Thermoelectric micro converter for energy harvesting systems

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***Abstract* - This paper presents a solution for energy microgeneration through energy harvesting by taking advantage of temperature differences that are converted into electrical energy using the Seebeck effect. A thermoelectric micro converter for energy scavenging systems that can supply low-power electronics was fabricated using thin-films of bismuth and antimony tellurides. Thin-films of a n-type bismuth (Bi_2Te_3) and p-type antimony (Sb_2Te_3) tellurides were obtained by thermal co-evaporation with thermoelectric figure of merit (*ZT*) at room temperature of 0.84 and 0.5, and power factors, $PF\times10^{-3}$ [$WK^{-1}m^{-2}$], of 4.87 and 2.81, respectively. The films were patterned by photolithography and wet-etching techniques. The goal for this thermoelectric micro converter is to supply individual EEG modules composed by an electrode, processing electronics and an antenna, where the power consumptions ranges from cents of μW to a few mW. Also, these wireless EEG modules allow patients to maintain their mobility while simultaneously having their electrical brain activity monitored.**

***Index Terms* - Energy harvesting, renewable energy sources, thermoelectric scavenging systems, microgeneration.**

I. INTRODUCTION

IN the present days, there is an increased interest in renewable sources of power, specially in applications that require high power levels [1-4]. There is also an increasing interest of ubiquitous electronic devices in the everyday life. Also, the complexity and the requirements of these devices do not know limits. The use of batteries can not be enough to ensure an uninterruptible working cycle. Thus, the association of such devices with the use of some kind of energy recovering system can reveal an interesting approach [5]. Energy scavengers are currently emerging for a number of applications from biomedical to automotive [4,6]. Typically, one can distinguish between two types of energy scavengers, e.g., macro-energy scavengers that are typically in the cm^3 range, and micro-energy scavengers that are typically in the mm^3 range and manufactured using micromachining techniques. Micro-energy scavengers are small electromechanical devices which harvest ambient energy and convert it into electricity [7]. Energy scavengers could harvest different types of energies. The solar energy can be harvested and stored by means of photovoltaic solar cells with a charge-integrating capacitor for periods of darkness [8], mechanical energy can be harvested with piezoelectric or electrostatic converters [9], electromagnetic energy can be harvested through radio-frequency resonators [10], and finally thermal energy can be harvested with thermoelectric generators [11].

The majority of the micro-energy scavengers are still in research and development phase. However, thermoelectric were the first one to appear in the market [7]. This was due to the easiness to fabricate these devices with solid-state technology and because they are based on a well established physical theory. In 1822, Seebeck noticed that the needle of a magnet is deflected in the presence of dissimilar metals that are connected (electrically in series and thermally in parallel) and exposed to a temperature gradient [11,12]. The effect observed is the basis for thermoelectric power generation. As illustrated in Figure 1, if the junctions at the bottom are heated and those at the top are cooled (producing a temperature differential), electron/hole pairs will be created at the hot end and absorb heat in the process. The pairs recombine and reject heat at the cold edges. A voltage potential, the Seebeck voltage, which drives the hole/electron flow, is created by the temperature difference between the hot and cold edges of the thermoelectric elements. The net voltage appears across the bottom of the thermoelectric element legs.

The efficiency optimization of these converters needs thermoelectric materials that are simultaneously good electric conductors to minimize Joule heating, poor thermal conductors to retain the heat at the junction, the Seebeck effect must be maximized, in order to produce the required voltage [13]. It exists a trade-off when a simultaneously optimization of these three properties is pursuited. The simple fact the electrons carry unwanted heat as well as electric current, will make the Seebeck effect to decrease when the electrical conductivity increases. The highest performance is obtained in the presence of heavily doped semiconductors, such as bismuth telluride or silicon germanium. In the case of semiconductors, the most desirable situation is when the base materials are both n- and p-doped in order to apply the same material system on both

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sides of the junctions [12]. Also, to be integrated in silicon microsystems, a thermoelectric generator must be small in size, light in weight and to have silicon compatibility. Thin-film generators are the most suited for microsystems application since they give the advantage of obtaining modules with minimum size and weight [13].

