A HUMAN-BODY THERMOELECTRIC ENERGY SCAVENGING MICROSYSTEM

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Abstract — *A thermoelectric energy scavenging microsystem is proposed, optimized to convert the small thermal power available in human-body applications. A Lithium solid-state thin-film battery is integrated in the same device as well as the ultra low-power electronics to charge battery and perform DC-DC conversion.*

Key Words: *Thermoelectric microsystems, energy scavenging, generator, telluride.*

I INTRODUCTION

Autonomous micro-generators are in demand for a wide range of applications. In this work, a human-body thermoelectric generator is proposed, capable of supply power to a wireless sensor network node, using the temperature difference between human-body and ambient temperature. Thermoelectric materials have been used from many years in generators and coolers as large scale devices. In the recent years, an effort has been done in the fabrication of microscale thermoelectric devices [1], using microsystems technology (thermoelectric thin-films deposition and pattern by photolithography). A few of these microdevices are proposed to work as generators, but their output voltage is very low since they were not optimized for human–body applications, where a small temperature different and a high thermal resistance are expected. The use of this kind of devices in human-body thermoelectric generators requires optimization of device thermal resistance to match the human thermal load output. Moreover, any of these devices includes a rechargeable battery, voltage-control and charge-control microelectronics, all in the same device. The maximum output power achieved in a thermoelectric device and ensuring a comfortable wearing device cannot exceed some teens of microwatts per square centimeter. Since many wireless sensors are powered in a peak basis, energy will be stored in the rechargeable battery. Ultra-low power electronics performs DC-DC conversion and charge the battery with maximum efficiency.

II EXPERIMENTAL

The basic cell of a thermoelectric micro-generator is composed of two thermoelectric column (n-type and p-type), as shown on Fig 1.

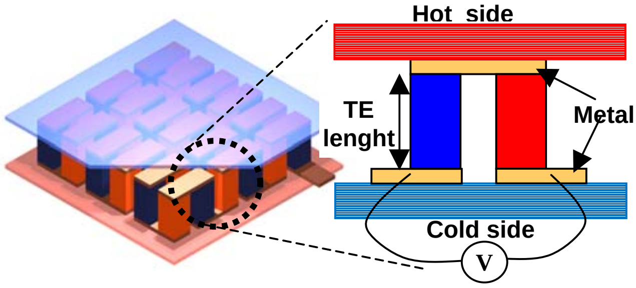

Fig 1: Artwork of a thermoelectric generator.

Each p-n thermoelectric pair can generate 300 μV/K. Larger output voltages are obtained when all the junctions are connected in series. A large number of p-n pairs per cm^2 can be obtained by reducing the cross sectional area of each column, but electrical resistance of the generator is also increased, thus reducing the available current. Available electrical power per cm^2 is not affected by this reduction. High-power output can be obtained reducing the length of the column. This reduction implies reducing the thermal resistance of the device, and larger thermal load is required to the hot and cold bodies, to maintain the temperature difference.

Human-Body Model

Previous works [2,3] has demonstrated the maximum amount of thermal energy that can be removed from human-body in a wearable thermal-generator without compromising the comfort, and maximizing the thermoelectric conversion. A thermal resistance of 100-300 $K/W/cm^2$ is expected in the wrist, where thermal flow can be converted with a thermo-bracelet. Also, temperatures between 27 ºC and 36 ºC can be found on different parts of body. Fig 2 shows a typical temperature map of a hand [4]. The ambient air temperature and thermal-converter to air thermal resistance also limits the maximum power available. Thermal resistance bellow 50 K/W/cm^2 can be achieved with a pin-heatsink.

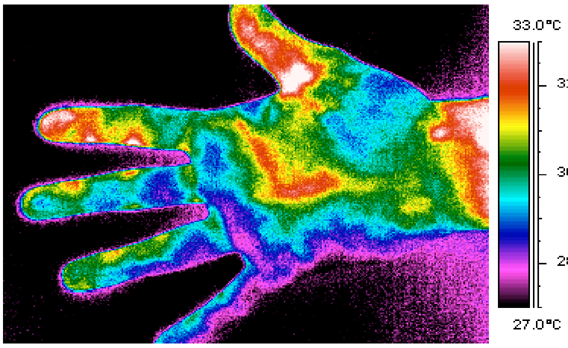

Fig 2: Hand temperature obtained by thermal imaging [4]

