Overview of Developments and Applications of Thermoelectrics Integrated with MEMS

Masashi Takahashi[*]

[*]OMRON Silicon Valley
3945 Freedom Circle, Suite 1070, Santa Clara, CA 95054, mtaka@omron-sv.com

ABSTRACT

Thermoelectric devices can be used for direct conversion of heat to electricity, which is one of the good solutions for recovering waste energy. A thermoelectric device can function whenever there is a temperature difference between the device and its surroundings. The performance of thermoelectric devices has improved significantly in this decade because of advances in related science and technology. However, larger market applications still remain elusive. The real-life application of thermoelectric devices can be greatly enabled by microelectrical mechanical systems (MEMS). In this paper, various types of thermoelectric materials and devices are introduced and categorized from the perspective of MEMS and the key issue corresponding to each type of device is discussed. By applying the MEMS-based integrated thermoelectric device, Wireless Sensor Networks can be practical and effective in the field of safety, health, and communication.

Keywords: energy harvester, thermoelectric, MEMS, Wireless Sensor Network

1 INTRODUCTION

We are faced with many energy and environmental problems such as the running out of fossil fuels, rapid increase in energy consumption by emerging-economy countries, and global warming. Against such a back ground, development of advanced clean energy technologies is critical because it can provide solutions to the above mentioned problems. Of the various clean technologies energy harvesting devices are a clever way of recovering waste energy. Energy harvesters convert to power wasted energy in the form of heat, vibration, pressure, sunlight, wind, and etc. Thermoelectric device is one form of an energy harvester, and utilizes heat. Thermoelectric devices have many advantages including the lack of moving parts that make them highly reliable. Additionally they do not need any chemical reaction and physical movement to generate the electricity. At first, the principles of thermoelectricity are described in this paper. Second, the state-of-the-art in thermoelectric device R&D is categorized. Finally, MEMS-based integrated thermoelectric devices and the applications for such devices are discussed.

2 THERMOELECTRIC PRINCIPLES

The efficiency of a thermal system, such as a thermoelectric device, is limited by the fundamental thermodynamic Carnot efficiency which is a function of the temperature differences existing in that thermal system. The greater the temperature difference, the higher the Carnot efficiency. Therefore, thermoelectric devices are most efficient when the temperature difference between the heat source and the heat sink is high. In general, a thermoelectric operates on the principle of combining different materials. For example, as shown in Figure 1, the combination of an n-type semiconductor and a p-type semiconductor in the presence of a temperature gradient will result in a voltage across the hot and cold sides of the system.

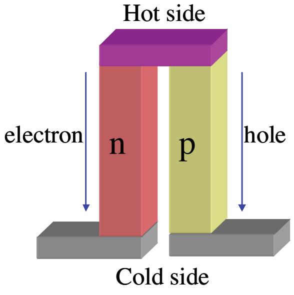

Figure 1: Thermoelectric flow

The performance of such a device is quantified by the figure of merit, ZT, where:

$$ZT = \frac{\alpha^2 \sigma T}{K} \tag{1}$$

α, σ, T and K are the Seebeck coefficient which is an intrinsic property of the material, electrical conductivity, thermal conductivity and the absolute temperature, respectively. To increase the thermoelectric efficiency (ZT), a large Seebeck coefficient and electrical conductivity are needed whereas the thermal conductivity should be small. In general, the Seebeck coefficient can be optimized by doping with consideration to the electrical conductivity, however, conventional materials are subject to the Wiedemann-Franz law which relates the thermal conductivity to the electrical conductivity and results trade-off. The thermal conductivity can be separated into the thermal conductivity of electrons and that of the lattice, and for most semiconductors, the thermal conductivity of the lattice is larger than that of electrons. Most researchers have tried to reduce the thermal conductivity of the lattice. Currently most commercial thermoelectric devices have a ZT of less than 1. The thermoelectric efficiency has remained limited for a long time for practical commercial devices, and so the applications have also been limited. Some practical uses have included substitute power converters for solar cell in space under poor sunlight conditions [1], and as a primary power source for wristwatches that take advantage of the temperature difference between human skin and the upper metal frame of the wristwatch [2]. To date, the most popular alloys for thermoelectric devices are Bi/Te and Pb/Te. However, there are two main problems. These alloys are very fragile when used in high temperature, and additionally, Bi, Te and Pb are heavy metals, which are harmful to humans and the environment. Therefore, the two pressing issues for thermoelectric devices are materials that increase the efficiency and lower the hazard risk.