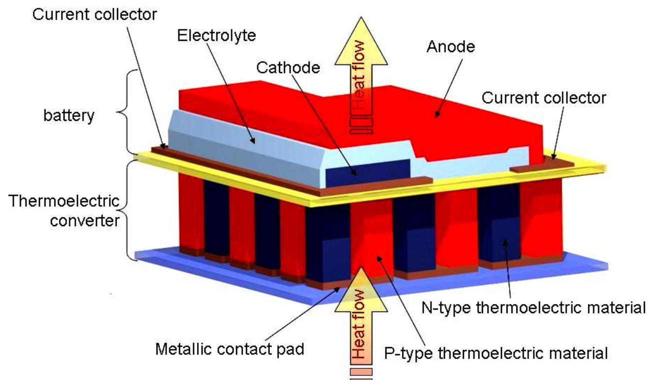


Fig. 1: Artwork of a thermoelectric microsystem. When the heat flows across the junction, a electrical power current is generated by the Seebeck effect. Practical thermoelectric generators connect large number of junctions in series to increase the operating voltage.

The integration of efficient solid-state thermoelectric micro converters with microelectronics is desirable for local cooling and thermoelectric microgeneration, since they can be used to stabilize the temperature of devices, decrease noise levels and increase operation speed. Also, microthermoelectric generators can be used in a lot of small low-power devices such as hearing aids or wrist watches. This has been showed by Seiko and Citizen with their commercialised thermoelectrically driven low-power wrist watches [14]. Despite the range of exciting applications, only few approaches to manufacture thermoelectric devices with small dimensions were reported up to now [14-17].

Due to silicon fabrication compatibility, polycrystalline SiGe alloys and polycrystalline Si are commonly used in thermopile applications. Their use in microcoolers has been attempted but the performance is very low, when it is compared with that of tellurium compounds, which have been used for many years in conventional large area cooling devices [18]. Tellurium compounds (n-type bismuth telluride, Bi_2Te_3 and p-type antimony telluride, Sb_2Te_3) are well-established room temperature thermoelectric materials and are widely employed by the industry, in conventional thermoelectric generators and coolers. Different deposition techniques were tried to obtain thin-films of these materials. Thermal co-evaporation, co-sputtering, electrochemical deposition, metal-organic chemical vapour deposition and flash evaporation are some examples. The fabrication of thermoelectric energy scavenging microsystems with tellurium alloys allows powering small electronic devices (up to units of mW) under temperature gradients below 10º C.

The performance of thermoelectric devices depends on the figure of merit (*ZT*) of the material [19], given by:

$$ZT = \frac{\alpha^2}{\rho\lambda}T \qquad (1)$$

where α is the Seebeck coefficient, ρ the electrical resistivity, λ the thermal conductivity and T the temperature.

In this paper, films with high figure of merit were deposited by co-evaporation and low-cost wet etching techniques were used to pattern thermoelectric micro converters. These micro converters were used in thermoelectric scavenging systems, to work as energy sources for low-powered devices such as micro sensor systems, where a temperature difference exists, between the two surfaces of the microgenerator.

