A Novel Miniature Thermomagnetic Energy Harvester

Chin-Chung Chen, Tien-Kan Chung*, Chi-Cheng Cheng, Chia-Yuan Tseng
Department of Mechanical Engineering, National Chiao Tung University, Hsinchu 30010, Taiwan

ABSTRACT

Nowadays, thermal-energy-harvesting is an important research topic for powering wireless sensors. Among numerous thermal-energy-harvesting approaches, some researchers demonstrated novel thermomagnetic-energy harvesters to convert a thermal-energy from an ambient temperature-difference to an electrical-output to power the sensors. However, the harvesters are too bulky to be integrated with the sensors embedded in tiny mechanical-structures for some structural-health-monitoring applications. Therefore, miniaturized harvesters are needed. Hence, we demonstrate a miniature thermomagnetic-energy harvester. The harvester consists of CuBe-beams, PZT-piezoelectric-sheet, Gd-soft-magnet, NdFeB-hard-magnet, and mechanical-frame. The piezoelectric-sheet and soft-magnet is bounded at fixed-end and free-end of the beams, respectively. The mechanical-frame assembles the beams and hard-magnet. The length×width×thickness of the harvester is 2.5cm×1.7cm×1.5cm. According to this, our harvester is 20-times smaller than the other harvesters. In the initial-state of the energy-harvesting, the beams' free-end is near the cold-side. Thus, the soft-magnet is cooled lower than its curie temperature (Tc) and consequently changed from paramagnetic to ferromagnetic. Therefore, a magnetic-attractive force is produced between the soft-magnet and hard-magnet. Consequently, the beams/soft-magnet are down-pulled toward the hard-magnet fixed on the hot-side. The soft-magnet closing to the hot-side is heated higher than its Tc and subsequently changed to paramagnetic. Consequently, the magnetic-force is eliminated thus the beams are rebounded to the initial-state. Hence, when the harvester is under a temperature-difference, the beams' pulling-down/back process is cyclic. Due to the piezoelectric effect, the piezoelectric-sheet fixed on the beams continuously produces voltage-response. Under the temperature-difference of 29˚C, the voltage-response of the harvester is 30.4 mV with an oscillating-frequency of 0.098 Hz.

Keywords: Energy Harvester, Power Generator, Thermal, Magnetic, Piezoelectric

1. INTRODUCTION

To date, thermal energy harvesting is one of the important research topics for powering wireless sensors network (WSN) [1-4]. Among substantial thermal energy harvesting approaches, some researchers demonstrated novel thermo-magnetic energy harvesters to harness the ambient thermal energy from a temperature difference in the environment and consequently convert the thermal energy to an electrical energy to power the wireless sensors [5-11]. However, the thermo-magnetic energy harvesters are too bulky to be integrated to the wireless sensor nodes implanted in human body for medical WSN applications and embedded in tiny mechanical structures for structural-health-monitoring WSN applications. Therefore, to be integrated with wireless sensors for these WSN applications, the thermo-magnetic energy harvesters have to be miniaturized. Hence, in this paper, we demonstrate a miniature thermomagnetic energy harvester. According to the dimension/size, our harvester is 20-times smaller than the other thermomagnetic energy harvesters. The details of the design, fabrication, testing, and result of the harvester are described in following sections.

2. DESIGN

The design and energy-harvesting process of the miniature thermomagnetic energy harvester is illustrated in figure 1 and 2, respectively. In figure 1, the harvester consists of CuBe-alloy cantilever beams, piezoelectric PZT sheet, Gd soft magnet, NdFeB hard magnet, and glass mechanical frame. The piezoelectric sheet is bounded at the fixed end of the beams while the soft magnet is fixed on the free end of the beams. The beams, piezoelectric sheet, and connected wires are clamped by the mechanical frame as the harvester.