Simulation

Maximum voltage output is obtained when the thermal-resistance of the thermoelectric legs is equal to the human-body and heatsink thermal resistance. A thermal-resistance above 200 K/W/cm^2 is desirable in the thermoelectric converter. Since each thermoelectric junction of Bi_2Te_3-Sb_2Te_3 can deliver an output voltage of 300 μV/K, more than 4000 junctions are necessary to obtain an output voltage (without load) of 10 V, under a temperature difference of 10 ºC, when body and heatsink thermal resistances are considered. Fig 3 shows the open-circuit voltage and power that can be obtained in a 1 cm^2 Bi_2Te_3-Sb_2Te_3 thermoelectric generator, as function of length of the column.

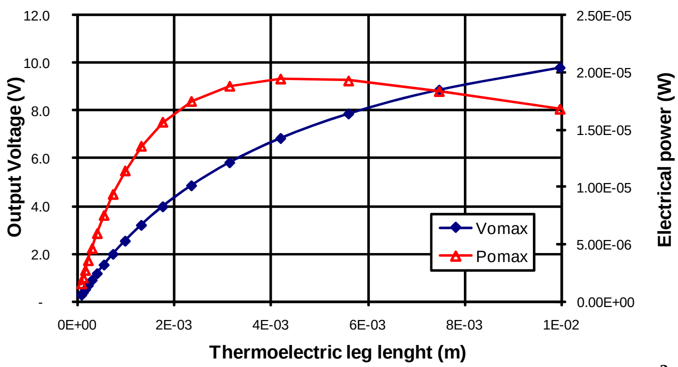

Fig 3: Open-circuit output voltage and power of a 1 cm^2 Bi_2Te_3-Sb_2Te_3 thermoelectric generator, plotted as function of length of column.

Fig 4 shows the temperature map of a single junction (2 thermoelectric elements) with the hot side in contact with the human-body (30 ºC, 150 K/W/cm^2) and the cold side kept at air (20 ºC) with a 50K/W/cm^2 heatsink, obtained with FEM simulation tool. The temperature difference of 5 ºC is obtained between the junctions (27 ºC at hot-side and 22 ºC at cold-side).

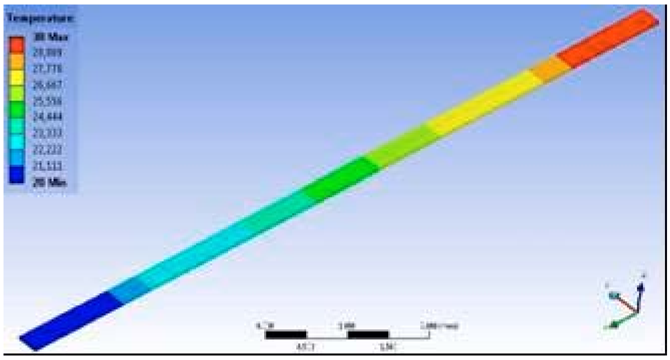

Fig 4: Temperature map of a thermoelectric pair in contact with body, obtained by FEM.

Thermoelectric Thin-Films

Bismuth telluride and antimony-telluride alloys are well-established thermoelectric materials for operation at room temperature, widely used in thermoelectric industry (macro-scale conventional Peltier modules), since they have a high Seebek coefficient (α), low electrical resistivity (ρ) and relatively low thermal conductivity (λ), at room temperature (T). The thermoelectric performance of thermoelectric materials is quantified with figure-of-merit (ZT) and power-factor (PF):

$$PF = \alpha^2 / \rho \qquad \textbf{Eq. 1}$$

$$ZT = \frac{\alpha^2}{\rho\lambda} T \qquad \textbf{Eq. 2}$$

Thin-films of these materials, with high figure-of-merit were fabricated by thermal co-evaporation. The precise control of the substrate temperature and deposition rate of each element of the compound (Bi, Sb, Te), during the deposition process, allows the fabrication of films slightly rich in tellurium, with a polycrystalline structure and figures-of-merit of 0.9 and 0.4 can be obtained, respectively in Bi_2Te_3 and Sb_2Te_3 films [5,6]. Fig 5 and fig 6 shows the influence substrate temperature and film-composition in the thermoelectric power factor, respectively for Bi_2Te_3 and Sb_2Te_3 films.