II. Fabrication

Two different approaches can be used for on-chip integration of thermoelectric devices: transversal (crossplane) and lateral (in-plane), depending on the direction in which the energy is removed, relative to the surface of the device. In this work, lateral heat flow is addressed, due to its easier fabrication process and compliance with planar technology. Figure 2 shows the fabrication process of thermoelectric micro converters. The p-type Sb_2Te_3 film is deposited by thermal co-evaporation followed by a thin layer (100 nm) of nickel (a). The use of thin layers of nickel help to avoid diffusion of the thermoelectric material into the next deposited layers. The photoresist is spun and p-type elements are patterned by photolithography (b), (c). The nickel is etched in a chromium etchant (Transene 1020), a thermoelectric film is patterned by wet etching in HNO3:HCl (d) and photoresist is removed. The n-type film is then deposited by co-evaporation, followed by a 100 nm nickel layer (e). The photoresist is applied and patterned by photolithography for n-type element definition (f), (g). Nickel is etched in a chromium etchant (Transene 1020), the n-type film is etched in HNO3 (h) and photoresist is removed (i). Contacts are deposited, starting with a 100 nm layer of nickel, followed by 1 μm of aluminium (j). The photoresist is spun and contacts patterned by photolithography (k). Nickel is etched in a chromium etchant (Transene 1020), and aluminium with a standard aluminium etchant (Transene type A). The photoresist is removed (l). A protective layer of Si_3N_4 can also be deposited by low-temperature hotwire chemical vapour deposition (HW-CVD) and patterned if required, depending on the application.

A. Deposition of thin-films

Thermoelectric films were fabricated by the thermal co-evaporation technique (Figure 3) in a high-vacuum chamber (with a base pressure of ~1×10^{-6} Torr). Two large molybdenum boats (baffled boxes, with a volume of 4 cm^3) are used at the same time, one for each of the elementary materials required to produce the desired compound.

The power applied to each boat is controlled independently, using two computed proportional-integral derivative (PID) controllers [20] to maintain the deposition rate at user-defined constant values, during the deposition process. Two thickness monitors (quartz crystal oscillators) are carefully placed inside the chamber in such a way that each of them receives material only from the boat it is monitoring. A metal sheet is placed between the two boats, to prevent mixing the both materials to occur at the quartz crystal sensors. Substrates are heated to the temperature set point (T_{sub}) in the range of 150-270 ◦C.

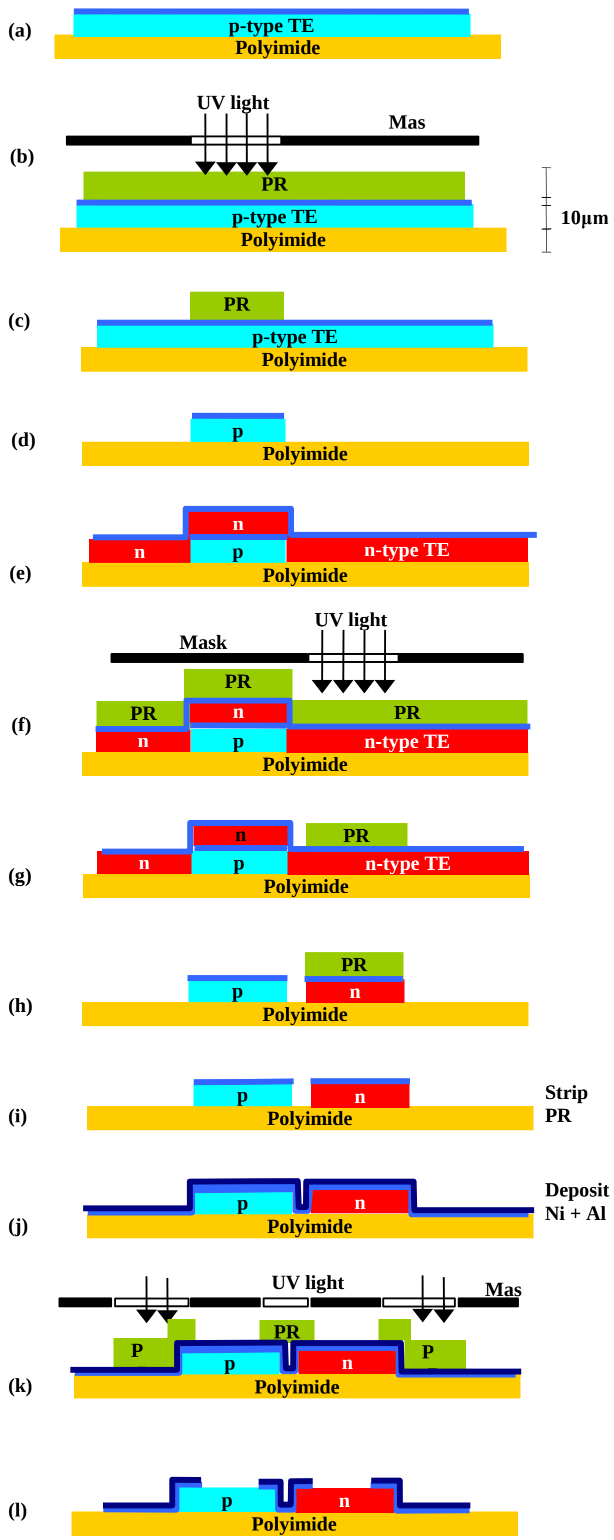
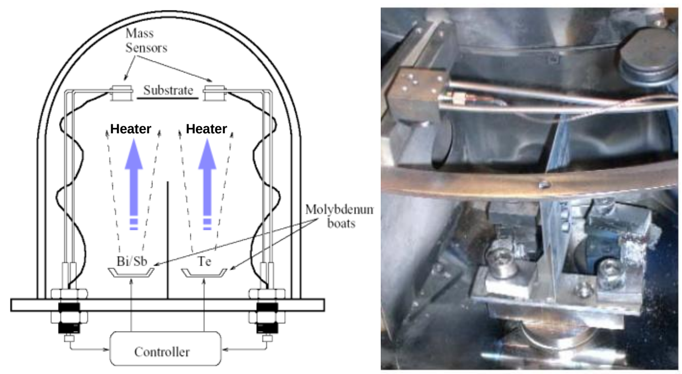