*tkchung@nctu.edu.tw; phone 886-3-5712121 ext. 55116; fax 886-3-572-0634

Active and Passive Smart Structures and Integrated Systems 2014, edited
by Wei-Hsin Liao, Proc. of SPIE Vol. 9057, 90570X · © 2014 SPIE
CCC code: 0277-786X/14/$18 · doi: 10.1117/12.2045294

The harvester's energy-harvesting process is shown in figure 2. Figure 2(a) shows the initial state of the process. In the initial state, the free end of the beams is near the cold side. At the cold side, the soft magnet is cooled. Thus, the temperature of the soft magnet is lower than its Curie temperature. This causes that the magnetic property of the soft magnet is changed from paramagnetic to ferromagnetic. After the soft magnet becomes ferromagnetic, a magnetic attractive force is produced between the soft magnet fixed on the beams and hard magnet fixed on the hot side. Due to the magnetic force, the beams with the soft magnet are pulled down toward the hard magnet fixed on the hot side as shown in figure 2(b). When the soft magnet is close to (but not contact) with the hot side, the soft magnet is heated. After the temperature of the soft magnetic is heated higher than its Curie temperature, the magnetic property of the soft magnet becomes from ferromagnetic to paramagnetic. Therefore, the magnetic attractive force is eliminated. Due to the spring-back force of the beams, the beams are pulled back to its initial state. The beams' pulling-down and pulling-back process is cyclic repeated when the harvester is placed in an environment with a constant temperature difference (i.e., the temperature difference is capable of producing the hot and cold sides for the harvester). Because the cyclic process causes the beams oscillated, the piezoelectric sheet fixed on the beams is periodically deformed. Due to the piezoelectric effect, the piezoelectric sheet continuously produces voltage response. That is, the energy-harvesting process of the thermo-magnetic energy harvester under a temperature-difference (or a thermal gradient) is achieved.