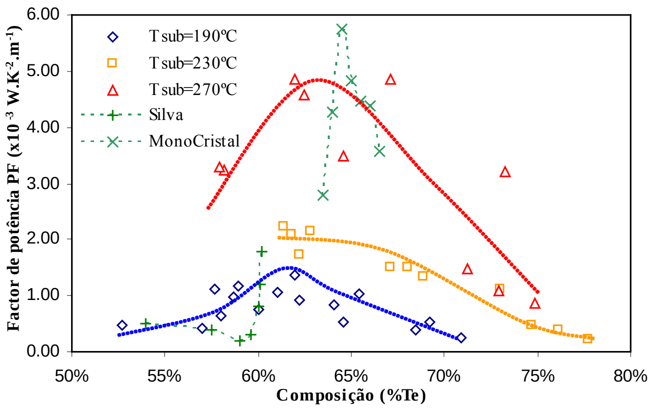

Fig 5: Power factor of Bi_2Te_3 films, as function of composition and substrate temperature. Results from literature [7] and from monocrystal [8] are also presented, for comparation.

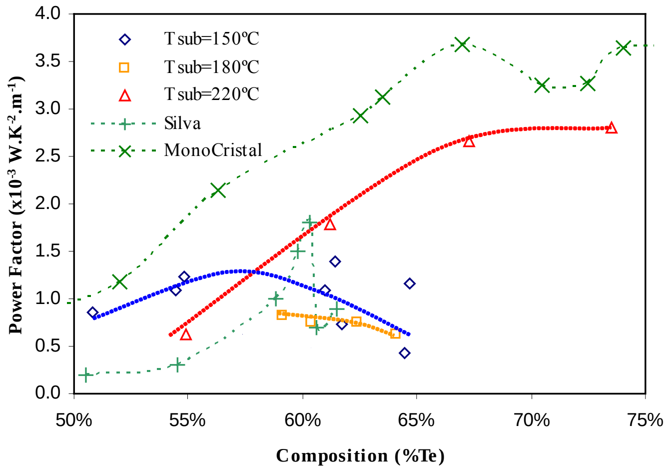

Fig 6: Power factor of Sb_2Te_3 as function of composition and substrate temperature. Results from literature [7] and from monocrystal [9] are also presented, for comparation.

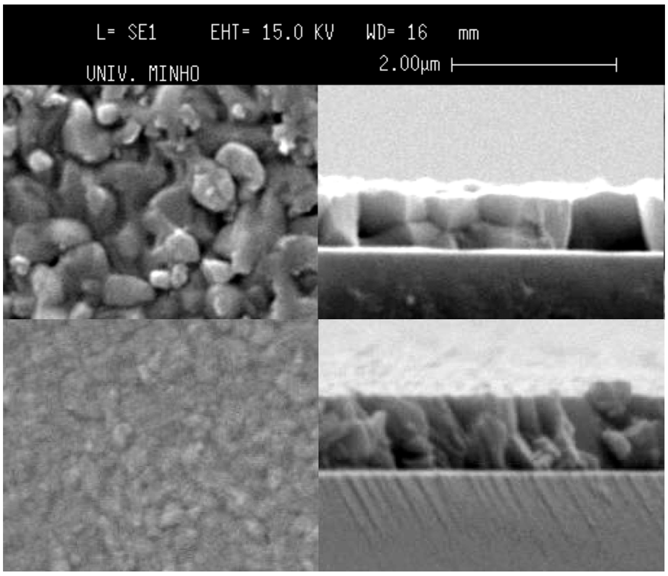

Fig 7: SEM top view (left) and cross-sectional (right) images of Bi_2Te_3 (top) Sb_2Te_3 (bottom) thin-films.

Battery

DC reactive sputtering technique was used in the deposition of thin-films to fabricate the solid-state lithium battery. The battery uses SnO_2, Lipon and $LiCoO_2$ materials respectively in the anode, electrolyte and cathode. SnO_2 have a maximum theoretical charge-storage capacity of 781 mAh/g and $LiCoO_2$ anode have a specific capacity of 140 mAh/g, with voltages between 3 V and 4.2 V. Lipon is sputtered from Li_3PO_4 target in N_2 plasma. The Lipon electrolyte has exceptional electrochemical stability and good Li^+ ion conductivity (2×10^{-6} S/cm). The self-discharge of the battery is ensured with the high electronic resistivity of the Lipon (10^{14} Ωcm).

