

Electromagnetic Energy Harvester by Using NdFeB Sputtered on High Aspect Ratio Si Structure

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Abstract. This study addresses the design optimization of the electromagnetic energy harvester consisting of the sputtered NdFeB film on a high aspect ratio corrugated Si structure and Au electroplated serpentine coil. The high-aspect-ratio Si structure has advantages that the magnetic flux density change is caused by distance change between the coil and magnet film on the fine-patterned corrugated Si, and it is easier to fabricate with high yield than previous study. We also optimized design parameters such as width and depth of the trench, coil size by using FEM analysis and theoretical calculations. Assuming the mass size of $10 \times 10 \text{ mm}^2$, the trench depth of the $400 \text{ }\mu\text{m}$, the vibration amplitude of $40 \text{ }\mu\text{m}_{p-p}$ and the vibration frequency of 100 Hz , the maximum output power of 12 nW and the maximum electromotive force of 4 mV are obtained for $60 \text{ }\mu\text{m}$ and $80 \text{ }\mu\text{m}$ magnet widths, respectively.

1. Introduction

Recently, wireless sensor network systems are used for various applications such as a human monitoring system, a tire pressure monitoring system, and a building central monitoring system. Some applications are often installed in a place where it is difficult to maintain. Additionally, some applications are required the continuous monitoring operation. For the reason, a wireless autonomous power generator is strongly required in this field. We have developed the vibratory MEMS electromagnetic energy harvesters. The harvester has advantages for its simple structure with coil and magnet structures, and has low output impedance from the coil resistance. In the previous work, the energy harvester consisted of a mass with buried NdFeB magnet array and an Au spiral coil. This buried magnet array has been fabricated by the NdFeB sputtering on the trenched Si structure and the mechanical polishing method [1]. For the $30 \text{ }\mu\text{m}$ gap between the $400 \text{ }\mu\text{m}$ line and space magnet array on the $10 \times 10 \text{ mm}^2$ mass and the Au coil, the output power from the harvester has measured to be 760 pW at 95 Hz and $400 \text{ }\mu\text{m}_{p-p}$ sinusoidal mass movement.

The output power of the electromagnetic energy harvester depends on vibrating frequency, the change amplitude of magnetic flux density attributed to the mass movement. In order to improve the harvesting energy, we focused on a miniaturization of the magnet array. By the miniaturization, frequency of the magnetic flux density changing becomes large. The serpentine-shaped coil instead of spiral coil has been proposed in previous work to fit the magnetic array because the serpentine coil are easy to be fabricated and has low electrical resistance without multilayer connection [3]. In this work, the high aspect ratio Si corrugated structure to realize finer pattern magnetic array. By using FEM analysis of magnetic field and theoretical calculations, the size of magnet array and coil are optimized for the maximum harvesting energy.



2. Fine fabrication process of magnetic material

2.1. Fabrication limitation of the previous work

The fine magnet array is required for higher gathering energy. Nevertheless, previously reported harvester had limitations for micro fabrication of magnetic material. Figure 1 shows fabrication process flow of magnetic array in previous work [1]. The NdFeB/Ta film sputtered on bottom of Si trench is used as buried magnet as shown in figure 1(c) and SEM image of figure 2. However, the thickness of the magnet film becomes non-uniform and hard to cover on narrow trench. Moreover, a difficulty of the control of the polishing process (figure 1(e)), which caused high yield loss.

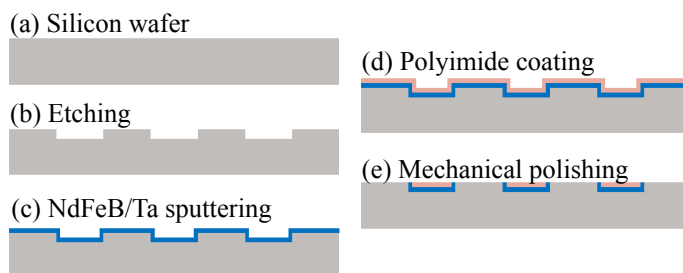


Figure 1. Fabrication process flow of the previously-reported magnet structure.

