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Procedia Engineering 5 (2010) 1176–1179

Procedia Engineering

www.elsevier.com/locate/procedia

Proc. Eurosensors XXIV, September 5-8, 2010, Linz, Austria

A Multi-source Micro Power Generator Employing Thermal and Vibration Energy Harvesting

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Abstract

This paper introduces a new cantilever type multi-source energy harvester generating electric power from both ambient heat and vibration. Harvesting energy from vibration was realized by electromagnetic conversion, whereas the energy generation from heat was supplied by making use of Seebeck effect of Cr-Al thermocouples implemented on the microcantilevers. The measured average Seebeck coefficient is 12 µV/K per thermocouple. A total voltage of 3.3 mV was generated from the thermoelectric part and 13.4 mV from the electromagnetic part of the device. Measured total power from the fabricated chip is 1.91 nW (1.12 nW from vibration, 0.79 nW from thermoelectric).

Keywords: energy harvesting; thermoelectric, electromagnetic; vibration; micro power generation

1. Introduction

Energy harvesting for wireless sensor networks has become a popular subject as low power electronic interfaces are evolved. Most of the time, energy generation from single source microgenerators is not even sufficient to meet the power requirement of low-power electronic interfaces. Thus, hybrid solutions utilizing multiple ambient energy sources in a single chip can be an option to overcome the low power issue.

Thermoelectric energy harvesting is a favorable option since ambient heat is always present in various environments such as mobile systems, industrial machines, and many components in a car. Several thick-film and thin-film thermoelectric microgenerators were previously introduced in literature [1-3]. High figure of merit thermoelectric materials (polysilicon, Bi_2Te_3 etc.) offer the best thermoelectric efficiency in most of the cases. However, the implementation of these materials to micro devices requires complicated and high-cost fabrication steps. At this point, metals having a high thermoelectric power factor are often used as thermocouple materials [1].

Energy harvesting from vibration is a commonly used technique due to its high energy density and abundance of vibration in nature. Piezoelectric, electrostatic, and electromagnetic energy conversion mechanisms are the methods used for energy harvesting from vibration [4]. Various vibration based electromagnetic energy scavengers were produced in METU MEMS Center [5, 6]. Also, vibration based energy harvesters using multiple conversion methods were previously reported in literature [7]. In this study, the design and development of a micro power generator utilizing both electromagnetic and thermoelectric energy harvesting in a single chip was introduced.

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doi:10.1016/j.proeng.2010.09.321

2. The multi-source harvester operation

Figure 1 shows the structure of the proposed multi-source energy harvester. The device consists of Parylene C cantilevers having two layers to utilize electromagnetic and thermoelectric energy conversion. On the bottom layer, coils are placed on Parylene C for the electromagnetic energy harvesting. On the other hand, thermocouples lie on the upper layer of the cantilever for thermoelectric energy conversion. There is an intermediate layer of Parylene C through coils and thermocouples to insulate them both electrically and thermally.

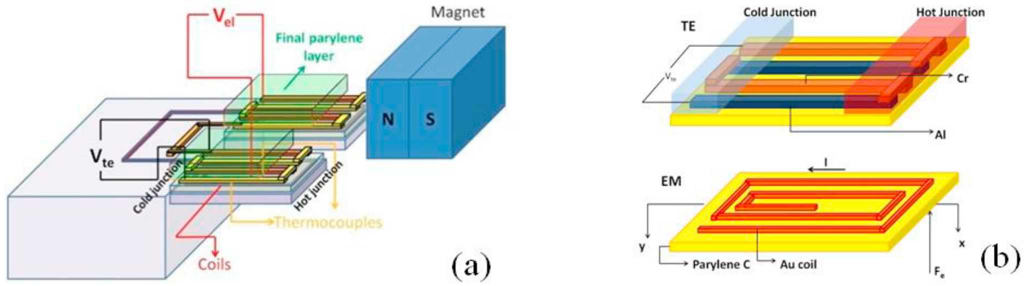

Fig. 1. (a) Structure of the multi-source energy harvester; (b) thermoelectric and vibration energy generation parts on the cantilever.

