MEMS Batch Fabrication of the Bipolar Micro Magnet Array for Electromagnetic Vibration Harvester

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Abstract. This article introduces a MEMS batch fabrication process of micro magnet array with bipolar magnetic pole for an electromagnetic vibration energy harvester. In order to obtain the large electromotive force from large magnetic flux density change, we established the fine patterned alternating magnetized bipolar magnetic structure. The batch fabrication process of bipolar magnet array is composed of two wafers processing with S-pole and N-pole magnetization and bonding process. By the prototype fabrication of bipolar magnet with the 200 μm SN-interval, we showed the usability of the batch fabrication process of the bipolar magnet array. In addition, we estimated the generated power of energy harvester with a bipolar magnet array. Compared to a harvester with monopolar magnet array, we showed the good result for bipolar one.

1. Introduction
In recent years, vibration electromagnetic energy harvesters are expected for a candidate of next generation power source for micro sensors. We have studied electromagnetic harvesters and trying to improve generated power by miniaturizing a magnet structure. Generally, implementing a minimized magnetic element into MEMS (Micro ElectroMechanical Systems) fabrication is difficult, however we have established that technique in our previous works. The miniaturized magnets on harvesting devices are fabricated by using buried and polished NdFeB magnetic material on the Si trench [1] and sputtered magnet on corrugated Si surface [2]. We have improved a change rate of a magnetic flux density by miniaturizing a magnet array, however there is a limitation to improve the power by using single direction, monopolar magnetic structure. Too fine monopolar magnet array showed decreasing of a flux density change because of the smoothing effect from the adjoining magnets.

In this paper, we propose a MEMS batch fabrication technique of a bipolar micro-magnet that is alternatively magnetized. The basic batch fabrication process and prototyping of the MEMS electromagnetic harvester is demonstrated. Furthermore, we estimate the generated power of the harvester with bipolar magnet array, and verify the usability of the bipolar magnet.
2. Bipolar magnet array

2.1. Construction of interdigitated comb structure
In our previous work, a magnetic material, NdFeB was deposited on the Si MEMS device then magnetized by pulse magnetizer with single direction strong magnetic field. Since the fine patterned magnetization with strong magnetic field is difficult, we choose the combination of two different magnetic pole fine patterned structures. Figure 1 shows a structure of prototype of a magnetic part. The N-pole and S-pole magnet comb fingers are combined after the each magnetization [3].

![Figure 1. Combination of N- and S-pole NdFeB magnetic film on MEMS structure. The chip size is 13.5 × 14 mm², the finger length of the each comb is 9.0 mm, the thickness is 0.5 mm, the finger width is 100 μm. The space between fingers is equal to the finger width.](image)

2.2. Fabrication process
In order to fabricate the micro bipolar magnet array, we have two challenges to meet. The first one is to establish high precision bonding technique of two wafers. Since each wafer has fine patterned Si comb finger structure with NdFeB magnetic film, the bonding equipment with precision alignment is essential to prevent a break of the fingers during an engaging process. The second one is use of a low temperature bonding method that can prevent the demagnetization [1] of NdFeB magnet during the fabrication step.

For the first issue, we use a wafer bonding system (Ayumi Industry Co., Ltd., Japan). By using infrared microscope, two wafers with comb finger structure can align with ± 5 μm accuracy. And for the second issue, we proposed using of the positive type photosensitive resin (OFPR-800; Tokyo Ohka Kogyo Co, Japan) for low temperature bonding. The resist can be indurated for bonding not to use a thermal treatment but to use a vacuum treatment.

Figure 2 shows the batch fabrication process flow of our bipolar magnet array. The processes are consisted of (a) S-pole magnet wafer process, (b) N-pole magnet wafer on the substrate wafer, and (c) final alignment and bonding process. As shown in Figure 2a, comb finger shape for S-pole magnet is patterned and etched by Deep-RIE. Twelve comb structures are batch fabricated on a single four-inch Si wafer simultaneously. Then the multilayer NdFeB/Ta (40 layers)[4] film was sputtered on the surface of the Si comb fingers. A pulse magnetization with magnetic field of 3.0 T are performed from bottom to top direction to make a S-pole magnetize wafer.

Figure 2b shows the process for N-pole wafer. It is similar to S-pole one, however there are additional steps for bonding with the substrate wafer. Due to the combination of the S-pole and N-pole comb fingers, an isolation structure for N-pole finger is required. At first the N-pole comb finger is patterned and etched with frame structure. Then the etched wafer is bonded on another substrate wafer by an adhesive photosensitive epoxy resin (KMPR1035; Nippon Kayaku Co, Japan). By patterning of KMPR1035, the comb finger part can be selectively bonded on to the substrate wafer. After the dicing process with appropriate cutting depth, except the comb finger are removed from the substrate. After
that, the pulse magnetized with same magnetic field is performed from top to bottom direction to make a N-pole magnetized wafer.

