'Smart Clothes' Self-Powered by Body Heat

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Summary

We report on the structure and function of miniaturized thermoelectric generators (in brief ‘thermogenerators’), possible applications and their integration into smart clothes. Several different types of these devices are investigated in order to compare their suitability for conversion of body heat into electrical energy. Thermographical analyses have been performed to locate areas of the dressed human body which provide satisfactory high temperature differences. We present a novel, specifically designed way of implementing the generators into textiles with regard to an optimized thermal coupling. In order to show the potential of these battery-free self-powering smart clothes, several selected systems out of a variety of imaginable future applications will be discussed.

Introduction

'Smart Clothes' are an effort to make electronic devices a genuine part of our daily life by embedding entire systems into clothing and accessories. This level of permanent and extensive data access will be revolutionary for the fields of communication, information, security, and health care. On one hand, to make this vision become reality, the presently available hardware must be further reduced in size and energy dissipation. On the other hand, the users of these embedded devices want to be more independent of power supply systems. Therefore, we strive for more convenient power supplies. Since the user produces energy as body heat in the order of several 10 watts, it is obvious to try and harness part of this energy. Miniaturized thermogenerators can exploit temperature differences between the surface of the human body and its environment by converting the heat flux into electrical energy. In many respects thermogenerators show favorable properties compared to batteries: they are washable, robust, consist of environmentally friendly materials and possess a virtually unlimited lifetime.
However, for many years thermogenerators have been restricted to niche applications such as power supplies for space missions [1]. With increasing efficiency of the thermoelectric materials, decreasing power consumption of microelectronic circuitry and reduced production cost, thermoelectric devices might now be heading for important breakthroughs.

Today battery-free wristwatches working on this principle are commercially available [2]. The energy consumption of the Seiko wristwatch is 1 microwatt with a driving voltage of 1.5 volts.

Striving for this direction, our goal is to evaluate different types of thermogenerators suited for comfortable integration into smart clothes. For this purpose, Infineon Technologies has created a novel micromachined thermoelectric generator chip ready for implementation [3] which has been significantly improved lately.

Furthermore, we care about application issues and therefore analyze the heat distribution of the dressed human body. The aim of this action is to find designated places for implementation of the devices. Locations of specific interest are close to the skin like wristbands, cuffs, collars, belts, jeans buttons, etc. In recent time, our team has built up skills and experience in textile integration of electric components to deal with challenges imposed by smart clothes.

Thermoelectric principle

Thermogenerators are electric circuits formed by so-called thermocouples. These consist of two dissimilar conducting or semiconducting bars joined at one end (see Fig. 1). Due to the thermoelectric Seebeck effect, a temperature difference between both sides of the thermocouple generates a voltage and hence an electrical current through an electrical consumer load. Large Seebeck effects are found in semiconducting materials like silicon followed by metals such as nickel and chrome [4]. A thermogenerator is composed of a large number of thermocouples that are electrically connected in series and arranged in meanders to make best use of a given area (see Fig. 2). In this way, a high total voltage and electrical output power is produced. An efficient thermoelectric generator should be built up of materials that possess a large Seebeck effect, a low electrical resistivity and a low thermal conductivity. From this point of view, silicon is a better thermoelectric material than metals. Even more promising are compound semiconductors such as bismuth tellurides because of their even lower thermal conductivity [5]. However, as these high-end semiconductors are non-disposable, difficult to produce and not compatible with standard silicon chip fabrication processes they will probably not be accessible to low cost applications in clothes.

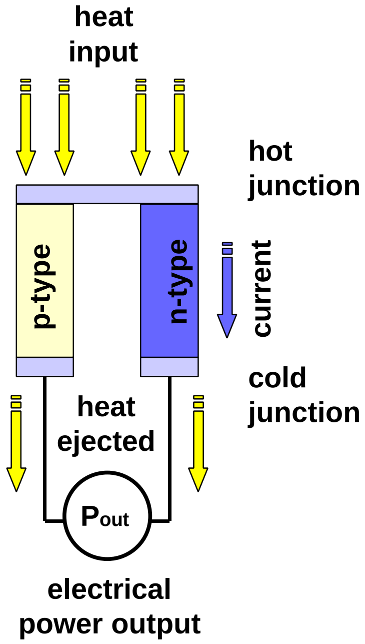

Fig. 1. Principle idea of a thermocouple.

