An energy scavenging microsystem based on thermoelectricity for battery life extension in laptops

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***Abstract* - This paper presents a solution to increase the nominal lifetime of batteries in laptops. New thin-film materials offer potentially greater efficiencies when converting heat to electricity using the thermoelectric effect. Applied to microprocessors, this technology can mitigate a number of critical problems as the critical amount of heat produced by laptops. The use of a thermoelectric scavenging microsystem based on the Seebeck effect can address this problem, by extracting waste heat from a high-end microprocessor, converting the heat to electricity using thin-film technology in silicon compatible materials. Applying a thermoelectric micro converter (that was fabricated using thin-films of bismuth and antimony tellurides) to a temperature gradient of 60 ºC, it is possible to obtain an efficiency of 3% and increase in the same amount, the lifetime of batteries.**

I. Introduction

Thermoelectricity uses a temperature gradient to generate an electrical current. This fundamental physical principle has been known since 1830. The advantages of this approach are that thermoelectric generators have no moving parts and are silent and robust, can be used in any situation where there is a temperature gradient, can be used in different temperature ranges via an appropriate material choice, and can be used in small lightweight appliances (e.g. laptops) as well as in large industrial applications where the heat generated can be scavenged. By acquiring, the thermal energy, provided by the CPU, this paper proposes the use of that energy and transform it into electrical current to expand the lifetime of the battery. This energy conversion is accomplished by using a thermoelectric device. Such a device was fabricated by thin-film deposition of n-type bismuth telluride (Bi_2Te_3) and p-type antimony telluride (Sb_2Te_3). One pair of a p-n thermoelectric device can generate 300 μVK^{-1}. Connecting a large number of these pairs it is possible to obtain larger output voltages. Considering that the CPU package is always hot, due to the heat generated by the integrated circuits within when the laptop is being used, it is always possible to obtain the necessary temperature difference, meaning that there is a limitless source of energy to be scavenged. Generally, the CPU is cooled down using a heatsink and a fan to accelerate the exchange of hot air that flows out of the package to the much cooler air outside the laptop's structure, i.e., ambient or room temperature. In order to anyone easily know how much heat a laptop can generate (and waste), a man who uses a hot computer on the lap for hours every day, may be reducing his chance of becoming a father [1]. In fact, a pilot study of twenty nine men shows that the combination of the legs together posture required to balance a laptop, and the heat generated by the processor elevates the scrotal temperature by up to 2.8ºC during use.

The thermal design power (TDP, [W]), is the maximum amount of heat which a thermal exhaust system must be able to dissipate from the CPU so that it will operate under normal conditions [2]. Considering a battery with the specifications, 4.8 Ah and 11.1 V, supplying a laptop with an INTEL CPU Duo T7200 with maximum TDP of 34 W, a general idea of the power consumption of the laptop is obtained: from $I.\Delta t$=4.8 Ah and assuming $P=V\times I$ [W], then $\Delta t=4.8(11.1/P)$, which leads to a lifetime of Δt=1.56 hours. It must be noted that I is the electric current, V is the voltage and P is the CPU's TDP.

As depicted in Figure 1, experimental results show that for a 60 ºC differential, the efficiency of a BiSbTe thermoelectric device reaches 3%. Thus, as seen in equation (1),

$$\Delta t' = 4.8\times(11.1\times P'/P^2) \qquad (1)$$

for an efficiency of 3%, the battery's lifetime reaches $\Delta t'$=1.61 hours. The quantity P' is the new power obtained with the scavenging system.

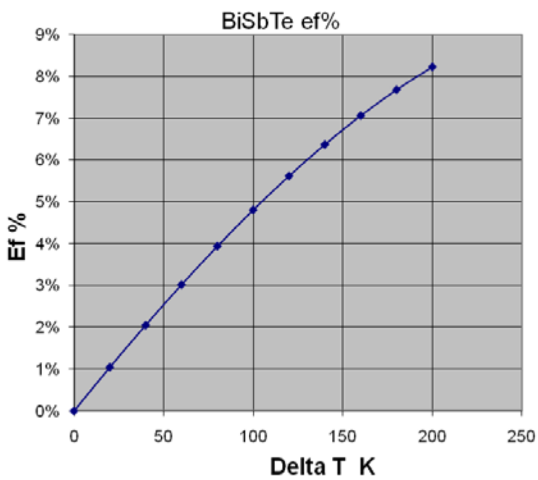


Fig. 1: Thermoelectric BiSbTe efficiency vs differential temperature.

