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Design, simulation, fabrication and characterization of a micro electromagnetic vibration energy harvester with sandwiched structure and air channel

Peihong Wang [a,*], Huiting Liu [b], Xuhan Dai [c], Zhuoqing Yang [c], Zhongzhu Wang [a], Xiaolin Zhao [c]

[a] School of Physics and Material Science, Anhui University, Hefei, 230039, China
[b] School of Computer Science and Technology, Anhui University, Hefei 230039, China
[c] Research Institute of Micro/Nano Science and Technology, Shanghai Jiao Tong University, Shanghai 200240, China

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ABSTRACT

This paper presents the design, simulation, fabrication and characterization of a novel electromagnetic vibration energy harvester with sandwiched structure and air channel. It mainly consists of a top coil, a bottom coil, an NdFeB permanent magnet and a nickel planar spring integrated with silicon frame. The prototype is fabricated mainly using silicon micromachining and microelectroplating techniques. The tested natural frequency of the magnet–spring system is 228.2 Hz. The comparison between the simulation and the tested results of the natural frequency shows that the Young's modulus of microelectroplated Ni film is about 163 GPa rather than 210 GPa of bulk Ni material. Experimental results indicate that the sandwiched structure and the air channel in the silicon frame of the prototype can make the induced voltage increase to 42%. The resonant frequency of the prototype at 8 m/s^2 acceleration is 280.1 Hz, which results from the nonlinear behavior of the magnet–spring system. The load voltage generated by the prototype is 162.5 mV when the prototype is at resonance and the input vibration acceleration is 8 m/s^2 and the maximal load power obtained is about 21.2 μW when the load resistance is 81 Ω.

1. Introduction

There has been a great advance in microelectronics technology and ultra low power Very Large Scale Integration (VLSI) design over the past decades. This advance has led to the generation and application of various new miniature sensor/actuators and microsystems. They have very small volume and low power consumption; they are wireless, portable and even embeddable. So they can be used in intelligent monitoring, health care, automotive industry, medical implants, wireless sensor networks, Microelectromechanical systems (MEMS), etc. However, power requirements place important limits on the capability of these devices, since the developing speed of conventional battery technology is far slower than that of integrated circuit technology described by Moore's law [1]. Batteries having limited lifetime, are bulky compared with microsystems, and need to be recharged. Moreover, batteries cannot power some embedded devices, which does not have any physical connections to the outside and it is hardly possible to periodically replace batteries for thousands of sensor nodes in wireless sensor network. Therefore, a renewable power source must be developed to substitute batteries or electrical cable to power these wireless microsystems.

Harvesting energy from the ambient environment and then converting it into electrical power is a very promising alternative to conventional power sources. Energy can be harvested from many ambient sources such as light, heat and vibration [2–5]. Solar cells supply excellent power in direct sunlight, but it is not convenient for embedded systems and not efficient in dim environment. Thermal energy can be scavenged from the environment with high thermal gradient; however, thermal gradient over MEMS scale is very small. Mechanical vibrations seem to be the most promising energy source since they are abundant in many environments. As a typical kind of energy harvesting techniques, various electromagnetic vibration energy scavengers have been developed [6–14] since Williams et al. reported the analysis of a micro-electric generator for microsystems in 1996. However, the structures of these reported energy harvester prototypes are same and consist of only one induced coil, a permanent magnet and a spring. In this structure, only the magnetic field close to the coil can be used to convert energy, although the magnetic field exists around the magnet. So the magnetic field is not used sufficiently.

We have presented an electromagnetic vibration energy harvester with an electroplated metal spring and a two-layer copper coil previously [15,16]. In this paper, a micro electromagnetic vibration energy harvester with sandwiched structure and

* Corresponding author.
E-mail addresses: wangpeihong2002@ahu.edu.cn, wangph168@hotmail.com (P. Wang).

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air channel is presented. Its sandwiched structure is clearly different with our previous work and other published prototypes. Its symmetrical arrangement of two coils can use the magnetic field more efficiently and the air channel in the silicon frame can decrease the air damping efficiently, both of which can increase the output performance of energy harvester. The prototype is fabricated mainly using microelectroplating and silicon micromachining techniques. Tested results show that the prototype has better performance compared with our previous work and other single coil structures.

2. Design and simulation

The 3-D schematic and cross-section view of the sandwiched electromagnetic vibration energy harvester are shown in Fig. 1. It mainly consists of a top coil, a bottom coil, an NdFeB permanent magnet and a Nickel (Ni) planar spring integrated with silicon frame. The magnet–spring system is used to harvest the mechanical vibration energy and the magnet–coil system is used to convert vibration energy into electrical energy. When outside vertical vibration is applied on the vibration energy harvester, the magnet will vibrate up and down relative to the coil, which results in the change of the magnetic flux through the coil. According to Faraday's law of induction, induced voltage is generated in the coil and induced current is generated in the circuit if the coil is connected into an outside circuit.

