Optimization and Experiment of Electromagnetic Energy Harvester by Using NdFeB Sputtered on High-aspect-ratio Corrugated Si

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Abstract. This paper shows a design optimization of MEMS (Microelectromechanical Systems) electromagnetic energy harvester by using finite element method (FEM) analysis to obtain a maximum generated power. The electromagnetic energy harvester consists of the sputtered NdFeB magnet film on a high-aspect-ratio corrugated Si structure and a counter Au serpentine coil. The each dimension of the device is optimally designed by using FEM simulation. After the prototyping with MEMS fabrication process, the measurement results of the power generation are 2.65 mV of the induced electromotive force and 7.60 nW of the output power with optimum load resistance of 231 Ω at the vibration condition of 100 Hz, 294 μm-p-p.

1. Introduction
Recent years, wireless sensor networks have been attracted in many fields such as human healthcare and infrastructure monitoring systems. Vibration electromagnetic harvester is one of the expected power sources for these systems because it has (1) high current generation unlike to electrostatic or piezoelectric harvesters, (2) simple mass-spring structure with magnets and coils, and (3) no limit to reduce the gap between magnet and coil because there is no pull-in or sticking issue.

In our first generation of the electromagnetic harvester was fabricated on the trench etched Si structure and the NdFeB magnetic material was sputtered and polished to fabricate a magnetic stripe [1]. The harvester generated 760 nW at vibration condition of 100 Hz, 400 μm-p-p. To improve a generated power, we have established the optimization for device design e.g. air gap between magnet and coil, length of adjoining magnet areas etc. in the second generation device [2]. However, the further miniaturization of magnet causes poor quality of the NdFeB magnet because the sputtered magnet film is difficult to deposit in the narrow Si trench. In order to overcome the issue, we propose third generation electromagnetic harvester that consists of the sputtered magnet film not in the trench but on a high-aspect-ratio corrugated Si surface.

In this paper, we describe the optimal design of the electromagnetic harvester with NdFeB magnetic array on the corrugated Si microstructure and single layer serpentine-shaped coil. The optimum dimensions are calculated by finite element method (FEM) and numerical analysis. We also show the prototyping of novel harvester and its experimental results for power generation.
2. Electromagnetic harvester

The principle of power generation by the electromagnetic harvester is shown in figure 1. The harvester is composed with the magnet structure and the coil structure. Our magnet structure has the micro magnetic pole array that produces the micro distribution of the magnetic flux density on magnets surface. The coil structure is fabricated on the mass-spring structure. When the coil mass is excited by external vibration, the relative position of the coil and the magnet is changed, and then a magnetic flux density passing through the coil is also changed. The induced electromotive force is produced by this electromagnetic induction, and the induced current flows in the coil. The induced electromotive force, $V$, is the following equation:

$$V = N \frac{d\Phi}{dx} \frac{dx}{dt}$$  

where $N$, $d\Phi/dx$, and $dx/dt$ denote the number of coil turns, magnetic flux changing ratio for position, and moving relative velocity between coil and magnet. From eq. (1), it is obvious that the much number of coil, fine pitch magnetic flux change and higher moving velocity are key issue for improving the electromotive force.

![Figure 1. Principle of power generation](image)

3. Optimal design of electromagnetic harvester

Figure 2 shows the structure of our electromagnetic harvester. The device size is $14 \times 14 \times 1 \text{ mm}^3$, and the effective area for power generation is $9 \times 9 \text{ mm}^2$. The magnet structure has the NdFeB magnet on a high-aspect-ratio corrugated Si surface (figure 2a). The coil structure has Au serpentine-shaped coil [3] with a single-layer coil wiring (figure 2b). Since there is no overlap area on the coil, the serpentine coil has very flat surface on the coil and has good capability to fabricate a fine patterned electrode. Thus, it is easy to decrease the air gap between the coil and the magnet array and increase the number of coil turns.

In order to maximize a generated power from the harvester, a structural optimization is required. We consider few device parameters for size optimization, i.e. corrugate-shaped Si trench pitch, $D$, line and space ration for the projection and the trench, $L:S$. By changing these parameters, we can estimate the total result for the harvesting energy that has a trade-off relationship on the (1) changing rate of the magnetic flux density of $d\Phi/dx$, (2) the impedance that proportional to the number of coil turns, $N$, and (3) the induced electromotive force, $V$ that depends on $N$ and $d\Phi/dx$. Therefore, it is possible to seek the optimal structure having a maximum generated power. The detailed optimal design flow has been described in references [2] and [3]. At first, we extracted the distribution of the magnetic flux density at the coil position that has a certain gap from the magnet surface (figure 2c) with magnet static field analysis on the FEM. To reduce the data number and to simplify the numerical calculation after the FEM analysis, we approximated the magnetic flux density distribution to a simple sinusoidal equation by using fast Fourier transform (FFT). Then, the induced electromotive force and the generated power for an arbitral external vibration are able to calculate with the approximation.

