A NOVEL MEMS ELECTROMAGNETIC ENERGY HARVESTER WITH SERIES COILS

*Zhong Liang Li, Meng Di Han, and Hai Xia Zhang**
National Key Laboratory of Science and Technology on Micro/Nano Fabrication, Institute of Microelectronics, Peking University, CHINA

ABSTRACT

A novel MEMS electromagnetic energy harvester with series coils was designed, fabricated and tested. The magnetic properties of permanent magnets were analyzed by MAXWELL and we enhanced magnetization through magnet arrays. An integrated method to fabricate permanent magnet was applied for fabrication, this MEMS compatible fabrication processes not only increased the production efficiency but also condensed the device's volume to 2.72 mm^3. The new structure with series coils improved the output voltage to 0.98 mV at resonant frequency 48 Hz and the power density can be 5.52 uW/cm^3.

KEYWORDS

Electromagnetic energy harvester, magnetic properties, series coils, MEMS compatible fabrication.

INTRODUCTION

As the power consumption of integrated system is scaled down in micro-nano fields [1], Micro energy harvester becomes a promising solution in low power consumption applications, such as remote sensor networks, portable electronics and biomedical implantable devices. Moreover, mass-fabricated small size energy harvesters can be integrated with other Micro-nano devices making the entire system compact and self-sustainable [2].

Among the energy sources in the environment, such as micro vibrations, solar energy and wind energy, vibrational energy exhibits unique advantages: almost available everywhere and can be easily converted to electrical power through many applicable methods, for example: piezoelectric, electrostatic and electromagnetic. The piezoelectric energy harvesting uses mechanical force to strain a piezoelectric material such as PZT (lead zirconate titanate) or PVDF (polyvinylidene fluoride) to separated charges and hence a potential difference, which can be utilized as electrical energy source. The electrostatic energy harvesting is simply based on changing capacitance value on account of vibrations, and this will cause a potential change, therefore the vibrational energy can be stored as electrical power in the capacitor. Electromagnetic energy harvester is the third type, it can generate power automatically with the relative movement between the coils and magnetic field, which avoids external operational power, its output current and energy density are much higher, and the internal resistance is relatively low compared with piezoelectric energy harvesters. Therefore, electromagnetic energy harvester has been extensively discussed recently.

The first milli-scale frequency up-converting electromagnetic harvester [3] was demonstrated using a bulk NdFeB magnet with an output power of 4 nW. Later, a micro-scale harvester [4] was fabricated and illustrated to generate a voltage of 0.57mV and power of 0.25nW from a single cantilever. A reported electromagnetic energy harvester [5], fabricated with high performance NdFeB magnets, has maximum output power of 0.53mW with a volume of 240mm^3.

However, the integration of high performance magnets in MEMS process is quite difficult. Manually assembled magnets caused the volume of the device increase and also are not applicable for batch fabrication. While traditional fabrication requires high processing temperature. In this paper, a MEMS compatible fabrication process with electroplated copper coils and permanent magnets was introduced. The electroplated CoNiMnP arrays are utilized as a permanent magnet and vibration mass which greatly decreased the volume of the device and makes the fabrication processes compatible with other MEMS processes. This device proves a relatively low power density due to the integrated fabrication process and a high output voltage based on enhanced permanent magnets.

DESIGN OF THE DEVICE

The device is designed to work with horizontal input vibrations and generate continuous pulse voltage. The schematic is shown in Fig.1, it consists of four parts: fixed series coils, supporting pillars (including vibrating beams), vibration plate and permanent magnet arrays. The coils lie in the bottom of the device and the vibrating plate is separated by 10 um space with the coils which allows for enough space for micro vibration. The vibrating beams are designed to be winding shape and have good flexibility which is beneficial to respond to environmental vibrations. The coils consist of two extraction electrodes which are used for energy scavenging. The vibrating plate is supported by four beams and holds the permanent magnets, thus the plate can move with input vibrations along the vibration beam direction and cause the magnetic field changes which result in coils cut the magnetic flux and generate pulse voltage.