Fig. 2:Fabrication steps of the thermoelectric micro converter.

B. Patterning

Thermoelectric Bi_2Te_3 and Sb_2Te_3 thin films (1 μm thick) were deposited on the kapton substrate. Transene's PKP negative photoresist was applied on the surface and test structures were patterned by wet etching in the HNO_3:HCl:H_2O etchant (pure HNO_3 and 37% HCl diluted in water). Figure 4 shows a planar thermoelectric micro converter fabricated on top of a 25 μm thickness kapton foil. As depicted in that figure, the contacts can be deposited on top or bottom of the thermoelectric films. Since Bi_2Te_3 and Sb_2Te_3 adhesion is higher on polyimid (kapton) films than on nickel metal pads, the use of top contacts process (as presented in Figure 2) avoids the need of depositing additional layers to promote the adhesion of thermoelectric films.



a) b)

Fig. 3: (a) The co-evaporation system; (b) the boats and the mass sensors placed inside the co-deposition chamber.

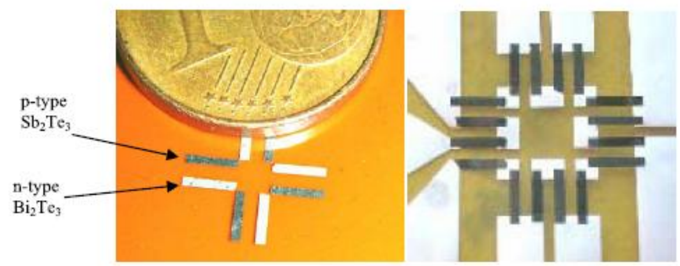


Fig. 4: Photography of n-type and p-type elements, before deposition of top contacts (left), and a photography of a thermoelectric micro converter with eight pairs of thermoelectric elements, fabricated with bottom contacts (right).

III. EXPERIMENTAL RESULTS

The in-plane film electrical resistance was measured using the conventional four probe van der Pauw method, at room temperature. The thermal conductivity was measured using the method proposed by Völklein [21]. The values 1.3 $Wm^{-1}K^{-1}$ and 1.8 $Wm^{-1}K^{-1}$ were obtained for the Bi_2Te_3 and Sb_2Te_3 films, respectively. The measurements of the Seebeck coefficient were made, by connecting one side of the film to a fixed temperature (heated metal block) and the other side to a heat sink at room temperature. Tables I and II show the results of these measurements in the selected samples of Bi_2Te_3 and Sb_2Te_3 films.