External vibration results in oscillation of the cantilevers. The relative movement of the cantilever with respect to the magnet induces an electric current through the coils, where the electromagnetic energy conversion takes place. The coils are connected in series to add up the power from each cantilever. Parylene C is chosen as the structural material since it allows large tip deflections, which results in an increased voltage output. The base motion given to the cantilevers is defined by Eq. (1).

$$y(t) = Y \cdot \sin(\omega \cdot t) \tag{1}$$

where Y is the amplitude of the base vibration, ω is the vibration frequency and t is the time.
The equation of motion for the cantilever is expressed as in Eq. (2).

$$m_{eq} \cdot \ddot{z} + b_{eq} \cdot \dot{z} + k_{eq} \cdot z = -m_{eq} \cdot \ddot{y} \tag{2}$$

where m_{eq} is the equivalent mass, k_{eq} is the equivalent stiffness of the cantilever, b_{eq} is the equivalent damping coefficient, $\ddot{z}$ is the acceleration of a point on the cantilever, z is the relative displacement of a point on the base with respect to the base, and $\ddot{y}$ is the acceleration of the base. The voltage generated due to vibration is equal to rate of change of magnetic flux with time and calculated by Eq. (3).

$$\varepsilon = \frac{-d\phi}{dt} = \frac{-d(\sum_{i=1}^{n}(\vec{B} \cdot \vec{A}_i))}{dt} \tag{3}$$

where ε is the generated voltage, ϕ is the magnetic flux density, B is the magnetic field strength at the coil location, $\vec{A}_i$ is the area of each coil turn, and t is the time.

Thermoelectric energy generation was realized by creating a temperature gradient between the end points of the thermocouples, by heating the tip of the cantilever with an ambient heat source. The cold junctions of these thermopiles are placed on the base of the cantilevers to ensure the heat flow to the Si substrate, which is used as a heat sink. The thermocouples are covered by an additional thermal insulation layer of Parylene C at the top to avoid heat absorption at the other regions of the cantilever except its tip point. The voltage generated is due to the Seebeck effect in the metals and is expressed as:

$$V_{te} = n \cdot \alpha \cdot \Delta T \tag{4}$$

where n is the number of thermocouples, α is the relative Seebeck coefficient of the metals used and ΔT is the temperature difference between the hot and cold junctions. The generated power (P_{te}) is calculated by Eq. (5) [8].

$$P_{te} = \frac{V_{te}^2}{R_{el}} \tag{5}$$

where V_{te} is the thermoelectric voltage and R_{el} is the electrical resistance of the thermocouples. The optimized design parameters and microgenerator features are given in Table 1.

Table 1. Features of the microgenerator design

Device dimensions	9.5x8x6 mm^3	Thermocouple length	860 µm
Magnet size	6x6x6 mm^3	Thermocouple width (Cr/Al)	13 µm/10 µm
Cantilever dimensions	0.89x0.67x0.012 mm^3	Thermocouple thickness	0.5 µm/0.2 µm
Thermocouples	Cr/Al	Magnet type	NdFeB (1.18 T)
Number of cantilevers	20	Coil Resistance	680 Ω
Number of thermocouples on a single cantilever	22		

3. Fabrication

Fig. 2 and Fig. 3 show the fabrication flow and fabricated prototypes, respectively. During the fabrication, first, an oxide layer of 1 µm was grown on Si substrate. The second step is to deposit and pattern 1 µm Parylene-C structural layer to define the shape of the cantilevers (Fig. 2. a). A Ti-Au layer of 0.22 µm was sputtered afterwards to form the coils (EM part) (Fig. 2. b.). After a second Parylene C insulation layer, Ti/Au layer was sputtered for electrical connection to the coils and interconnects. On an intermediate Parylene C insulation layer, the thermocouples were fabricated (Fig. 2. f-i). A final Parylene C insulation layer was deposited and cantilevers are released using backside etching of Si substrate and SiO_2 layer (Fig. 2. k-l).

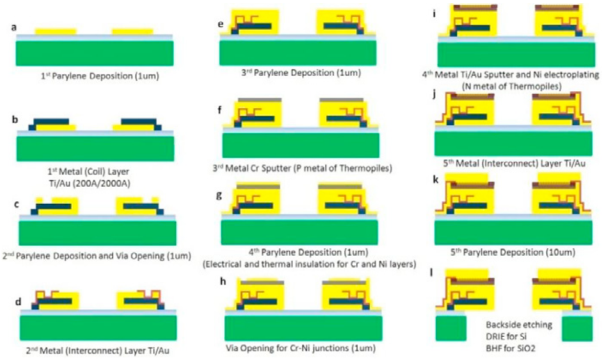

Fig. 2. Fabrication flow for the hybrid electromagnetic-thermoelectric energy harvester.