The ideal location to insert the thermoelectric device in the heatsink must be identified. A finite element method (FEM) tool was used. Figure 2 shows the simulation results of the temperature gradient across the heatsink. For this simulation, two target temperatures were defined: the component temperature (junction temperature@100º C) and the local processor ambient temperature@40º C.

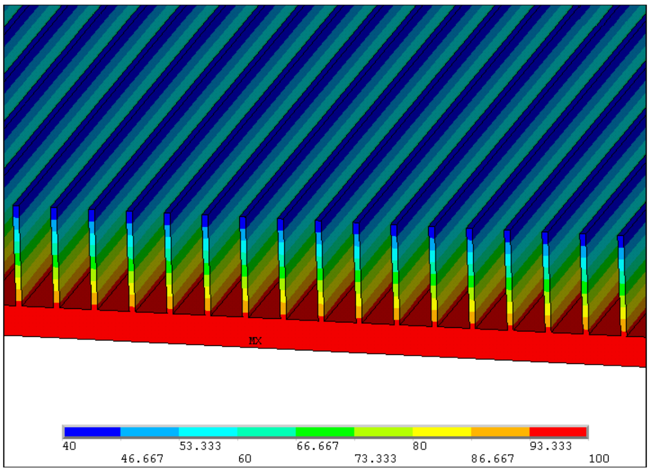


Fig. 2: Illustration of the temperature gradient across the heatsink using a FEM tool.

From the simulation, one may conclude that the most efficient position of the thermoelectric devices is vertical, along the pillars of the heatsink.

Figure 3 illustrates the cooling and exhaust systems, with the thermoelectric device joined in-between the heatsink pillars. The heatsink is a passive cooler that transfers the heat dissipated by the CPU outwards. The CPU is attached to the heatsink through a thermally conductive compound. This material, called thermal interface material (TIM), prevents voids and air gaps, in this junction, enhancing the heat spread between the die and the heatsink. The cooling fan is an active cooler that transfers the hot air flowing from the heatsink to the much cooler ambient air. Considering this normalized system, the best spot to place the thermoelectric device is where the temperature gradient will occur more rapidly and abruptly. The electrical low power signal that the thermoelectric devices generate will then be amplified by the step-up DC/DC converter.

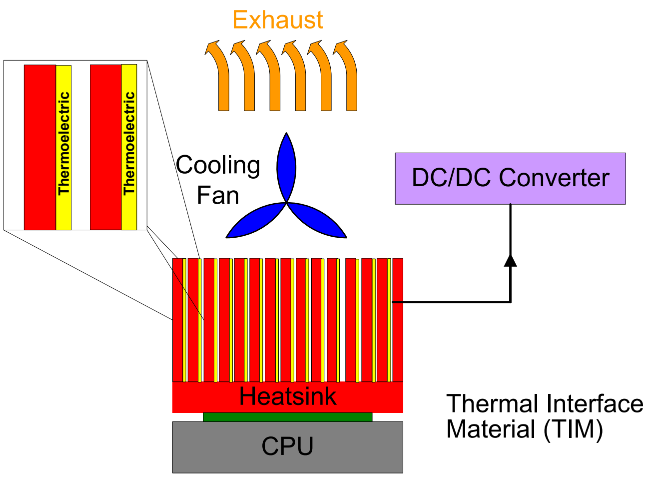


Fig. 3: Illustration of the CPU passive heat sink cooling apparatus and active air exhausting system with the thermoelectric scavenging devices connecting to the step-up converter stage.