In the both tables, the first column lists the number of the selected sample, the second column contains the values of the

Seebeck coefficient, α, the third column has the electrical resistivity, ρ, of the films. The fourth column list the *PF* for the selected samples of Bi_2Te_3 and Sb_2Te_3, whose values were calculated using the following equation:

$$PF = \alpha^2 / \rho \quad [WK^{-1}m^{-2}] \tag{2}$$

It must be noted that behind the figure of merit (*ZT*), the power factor, *PF* [$WK^{-1}m^{-2}$] is perhaps the most important value in a thermoelectric converter and gives the electric power versus the area where the heat flow happens, plus the temperature gradient between the hot and the cold sides. Also, the tables I and II present the corresponding figures of merit (*ZT*), which were calculated from the equation (1).

TABLE I: PROPERTIES OF THE SELECTED SAMPLES OF Bi_2Te_3 FILMS.

Film	α [μVK^{-1}]	ρ [$\mu\Omega$.m]	$PF\times10^{-3}$ [$WK^{-1}m^{-2}$]	*ZT* @ 300 K
#1	-74	5.7	0.96	0.19
#2	-180	16.6	1.95	0.4
#3	-156	11.3	2.16	0.43
#4	-152	13.4	1.72	0.34
#5	-248	12.6	4.87	0.97
#6	-220	10.6	4.57	0.91

TABLE II: PROPERTIES OF THE SELECTED SAMPLES OF Sb_2Te_3 FILMS.

Sample	α [μVK^{-1}]	ρ [$\mu\Omega$.m]	$PF\times10^{-3}$ [$WK^{-1}m^{-2}$]	*ZT* @ 300 K
#7	91	7.6	1.09	0.22
#8	140	14.0	1.40	0.28
#9	156	9.2	2.66	0.53
#10	188	12.6	2.81	0.56

The in-plane electrical resistivity, carrier concentration and Hall mobility were measured at room temperature using the conventional four probe van der Pauw geometry. A DC magnetic field of 80 mT was applied for Hall measurements. The Seebeck coefficient, α, was measured by connecting one side of the film to an heated metal block at a fixed temperature and the other side to a heat sink kept at room temperature, with a temperature difference between both sides below 10 ºC. A spot of ≈5 mm×5 mm is considered for electrical properties. Thermal conductivity was measured using the technique developed in [21]. The measurements made in the selected samples showed an absolute value of the Seebeck coefficient in the range of 150-250 μVK^{-1}, and an in-plane electrical resistivity of 7-15 $\mu\Omega$m.

In a conventional thermoelectric element, the effect of the electrical contact in the interface with the metal is usually not taken into consideration, which is acceptable as the conctact between the two conductors is significantly smaller than the electrical resistance of the thermoelements [22]. The influence of electrical contact resistance cannot be disregarded in on-chip integrated thermoelectric devices, due to the size of the contact relative to the length of the thermoelectric converter [23]. For comparison, the contact area of a conventional thermoelement is in the order of 1×1 mm^2, while that of the integrated thermoelement is in the order of 10×10 µm^2 (i.e., an area reduction of 10^4). Electrical contacts are made at both the hot and cold junction of the device. Since the hot junctions are considered to be in direct contact with ambient, the Joule heat generated in these junctions is absorbed locally and does not affect the maximum temperature difference. However, Joule heat generated due to the electrical contact at the cold junctions has to travel trough the entire length of the device to reach the ambient [22]. The contact resistance between the thermoelectric material and the metallic contact was measured with the help of the Transmission Line Model (TLM) method [24]. The measurements showed for the n-type and for the p-type materials, a maximum contact resistivity of 2×10^{-7} Ωm^2 and 5×10^{-7} Ωm^2, respectively.