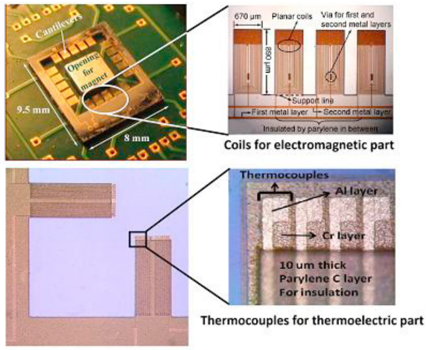

Fig. 3. A close up on coils are shown on the top [9]. On the bottom close up views of implemented thermocouples on cantilevers are shown.

4. Performance evaluation of the multi-source generator

The thermoelectric scavenging performance was evaluated by indirectly heating the silicon substrate. The thermal simulation on one cantilever was also performed on ANSYS Workbench. A voltage of 3.3 mV DC and a power of 0.79 nW is generated from the thermoelectric part of the device. ANSYS simulation results of the temperature profile and comparison between the simulated and measured voltage on one cantilever can be seen in Fig. 4 and Fig. 5.

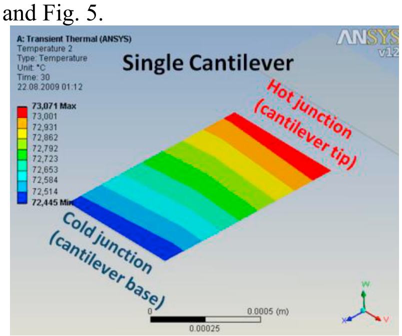

Fig. 4. ANSYS simulation result showing the temperature profile on one cantilever

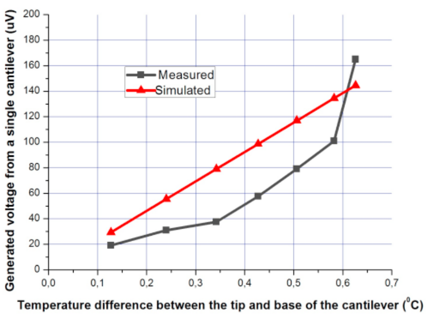

Fig. 5. Comparison of calculated and measured values of the generated thermoelectric voltage

The vibration tests were performed on a shaker table at a frequency of 3.45 kHz, which is the resonance frequency of the cantilevers. A vibration amplitude of 1 µm was supplied to the base to provide the oscillation motion of the cantilevers. The AC voltage obtained from the electromagnetic part is 13.4 mV p-p and the power generated is 1.12 nW. Fig. 6 shows the measured electromagnetic voltage from a single cantilever and 5 consecutive cantilever arms [6]. The operation characteristics and test results for the thermoelectric and electromagnetic part were presented in Table 2.

Table 2. Performance characteristics of the multi-source energy harvester.

	EM Scavenger	TE Scavenger	Total
Vibration Amplitude	1 µm	-	
Operation Frequency	3.45 kHz	-	
Distance between cantilevers to magnet	500 µm	-	
Coil Resistance	15 kΩ	-	
Thermocouple resistance	-	0.69 kΩ	
Maximum power	1.12 nW	0.79 nW	1.91 nW
Maximum voltage	13.4 mV	3.3 mV	16.7 mV

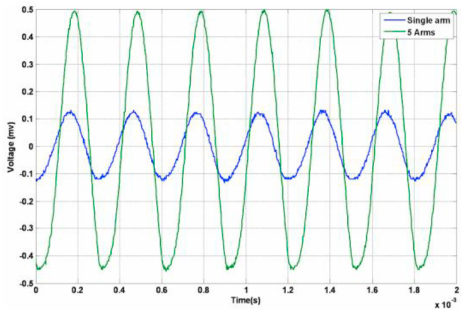

Fig. 6. Measured electromagnetic voltage from a single arm and 5 consecutive cantilever arms [6].

5. Conclusion

A multi source energy harvester, using multiple energy sources (heat and vibration) to produce electrical energy was introduced. The simulation and initial test results were obtained for the device. A total voltage of 16.7 mV was generated from the device. Measured total power from the fabricated chip is 1.91 nW (1.12 nW from EM, 0.79 nW from thermoelectric). Use of materials with higher Seebeck coefficients and isolating tips of the cantilevers from the silicon layer by releasing will improve the thermoelectric efficiency of the chip in later versions. Although the generated power level is in nanowatts range, these results are promising to show that multi-source energy harvester designs can be fabricated on the same chip with compatible fabrication flows. Power level for this particular device can be increased significantly by increasing the cantilever number, by using high Seebeck coefficient materials, and/or by optimizing the layer thicknesses for better thermal and vibration based harvesting.

Acknowledgements

This work was supported by The Scientific and Technological Research Council of Turkey (TUBITAK) under Grant Number 104E119.

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