Powering a Cat Warmer Using Bi_2Te_3 Thin-Film Thermoelectric Conversion of Microprocessor Waste Heat

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I. INTRODUCTION

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 in one fell swoop: the dangerous amount of heat produced by laptops [14], [17], climate-change inducing electricity consumption [11], and unhappy house-cats that are insufficiently warm [1]. Figure 2 depicts an apparatus that addresses these three problems comprehensively, by extracting waste heat from a high-end microprocessor, converting the heat to electricity using thin-film technology, and using the resultant current to power a portable cat warmer.

The thermoelectric effect discovered by Seebeck in 1822 can be utilized to convert heat differentials into electric voltage [6]. When one end of metal is heated, it behaves like a battery, as the thermal gradient causes the electrons to diffuse and the phonons[1] to vibrate. The vibrating phonons preferentially allow some electrons to diffuse towards one end, creating a difference in potential. The efficiency of thermoelectric generators (TEG) is generally low (2-4%), but recent advances in nanotechnology indicate that newer materials can improve the efficiency at least two-fold [5]. TEG made out of new nanomaterials can benefit microprocessors; even a 6W recovery from a 100W processor can be enough to drive the processor cooling fan, power up certain microarchitectural structures, or ensure that house-cats are sufficiently cozy.

II. A BRIEF AND INCOMPLETE HISTORY OF THERMOELECTRIC GENERATION

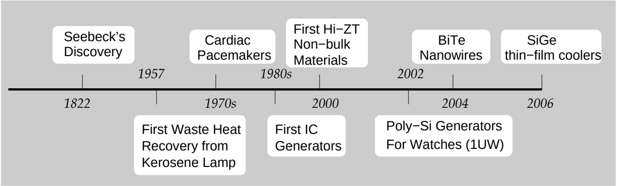

Fig. 1. A Brief (and Incomplete) History of Thermoelectric Generation

Min and Rowe [10] trace (Figure 1) the first instance of thermoelectric generation from wasted heat back to 1957. The invention is credited to Ioffe et al. who used heat from kerosene lamp to power a radio. Min and Rowe also report that cardiac pacemakers powered by TEG were invented and used in the 1970s, driven by heat from decaying radio isotopes. The 1980s saw the first efforts towards IC-based TEGs [7]. These and more recent CMOS TEGs [4], [12] produce power in the order of microwatts and are used in low-power devices such as sensors or body-heat-powered wrist watches.

During the late 1990s, the ability to photograph lattice structures (through x-ray diffraction), coupled with high precision fabrication techniques for nanoscale engineering, enabled the development of newer materials that are better suited for TEG [8]. These new materials have a higher figure-of-merit (ZT) compared to traditional "bulk" manufactured devices and are usually referred to as *thin-film* devices; a Si bulk device has a ZT of around 0.04, whereas a Bi_2Te_3 thin-film device has a ZT of 2.37 at 300K [15]. These thin-film devices and self-assembled nanowires [9], [13], [18] promise excellent thermoelectric conversion ratios and have rekindled the interest in TEG. In fact, recently an on-chip thermoelectric refrigerator for cooling microprocessors was built using $SiGe$ thin-film technology [16]. Researchers have also proposed some non IC based bulk TEG for utilizing microprocessor waste heat [2], [3]. Unlike these TEGs, thin-film TEGs can be integrated within the microprocessor.

III. THERMOELECTRIC GENERATION

The maximum efficiency of any conversion process – the Carnot efficiency – is defined by the following equation:

$$Carnot = \frac{(T_h - T_c)}{T_h} \tag{1}$$

where T_h is the temperature of the hot end and T_c is the temperature of the cold end. Assuming a 50K temperature differential, with the hot end at 350K, the maximum possible conversion efficiency is 14%. In practice, however, the efficiency depends on several material properties including the Seebeck Coefficient (α) [2], the thermal conductivity (ρ) and the

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[1] A phonon is a fundamental quantum mechanical vibration mode of a material that is used to explain sound in solids.

[2] The open circuit voltage induced per unit temperature difference.

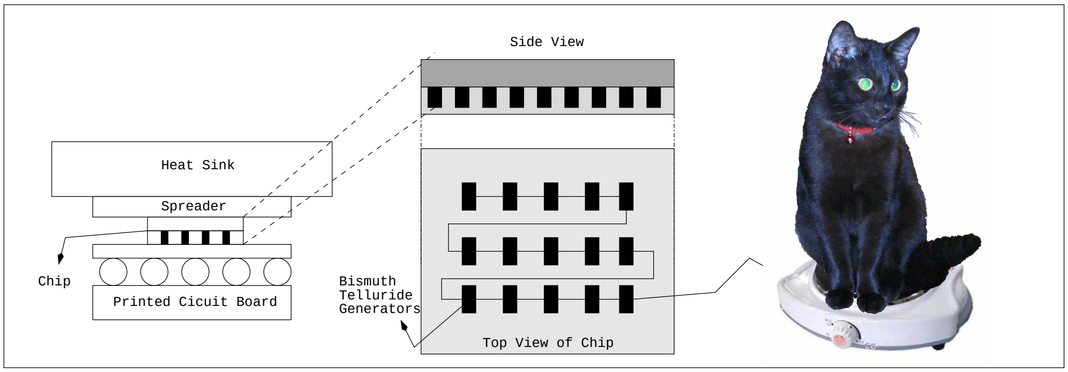

Fig. 2. A Microprocessor-Powered Bi_2Te_3 TEG Cat-Warmer

electrical conductivity (λ). These factors are captured with a single number–the *figure-of-merit* (ZT) of the material:

$$ZT = \frac{\alpha^2 T_a}{\rho\lambda} \quad (2)$$

The efficiency also depends on the generator resistance, R_g, which should be small to limit the energy lost due self-heating of the wire from the current induced in the generator (the joule heating or the I^2R_g heat loss in the generator). The low resistance requirement precludes the use of wires running in the plane of the chip, say from a hot-spot to the cooler periphery. However, thick vertical vias running down the chip layers provides a satisfactory low resistance alternative (Figure 2). The maximum power delivered by a thermoelectric system can be derived [6] to be:

$$Power = \frac{1}{R_g}\left(\frac{\alpha \times (T_h - T_c)}{\sqrt{(1 + ZT_a)} + 1}\right)^2 \quad (3)$$

Electrical Resistivity (ρ)	$1.2 \times 10^{-5} \Omega M^{-1}$
Seebeck Coefficient (α)	$243\mu V K^{-1}$
Thermal Conductivity (λ)	$0.97 W m^{-1} K^{-1}$
Figure of Merit: Z.T	2.37
Temperature at hot end (T_h)	350K
Temperature at cold end (T_c)	300K
Average Temperature (T_a)	325K
Silicon wafer height (L)	$5 \times 10^{-4} M$
Via Area (A)	$1cm^2$

TABLE I
TABLE OF CONSTANTS. FROM [15]

Using the constants from Venkatasubramaniam et al. [15] (summarized in Table I) in equation 3, we estimate that the maximum power that can be generated from one generator is 0.5W. By chaining multiple generators in series as shown in Figure 2, it is possible to produce the 6W required to power a gentle cat warmer for those cold Texas nights.

IV. LIMITATIONS AND FUTURE DIRECTIONS

In this paper we have assumed that thin-film devices can be effectively integrated into the semiconductor manufacturing process. Thin-film devices are fabricated using molecular beam epitaxy. There is some evidence that fabrication is possible [16] but the economic feasibility of this process is unclear. Furthermore, reductions in microprocessor die sizes may decrease the number of generators that can be placed on the die and hence decrease the total power output. However, a smaller die size may produce a higher temperature gradient, enabling more efficient TEGs. In the future, these on-chip TEGs may open up new power-performance tradeoffs for architects to examine. We note, however, that even highly efficient TEG can only reclaim one billionth of the theoretical power overhead in modern processors–the theoretical energy required to execute a program is in the order of nanoJoules, measured in energy per bit flip. In the future, with new architectures, execution models and materials, it should be possible to save/harvest enough power to drive a cat shaver, a cat petter or even a robotic cat companion.

REFERENCES

[1] Mother Goose Nursery Rhymes. ”The Cat and the Fiddle and Pussy-Cat by the Fire”.

[2] G.L. Solbrekken et al. Experimental Demonstration of Thermal Management Using Thermoelectric Generation. *Itherm*, 2004.

[3] G.L. Solbrekken et al. Thermal Management of Portable Electronic Equipment Using Thermoelectric Energy Conversion. *Itherm*, 2004.

[4] A. Jacquot et al. Fabrication and Modeling of an In-plane Thermoelectric Micro-Generator. *21st International Conference on Thermoelectrics*, 2002.

[5] A. Majumdar. Thermoelectricity in Semiconductor Nanostructures. *Science*, 303(5659):777–778, 2004.

[6] D. M. Rowe, editor. *CRC Handbook of Thermoelectrics*. CRC Press, 1995.

[7] D. M. Rowe et al. Minature Low-Power/High-Voltage Thermoelectric Generator. *IEE Electronic Letters*, 1989.

[8] F. J. DiSalvo. Thermoelectric Cooling and Power Generation. *Science*, 285:703–706, 1999.

[9] Dresselhaus et al. Low-Dimensional Thermoelectric Materials. *Physics of the Solid State*, 41(5), May 1999.

[10] G. Min and D. M. Rowe. Recent Concepts in Thermoelectric Power Generation. *21st International Conference on Thermoelectrics*, 2002.

[11] A. Gore. *An Inconvenient Truth*. Rodale Inc., 2006.

[12] M. Strasser et al. Micromachined CMOS Thermoelectric Generators as On-Chip Power Supply. *The 12th International Conference on Solid State Sensors, Actuators and Microsystems*, 2003.

[13] Menke et al. Bismuth Telluride Nanowires Synthesized by Cyclic Electrodeposition Stripping Coupled with Step Edge Decoration. *Nano Letters*, 9(10), August 2004.

[14] Philip Cohen. Hot Laptops May Reduce Male Fertility. www.newscientist.com/aricle.ns?id=dn6777.

[15] Rama Venkatasubramanian et al. Thin-film Thermoelectric devices with High Room-Temperature Figures of Merit. *Nature*, 413:597–602, 2001.

[16] Yan Zhang et al. On-Chip High Speed Localized Cooling Using Superlattice Microrefrigerators. *IEEE Transactions on Components and Packaging Technologies*, 29(2), June 2006.

[17] Yefim Sheynkin et al. Increase in Scrotal Temperature in Laptop Computer Users. *Human Reproduction*, 20(2):452–455, 2005.

[18] Zhao et al. Bismuth Telluride Nanotubes and the Effects on the Thermoelectric Properties of Nanotube-Containing Nanocomposites. *Applied Physics Letters*, 86(06211), Feb 2005.