The measurements also showed for the Bi_2Te_3 and Sb_2Te_3 films, figures of merit (*ZT*) at room temperatures of 0.84 and 0.5, and power factors, $PF\times10^{-3}$ [$WK^{-1}m^{-2}$], of 4.87 and 2.81, respectively.

Using thermoelectric converters for human-body energy harvesting requires the generator thermal resistance to be matched to human-body and heat-sink thermal loads. Maximum voltage output is obtained when the thermal resistance of the thermoelectric legs is equal to the heatsink and human-body thermal resistances. A thermal resistance of 200 $KW^{-1}cm^{-2}$ is desirable in the thermoelectric micro converter. Since each thermoelectric junction of Bi_2Te_3-Sb_2Te_3 can deliver an output voltage of 300 μVK^{-1}, more than 4000 junctions are necessary to obtain an output voltage (without load) of 10 V, under a temperature difference of 10 ºC. Figure 5 shows the open-circuit voltage and power that can be obtained in a 1 cm^2 Bi_2Te_3-Sb_2Te_3 thermoelectric generator, when the length of columns up to 10 mm. Maximum power output is obtained with column length of 4 mm.

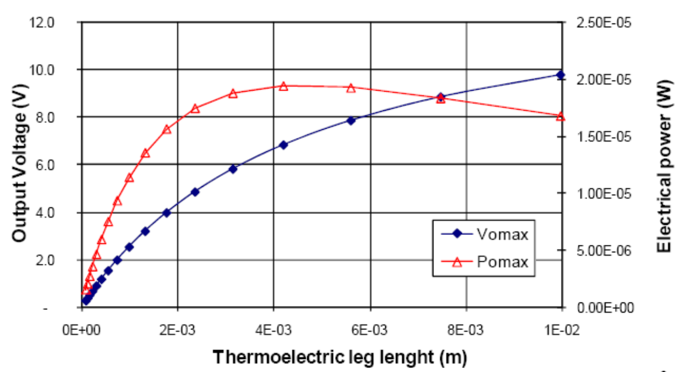


Fig. 5: Open-circuit output voltage and power of a 1 cm^2 Bi_2Te_3-Sb_2Te_3 thermoelectric generator, plotted as function of length of column.

IV. APPLICATIONS

Energy harvested wireless sensors must be powered in a peak basis because a temperature gradient could not always be present, thus the energy must be stored in a capacitor (*storage capacitor*) for later use by the electronic system to be powered [9], or in a rechargeable microbattery of Li-ion type (integrated in the system) [25]. In both cases, ultra-low power electronics performs DC-DC rectification with a variable conversion factor. Figure 6 shows a simple step-up converter. The step-up conversion is made with the help of the capacitor C_{up} and the inductor L_{up}. The current at the output of the thermoelectric micro device charges this capacitor, then the switch SW is systematically closed and open, with a high frequency. However, it remains closed during a very short time in order to reduce the losses. In order to meet this requirement, the command signal must have a very low duty-cycle to avoid the over-discharge of the capacitor C_{up}. When SW opens, the stored energy in the inductor L_{up} forces the capacitor C_{up} to discharge through the diode D, e.g., a DC rectification is present. Then, the current charges the high-charge-capacity capacitor, C_{store}, which further connects to a DC regulator.

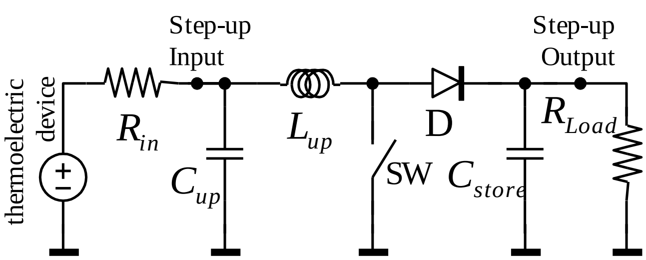


Fig. 6:Schematic of a simple step-up circuit.