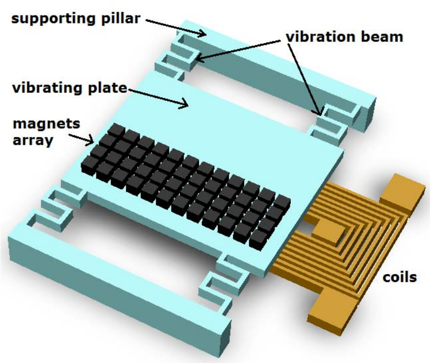

Figure 1: Schematic of energy harvester with series coils

The fixed coils and vibrational magnet arrays structure is carefully designed and has the following advantages, first, the fixed coils avoid the movement of electrical connections which enhance the reliability of the device. Second, employing the magnet as mass can decrease the total mass and furthermore increase the output voltage greatly. Besides, the magnets are fabricated at the final step so that the fabrication process is easier and more reliable.

The coils of the device are designed to be series connected to each other and can contribute to a cumulated output voltage which increases the output voltage greatly. As is shown in Fig.2, the magnets are located above the effective coils and generate strong magnetic flux which can cover the effective coils only. When the magnets move with input vibration, the effective coils cut the magnetic flux and generate induced voltage while the non-effective coils do not experience great magnetic flux variation since they are relatively far from the magnets. With the magnets moving in one direction, the effective coils can generate induced voltage in the same direction and the voltage can be added because of end-to-end connection. Consequently, the total output voltage is N times of one single coil induced voltage (N refers to the number of coils).

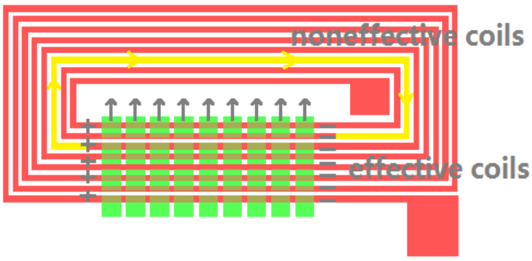

Figure 2: Illustration of the series coils

The magnetic property of the permanent magnets is the key factor of device. Therefore, the permanent magnet must be also designed, simulated and optimized. Shape and geometry size have a significant influence on magnetic flux density under same magnet thickness. The simulation of the magnetic flux density by MAXWELL was carried out to investigate the different magnetic flux characteristics between magnet arrays and block magnet. Fig.3 gives out four different shape simulation results, namely whole block, strip arrays, short strip arrays and square arrays respectively. It is easy to find out that the magnetic flux density of the permanent magnets condensed at the edges. For whole block magnet, the edge is around the magnet area, so the magnetic flux density is quite small at central part. But for strip arrays and short strip arrays, the central part contains edges and has relatively stronger magnetic flux density. While for square arrays, the edges are uniformly distributed at the magnet area and the magnetic flux density is relatively strongest among these shapes. Based on this analysis, square magnet arrays were selected to enhance the output voltage.

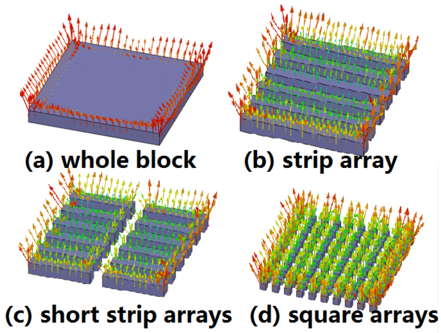

Figure 3: Magnetic properties simulation of the permanent magnet arrays

FABRICATION

This device is fabricated with MEMS compatible techniques and can be suitable for batch fabrication processes based on [6]. The fabrication processes are illustrated in Fig.4. First, SiO_2 was deposited on silicon wafer by thermal oxidation which serves as an insulating layer. And then Titanium and Copper were sputtered on SiO_2 as a seed layer for electrodeposition. The coils and supporting pillars of 10 um were electroplated on seed layer patterned by photoresist. Here the 10 um thick supporting pillars can separate the vibration plate with coils by identical thickness. Afterwards, we sputtered seed layer for the second time with the same parameters and the vibrating plate was electroplated. Finally, CoNiMnP alloy arrays were fabricated by electrodeposition technique. After all these fabrication processes, the devices were cut into samples and assembled onto a PCB operational amplifier circuit to be tested.

