AN ELECTROMAGNETIC ENERGY HARVESTER WITH INTEGRATED MAGNET ARRAY

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Abstract: An electromagnetic energy harvester with integrated CoNiMnP permanent magnet array is designed, fabricated and tested. Mechanical and magnetic simulations are performed to investigate the vibration characteristics and magnetic field distribution. The size and shape of the device are also optimized. CoNiMnP permanent magnet array is fabricated using electroplating technology instead of manually assembly which is compatible with MEMS batch process, and greatly increases the production efficiency. The output of the fabricated prototype is tested under different frequencies and the maximum open-circuit AC peak-peak voltage is obtained at the frequency of 124 Hz.

Keywords: electromagnetic, energy harvester, electroplating, magnet array

INTRODUCTION

In recent years, wireless sensor network is becoming widely used among various applications such as bio-implantable devices, embedded systems and portable electronics. For stable performance, power sources of these devices should have long lifetime. Besides, the development microelectronics calls for the integration of the power sources. It is obvious that the traditional methods of power supply are unable to meet the need. Scavenging energy from the ambient sources is a new way of energy supply. There are many energy sources in the environment, such as vibration, heat, solar energy and wind energy[1]. Compared with other kinds of energy, vibration is almost available everywhere and can be easily utilized through MEMS technology. MEMS energy harvester can automatically convert vibration from the environment to electrical energy, which is a promising substitute for battery to drive low power consumption microelectronic devices.

In general, the techniques of energy harvesting bases on electrostatic, piezoelectric and electromagnetic transduction[2, 3]. Among various kinds of energy harvester, electromagnetic energy harvester has relatively low impedance and can generate voltage without external power supply. However, batch fabrication of this kind of device has encountered difficulties. The magnets used in electromagnetic energy harvesters are usually manually assembled[4, 5], which is not compatible with IC fabrication. To overcome this difficulty, CoNiMnP permanent magnets have been electroplated with high performance[6] and energy harvester using this kind of permanent magnets have been fabricated[7].

In this work, a novel electromagnetic energy harvester with integrated magnet array is designed, fabricated and tested. Simulations are carried out first to study the relationship between the output performance and structure of the harvester. MEMS micromachining technology is used during the whole fabrication process which greatly increases the production efficiency and scales down the volume of the device.. Experimental results show that the prototype can generate 102 µV open-circuit AC peak-peak voltage at 124 Hz.

THEORETICAL ANALYSIS

Fig.1 shows a general model to describe the energy harvester, which consists of a spring (k), a damper (b) and a seismic mass (m) [2]. The damper can be divided into two parts: mechanical damping (b_m) and electrical damping (b_e).
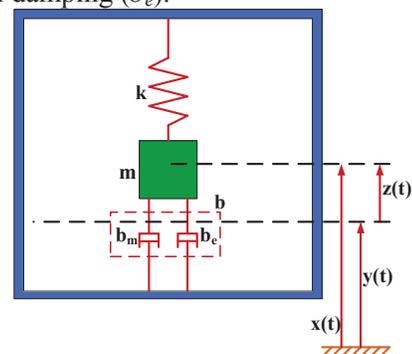

Fig 1 : Model of an energy harvester

The vibration from the excitation or the environment drive the generator housing to vibrate with a displacement of *y(t)*. Because of the spring and

the damper, there will be a relative displacement $z(t)$ between the mass and the housing. According to Newton's second law, the differential equation of the motion can be described as following:

$$m\ddot{z}(t) + (b_m + b_e)\dot{z}(t) + kz(t) = -m\ddot{y}(t) \quad (1)$$

where m is the seismic mass, k is the spring stiffness, b_m and b_e are the mechanical and electrical damping coefficient respectively. The power transferred to the mass can be expressed as the product of force and velocity:

$$p(t) = -m\ddot{y}(t) \times \dot{x}(t) \quad (2)$$

where $\dot{x}(t)$ is the sum of $\dot{y}(t)$ and $\dot{z}(t)$. Given a sinusoidal vibration, namely $y(t) = Y_0 \cos(\omega t)$, the generated power can be calculated from Eq. (1) and Eq. (2). In particular, when the device operates at resonance, maximum power is obtained:

$$P = \frac{mY_0\omega_n^3}{4(\dfrac{b_m}{2m\omega_n} + \dfrac{b_e}{2m\omega_n})} \quad (3)$$

where $\omega_n = \sqrt{k/m}$ is the resonant frequency of the energy harvester.