3 LATEST DEVELOPMENTS

In this decade, some new approaches in thermoelectric devices have appeared that use nanotechnology and MEMS. Next the latest approaches for material design, device design and thermionic energy conversion (another way of converting heat to electricity) are described.

3.1 Material design

As described previously, maximizing ZT it is the key to create a useful thermoelectric device. In 1993 the quantum effect was proposed to increase ZT significantly [3][4]. The fundamental idea lies in limiting the dimension of the electronic orbit of an atom – better known through the concept of quantum dots and quantum wells, both of which are nanostructures. A superlattice is called an artificial lattice and it is designed to obtain the desired property of material. Quantum dot and stacked atomic layers are typical methods to make a superlattice (see Figure 2). The following three research efforts portray the activities in material design for the next generation of thermoelectric devices.

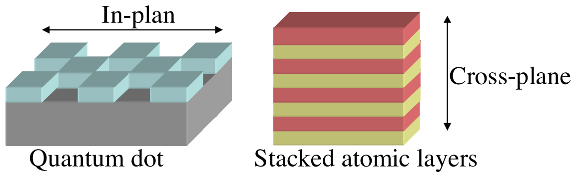

Figure 2: The direction of effect by superlattice

First, by layering the atomics alternatively and constraining the movement of electrons, phonon vibrations can be reduced, which leads to the decline of thermal conductivity in the out-of-plane direction. A ZT of around 2.5 using this method has been realized, and this is by far the most competitive figure of merit to date [5]. However, this process currently remains expensive.

The second material design activity is in designing thermoelectric nanocomposite materials by mixing various atoms and nanoparticles/nanowires to the host material to scatter the phonon by properly choosing the mismatch of electron properties so that the electrical performance can be maintained. The combination of Si nanoparticles with Ge microparticles in various atomic ratios by hot pressing method has been demonstrated [6]. This approach is simple and relatively inexpensive, however, it is a bulk process. To anticipate the randomness of nanoparticle behaviors, Monte Carlo simulation methods have been also demonstrated – prior to the actual fabrication [7]. On the other hand, nanocomposites using Bi nanowires have been also developed [8]. Bi nanowires whose diameters is 9 nm are embedded into the host material, porous alumina. Compared with bulk Bi, the thermoelectric power is much higher.

The third research activity of note is that UC Berkeley and Lawrence Berkeley National Laboratory have demonstrated the possibility that even silicon can be a candidate for thermoelectric material by forming its nanowire [9]. The thermoelectric performance highly depends on the diameter and roughness of the nanowire. To make silicon nanowires, aqueous electroless etching method with AgNO3 and HF acid is developed. The nanowire diameter is designed to be less than 50 nm and the mean roughness height is typically between 1-5 nm. In their study, a ZT of 0.6 was achieved at room temperature. The researchers were able to lower the thermal conductivity by a factor of hundred. It is believed that this phenomenon happens by a quantum confinement effect, and further theoretical research is on going. While a ZT of 0.6 may appear not to be a noteworthy achievement, the fact that the researchers achieved it with silicon has tremendous commercial implications. One of the big challenges is to characterize and localize these silicon nanowires to the desired area. Therefore, self-assembly techniques will have to be developed as a key to manufacturability.

3.2 Device design

In this section the thermoelectric devices fabricated by MEMS will be discussed. These devices are miniaturized and packaged using MEMS. As will be seen, the thermal design in such devices is also an important packaging issue.

Researchers at JPL and Caltech have utilized vertically arrayed thermoelectric devices using conventional thermoelectric material [10]. They used standard MEMS processes in conjunction with a newly developed electro chemical deposition process with thick photoresist to make 10-50 um thick layer of p-type and n-type Bi2Te3 alloys. After fabricating the thick thermoelectric array, a Pb-Sn layer is used for flip-chip bonding between the p-type and n-type Bi2Te3 with each other. This is the demonstration of potentially a good solution of an electro-chemical process for a thermoelectric device with MEMS.

There are other researchers developing lateral arrayed thermoelectric devices [11][12]. Approaches are using standard semiconductors as a thermoelectric material, and standard CMOS process technology and MEMS technology are being selected as fabrication methods of choice. MEMS fabrication techniques allow these devices to incorporate a large number of thermocouples on a membrane for a cascade connection and thereby creating a thermoelectric device. FEM simulations are commonly used to design such systems. While these devices are currently limited by the available materials, they are very attractive because of the very reasonable fabrications and integration techniques.