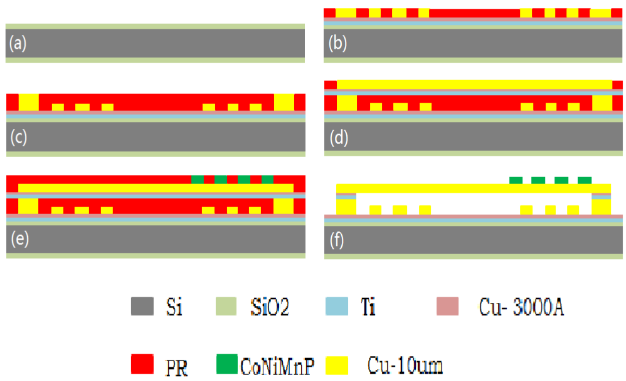

Figure 4: Fabrication process flow of the energy harvester

The microfabrication of CoNiMnP permanent magnets with electrodeposition technology was optimized for MEMS applications in our previous work [7]. The fabrication was carried out in electrolyte with 8 ASD current density applied at room temperature. The primary constituents of the electrolyte are cobalt chloride, nickel chloride and manganese sulphate. Boric acid is added to maintain concentration of the cobalt cations. The composition of the electrolyte is listed in Table 1. The magnetic properties were improved by application of strong external magnetic field which was provided by two parallel magnets with magnetic flux density of 5000 Gs. An air agitator was also applied to maintain the uniformity of the electrolyte during electrodeposition.

Table 1: Composition of CoNiMnP electrolyte.

Constituent	Concentration
$CoCl_2 \cdot 6H_2O$	24 g/L
$NiCl_2 \cdot 6H_2O$	24 g/L
$MnSO_4 \cdot H_2O$	3.4 g/L
NaH_2PO_2	4.4 g/L
H_3BO_3	25 g/L
NaCl	24 g/L
$C_{12}H_{25}O_4NaS$	0.3 g/L
Saccharin	0.9 g/L

Fig.5 shows the SEM pictures of the fabricated device, (a) gives the concise view of the device, (b) shows the real device's gap between coils and vibration plate is 10 um and the vibration beam as an impending part, (c) shows a straight and clear view of the coils and (d) is the electroplated permanent magnet arrays uniformly arranged with smooth surface. With the above MEMS compatible fabrication process, we can achieve an IC-integrated device and the repeatability of the device has also been illustrated by multiple samples experiment.

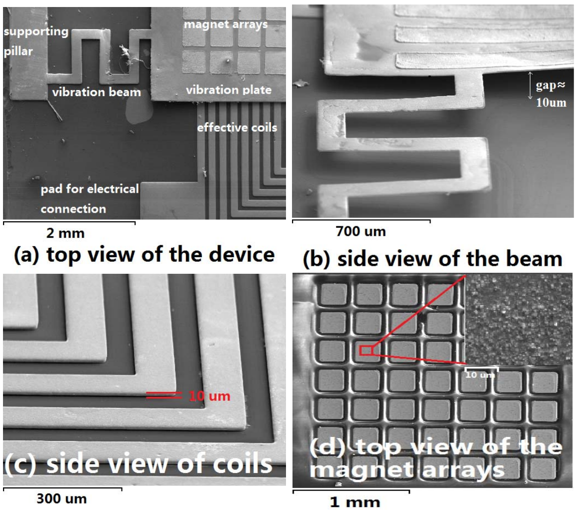

Figure 5: SEM photos of the fabricated energy harvester

The Table 2 gives out the specific dimensions of the device. The device's total height is just 40 um (including 10 um-coil layer, 10 um-vibration plate layer, 10 um-magnet layer and 10 um- space) and the total area of the device is 6.8×10^7 um^2. As a result, the total volume of the device is only 2.72 mm^3 which is greatly decreased compared with previous manual fabricated device [8].

