COLLISION-FREE STRUCTURE USING THIN-FILM MAGNET FOR ELECTROSTATIC ENERGY HARVESTER

S Yoshii, K Yamaguchi, T Fujita, K Kanda and K Maenaka
Graduate School of Engineering, University of Hyogo
2167 Shosha, Himeji, Hyogo 671-2280, Japan
E-mail: ei16k019@steng.u-hyogo.ac.jp

Abstract. This paper proposes collision-free structure using NdFeB thin-film magnet for vibration energy harvesters. By using stripe shaped NdFeB magnet array on the Si MEMS structure, we finally obtained 3 mN of magnetic repulsive force on 8 × 8 mm² specimen with 40 µm air-gap.

1. Introduction
Recently, many researches of IoT (Internet of Things) using the wireless network for machinery, buildings and the human body monitoring [1] are actively studied. Energy harvesting techniques are also attracted attention for autonomous power source for IoT [2]. We study an electrostatic energy harvester among the vibration energy harvesters [3], which generates electric power by the changing in capacitance and the bias voltage between the electrodes when a mass vibrates. The high voltage and the narrow air-gap structure are required for high performance harvesters [4], however an electrostatic attractive force that causes pull-in phenomenon simultaneously is increased. In order to prevent the pull-in phenomenon, stopper mechanism [5], bipolar charging method [6], electrostatic repulsion [7] have been reported. Since the pull-in prevention measure with physical collision reduces the long-term reliability in durability, we propose a collision-free structure using a magnetic repulsive force with sputtering NdFeB/Ta multilayer thin-film magnet. NdFeB/Ta multilayer thin-film magnet have strong magnetic properties, however it difficult to fabricate in MEMS (Micro Electromechanical Systems) devices. In our previous studies, the deposition and microfabrication technology with RF magnetron sputtering of NdFeB/Ta multilayer was successfully developed [8][9].

In this study, the characteristics of magnetic repulsion force for vibration energy harvester are confirmed in simulations and measurements. Comparing with previous work of stripe shaped magnet [10], magnetic repulsive force (MRF) of striped magnet with optimized dimension shows 10 times larger than normal shape on 30 µm air-gap structure.
2. Demagnetizing field reduction by microfabrication magnet

2.1. Magnetic levitation

Figure 1 shows the preliminary experiment of magnetic levitation by MRF generated from 15 μm thick NdFeB/Ta film on a 8 × 8 × 0.5 mm³ Si specimen guided by Teflon side-wall. One specimen floats 2 mm above another same specimen by the MRF.

![Figure 1. Preliminary result of magnetic levitation on Si specimen.](image)

2.2. Electromagnetic field analysis

To realize an optimal dimension of magnet structure, an integral element method analysis (Qm ver 3.01, Shift lock Ltd., Japan) is performed in an effective volume of 8 mm × 8 mm × 15 μm. A magnetic flux density distribution at the position of 30 μm from the thin magnet surface is shown in Fig. 2 (a). Magnetic properties for simulation were from NdFeB/Ta laminated film produced in previous studies. The residual magnetic flux density of 1 T, the coercive force of 1 MA/m, the relative permeability 1.1 were adopted. Figure 3 shows a calculated magnetic flux density profile for the striped sample shown in Fig. 1. The magnetic flux density is accumulated on the edge and extremely low in the center part because of a demagnetization that is caused by a low structural aspect ratio. In order to increase the magnetic repulsive force, we reduced the demagnetizing field by increasing the aspect ratio by using a striped shape magnet. Figure 4 shows a calculated magnetic flux density profile for striped shape magnet with 50 μm width and 40 μm interval. Then the magnetic flux density is changed dramatically for transverse direction, however, uniformly spread along to a longitudinal direction.

The MRFs versus in-plane magnet positions for normal and striped shaped magnets are shown in Figs. 4 and 5. Figure 4 shows the MRF of 15 mN with 30 μm air-gap in a state that each magnets completely opposite (position = 0 μm). Because of the demagnetization, it can be confirmed that when one of the magnets is moved in the horizontal direction (X- or Y-direction), the MRF is greatly reduced and attractive force also appears in further movement. Figure 5 shows the MRF from 70 μm width and 70 μm interval striped magnet with 30 μm air-gap. There are two lines for transvers (X-direction) and longitudinal (Y-direction) movements. From the results, the MRF for transvers movement was changed according to stripe interval, however the MRF for longitudinal movement shows very low decrease. We confirmed that the MRF from striped shape magnet shows 10 times higher intensity than normal one and it has wide operation range along to longitudinal direction.

In our previous study, we investigate optimal dimensions i.e. magnet width, interval for several air-gaps by calculating the maximum MRF. For 30 μm air-gap, we obtained 70 μm width and 70 μm interval magnet shows the maximum MRF of 130 mN [10]. Each air-gap has optimum dimension and the MRF increases as narrowing gaps.
Measurements of the MRF
To confirm the MRF from the fabricated device, we measured the MRF by using a precision electronic force balance. The specimen with magnetic film can be held in parallel and aligned by XYZ-θ stage (Fig. 6). Figure 7 shows the MRFs for transvers and longitudinal movement of 40 µm air-gap specimen. The magnet specimen was fabricated with dimension of 50 µm width and 40 µm interval in 8 × 8 mm² active area. The result shows similar tendency of the preliminary simulation result that shown in Fig. 5. However the MRF is extremely low compare to the simulation result with same dimensions (Fig. 8). The measured amplitude of the MRF was about 3 mN and 6% of the analysis one. We assumed that the reduction of the MRF was caused by a degradation of the NdFeB material. We adopted the magnetic flux density of 1 mT from the previous result for simulation, however the measured result from the present NdFeB film shows 0.05 mT that is 4% of the analysis condition. It was confirmed that the MRF is reduced by the magnetic failure of the magnets. We are evaluating various sputtering conditions of NdFeB film, and trying to find a cause of the material degradation.

(a) Structure    (b) Magnetic flux density

**Figure 2.** Analysis model and result of the thin-film normal shape magnet.

(a) Structure    (b) Magnetic flux density

**Figure 3.** Analysis model and result of the striped shape magnet.

(a) Structure    (b) Magnetic flux density

**Figure 4.** MRF vs. horizontal position shift for normal shape magnet.

(a) Structure    (b) Magnetic flux density

**Figure 5.** MRF vs. horizontal position shift for striped shape magnet.

**Figure 6.** Schematic of the force measurement set-up
3. Conclusion

In this study, we proposed collision-free structure using the NdFeB film for its repulsive force. The demagnetizing field in low aspect thin-film magnet can be reduced by using striped shape structure with optimum dimension. Although it showed low amplitude of the repulsive force because of material degradation, we confirmed that the striped magnet is useful mechanism for collision-free in wide travel range vibration harvesters.

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