3.3 Thermionic energy converter

A thermionic energy converter is different from a conventional thermoelectric device. However, it deserves a discussion here. The principle of this phenomenon was discovered by Edison in 1883, but recently this method is being developed by nanotechnology and MEMS. This device is composed of two electrodes which face each other and are packaged in a tiny vacuum space. By heating one of the two electrodes beyond its material work function, the electrons can be emitted from its surface, and collected on the opposite electrode, and thereby generating an electric current. Therefore, we do not have to consider the thermal conductivity of the lattice, so the efficiency is generally better than that of the conventional thermoelectric devices. The intensity of the electric current is given by

$$J = AT^2 \cdot \exp\left(-\frac{\phi}{kT}\right) \tag{2}$$

where, A, T, ϕ and k are constant, absolute temperature, work function and Boltzmann constant, respectively. To increase the efficiency, first, it is obvious that this device should work in high temperature with a very large temperature difference between the emitter and the collector. Next, this device also needs materials whose work function is very low. Thermal expansion and the induced stress make good thermal isolation between the emitter and the collector challenging (see Figure 3).

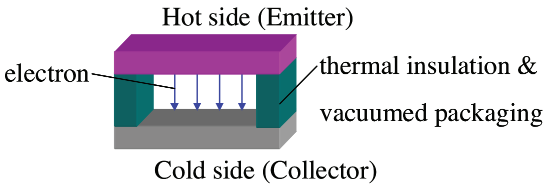

Figure 3: Concept of MEMS thermionic energy converter

Therefore, the main challenges can be divided two parts; the micro-scale thermal design and the investigation of special materials for MEMS process. Latest research on miniaturized thermionic energy converter developed by MEMS is focused on packaging [13][14]. There is also research on studying diamond and carbon nanotubes as suitable thermionic emitters [15][16][17]. The combination of device miniaturization and special materials development is indispensable. Simultaneously, the reliability under high temperature is a big challenge as well.

4 FUTURE RESEARCH

Beginning with the development of new thermoelectric material future research should be focused in the development of practical devices as well. MEMS enable such devices not only to be small, but also integrated into an overall system which includes integrating with CMOS and other sensors. Such integration can produce smart and self-sustaining devices.

The concept of Wireless Sensor Network is a promising future technology. Early research in Wireless Sensor Network was from “Smart Dust” at UC Berkeley, which is based on the approach of the distributed sensor network [18]. This technology needs integrated intelligent modules composed of a power source, RF circuit, CPU, memory and sensors (see Figure 4). By changing the sensors and the programmable algorithms, this integrated module can be adapted for various applications. In such a Wireless Sensor Networks, the battery issue is very serious, and “micro-AMPS” at MIT is one of the projects seeking an energy-optimized solution [19]. The combination of both an energy harvester and a low energy consumption module is imperative for Wireless Sensor Networks to be successful. With this background the MEMS thermoelectric module is attractive as a power source.

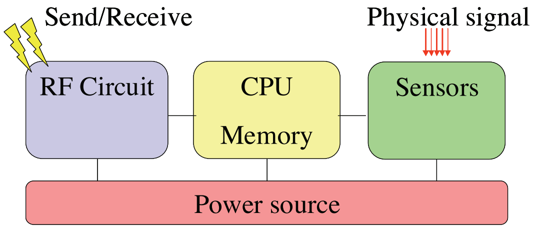

Figure 4: Minimum module composition

MEMS thermoelectric modules can be attached to the wall, window, ground, human, exhaust, and etc, wherever a temperature difference can be achieved easily. Once they are installed, there is no need for maintenance such as in a battery change, and thereby solving a key problem for ubiquitous Wireless Sensor Network. Some specific examples are cited below. In all these cases, a dynamic interaction is required between the item being monitored/serviced and the Wireless Sensor Network.

- Home/Office security & air-conditioning.

  This system has many modules disposed at every window. These modules include an accelelometer for detecting glass cracking and temperature sensor for sensing the peripheral temperature. By collecting the distributed information from each module, the system can recognize the whole home/office situation, and know to issue warnings or maintain the hot/cold environment at desired set points.

- Human health monitoring

This module can be wearable or implantable, and includes a pressure sensor and other biosensors. This system is especially useful for senior citizens living by themselves. This module monitors their body all day. If there is something wrong, the system suggests consulting a doctor, or informs a caretaker through various modes of communication, such as the telephone or the internet.

- Context awareness & Gaming

This system can be composed of many distributed modules and wearable or implantable modules attached to the members of the gaming community. Interactive networking between the distributed network can be used for context awareness, and to track of human activity.