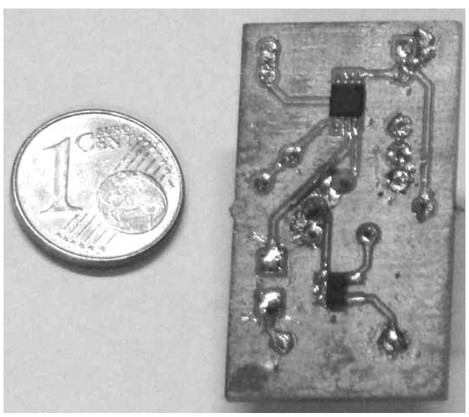


Fig. 7: A photography of the charge-pump, followed by the step-up.

Because the target goals for the proposed thermoelectric micro converter are biomedical applications, a more compact solution for the power circuit is mandatory. Using discrete but still compact solution it was mounted a first circuit prototype to make the step-up conversion [5]. Figure 7 shows such circuit, which is composed by a charge-pump (CP) followed by a DC-DC step-up converter. When the voltage at the output of the thermoelectric device rises above a certain value (in this circuit, the chosen voltage was 300 mV), the CP activates an output pin that will activate the DC-DC step-up circuit. In this situation, a short circuit is established between the thermoelectric device and the input of the DC-DC step-up. Then, the step-up puts a regulated IC-compatible voltage to supply the electronics. The measurements made in this prototype showed that when the voltage at the output of the thermoelectric micro device crosses above 300 mV, then the output of CP will enable the step-up which will rise the voltage up to 3 V.

A. *Wireless EEG as a biomedical application*

Temperatures ranging from 27 ºC to 36 ºC can be found on different parts of body. However, higher temperature gradient in relation to the ambient, is found in the forehead and nose. The standard wireless EEGs (electroencephalogram) use a braincap with wires running from the electrodes position to a bulky central unity (amplification, signal filtering and analog-to-digital conversion) [26]. A more interesting solution is to use compact wireless EEG modules, where the electronics, the antenna and each electrode are mounted together. The power supply of such modules is obtained locally from the thermoelectric generator. This solution allows to integrate additional electronics (amplification, filtering and high-resolution digital conversion), for local signal processing inside these small-size individual wireless EEG modules.

It is possible to use either bipolar or unipolar electrodes in the EEG measurement. In the first method the potential difference between a pair of electrodes is measured, but an electrode placed in a reference position is needed for all modules. In the second method, the potential of each electrode is compared, either to a neutral (the reference) electrode or to the average of all electrodes.

Figure 8 shows the full block diagram of the wireless EEG module and the thermoelectric module, where it can be seen the electrode connected to an amplifier, followed by an analog-to-digital converter (ADC). In order to meet the EEG specifications, the amplifier was designed to have enough gain, to amplify signals with amplitudes of only 70 μV. The ADC must have at least a resolution of 22 bits and a minimum sampling frequency of 2000 Hz.

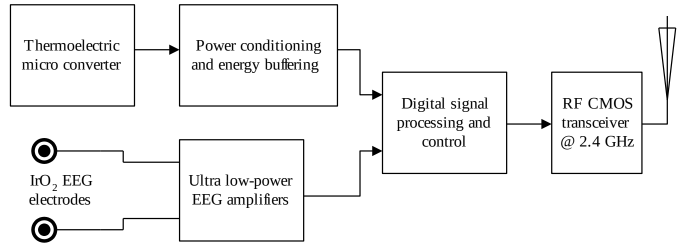


Fig. 8:The system architecture behind the wireless autonomous EEG system powered by the body heat recovered with the proposed thermoelectric micro converter.

Plug-in-play wireless EEG modules were previously demonstrated by the authors [27]. In this work, a thermoelectric generator with charge-pump and DC-DC conversion is proposed. Figure 9 shows an artist impression of the thermoelectric scavenging system and an wireless EEG module, both attached to a cap (the zoomed part in that Figure). The temperature gradient between forehead and the environment will generate energy in the thermoelectric micro device to supply the modules.