Table 2: Geometry sizes of the energy harvester

coils	Number of turns	8
	Total length(um)	52000
	Width(um)	80
	Height	10
Magnet arrays	Number of units	4*12
	Total area (um^2)	4.5*10^6
	Height(um)	10
Vibrating plate	Area (um^2)	2.3*10^7
	Height(um)	10

RESULTS AND DISCUSSION

The device was tested through a vibration system as shown in Fig.6 (a) and the photo of the packed sample is shown in Fig.6 (b). The system consists of five parts: a signal generator, a power amplifier, a vibration machine, an amplifier circuit and an oscilloscope. The vibration machine was used to simulate environmental vibrations with frequencies vary from 1 Hz to 100 Hz which can be controlled by signal generator. And the vibration acceleration can be controlled by the power amplifier. The output voltage of the device was amplified through the operational amplifier circuit and sent to oscilloscope to be recorded.

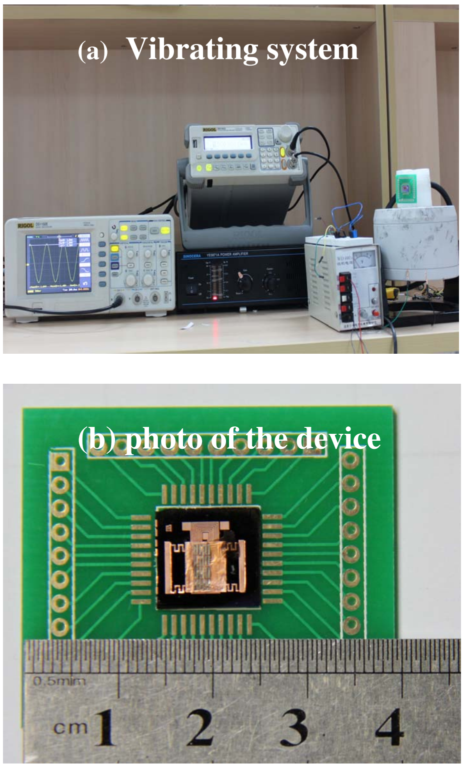

Figure 6: (a) Picture of the vibrating system; and (b) Photo of the device

A sweep frequency test from 1 Hz to 100 Hz under acceleration 1.2 g was carried out. The output voltage as a function of vibrating frequency is shown in Fig.7. It can be concluded that three resonant frequencies were observed, 48 Hz, 83 Hz and 94 Hz respectively. The maximum output voltage is 0.98mV, the maximum output power is 0.015 uW under a load resistance of 45 ohm and the power density was 5.52 uW/cm^3. This peak value of output voltage happens at a wide frequency range of 45-55 Hz which is very promising in applications of low frequency environmental vibrations. Furthermore, the output voltage and power can be increased with the length of coil expands and the thickness of magnet increases. This device can be utilized to generate energy from environmental vibrations.

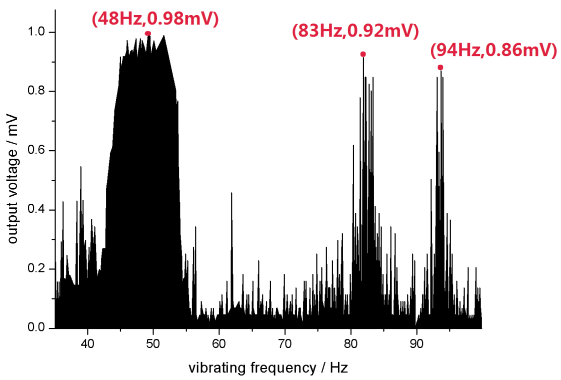

Figure 7: Output voltage

CONCLUSIONS

This paper reports a novel MEMS compatible electromagnetic energy harvester with series coils. The whole fabrication processes of this device are IC-compatible and can be introduced as batch fabrication method.

The structure of the device is carefully designed. The fixed coils and vibrational permanent magnets structure makes the devices more efficient and easy to fabricate. The coils are series connected to each other which contributes to greater induced voltage. The permanent magnets are also designed to be arrays instead of block to increase the magnetic flux density and in turn increase the output voltage.

An output voltage of 0.98mV and a power density of 5.52 uW/cm^3 have been achieved by the device. Further enhancement, such as longer coils and stronger magnets can be applied to increase the output voltage. Besides that, further work may also apply to innovative structure design of this device, such as series coils arrays and 3D structure.

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CONTACT

*Haixia Zhang, Email: zhang-alice@pku.edu.cn; Tel: +86-10-6276-6570; Fax: +86-10-6276-7742.