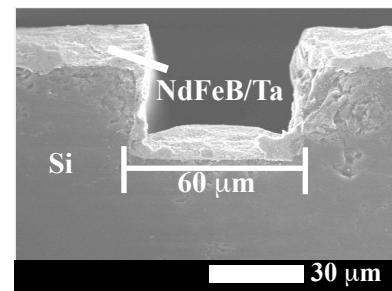


Figure 2. SEM image of NdFeB/Ta multilayer film sputtered on 60 μm width of Si trench and dike with 30 μm depth.

2.2. Magnet material on high aspect ratio corrugated Si structure

We proposed the novel fabrication process for high-aspect-ratio corrugated magnet structure as shown in figure 3. At first, a Si trench is etched to be 300 μm depth by DRIE (Deep Reactive Ion Etching). Then, NdFeB/Ta multilayer film is sputtered on the high aspect ratio corrugated Si substrate. Finally, the fine magnet array is obtained.

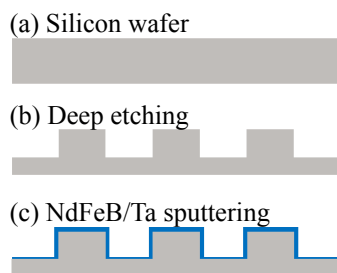


Figure 3. Fabrication process flow of the proposed magnet structure.

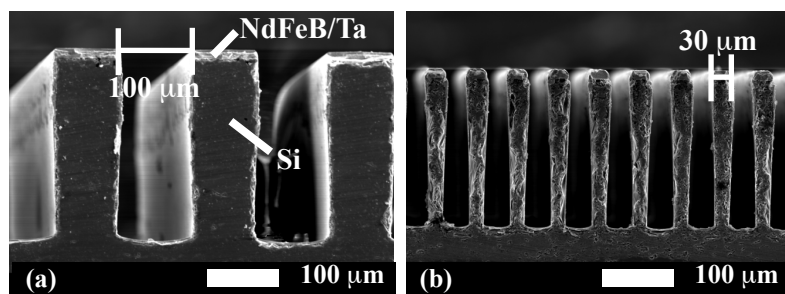


Figure 4. SEM image of NdFeB/Ta multilayer film sputtered on various dimensions of Si trenches. The pitches of Si trenches are 100 μm (a) and 30 μm (b), respectively.

Figure 4 shows the cross sectional SEM image of magnetic array with pitch of (a) 100 μm and (b) 30 μm . The thicknesses of the NdFeB/Ta deposited on the top and the bottom of Si trench are 13 μm and 3 μm , respectively. Obviously the burying the magnet film on bottom of the high aspect ratio Si trench was difficult.

3. Optimization of serpentine coil and magnetic array on corrugated Si

3.1. Schematic diagram of the coil and the magnet

The schematic diagram of the proposed harvester is shown in figure 5(a). The harvester consists of two structures, the Au serpentine coil structure on the substrate and the magnet array on corrugated Si trench on the moving mass. These structures are stacked and magnet array and coils are located with relative distance each other. Then the magnetic flux density across the coil changes according to the magnet movement. As a result the electromotive force (EMF) is generated in accordance with Faraday's law of induction. In order to obtain the maximum harvesting energy, we investigated the optimum size of the device.

Considering to improve the harvesting power, there are three trade-off parameters to optimize. (1) Width of the magnetic bump for magnetic flux density change frequency, (2) width of the magnetic trench to maximize the amplitude of magnetic flux density gradient, (3) line and space of the serpentine coil unit and its multistage connection number (figure 5(b)).