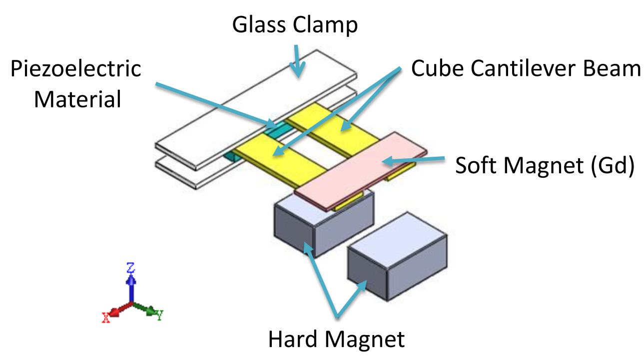

Figure 1: The illustration of the miniature thermomagnetic energy harvester

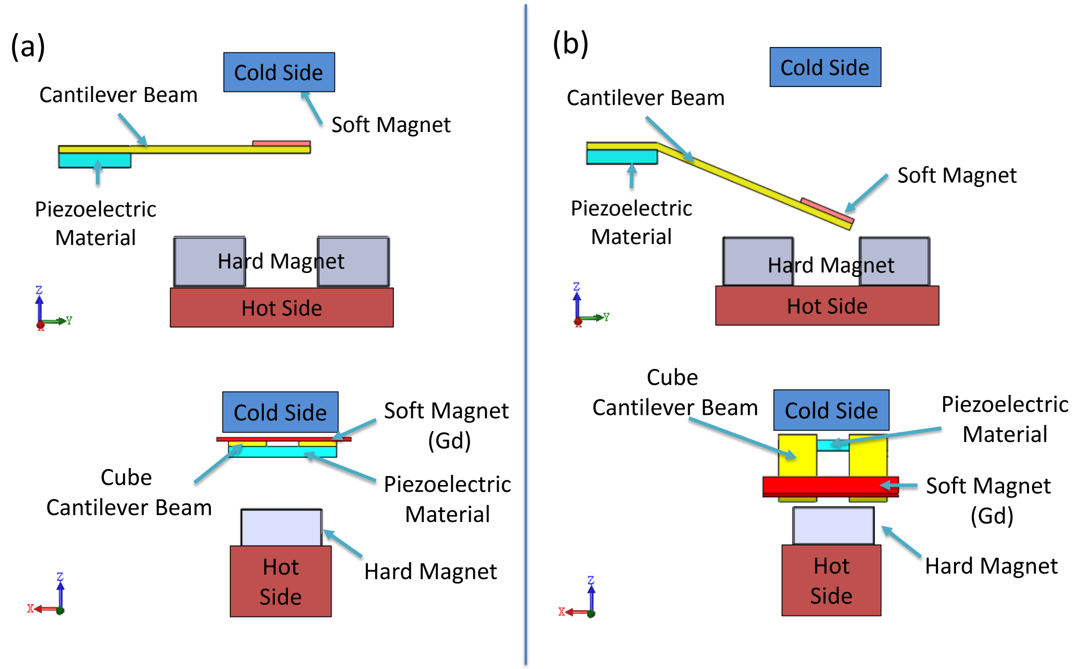

Figure 2: The energy-harvesting process of the miniature thermomagnetic energy harvester: (a) the initial state, the beam is near the cold side. (b) the beam is near the hard magnet fixed on the hot side.

3. FABRICATION

The miniature thermomagnetic energy harvester we fabricated is shown in figure 3. The harvester consists main four components: a CuBe cantilever beam with a Gd soft magnet sheet (the Curie temperature is near room temperature), NdFeB hard magnets, PZT piezoelectric sheet, and mechanical clamp. The CuBe cantilever beam and the Gd soft magnet is altered from a CuBe thin sheet and Gd thin sheet, respectively. The length × width × height of the CuBe cantilever beam and the Gd soft magnet is 25 mm×5 mm × 10 μ m and 20 mm × 7mm × 250 μ m, respectively. After the CuBe beam and Gd soft magnet are fabricated, we attach the Gd soft magnet on the CuBe beam through adhesive binding. We altered a PZT-5H thin plate into the PZT piezoelectric sheet. After this, the PZT sheet and CuBe beam are assembled by the mechanical glass-clamp. Finally, the NdFeB magnets (the length × width × height of each NdFeB magnet is 10mm ×5 mm ×5 mm) are fixed on the mechanical frame. After this, the energy harvest is fabricated. Regarding to the dimension of the harvester, the length, width, and thickness of the harvester is approximate 2.5 cm, 1.7 cm, and 1.5 cm, respectively. According to this dimension/size, our energy harvester is 20-times smaller than the other representative thermomagnetic energy harvesters [10, 11].

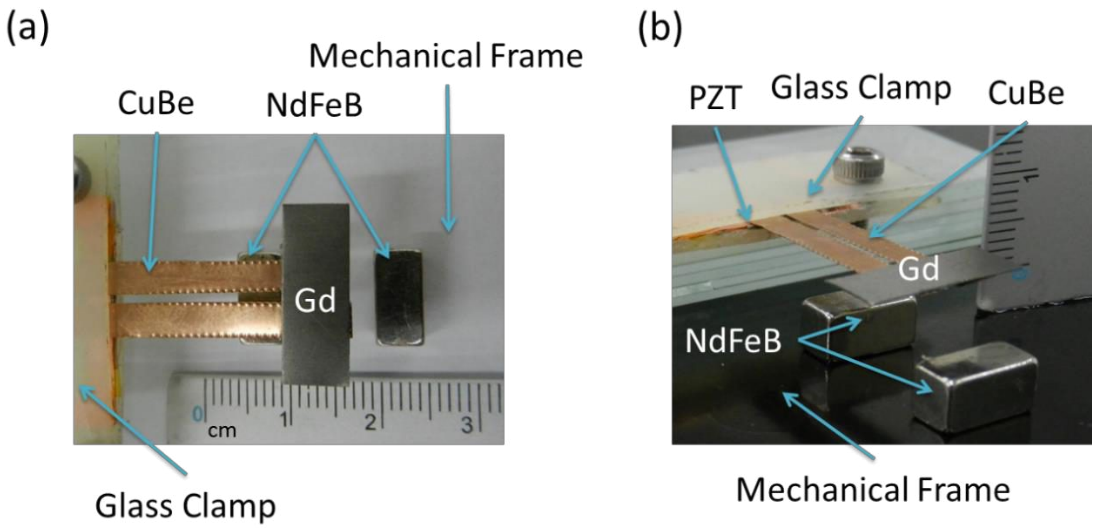

Figure 3: (a) Top view and (b) side view of the miniature thermomagnetic energy harvester