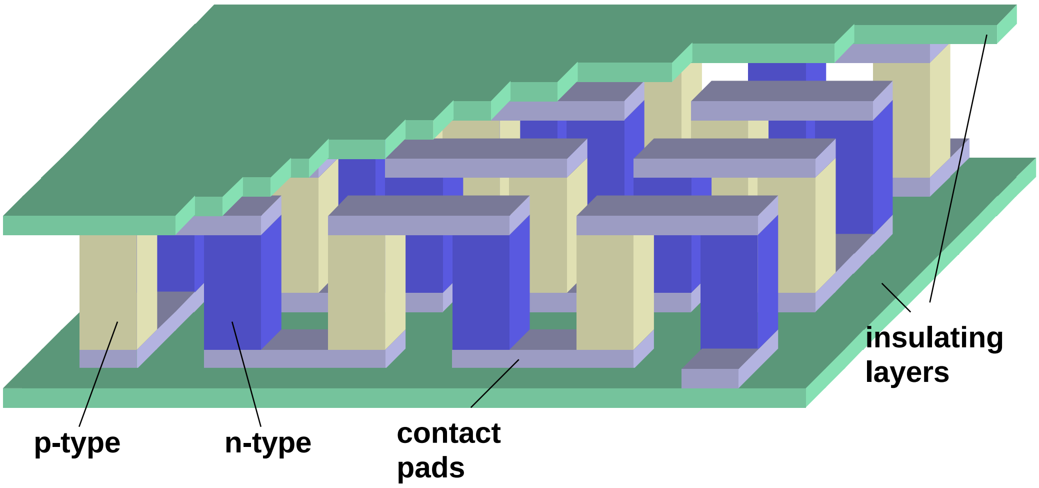

Fig. 2. Schematic view of a thermogenerator that consists of n- and p-type thermoelectric legs.

For a temperature drop of 5 °C across the device, the novel silicon-processed Infineon thermogenerator chip produces an electrical output power of 1.0 microwatt per cm^2 under load and an open circuit voltage of 10 volts per cm^2. These values are in the range suitable for application in wristwatches (see above). For comparison, a thermogenerator previously presented by the company D.T.S. [6] generates an electrical output power of 1.5 microwatts per cm^2 and an open circuit voltage of 3 volts per cm^2. This device is made from laminated foils of high-end compound semiconductors. As can be seen from these numbers, the choice of silicon does not necessarily mean a major loss in efficiency but certainly leads to gains in fabrication ease and cost.

To conclude, the desired type and size of a thermogenerator powered by body heat will depend on the power consumed by the application and furthermore on an attractive price.

Temperature differences in clothes

Obviously, at arctic temperatures high temperature differences appear between the outside and the inside of our clothes. However, for a reliable and constant power supply we consider temperature profiles at moderate ambient temperatures on a person wearing thin textiles. Moreover, we need to know how the temperature is influenced by transpiration, especially for self-powered electronic equipment carried during sporty activities.

We performed investigations, on a female and a male test-person. Those were equipped with sensors for temperature and dampness directly on their skin at the wrist, breast, waistline and forehead. These regions of the body can easily be equipped with thermogenerators placed within the clothing. For the clothing of the male person we chose a cotton T-shirt, polyester slacks, a pulse monitoring device and a polyester cuff with implemented thermogenerator. The female test-person wore a bike dress, featuring a conventional polyester T-shirt and a windblocker vest. Before the test, sample thermogenerators had been implemented into her polyester bike shorts, cuffs and a polyester headband. The values of the sensors were monitored regularly during the test.

Infrared images of the test-persons were taken at an ambient temperature of 15 °C before and after a light workout (Fig. 3, Fig. 4). To summarize the results: after the workout, the skin temperature decreased by approx. 1-2 °C in all regions covered with textiles. When exposed to air, the skin temperature dropped by approx. 4 °C below the initial temperature due to sweating. The temperature differences between skin and clothes varied between 2 and 17 °C. Comparatively small temperature differences were detected at the wrists (4-6 °C) which generally show a low skin temperature. In contrast, at the neck region, which shows a very high skin temperature, the collar of the windblocker vest leads to a temperature difference of 17 °C making this region very attractive for power generation.