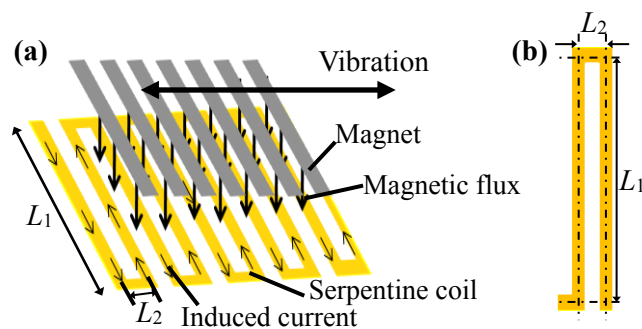


Figure 5. Schematic diagram of the power generation. Overall view (a) and definition of coil unit (b).

3.2. Design optimization of the harvester

For comparison with the previous work, we assume the volume and the area of the magnet and coil structure $14 \times 14 \times 0.4 \text{ mm}^3$ and $9 \times 9 \text{ mm}^2$, respectively. In addition, the thickness and the width of the electroplated coil, air gap between magnet bump and coil are defined as $4 \text{ }\mu\text{m}$, $20 \text{ }\mu\text{m}$, and $30 \text{ }\mu\text{m}$, respectively. The FEM analysis model is shown in figure 6. The magnet thicknesses on top, bottom and sidewall are set as $13 \text{ }\mu\text{m}$, $3 \text{ }\mu\text{m}$ and $5 \text{ }\mu\text{m}$, respectively from the preliminary experimental results as shown in figure 4. And then, the magnetic field intensity is defined as 1.0 MA/m from a bulk NdFeB value. Figure 7 shows some results of magnetic flux density with $30 \text{ }\mu\text{m}$ air gap for 100, 60 and $40 \text{ }\mu\text{m}$ line and space of corrugated array.

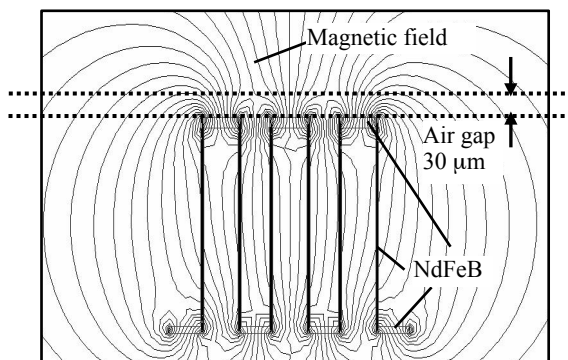


Figure 6. Resulting contour plot of the magnetic flux line calculated by FEM.

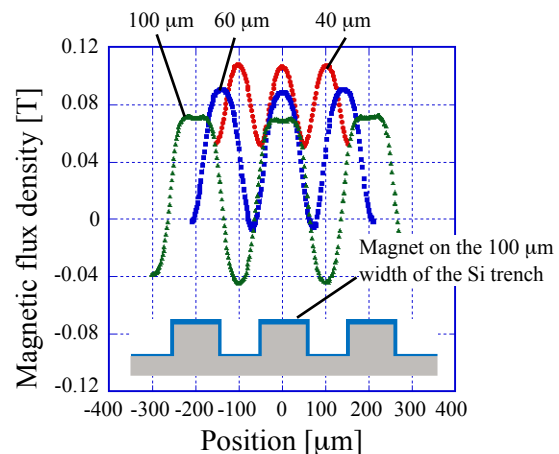


Figure 7. Magnetic flux density with $30 \text{ }\mu\text{m}$ air-gap for $40 \text{ }\mu\text{m}$, $60 \text{ }\mu\text{m}$ and $100 \text{ }\mu\text{m}$ magnet width.

Since the magnetic flux density on position x , $B(x)$, from the FEM analysis was cyclically changed, it is represented from Fourier transform by

$$B(x) = \sum_{n=1}^k (a_n \cos[2\pi f_n x + \theta_n] + b_n \sin[2\pi f_n x + \theta_n]), \quad (1)$$

where a_n is the real number component of the amplitude, b_n is the imaginary number component of the amplitude, f_n is the frequency and θ_n is the initial phase. The EMF can be calculated from the magnetic gradient and the applied vibration velocity. The serpentine coil unit can simply be divided to two wires which are outward and inward wires as shown in figure 5(b). The EMF of single unit coil, $V_1(t)$, is represented by