For the simulation condition, the interval of coil line, $l_2$, is a-half of the corrugate-shape trench pitch of $D$. The cross-sectional area of Au coil line is set to $6 \times 20 \mu\text{m}^2$ and Au resistivity is $2.21 \times 10^{-8} \Omega\text{m}$. From the measurement results, the thicknesses of magnet films are $16 \mu\text{m}$ and $4 \mu\text{m}$ for top and bottom of the corrugated Si structure, respectively. And the coercive force of our NdFeB magnet is...
0.9 MA/m. The gap between coil and magnet array (figure 2c) is 30 μm as same as previous work’s value. Figure 3 shows generated power for changing the trench pitch of D and the ratio of the projection and trench, L:S.

![Magnet structure](image1) ![Coil structure](image2) ![Cross-section of harvester](image3)

**Figure 2.** The detailed structure of the electromagnetic harvester. (a) Magnet structure, where $D$ is trench pitch and $L:S$ is ratio of line and space. (b) Structure of serpentine coil with folding lengths of $l_2$ and fixed length of 9 mm. (c) Cross sectional view of the harvester that has air gap.

![Simulation result](image4)

**Figure 3.** Simulation result with the 30 μm gap and the sinusoidal vibration (200 Hz, 200 μm$_{p-p}$). The optimal impedance and the optimal number of turns coil are varied with changing the trench pitch.

From the simulation results for 30 μm air gap, the optimal structure has 140 μm of trench pitch and 4:6 of $L:S$ ratio. In that dimension, the number of coil turns is 64 and its impedance is 204 Ω. Finally, the generated power of 20.7 nW at the vibration condition of 200 Hz, 200 μm$_{p-p}$ are calculated. The result cannot compare with the previous work because of the different vibration condition, but we investigate the design optimization method.

In addition, we changed the gap between coil and magnet from 40 μm to 2 μm. The result of power estimation is shown in figure 5. All simulation results are after the optimization for each air gap. It is clearly to show that the narrower air gap and narrower trench pitch both are increasing the generated power.

![Simulation result](image5)

**Figure 4.** Simulation result for various air gap between the coil and the magnet. The vibration condition is fixed as the frequency of 200 Hz and the amplitude of 200 μm$_{p-p}$. 
4. Fabrication of prototype and measurement
We fabricated the prototype that has no support spring but has magnet array and coil structure. We used optimal design dimension for 30 μm air gap, 140 μm trench width and 4:6 line and space ratio. Figure 5 shows the fabrication process flow of the prototype. Figure 5a shows fabrication of the magnet part. The micro corrugated shape on the Si wafer is fabricated by DeepRIE, and then sputtered the NdFeB/Ta multilayer film [4]. Then the magnet on the corrugated Si is magnetized with a pulse magnetization of 3.0 T magnetic field. As shown in the SEM image in figure 6, the NdFeB/Ta multilayer film is successfully covered on the top of the corrugated area. After the magnetization, the magnetic property is obtained as shown in figure 7. The magnet film shows 1.2 T magnetic flux density for the vertical axis.

The coil fabrication process is shown in figure 5b. The serpentine shaped spring was patterned with positive type photo resist (AZP-4620; AZ Electronic Materials plc, USA) on the Au/Cr seed layer for electroplating. The 20 μm width and 6 μm thickness Au coil is fabricated by the electroplating. Figure 8 shows the fabricated prototype of the coil and the magnet chip. The trench pitch of magnet and its ratio of L:S are 140 μm and 4:6, respectively. The coil impedance for the number of turns 64 is 231 Ω.

We performed vibration test. The coil chip was set above the fixed magnet chip with 30 μm constant air gap, and then vibrated by a shaker (ET-126B-1; Labworks Inc., USA). Since the coil mass is not supported by the spring but set on the shaker head, we can apply arbitrarily frequency and amplitude combination as the mass vibration. Figure 9 shows measurement apparatus to measure the electromotive force and applied acceleration of the mass, which measured by the accelerometer (MMA7361L; Freescale Semiconductor Inc., USA).
In order to compare with our previous work, the coil chip was vibrated at the sinusoidal vibration of 100 Hz, 294 \( \mu \text{m}_{\text{p-p}} \). Figure 10a shows the harvesting result of the measured electromotive force, power and applied acceleration to the mass, which measured by the accelerometer. The device generates 2.65 mV electromotive force and 7.60 nW power with optimum load resistance of 231 \( \Omega \). On the same condition, we also simulated harvesting energy by using the FEM and numerical calculation method. Figure 10b shows the induced electromotive force of 2.99 mV and the generated power of 9.65 nW with same load resistance. These results from the measurement and simulation show the extremely high agreement. Therefore this optimization and design strategy could be useful for future design of high performance electromagnetic harvester.

5. Conclusion
We demonstrated the design optimization method for NdFeB electromagnetic vibration harvester with Si corrugated structure. The optimal structure for 30 \( \mu \text{m} \) fixed air gap has 140 \( \mu \text{m} \) trench width and 6:4 line and space ratio. From the measurement of the fabricated prototype, the harvested power of 7.60nW at the vibration of 100 Hz, 294 \( \mu \text{m}_{\text{p-p}} \) is obtained, which is about ten times large power from the previous work with same condition. We also investigated the numerical calculation method shows good agreement with the measurement data of the actual harvester. It will be a strong tool for the design optimization for the harvester.

References
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