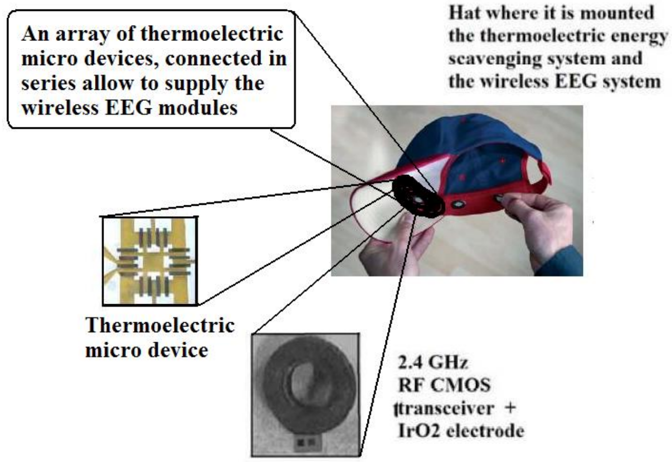


Fig. 9: A sketch of the thermoelectric scavenging system with an wireless EEG module.

V. Conclusions and Future Work

This paper presents a thermoelectric micro converter to supply low-power electronics, where the power consumption ranges from cents of μW to a few mW. The micro converter is made of thermoelectric structures based on thin-films of n-type bismuth telluride (Bi_2Te_3) and on p-type antimony telluride (Sb_2Te_3). The measurements showed that the deposited films present thermoelectric properties comparable to those reported for the same materials in bulk form, as is the case of the materials used in conventional macro-scale Peltier modules. The absolute values of the Seebeck coefficient are in the range of 150-250 μVK^{-1} and the in-plane electrical resistivity is in the 7-15 μΩm range. The measurements also showed for the Bi_2Te_3 and Sb_2Te_3 films, figures of merit (*ZT*) at room temperatures of 0.84 and 0.5, and power factors, $PF\times10^{-3}$ [$WK^{-1}m^{-2}$], of 4.87 and 2.81, respectively. The proposed converter uses the Seebeck effect for doing the thermoelectric conversion, using microsystems techniques and suitable to be integrated with electronics. Target applications for this thermoelectric micro converter include the wireless EEG and uses the temperature gradient between the ambient and the forehead to supply the wireless modules.

Future research pursuits the operation from low temperature gradients (a minimum temperature difference of 3 ºC between ambient and thermo-source must provide an IC-compatible voltage). Today, the best commercial thermoelectric modules (made of Bi, Sb and Te compounds) have *ZT* of one, despite many approaches to find compounds with high performance. In conventional 3D crystalline systems it is difficult to control each of the following are interrelated factors to improve *ZT* [28], e.g., the Seebeck voltage per unit of temperature, the electrical conductivity, and the thermal conductivity. This means that an increase of the Seebeck voltage per unit of temperature, usually results in a decrease of the electrical conductivity. Moreover, a decrease of the electrical conductivity leads to a decrease of the electronic contribution to the thermal conductivity, following the Wiedemann–Franz law. However, if the dimensionality of the material is decreased, the new variable of length scale becomes available for the control of materials properties, due to differences in the density of electronic states. Recent work with BiSbTe superlattices demonstrated an enhancement in the *ZT* to about 2.4 [29] and 1.4 [30]. Thus, thermoelectric micro devices with high figures of merit, based on superlattices, are the key to generate power from low-temperature gradients for biomedical applications.

In the future research, both Hot-wire Chemical Vapour Deposition (HW-CVD) and sputtering deposition systems will be used to build nanostructured superlattices. Both techniques allow a reduced substrate temperature, essential to reduce interdiffusion of layers. It is also possible to deposit amorphous, nano-crystalline or micro-crystalline films.

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