$$V_1(t) = v(t)B(x)L_1 - v(t)B(x + L_2)L_1, \quad (2)$$

where $v(t)$ is the vibration velocity of the mass and $B(x)$ is the arbitrary magnetic flux density on the position of x . Thus the EMF of the multistage of the serpentine coil, $V_n(t)$, is represented by

$$V_n(t) = n\{v(t)B(x)L_1 - v(t)B(x + L_2)L_1\}, \quad (3)$$

where n is the connection number of the unit coil. According to equation (3), the output voltage is the difference of the Lorentz force generated on one coil to adjacent coil. Finally, the effective power of the harvester, $W(t)$, is represented by

$$W(t) = \frac{V_n(t)^2}{4R_c}, \quad (4)$$

where R_c is an resistance of the serpentine coil as large as optimum resistance. When connection number of n is increased, the EMF and the R_c are also increased because these are proportional to n . Therefore its trade-off. There will be optimum values for the magnet array and coil sizing. Figures 8 and 9 show the harvesting voltage and power results for applying the sinusoidal vibration of 100 Hz, the amplitude of 400 $\mu\text{m}_{\text{p-p}}$ to the harvester with 200, 300 and 400 μm trench depth, respectively.

These results are not considered the width of Au coil. Therefore, the actual result requires additional calculation for moving average of the magnetic flux density with the coil width of 20 μm . The harvesting energy is increasing as the decreasing of the magnet line and space. The maximum harvesting voltage 4 mV is obtained that the width and the depth of the corrugated Si structure are 60 μm and 400 μm , respectively. Then, the maximum harvesting output power is 12 nW when the width and the depth of the corrugated Si structure are 80 μm and 400 μm , respectively.

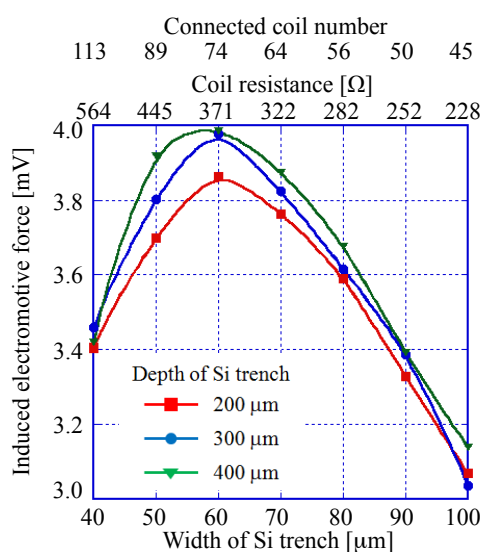


Figure 8. Induced electromotive force estimated from various width and depth of the high-aspect-ratio magnet structures.

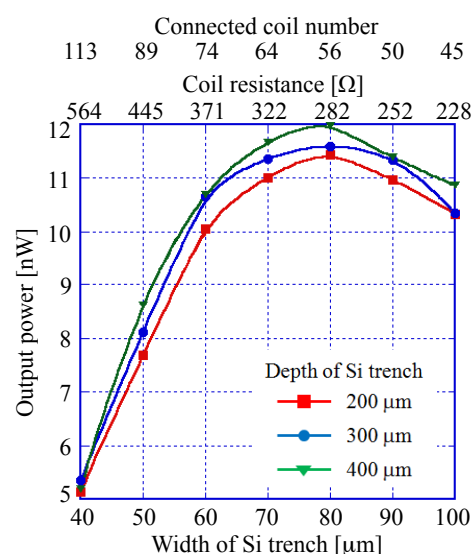


Figure 9. Output power estimated from various width and depth of the high-aspect-ratio magnet structures.

4. Conclusion

We described the energy harvester with the NdFeB array on high aspect ratio corrugated Si structure. By the optimization of the harvester design by FEM analysis and theoretical calculations, the estimated harvesting voltage of 4 mV was obtained. The output power of 12 nW with 282 Ω of optimum load was also obtained. These estimated values were approximately 16 and 15 times as large as previous device respectively.

References

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