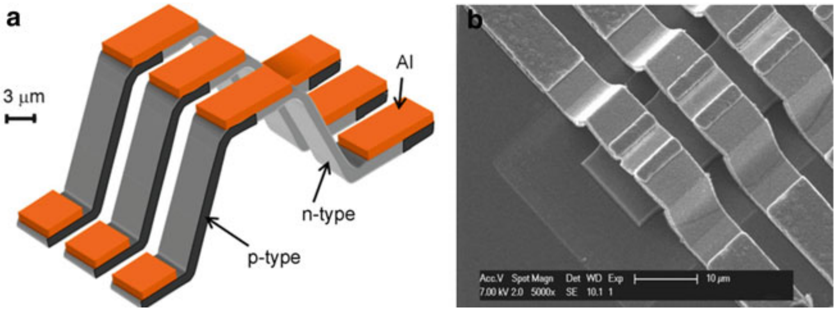

Fig. 2.14 Surface micromachined arcade thermopile. (**a**) The conceptual design of a thermocouple. Three thermocouples are shown. (**b**) An SEM picture of a poly-SiGe thermopile test structure with a 6 µm topography and a critical dimension of 3 µm (reproduced from Su et al. 2010 with permission from Elsevier)

(Xie et al. 2010). To obtain performance characteristics shown in Fig. 2.13b, a film technology for BiTe materials still must be developed. Thick-film BiTe processes have already been demonstrated (Böttner et al. 2004; Snyder et al. 2003). In the near future, thermoelectric properties of film-based BiTe are expected to approach those of bulk materials, but this is not an easy technological task.

Miniaturizing of thermopiles offers a potential for essential reduction of the fabrication cost. The expected production cost of micromachined thermopiles is by a factor of 100–1,000 less than the cost of today's thermopiles on the market because only 1–2 mm^2 of the wafer is required for a compact wearable TEG. A film-based thermopile on a polymer tape could require several square centimeters of the tape, a hundred times larger area. However, the low cost of thick-film and inkjet technologies, and the tape itself could result in a low cost, too. Therefore, wearable thermopiles can be very competitive on cost with the batteries in mass production.

2.9 Conclusions

The theory of a wearable TEG shows that a power of 10–30 µW/cm^2 can be produced for a typical person indoors. These values have been also practically obtained in different prototypes of wearable self-powered wireless sensor nodes powered either thermoelectrically or by using hybrid thermoelectric-PV generators. The evolution of body-powered devices during 6 years of their development indicates that only low-power applications, i.e., those consuming below 1 mW, can be unobtrusively powered indoors by using human body heat. This means that practically none of medical devices existing on the market can be turned into self-powered ones. On the other hand, it has been shown that most of the wireless health monitoring and medical devices can work at a power of less than 1 mW with no loss in the signal quality. Further miniaturizing energy scavengers can be done in case of electronics with less power consumption and with lower power radio. The related research is ongoing worldwide. A simple wireless sensor consuming 10 μW has already been demonstrated (Pop et al. 2008). Such sensor can be powered by a very small TEG, because only 1–3 cm^2 of the human body area is needed to get the required power. However, to obtain a voltage of at least 1–2 V in such a small TEG, film-based miniaturized thermopiles must be developed. In the near future, an optimized wearable TEG is expected to outperform any existing battery of the same weight in less than 1 year of its use. A possibility of low-cost fabrication technology and green energy are also very attractive features of the discussed devices. Therefore, a TEG can become a good candidate for serving as a lifetime power supply for low-power wearable electronics in the near future.

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