The model used for the thermoelectric device is given by the equation (2) [3], and it represents the thermoelectric coefficient-of-performance. This coefficient is defined as the ratio between the heat flux at the cold junction q_c with W, where W is the rate at which electrical energy is supplied, Z is the figure-of-merit, T_1 and T_2 are the temperatures at two different locations and T_M is the mean temperature $(T_1+T_2)/2$.

$$\Phi_{max} = \frac{q_C}{W} = \frac{T_1\left[\left(1+ZT_M\right)^{\frac{1}{2}} - \frac{T_2}{T_{1\,1}}\right]}{\left(T_2 - T_1\right)\left[\left(1+ZT_M\right)^{\frac{1}{2}}+1\right]} \qquad (2)$$

A general way to express the figure-of-merit of a thermoelectric material is the product ZT [4]:

$$ZT = \frac{\alpha^2}{\rho\lambda}T \qquad (3)$$

where α is the Seebeck coefficient, ρ the electrical resistivity, λ the thermal conductivity and T the temperature. Furthermore, the power factor, PF [$WK^{-1}m^{-2}$] that gives the electric power versus the area where the heat flow happens, plus the temperature gradient between the hot and the cold sides, is given by:

$$PF = \frac{\alpha^2}{\rho} \qquad (4)$$

II. System Architecture

The general architecture of the energy scavenging system can be seen in Figure 3. The thermoelectric devices generate electrical power. This electric signal must be amplified using a DC/DC step-up converter. In addition, there is a controlling stage that will function as a switch. This stage controls the charging of the battery by the thermoelectric device.

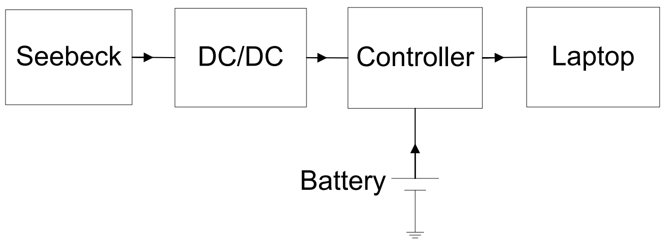


Fig. 3: Block diagram of the system architecture.

III. Thermoelectric Design

Thermoelectric generator

The thermoelectric generator must be silicon compatible in order to integrate the microelectronics. 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. The SEM cross-sectional and surface images of the films can be seen in Figure 4.

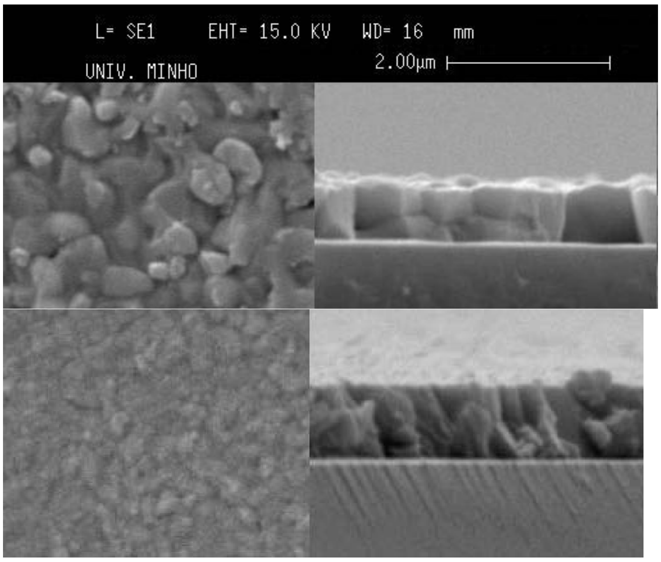


Fig. 4: SEM top view (left) and cross-sectional (right) images of Bi_2Te_3 (top) Sb_2Te_3 (bottom) thin-films.