4. TESTING

After fabrication, the magnetic moment of the Gd soft magnet of the harvester at different temperature (i.e., M-T curve) is measured by superconducting Quantum Interference Device under a magnetic-bias of 500 Oe. The Curie temperature of the Gd soft magnet is estimated by analyzing the slope of the M-T curve (magnetic moment under different temperature). To measure this experimental Curie temperature is to confirm whether the real/experimental curie temperature of the Gd magnet is suitable for our design. After the confirmation, the harvester is tested as shown in figure 4. The harvester is set on a hot plate (as the hot side). The ice (as the cold side) is placed at a constant distance above the top of the harvester. A constant temperature difference is generated by the hot plate and ice. Under the temperature difference, the voltage response of the harvester is produced and subsequently measured by the oscilloscope.

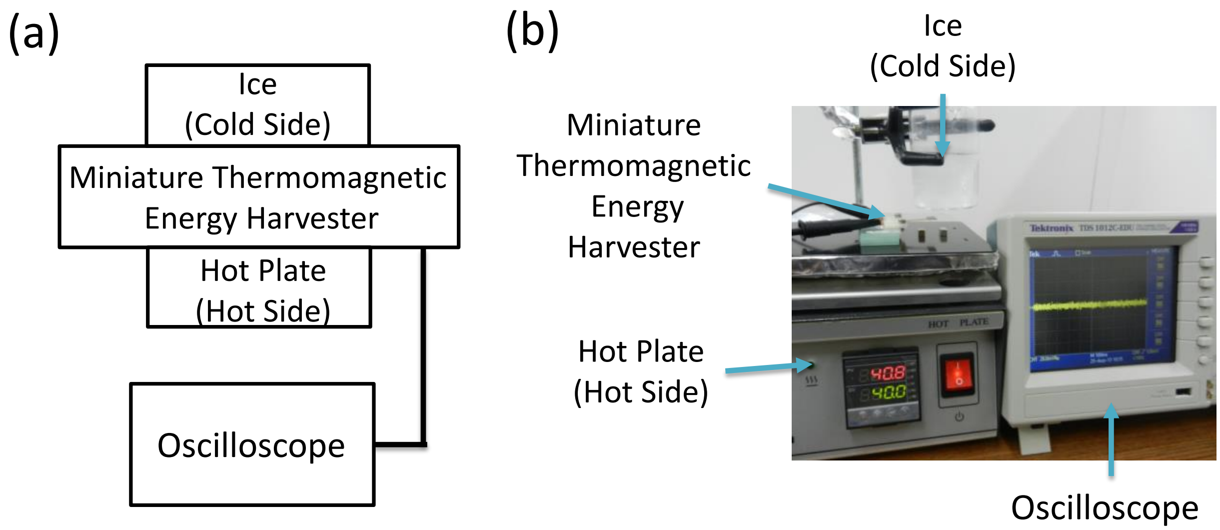

Figure 4: (a) The illustration and (b) photograph of the testing setup of the miniature thermomagnetic energy harvester

5. RESULT AND DISCUSSION

Figure 5 is the M-T curve of the Gd magnet. The measured magnetic moment of the soft magnet Gd at different temperature (i.e., M-T curve) is shown in figure 9. We know the soft magnet Gd becomes paramagnetic from ferromagnetic is the Curie temperature of this material. By analyzing figure 5, we estimate the Curie temperature of soft magnet Gd is in the range of 22 ˚C to 32 ˚C. That is, the soft magnet Gd is approximate at room temperature we designed. Through this analyzing, the harvester is able to demonstrate the thermal energy harvesting process utilizing this soft magnet Gd.