In general, our investigations show that temperature differences of at least 5 °C can be achieved at moderate ambient temperatures within the clothes in touch with the skin. The temperature differences determined by the implemented thermogenerators correspond well with the values measured through the infrared analysis.

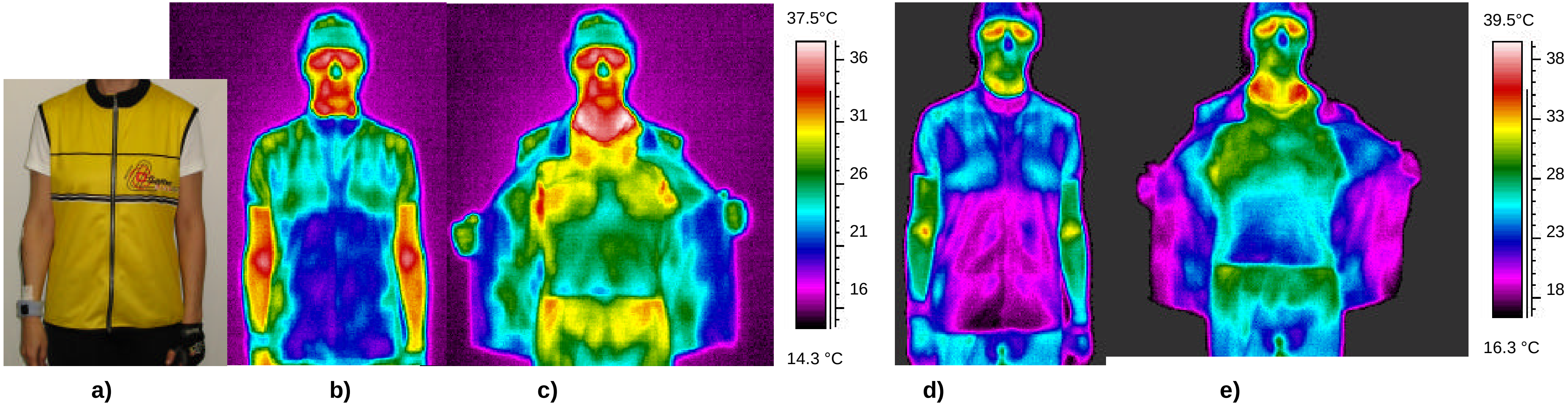

Fig. 3. Bike wear on a female test-person: polyester T-shirt, windblocker vest and polyester bike shorts, a) photograph, b) thermographical image with closed windblocker vest, c) thermographical image directly after opening the windblocker vest; d) and e) after light workout, the scale on the right gives the corresponding temperatures for the different colors; the ambient temperature is 15 °C.