Microelectronics

Ultra-low power electronics performs DC-DC rectification with a variable conversion factor and recharge the battery. The circuit depicted in Fig. 8 makes the step-up conversion, with the help of the capacitor C_{up} and the inductor L_{up}. This capacitor is charged with the current absorbed from the thermoelectric device, then the switch SW is systematically closed and open, with a fast frequency. However, it remains closed by a very short time, thus, the command wave must have an extremely low duty-cycle, in order to avoid the over-discharge of the capacitor C_{up}. When it is open, the energy stored in the inductor L_{up}, forces the capacitor C_{up} to discharge through the diode D, which also makes a DC rectification. Then, the current charges the high-charge-capacity capacitor, C_{store}, which further connects to a circuit that performs a DC regulation.

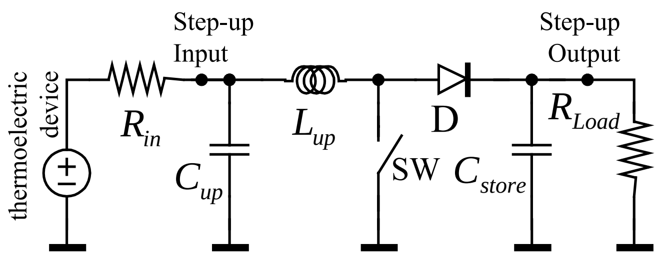

Fig 8: Schematic of the step-up circuit.

III DISCUSSION AND RESULTS

Simulation results demonstrated that the optimum length of the thermoelectric column (to obtain maximum output power) depends on the thermal resistance of contact to the heat and cold bodies. In a typical wrist bracelet, 1 cm^2 generator, with hot-side temperature of 30 ºC and thermal resistance of 150 $K/W/cm^2$, and a cold-side at 20 ºC with an heatsink of 50 $K/W/cm^2$, the maximum power (20 µW) is obtained with a thermoelectric column of 4 mm in length. An open loop voltage of 7 V is present, in a generator with 4760 thermoelectric pairs. To fabricate such 3D structure, a device as suggested in fig. 9 is proposed.

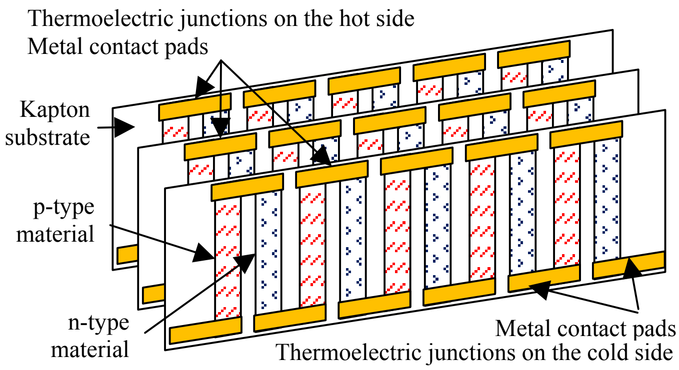

Fig 9: Artwork of the proposed device. Foils with thermoelectric junction are stacked to obtain a large number of junctions. The last foil includes de Li battery and the charge-control circuit.

On a kapton polyimide substrate, 30 µm of thickness, thermoelectric elements with 10 µm of film thickness are patterned, to obtain 4 mm x 100 µm columns, connected in series with metal contacts. To obtain the suggested number of junctions, several substrates are stacked. The last substrate is reserved for fabrication of the thin-film battery, where microelectronics die is also glued.

IV CONCLUSIONS

A human-body thermoelectric energy scavenging microsystem, that includes Li battery and microelectronics on the same device, is proposed. Simulation results, including body-contact and heatsink thermal resistances, shows that 20 $\mu W/cm^2$ can be obtained, optimizing the length of the thermoelectric columns to 4mm. In a device with 4760 thermoelectric junctions, an output open-circuit voltage of 7 V is available. A method is proposed to fabricate such 3D structure. A thin-film solid-state battery is presented, using lithium compounds. This battery stores energy so it can be used in a peak basis. Thermoelectric thin-films, with high figure-of-merit (ZT=0.9 in n-type and ZT=0.4 in p-type film) were obtained by co-evaporation. Detailed parameters of deposition process are presented.

ACKNOWLEDGMENTS

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