Finally, two oppositely magnetized wafers are bonded by using wafer-bonding system in vacuum pressure (Figure 2c). The OFPR-800 photoresist is spin coated on the N-pole finger on the substrate wafer. The wafer is accurately and quickly aligned with the S-pole wafer and engaged each other. By keeping the wafer in a 1.0 mPa high vacuum chamber, two wafers are rigidly bonded. Figure 3 shows photographs on fabrication steps of S-, N-pole magnet and bipolar magnet wafer.

![Figure 2](image1.png)

**Figure 2.** This is the Process flow of bipolar magnet array which are composed (a) S-pole magnet, (b) N-pole magnet and (c) bonding process.

![Figure 3](image2.png)

**Figure 3.** Prototype of bipolar magnet array

2.3. Evaluation

Figure 4 shows the magnetic flux density profile of the prototype that has 100 µm finger width and 100 µm finger space. We used small sized Hall IC with die size of 50 × 50 µm² (HG-0711; Asahi Kasei Co, Japan) for high-resolution measurement. From the magnetic flux density profile, the peak flux density interval is around 400 µm and is obviously similar as comb-finger size. The measurement result also shows good agreement with the FEM analysis result (ANSYS 14.5). The figure shows two-simulation result for electromagnetic flux density profiles 250 µm and 300 µm above the magnet surface. Considering the package thickness of Hall IC, the Hall IC shows reasonable value for flux density measurement.
It is difficult to measure magnetic flux density profile of 30 µm gap that is gap between the bipolar magnet and the harvesting coil in actual device, because of the spatial resolution limitation of Hall IC. Thus, we simulated the magnetic flux density profiles on 30 µm gap for monopolar and bipolar magnetic structure as shown in Figure 5. The bipolar magnet array shows as high as 0.3 T magnetic flux density change, which is almost double of a monopolar one.

![Figure 4](image1.png)  
**Figure 4.** This shows the magnetic flux density profile of bipolar array magnet with 100 µm finger width. In addition, the FEM analysis results at 250 µm gap and 300 µm gap from the magnet surface is presented for comparison of the measurement.

![Figure 5](image2.png)  
**Figure 5.** Analysis results of Magnetic flux density at 30 µm gap for monopolar and bipolar magnet array with 100 µm finger width.

3. Energy estimation from electromagnetic harvester

3.1. Structure of harvester

Figure 6a shows the cross sectional view of our electromagnetic energy harvester using the bipolar magnet array. The harvester is composed by the moving coil layer and the fixed bipolar magnet structure. The coil structure is on the spring-mass mechanical resonator. The coil with serpentine shape is made of 8 µm thickness electroplating Au [5] as shown in Figure 6b. Compare to the spiral coils, this serpentine coil is easily miniaturized according to miniaturization of magnet array.

![Figure 6](image3.png)  
**Figure 6.** Electromagnetic harvester with bipolar array magnet. The device size is 13.5×14×1.5 mm³, the both of magnet area and coil area are 10×10 mm².
3.2. Power generation estimation
By using the structure and dimension of our electromagnetic vibration energy harvester described above, we try to estimate the harvested energy from the approximated magnetic flux density profile and numerical calculation [2]. Combining of the approximation equation for magnetic flux density from the FEM analysis and electromotive force from the serpentine coil, we can calculate a harvested energy from the various sizes of magnetic comb-fingers.

The gap between magnets and coils is set to 30 µm, the thickness of magnet film on the Si structure is measured value of 27 µm and the magnetic coercive force is 0.9 MA/m. The sectional area of Au coil line is 20 × 8 µm² and its resistivity is 2.21 ×10⁻⁸ Ωm. The Q-value of the spring-mass structure is set to 100 from the previous work. Figure 7 shows the generated power of the harvester and coil impedance with bipolar magnet array and monopolar magnet array. The bending number of the serpentine coil is depended on the rise and fall of the magnetic flux density profile. Since the bipolar magnet array makes half number of undulation with same width and space of the comb-finger for monopolar magnet array. Thus the coil impedance of bipolar magnet array shows half of the monopolar one. From the estimation result, the device using bipolar magnet array generates 3.12 µW at the optimum comb-finger width of 40 µm when applying a mass vibration with resonant frequency of 400 Hz and amplitude of 4 µm_p-p.

Figure 7. Generated power and impedance of the harvester versus interval of magnet comb-finger width and space. This graph shows both harvester with bipolar magnet and harvester with monopolar magnet at sin vibration(400 Hz, 4 µm_p-p). The size of the serpentine coil is designed by the magnetic flux density profile.

4. Conclusion
We demonstrated the MEMS batch fabrication process of bipolar magnet array. The comparison of the measurement results and simulation results, it is investigated that the simulation can be useful for magnetic flux density profile approximation. By using approximation, we found the optimum width of magnet comb finger of bipolar array. It showed 3.12 µW maximum power from the 400 Hz resonant mode vibration with 4 µm_p-p amplitude.

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