ELECTROMAGNETIC ENERGY HARVESTER FABRICATED WITH ELECTRODEPOSITION PROCESS

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Abstract: A novel electromagnetic vibration MEMS energy harvester have been designed, simulated and microfabricated. The volume of the MEMS harvester was about 5mm×5mm×1mm. The highlight features of the harvester were the low frequency vibration energy harvesting and high property permanent magnet and copper electrodeposition technology which made the fabrication process IC compatible. It consists of fixed copper coils on the substrate and electrodeposited central CoNiMnP permanent magnets on the movable copper planar plate with six beams. The structure and magnetic field has been simulated and optimized with Finite Element Method software. The maximum output voltage was 3.8μV at 102Hz and the output power was in nano Watt scale.

Keywords: electromagnetic, energy harvester, electrodeposition magnet

INTRODUCTION
The development of microelectronic technology has scaled down the volume of the integrated MEMS system and reduced the system power consumption to micro and nano watt level, especially for the implant system, portable device and sensor network [1], meanwhile, they require the powering devices with smaller volume and high energy density. Unfortunately, the traditional power supply device, such as battery, couldn’t match these requirements. For example, the battery always too large to be integrated with IC circuit and the limited lifetime requires periodical replacement or recharge. The power supply became a crucial problem in micro integrated system.

The energy harvester was an alternative approach to powering the integrated system. It generates electrical power from ambient energy in the environment. Many energy sources are available in the nature, such as the solar, thermal and vibration, etc. The vibration power was the most common sources and easily to be harvested to electrical power with electromagnetic, piezoelectric and electrostatic energy transduction mechanisms. Moreover, the magnetic energy harvester poses more advantages compared to others such as it has not only the best energy density, but also the advantage of without operation voltages and control circuits [2]. However, the difficulty of fabricating magnet has been a big challenge for this device. Traditional high quality magnet fabrication process requires deposition or post-deposition annealing at very high temperature which are incompatible with IC fabrication. The magnets used in the fabricated electromagnetic harvester were in large size and assembled manually [3]. In [4], a simple cantilever beam was always utilized as vibration part, but its bad mechanical properties were limited its quality.

In this paper, a novel integrated MEMS electromagnetic energy harvester was designed and fabricated with compatible IC process. CoNiMnP permanent magnets were electrodeposited in the device with high performance [5]. The vibration plate with six symmetrical beams was designed to improved its performance. The coils and the beams were fabricated with copper electrodeposition process. The design of mechanical properties of the vibration structure and the magnetic field distribution was analyzed and optimized by Finite Element Method (FEM) software for low frequency energy harvesting. The fabrication process and testing results was fully investigated.

PRINCIPLE OF DEVICE
The magnetic harvester converts kinetic energy into electrical energy by electromagnetic transduction
mechanisms. A general spring-mass model was built to
describe the harvester system by C.B. Williams and
R.B. Yates [6], as shown in Figure 1, and it was
discussed below.

![Fig 1: Model of a spring-mass energy harvester](image1.png)

The vibration energy from excitation was
transferred into the kinetic energy of the mass (M), the
elastic potential energy in the spring (K) and the
energy losses in the damper (d) which consists of
mechanical damping coefficients $d_d$ and electrical
damping coefficients $d_e$. The electrical energy exacted
from the electric damper was harvester output power.

The differential equation of motion with an excitation $y(t)=y\cos\omega t$ was described as:

$$m\ddot{z}(t) + \delta\dot{z}(t) + kz(t) = my\omega^2 \cos\omega t$$  \hspace{1cm} (1)

Where $k$ is the spring stiffness and $\delta$ is the
damping coefficient. When the device was operated
resonance at the input frequency, the maximum
electrical power was:

$$P = \frac{m\delta\omega^2 y^2}{4\delta^2}$$  \hspace{1cm} (2)

Where $\omega_n = \sqrt{k/m}$ is the system nature
frequency [7]. It is shown that power is linearly
proportional to mass and nature frequency decreased
with more vibration mass.

**SYSTEM DESIGN**

The harvester was designed to convert vibration
energy to electrical energy by electromagnetic
transduction mechanisms, as shown in Figure 2, which
consists of the coils, magnets and beams. The copper
coils were fixed on the substrate and the center
ring-shaped magnet was built on planar plate supported
by six beam suspending in the center of the coils as
vibration parts. Six side magnets were fixed around to
enhance the magnetic field. When the vibration beams
with the ring-shaped magnet were oscillating up and
down above the coils with input excitation, the
magnetic flux was cut by the coils and the vibration
energy was converted to electrical energy.

![Fig 2: Micro electromagnetic energy harvester](image2.png)

As discussed before, the power is linearly
proportional to vibration mass. So the magnet was
designed on the vibration plate to increase the vibration
mass. The benefits was obvious, first, the increase
mass will increase output power, then, the nature
frequency of the beam will decreased and resonance
with low frequency excitation, which was good for the
low frequency vibration energy harvesting. What’s
more, the magnets can be electrodeposited on the
copper vibration plate directly which simplified the
fabrication process.

The vibration characteristics of six suspended
copper beams with integrated magnet were studied by
the Coventorware™. The displacement of modes was
shown in Figure 3. In the first mode, the central plate
oscillating up and down and reaches its maximum
amplitude about 1\(\mu\)m. But in the second mode and
third mode, the plate acts a rotational movement,
which affects the power output.

The CoNiMnP magnet has high coercivity and high
energy density. But the arrangement of the magnets
will great affect the magnet field distribution. It was
simulated with Maxwell software, as shown in Figure
4. The magnetic flux density in the gap between the
central and the side magnet was much higher than
between side magnets. It is obviously that the magnetic
field was sharply decreased from the surface and the
coils within 100µm from the magnet surface have higher magnetic flux density, which require the coils placed close to the magnets. Based on that, the path of coils was optimized as three turns and surrounding closely to the magnet. The magnets was arranged with movable central magnet and fixed six side magnets around. It is proved that this arrangement made the magnet field distribution more uniform in the space for performance improvement.

FABRICATION PROCESS

The feature of the harvester was the integrated
MEASUREMENT AND DISCUSSION

The harvester was tested with the instruments including a dynamic signal analyzer, a power amplifier and a shaker. The tested result was shown in Figure 7. The observed peak output voltage was 3.8μV at 102Hz with an acceleration of 2g and there were three peaks below 400Hz. The output power tested with optimum load resistance was in nanoWatt scale. Compared with other magnetic harvester, the vibration mass was the 10μm magnetic film in the center, which was much lighter than the bulk magnets. It greatly affects the maximum value of output power. For higher power output, thicker magnets should be electrodeposited to increase the weight by control fabrication time.

CONCLUSION

A microfabricated electromagnetic energy harvester was presented. The permanent magnets were electrodeposited for IC compatible fabrication process. The symmetrical vibration structure was studied and magnets arrangement was simulated for better performance. This device was favorable to integrated with micro system and suitable for low frequency powering applications.

ACKNOWLEDGEMENTS

This work was supported in part by Fund of National Key Laboratory of Nano/Micro Fabrication Technology under Grant 9140C7901080902.

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