Figure 5 shows a planar thermoelectric micro converter, which was fabricated on top of a 25 μm thickness kapton foil. As depicted in the Figure, the contacts can be deposited on top or bottom of the thermoelectric films. Since, Bi_2Te_3 and Sb_2Te_3 thin-films adhesion is higher on polyimide (kapton) films than on nickel metal pads, the use of top contacts process avoids the need of depositing additional layers to promote the adhesion of thermoelectric films.

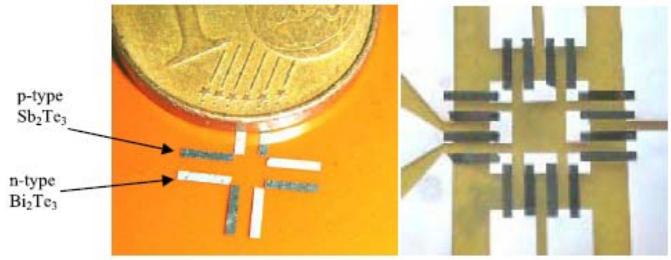


Fig. 5: Photograph of n-type and p-type elements, before deposition of top contacts (left), and a photograph of a thermoelectric micro converter with eight pairs of thermoelectric elements, fabricated with bottom contacts (right).

DC-DC conversion

Ultra-low power electronics performs DC-DC rectification with a variable conversion factor. Figure 7 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 opened, with a fast 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. Figure 8(a) shows a photograph of a first prototype of the simple step-up converter presented in Figure 7, however as the goal is an integrated thermoelectric scavenging energy system, then a more compact solution for the power circuit is mandatory. Thus, using discrete but still compact solution, it was mounted a first circuit prototype to make the step-up conversion. Figure 8(b) shows such a circuit, which is composed by a charge-pump (CP) [5] followed by a DC-DC step-up converter [6].

IV. RESULTS

A. Thermoelectric converter

For the selected samples of Bi_2Te_3 and Sb_2Te_3 films, the absolute value of the Seebeck coefficient in the range of 150-250 μVK^{-1}, and an in-plane electrical resistivity of 7-15 $\mu\Omega m$ were obtained. The measurements also shown 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 maximum power output is obtained when the thermal resistance of the thermoelectric legs is equal to the heatsink thermal resistance (about 50 $KW^{-1}cm^{-2}$), corresponding to thermoelectric elements with 1 mm of length (Figure 9). However, to reduce the additional thermal resistance introduced to CPU heatsink, a lower thermal resistance of thermoelectric legs could be achieved, reducing the length of thermoelectric elements. Since each thermoelectric junction of Bi_2Te_3-Sb_2Te_3 can deliver an output voltage of 300 μVK^{-1}, more than 3700 junctions are necessary to obtain an output voltage (without load) of 11.1 V, under a temperature difference of 60 ºC. Figure 9 shows the open-circuit voltage and power that can be obtained in a 1 cm^2 Bi_2Te_3-Sb_2Te_3 thermoelectric generator.

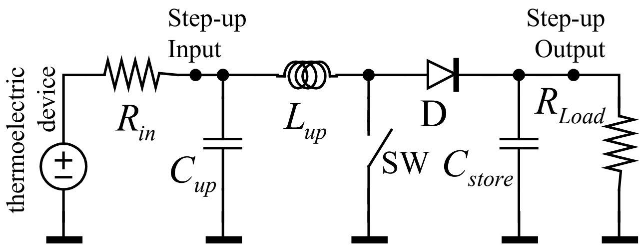
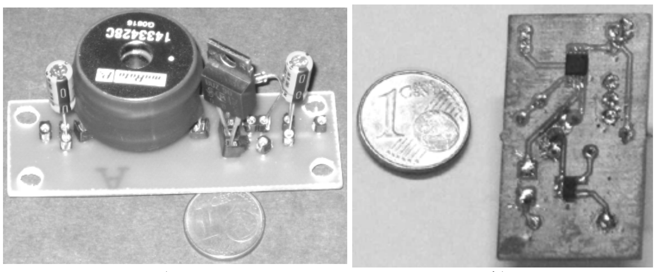


Fig. 7: Schematic of a simple step-up circuit.



a) b)

Fig. 8: Photographs of a) a prototype of the simple step-up converter, and b) of the charge-pump, followed by the step-up.