In the sandwiched structure, the top coil and the bottom coil are located symmetrically on each side of the magnet, respectively. So when the energy harvester is working, the top coil and the bottom coil can generate same electrical energy. As a result, the generated electrical energy of the energy harvester is increased after top coil and bottom coil are connected in series. If the sandwiched structure is sealed, the inner air will generate air pressure on the magnet–spring system to damp their vibration and so decrease the amplitude of the magnet when the device is working. If the structure is with air channels, the inner air will flow freely and so will not damp the vibration of magnet–spring system. So the air channel in the silicon frame can decrease the air damping effect and then the output performance of the energy harvester can be increased further. Moreover, the gap between the magnet and the coil can be controlled by using silicon frame with different thickness or multiple silicon frames with same thickness. The glass substrate with top coil is like a cap so that it can protect the magnet–spring system and does not increase the total volume additionally.

The design, modeling and simulation details of vibration energy harvester with single coil structure have been reported in our previous work [15,16]. Here we simulate and discuss the influence of the Young's modulus of Ni on the natural frequency of the mass–spring system, since there is a great difference between the Young's modulus of bulk Ni material and that of microelectroplated Ni film. In the simulation, the Young's modulus of bulk Ni material is defined as 210 GPa [17] and that of microelectroplated Ni film 163 GPa [18]. Fig. 2 shows the simulation results about the relationship between the natural frequency of Ni spring and the spring's thickness under different Young's modulus of Ni material. As seen from Fig. 2, the natural frequency of Ni spring increases with the thickness of the Ni spring. Meanwhile, the natural frequency of Ni spring with 210 GPa Young's modulus is always bigger than that with 163 GPa Young's modulus. Moreover, the thicker is the Ni spring, the bigger is the difference between the natural frequencies under different Young's modulus.

3. Fabrication

The presented sandwiched electromagnetic vibration energy harvester is fabricated using MEMS micromachining technique. The fabrication process of the micro two-layer copper coil has been described previously [15,16]. The nickel planar spring on the silicon frame with air channel is fabricated using microelectroplating and silicon micromachining technique. The detailed fabricated process is shown in Fig. 3 (a)–(h). Fig. 3(a) shows that the photoresist (AZ P4903) is spin coated on the backside of a double-side polished silicon wafer, which is thermally oxidized on both sides and then patterned by photolithography. Fig. 3(b) shows that the exposed SiO_2 layer is wet etched using HF solution and then the photoresist is removed. Fig. 3(c) shows that the exposed

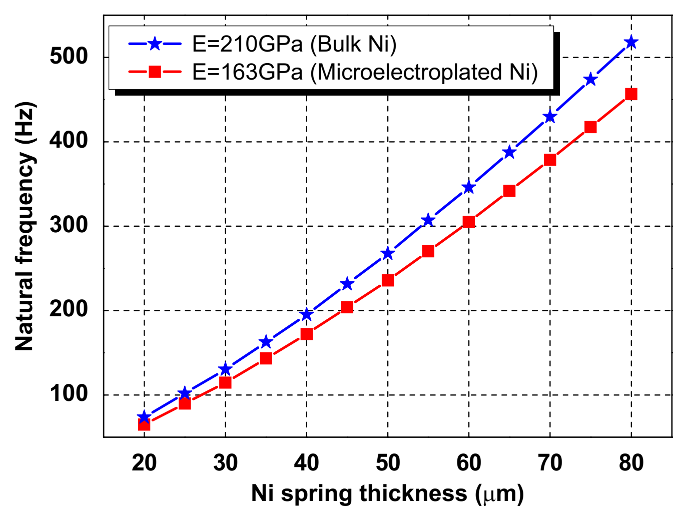

Fig. 2. Natural frequency of the magnet–spring system versus spring thickness with different Young's modulus of Ni material.

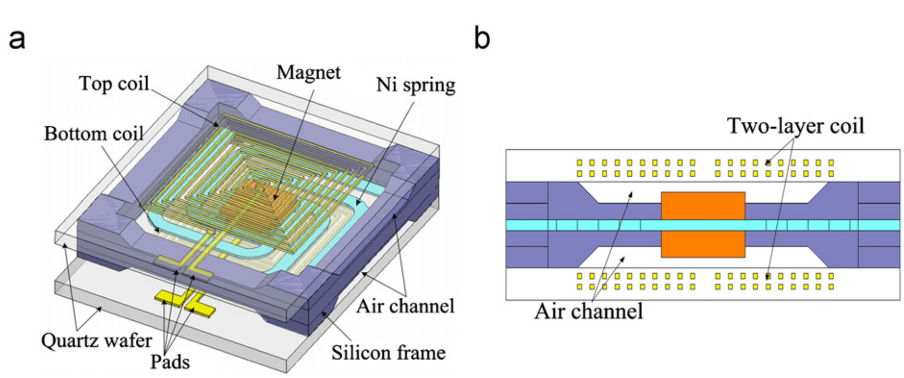

Fig. 1. Schematic of the sandwiched vibration-based power generator: (a) 3-D view, (b) cross-section view.