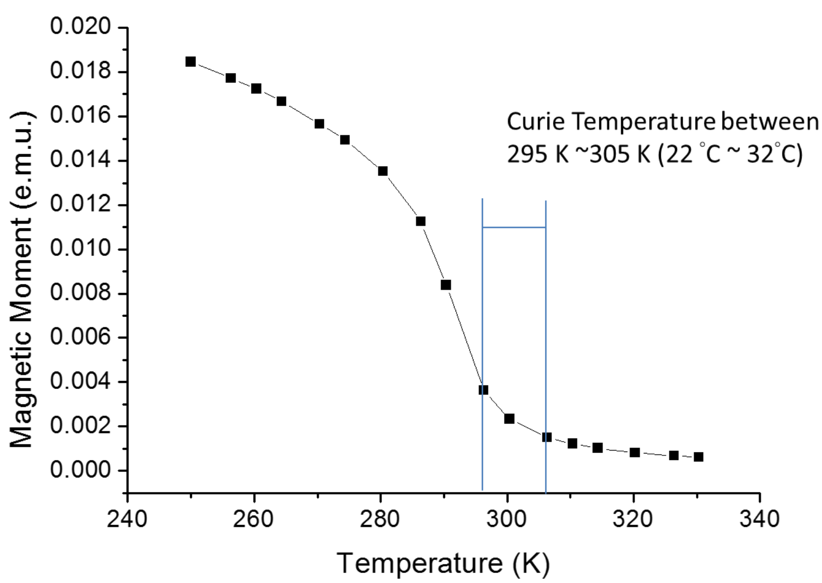

Figure 5: The magnetic moment of the Gd soft magent of the harvester at different temperature under a magnetic bias of 500 Oe

The voltage response of the miniature thermomagnetic energy harvester at the temperature difference of 29 ˚C (the temperature of the cold and hot side is 6 ˚C and 35 ˚C, respectively) is shown in figure 6. In figure 6, the voltage response of the harvester we measured is up to 30.4 mV. The cycling frequency of the thermal energy-harvesting process is approximate 0.098 Hz. In each energy-harvesting cycle, there are two major voltage responses. When the Gd soft magnet on the CuBe beam is cooled down by approaching to the cold side, the Gd soft magnet becomes ferromagnetic. This causes the magnetic attractive interaction between Gd soft magnet on the CuBe beam and the NdFeB hard magnet on the mechanical frame. Due to this attractive interaction, the CuBe beam is attracted toward the NdFeB hard magnet and consequently bent. Therefore, the PZT piezoelectric sheet is deformed by the deflection of the CuBe beam and subsequently produces the voltage-peak of approximate 30.4 mV due to the piezoelectric effect. When the Gd soft magnet is heated by the hot side, the Gd magnet becomes paramagnetic resulting in reducing the magnetic attractive interaction. Eventually, the magnetic-attractive interaction is eliminated. Hence, the spring-back force bounces the CuBe beam back to its original location. This produces another voltage-peak which is also approximate 30.4 mV. According to these, both voltage peaks in each cycling process of our miniature thermomagnetic energy harvesting are comparable than other representative thermomagnetic harvesters [10,11] while the volume of our harvester is 20-times smaller than the other harvesters. To sum up, this result shows the harvester we demonstrated is capable of harnessing the thermal energy from the ambient temperature-difference and consequently converting the thermal energy to the electrical output. The most important is, our harvester's voltage-response per volume is much higher than that of other harvesters.