DESIGN OF THE DEVICE

The structure of the harvester is shown in Fig. 2, which consists of coils (conducting rods), vibrating plate and integrated magnet array. When vibration in the environment drives the plate to move along y direction, conducting rods cut the magnetic field many times during one vibration cycle, which multiplies the induced voltage.
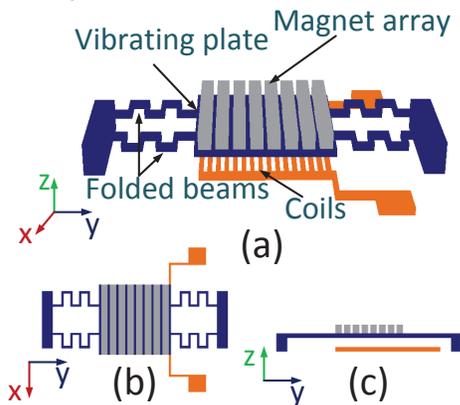
Figure 2. Schematic picture of the energy harvester: (a)3D view. (b)Top view. (c) Side view.

Finite Element Method (FEM) simulation is performed to prove the effectiveness of energy harvester. As shown in Fig. 3(a), increasing the number of conducting rods from 2 to 8, the induced voltage increases from 30.59 μV to 89.56 μV. The induced voltage can also be increased by increasing the number of magnets (Fig. 3(b)).
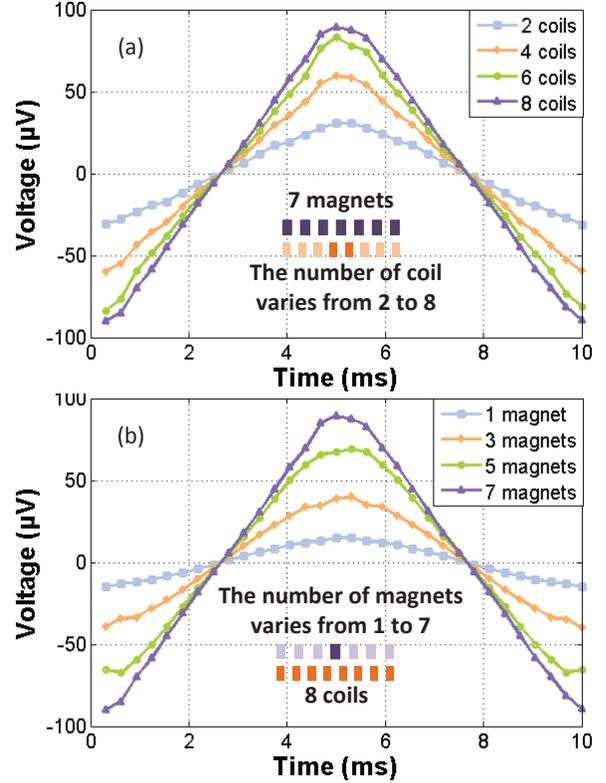
Figure 3. Induced voltage versus the number of coils and magnets by FEM simulation.

To optimize the size and shape of the harvester, FEM (finite element method) simulation is conducted. Firstly, electromagnetic transient simulations are performed in Maxwell 2D to optimize the size of the coil. Simulation results show that the induced voltage increases with the decreasing of line width and spacing of the coil. Considering the limitation of the fabrication process, we set both the width and the spacing of the coil to be 80 μm. Secondly, structure of the beams around the vibrating plate are specially designed through mechanical simulations (Fig. 4(a)). Given a force along Y-axis, the vibrating plate can vibrate at a amplitude of 1.1 μm. Four folded beams are used in our device which increases the effective length of the beam thus reducing the resonant frequency to a certain extent. Finally, distribution of the magnet array is optimized in Maxwell 3D using magnetostatic simulation. It has been proved that the magnetic field at the edge of the magnet is much stronger than that at the center. Therefore, using magnet array can largely increase the average

magnetic field in the effective area. Fig. 4(b) shows the optimized magnetic field of the magnet array. For each conducting rod, the induced voltage can be expressed as:

$$V_i = BLv \qquad (4)$$

where B is the instantaneous magnetic flux density on the conducting rod, L is the length of the conducting rod and v is the relative velocity of the movement. According to the above equation, the increased B can improve the induced voltage, which means the use of magnet array is an effective way to enhance the output of electromagnetic energy harvester.
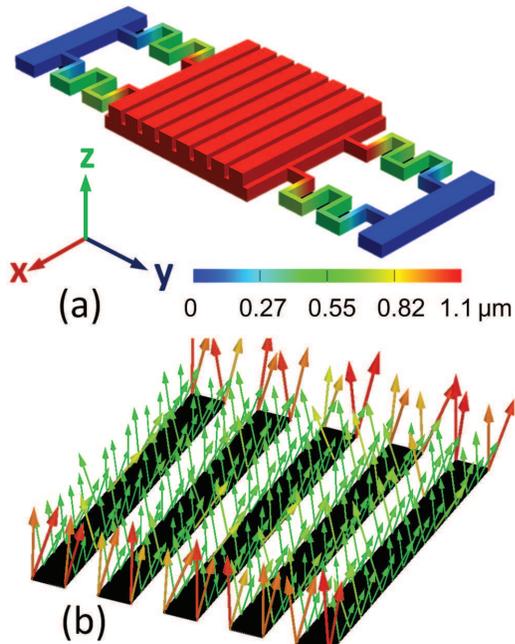

(a)

0   0.27   0.55   0.82 1.1 µm

(b)

Figure 4. FEM simulations: (a) Mechanical simulation of the vibrating plate. (b) Magnetic field distribution of the magnet array.

FABRICATION PROCESS

The permanent magnet in our device is fabricated through electroplating instead of manually assembly, which can greatly increase the production efficiency. Moreover, the use of electroplating technology can fabricate magnets with any pre designed shape. Fig. 5 shows the detailed fabrication process. First, titanium and copper are sputtered on silicon substrate as the seed layer (Fig. 5(a)). Next, copper coils are electroplate with the height of 10 µm (Fig. 5(b)). Then, two side pillars are electroplated to support the vibrating plate (Fig. 5(c)). As the next step, the copper vibrating plate with four folded beams is electroplated onto the copper seed layer (Fig. 5(d)). Given a Afterward, 10 µm CoNiMnP magnet array is

electroplated directly on the plate (Fig. 5(e)). The fabrication of the energy harvester is completed after removing photoresist and seed layers (Fig. 5(f)). SEM photos of the device are shown in Fig. 6.
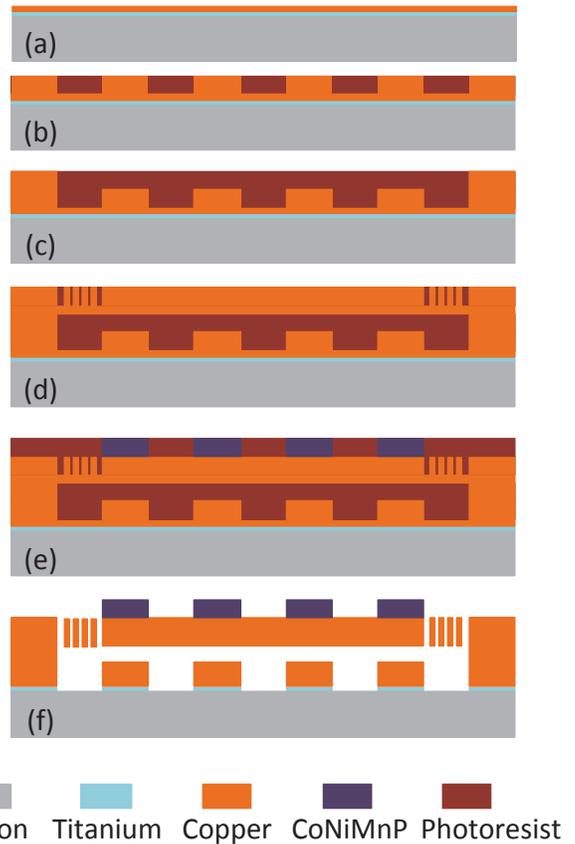

Slicon   Titanium   Copper   CoNiMnP   Photoresist
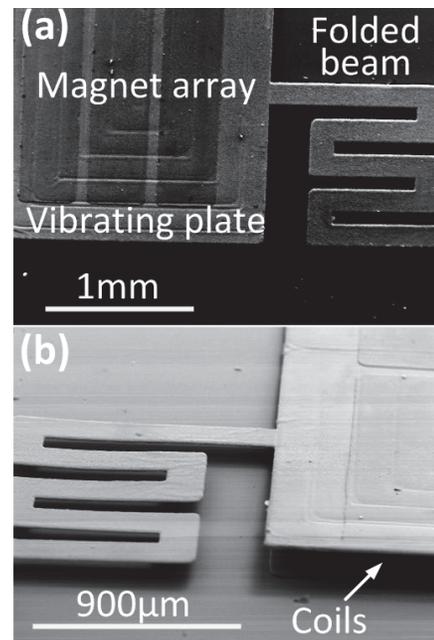
Figure 5. Fabrication process.

Figure 6. SEM photos of the energy harvester.