5 SUMMARY

Advanced research on thermoelectric is introduced in this paper. While some major breakthroughs in materials and engineering are required for wider practical adoption of this technology, nanotechnology and MEMS have enabled applications in many areas already. For example, by adding a thermoelectric device integrated by MEMS into a Wireless Sensor Network module, the Wireless Sensor Network itself can become more feasible by solving the battery problem.

6 ACKNOWLEDGEMENT

Author would like to thank Dr. Shyam Venkatesh, director of OMRON Silicon Valley, for his support and feedback on this work.

REFERENCES

[1] Research and Development of the U.S. Department of Energy, “RTG -- history and new horizons,” http://www.osti.gov/accomplishments/rtg.html

[2] M. Kishi, H. Nemoto, T. Hamano, M. Yamamoto, S. Sudou, M. Mandai and S. Yamamoto, “Micro-thermoelectric modules and their application to wristwatches as an energy source,” 18th International conference on thermoelectrics, 302-307, 1999

[3] L. D. Hicks and M. S. Dresselhaus, "Effect of quantum-well structures on the thermoelectric figure of merit," Phys. Rev. B., 47-19, 12727-12731, 1993

[4] L. D. Hicks and M. S. Dresselhaus, "Thermoelectric figure of merit of a one-dimensional conductor," Phys. Rev. B., 47-24, 16631-16634, 1993

[5] R. Venkatasubramanian, E. Siivola, T. Colpitts and B. O’Quinn, “Thin-film thermoelectric devices with high room-temperature figures of merit,” Nature, 413, 597-602, 2001

[6] T. Harris, H. Lee, D. Z. Wang, J. Y. Huang, Z. F. Ren, B. Klotz, R. Dowding, M. S. Dresselhaus and G. Chen, “Thermal conductivity reduction of SiGe nanocomposites,” Mat. Res. Soc. Symp. Proc., 793, S7.2.1-S7.2.6, 2004

[7] M. Jeng, R. Yang and G. Chen, “Monte Carlo simulation of thermoelectric properties in nanocomposites,” 24th International conference on thermoelectrics, 21-26, 2005

[8] J. P. Heremans, C. M. Thrush, D. T. Morelli and M. Wu, “Thermoelectric power of bismuth nanocomposites,” Phys. Rev. Lett., 88-21, 216801-1-216801-4, 2002

[9] A. I. Hochbaum, R. Chen, R. D. Delgado, W. Liang, E. C. Garnett, M. Najarian, A. Majumdar and P. Yang, “Enhanced thermoelectric performance of rough silicon nanowires,” Nature, 451, 163-167, 2008

[10] J. -P. Fleurial, G. J. Snyder, J. A. Herman, P. H. Giauque, W. M. Phillips, M. A. Ryan, P. Shakkottai, E. A. Kolawa and M. A. Nicolet, “Thick-film thermoelectric microdevices,” 18th International conference on thermoelectrics, 294-300, 1999

[11] M. Strasser, R. Aigner, M. Franosch and G. Wachutka, “Miniaturized thermoelectric generators based on poly-Si and poly-SiGe surface micromachining,” Sensors and actuators A, 97-98, 535-542, 2002

[12] N. Kockmann, T. Huesgen and P. Woias, “Microstructured in-plane thermoelectric generators with optimized heat path,” The 14th international conference on solid-state sensors, Actuators and microsystems, 133-136, 2007

[13] P. G. Tanner and D. A. Fraser and A. D. Irving, “Developments in thermionic energy converters,” IEEE proc.-Sci. Meas. Technol., 152, 1-6, 2005

[14] D. B. King, K. R. Zavadil and J. A. Ruffner, “Results from the microminiature thermionic converter demonstration testing program,” AIAA, 2844, 272-282, 2000

[15] F. A. M. Koeck and R. J. Nemanich, “Field penetration and its contribution to field enhanced thermionic electron emission from nanocrystalline diamond films,” Diamond & related materials, 15, 2006-2009, 2006

[16] V. S. Robinson, Y. Show, G. M. Swain, R. G. Reifenberger and T. S. Fisher, “Thermionic emission from surface-terminated nanocrystalline diamond,” Diamond & related materials, 15, 1601-1608, 2006

[17] R. O. Loutfy, M. Samandi, A. Moravsky and S. Strange, “Carbon nanotubes as thermionic emitters,” Space technology and applications international forum, 773-780, 2004

[18] University of California, Berkeley, “Smart Dust,” http://robotics.eecs.berkeley.edu/~pister/SmartDust/

[19] B. H. Calhoun, N. Verma, D. D. Wentzloff and S. Cho, “Design considerations for ultra-low energy wireless microsensor nodes,” IEEE Transanctions on computers, 54-6, 727-740, 2005