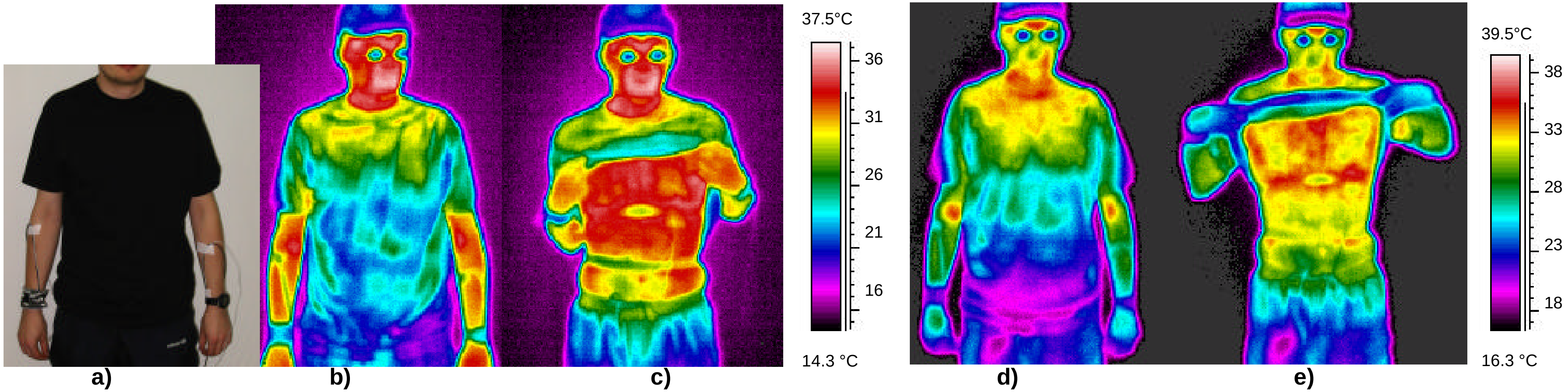

Fig. 4. Cotton T-shirt and polyester slacks on a male test-person: a) photograph, the attached sensors monitor skin temperature and dampness, b) thermographical image, c) thermographical image of the skin directly after lifting the T-shirt showing the temperature difference caused by the pulse sensor at the breast and the attached sensors for temperature and dampness at the waistline, d) and e) after light workout; the scale on the right gives the corresponding temperatures for the different colors; the ambient temperature is 15 °C.

Implementation of thermogenerator systems

In order to gain a high temperature difference the generators are integrated directly within the fabric of the clothes with good thermal contact to the skin. Fig. 5 shows the schematic cross-section of an integrated thermogenerator. For coupling to the outside world small copper plates are placed both at the warm and cold ends utilizing the high thermal conductivity of this metal. Irritation and discoloration of the skin are avoided by silver or gold plating. The thermogenerator is encapsulated using polyurethan. The electrical contacts are formed by interconnects to silverplated copper wires, which are interwoven within the textile. A buffer capacitor for storing the generated energy can be integrated directly into the power generation device or in a separate region of the clothes. Fig. 6 shows a photograph of the silverplated outside of the thermogenerator integrated into an elastic band that ensures a close contact to the skin.

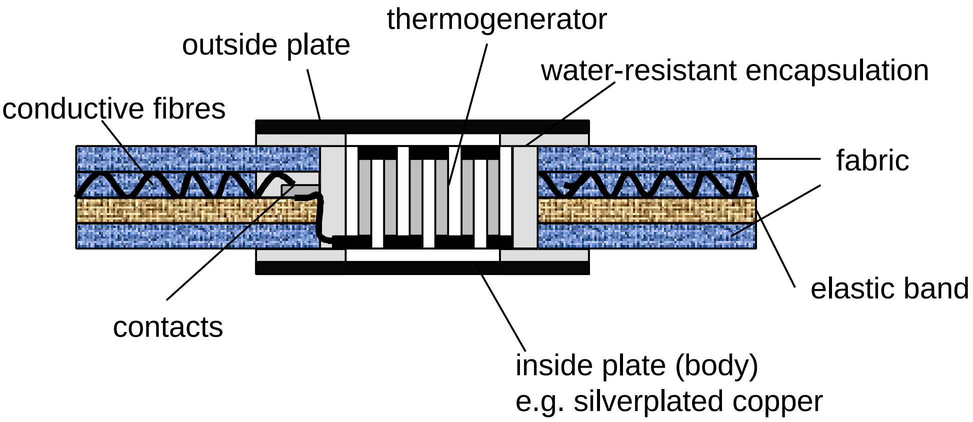

Fig. 5. Schematic cross-section of a thermogenerator integrated into fabric with water-resistant encapsulation.

Fig. 6. Outside plate of an integrated thermogenerator, suited for an active area of 1 cm².

Possible applications

Thermogenerators have a wide variety of potential applications in smart clothes. Wristwatches have a power dissipation of approximately 1-10 microwatts. A power output of 100-300 microwatts is sufficient for powering medical sensors (e.g. temperature, dampness or heartbeat sensors) and transmitting the data in a wireless way to a monitoring device. This can give at-risk patients more freedom from stationary devices and cables. Nearly the same power is needed for novel high-tech hearing aids which can save a lot of money compared to the use of batteries. With decreasing power dissipation of new generations of microprocessors and displays, body-heat powered personal assistant devices appear feasible in future.

Conclusion

Several kinds of recently published miniaturized thermogenerators are suitable for power generation in the temperature regime of the human body. Silicon-based thermogenerators have the advantage of being a low-cost energy supply and consisting of environmental friendly material. At given temperature differences within the clothes of 5 °C, an output power of several microwatts per cm² is achievable. Thermogenerators on this technological basis when integrated into fabrics show full functionality. The generated power is sufficient for supplying medical sensors and microelectronic circuitry. Wireless data transmission is possible by using larger active areas.

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