MEASUREMENT AND DISCUSSION

The output voltage of the harvester is tested using vibration system shown in Fig. 7. The source is produced by dynamic signal analyzer and amplified by an amplifier to drive the vibration generator. Energy harvester and accelerometer is placed on top of the vibrator. Given a vibration, both the induced voltage and acceleration is recorded in the dynamic signal analyzer. Under the acceleration of 0.2g, the peak output voltage reaches 102 µV at 124 Hz as shown in Fig. 8. Compared with other electromagnetic energy harvester, the volume of the permanent magnet in our device is much smaller, which leads to relatively low output voltage. Increasing the thickness of electroplated CoNiMnP magnet array, the induced voltage can be greatly improved due to the increasing of magnetic flux density.
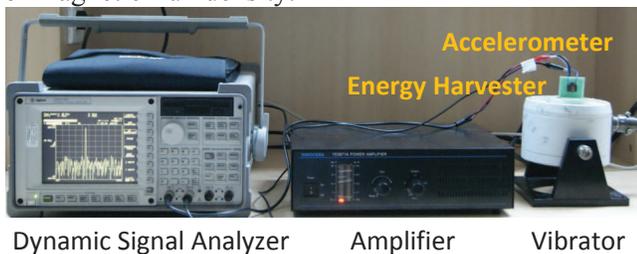

Dynamic Signal Analyzer　　Amplifier　　Vibrator
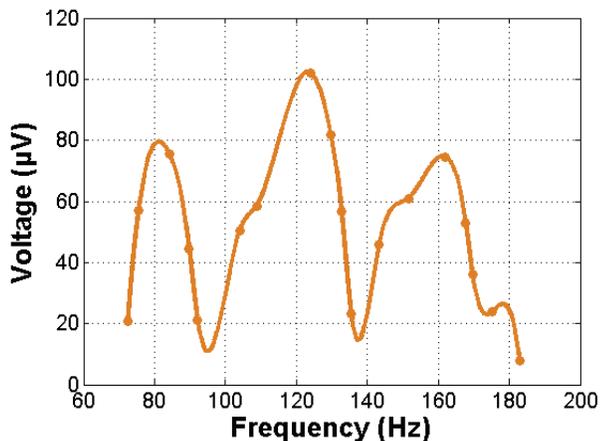
Figure 7. Testing system

Figure 8. Induced voltage versus frequency at the acceleration of 0.2g.

CONLUSIONS

A novel electromagnetic energy harvester is designed, fabricated and tested in this paper. The device consists of copper conducting rods, vibrating plate with four folded beams, and CoNiMnP permanent magnet array. Based on mechanical simulation, the folded beams are specially designed to reduce the resonant frequency. Besides, multiple conducting rods and magnet array are used to increase the output voltage. CoNiMnP permanent magnet are directly electroplated onto the vibrating plate, which is compatible with MEMS batch fabrication process. Measurement and analysis of the prototype is conducted using the dynamic signal analyzer. The tested peak output voltage reaches 102 µV at 124 Hz under the acceleration of 0.2g.

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REFERENCES

[1] Glynne-Jones P., Tudor M.J., Beeby S.P., White N.M. 2004 An electromagnetic, vibration-powered generator for intelligent sensor systems *Sens. Actuators A, Phys.*, **110** 344-349

[2] Williams C., Yates R.B. 1996 Analysis of a micro-electric generator for microsystems *Sens. Actuators A, Phys*, **52** 8-11

[3] Mizuno, M., Chetwynd D.G. 2003 Investigation of a resonance microgenerator. *J. Micromech. Microeng.* **13** 209-216

[4] Wang P.H, Liu H.T., Dai X.H., Yang Z.Q., Wang Z.Z., Zhao X.L. 2011 Design, simulation, fabrication and characterization of a micro electromagnetic vibration energy harvester with sandwiched structure and air channel *Microelectron. J.* **43** 154-159

[5] Sari I., Balkan T., Kulah H. 2010 An electromagnetic micro power generator for low-frequency environmental vibrations based on the frequency upconversion technique. *J. Microelectromech. Syst.* **19** 14-27

[6] Yuan, Q., Fang D.M., Li X.H., Zhang H.X. 2010 Electrodeposition of CoNiMnP-based permanent magnetic film *International Conference on Nano/Micro Engineered and Molecular Systems (Xiamen, China, 20–23 January 2010)* 883-886

[7] Yuan, Q., Sun X.M., Fang D.M., Zhang H.X. 2011 Design and microfabrication of integrated magnetic MEMS energy harvester for low frequency application *Solid-State Sensors, Actuators and Microsystems Conference (Beijing, China, 5-9 June 2011)* 1855-1858