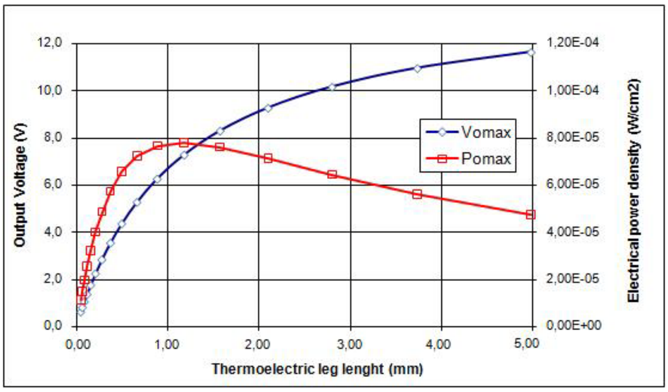
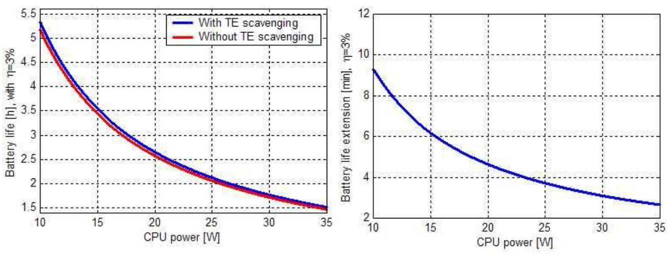


Fig. 9: Open-circuit output voltage and power of a 1 cm^2 Bi_2Te_3-Sb_2Te_3 thermoelectric generator, plotted as function of the leg length.

B. Battery extension

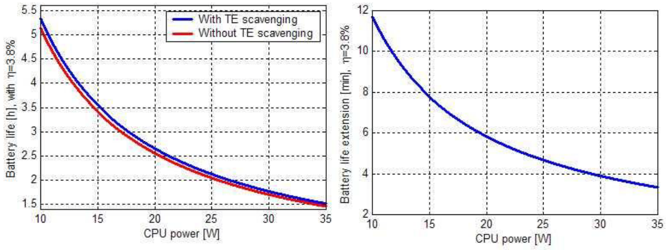
Two assessments were made in order to quantify the amount of time in the battery extension. The power was swept in a typical range found in commercially available CPUs (from 10 to 35 W). Figure 10a) shows the battery lifetime (in hours) with (blue line) and without (red line) thermoelectric harvesting and Figure 10b) presents the increase in the lifetime of the battery (in minutes), for a thermoelectric efficiency of 3%, i.e., 60 ºC temperature gradient.



a) b)

Fig. 10: Battery extension analysis at 3% efficiency obtained for a temperature gradient of 60 ºC.

Figure 11 shows the same results, but for a thermoelectric efficiency of 3.8%, i.e., 75 ºC temperature gradient.



a) b)

Fig. 11: Battery extension analysis at 3.8% efficiency obtained for a temperature gradient of 75 ºC.

V. CONCLUSIONS

This paper presents a thermoelectric scavenging microsystem to increase the nominal lifetime of batteries in laptops. The use of thermoelectric generators made of tellurium compounds (n-type bismuth telluride, Bi_2Te_3 and p-type antimony telluride, Sb_2Te_3) share the advantage of being silicon compatible in order to integrate the microelectronics, at the same time are materials that are widely employed by the industry, in conventional thermoelectric generators and coolers. Due to the availability of fabrication processes it is easy to fabricate the generators. The thermoelectric device will generate electrical power and then, ultra-low power electronics performs DC-DC rectification with a variable conversion factor. For such a purpose there is a DC/DC step-up converter to elevate the output electrical signal generated in the thermoelectric device. The results show that with temperature gradients of 60 ºC and 75 ºC, it is possible to extend the battery of a laptop by 3% and 3.8% respectively.

ACKNOWLEDGMENT

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