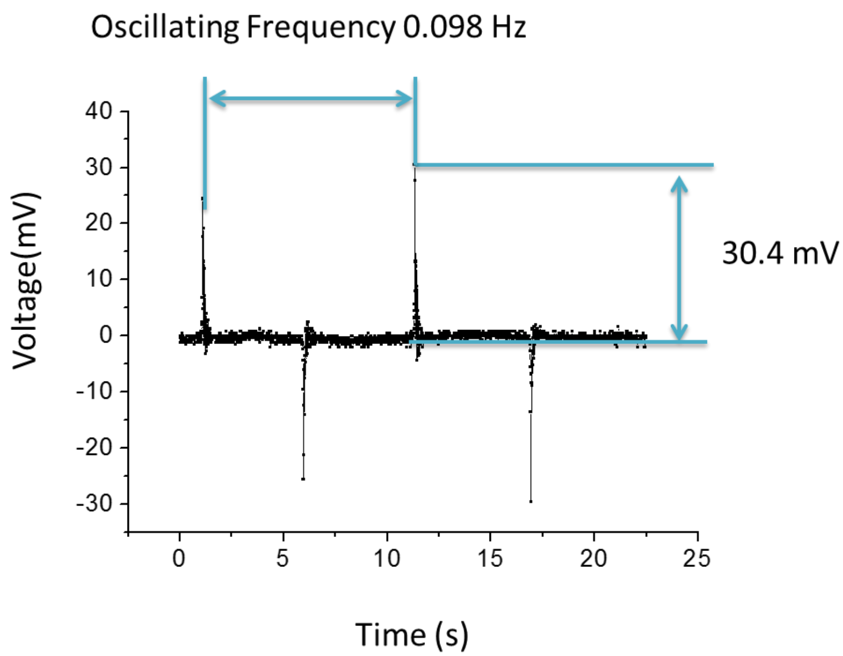

Figure 6: The voltage response of the miniature thermomagnetic energy harvester under the temperature difference

6. CONCLUSION

We successfully demonstrated a miniature thermomagnetic energy harvester. The harvester is capable of harnessing the thermal energy from the ambient temperature-difference and consequently converting the thermal energy to the electrical output. The most important progress we achieved is that the dimension/size of the thermomagnetic harvester is 20-times smaller than other representative thermomagnetic harvesters while the voltage output of these harvester are comparable. In the future, the harvester will be continuously improved to increase its voltage output and be miniaturized by advanced semiconductor manufacturing technology in order to integrate with sensors toward self-powered wireless sensors.

ACKNOWLEDGEMENT

Support for this work was obtained from the Taiwan National Science Council (NSC Grant No. 102-2221-E-009-034- and NSC Grant No. 102-2625-M-009 -005-).

REFERENCES

[1] Wright, P. K., Dornfeld, D. A., Hillaire, R. G. and Ota, N. K., "A wireless sensor for tool temperature measurement and its integration within a manufacturing system," Transactions of the North American Manufacturing Research Institute of SME., 63-70 (2006).

[2] Farinholt, K. M., Miller, N., Sifuentes, W., MacDonald J., Park G., and Farrar C. R., "Energy harvesting and wireless energy transmission for embedded SHM sensor nodes," Structural Health Monitoring, (9), 269-280 (2010).

[3] Fan, Z., Gao, R. X., and Kazmer, D. O., "Self-energized acoustic wireless sensor for pressure-temperature measurement in injection molding cavity," IEEE Sensors Conference, 65-68 (2009).

[4] Leonov, V., Torfs, T., Fiorini, P., Van Hoof, C., "Thermoelectric converters of human warmth for self-powered wireless sensor nodes," IEEE Sensor Journal, (9), 650 -657 (2007).

[5] Ujihara, M., Carman, G. P. and Lee, D. G., "Thermal energy harvesting device using ferromagnetic materials," Applied Physics Letters, 91(9), 093508 (2007).

[6] Bulgrin, K. Y., Ju, Y. S., Carman, G. P. and Lavine, A. S., "An investigation of a tunable magnetomechanical thermal switch," Journal of Heat Transfer, 133(10), 101401 (2011).

[7] Bulgrin, K. Y., Ju Y. S., Carman G. P. and Lavine A. S., "A coupled thermal and mechanical model of a thermal energy harvesting device," ASME International Mechanical Engineering Congress and Exposition, Proceedings, 6, 327-335 (2010).

[8] Carlioz, L., Delamare, J. and Basrour, S., "Temperature threshold tuning of a thermal harvesting switch," Solid-State Sensors, Actuators and Microsystems Conference, 1385-1388 (2009).

[9] Carlioz, L., Delamare, J. and Basrour, S., "Hybridization of magnetism and piezoelectricity for an energy scavenger based on temporal variation of temperature," Symposium on Design, Test, Integration and Packaging of MEMS/MOEMS, 311-313 (2008).

[10] Chung, T. K., Tseng, C. Y., Chen, C. C. and Wang, C. M., "Design, fabrication, and testing of a thermal/mechanical/magnetic hybrid energy micro-harvester," ASME 2012 Conference on Smart Materials, Adaptive Structures and Intelligent Systems, 249-254 (2012).

[11] Chung, T. K., Shukla, U., Tseng, C. Y., Chen, C. C. and Wang, C. M., "A magnetic/piezoelectric-based thermal energy harvester," Proc. SPIE 8688, 86880M (2013).