MEMS Narrow Gap Electromagnetic Harvester with Mitigation of Curvature Distortion

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Abstract. The narrowing air-gap between coil and magnet of electromagnetic energy harvester is one of the most important parameter to improve the generated power. Because of the sputtering 15 µm thickness NdFeB/Ta multilayer film with high temperature annealing, the large curvature distortion is occurred on Si substrate. In this paper we demonstrate a compensation method for residual stress on the sputtered NdFeB magnetic film on Si wafer. By using both-side sputtering method, we reduced the residual stress, which reduces the reliability of MEMS fabrication and performance of harvesters, from 144 MPa to 9.4 MPa. The electromagnetic type energy harvester with narrow gap of 20 µm was successfully fabricated and evaluated.

1. Introduction
Recently the wireless sensor network systems for automotive e.g. TPMS (Tire Pressure Monitoring Systems) [1] and for human monitoring systems [2] are collecting lot of attentions. These systems are typically composed of sensors, MPU, battery and wireless transmitter. The battery i.e. power source without maintenance or replacing is most vital part of the systems.

The vibration energy harvesting has various method and mechanism of power generation. We studied the electromagnetic harvester that consists of coil and magnet, which has some features e.g. (1) large harvesting current by low output coil impedance, (2) no pull-in problem unlike to electrostatic type harvester and (3) simple and easy to fabricate structure.

In order to improve a generated power, it is required that the rapid and large transient change in magnetic flux density passing through a coil. Accordingly, a strong magnet and large stroke range of vibration are required. However these are both difficult in MEMS (micro electromechanical systems) fabrication. In the previous work, we have already succeeded to establish the combination of Si MEMS structure and NdFeB/Ta multilayer magnet film [3]. Then we demonstrated the electromagnetic harvester with corrugated shape magnet and serpentine coil, which generates 2.67 mV of electromotive force (EMF) and 7.6 nW of power at constant amplitude vibration of 100 Hz, 300 µm_p-p. The result was obtained from the optimized design on 30 µm air-gap [4]. Designing the optimal dimensions for electromagnetic type generating maximum power, it is essential that the equivalent and the improvement of both the attenuation coefficient of electrical and mechanical with resonant state. In order to obtain a large electrical attenuation coefficient, a narrow gap and a miniaturization of effective generation areas are required, however it is the issue that large curve in substrate is occurred.
by high temperature annealing process of magnet sputtering.

In this paper, for the narrow gap harvester, we demonstrate the improvement method of mitigating the internal stress by deposition magnet film to both sides of substrate. In addition, we fabricate the prototype harvester with 20 μm of narrow gap.

2. Electromagnetic harvester

2.1. Device structure and principle

The electromagnetic harvester consists of magnet, coil and mass-spring structures (Fig. 1). The chip size including frame, effective power generation areas i.e. coil and magnet are 15×12×1 mm³, 10×10 mm², respectively. The coil structure has the serpentine shaped [5] with Au on a Si mass that supported by Si linear spring. In the opposing section, the magnet array is made by NdFeB/Ta multilayer sputtering on the corrugated Si. The magnet film with 40 layers and total 15 μm thickness is deposited on a Si structure with trench depth of 300 μm (Fig. 2). The corrugate shaped magnet array produces the periodical distribution of magnetic flux density through the coil. The interval of coil line is designed with synchronizing a change of magnetic flux. Therefore when a mass vibration causes magnetic flux changing through the coil surface, and then EMF will be generated on the coil.

![Figure 1. Schematic of harvester](image1)

![Figure 2. Cross-sectional SEM image of magnet on corrugated Si. Thickness of magnets are top of 15 μm, wall of 6 μm and bottom of 3 μm.](image2)

2.2. Estimation of power generation with Lorentz force consideration

The electromagnetic type energy harvester is belonging to the velocity damped resonant generator (VDRG) model (Fig. 3). The Lorentz force \( F(t) \) is proportional to vibration velocity \( \dot{x}(t) \) of coil mass. In the VDRG model, the maximum power will be generated when the coil mass vibrates at the resonant state and the electrical attenuation coefficient, \( c_e \) i.e. Lorentz force equals to the mechanical attenuation coefficient, \( c_m \) [6]. \( c_m = mω^2Q_m \) can be designed by changing the mass-spring parameters i.e. coil mass: \( m \), resonant angular frequency: \( ω \) and mechanical Q-factor: \( Q_m \). \( c_e \) is decided by effective power generation areas i.e. magnet and coil structure. \( c_e \) is depicted by following equations:

\[
\frac{c_e}{\dot{x}} = \frac{F(t)}{\dot{x}} = \frac{WL^2}{4\rho SP(L+P/2)}\Delta B_y (x)^2
\]

\[
(\Delta B_y (x) = B_y (x) - B_y (x + P/2))
\]

where \( W \), \( L \), \( ρ \), \( S \), \( P \) and \( \Delta B_y \) are length of coil, width of coil, resistivity, sectional area of coil, magnet pitch and peak-to-peak of magnetic flux density for vertical direction, respectively (Figs. 4 and 5). In order to increase \( c_e \) and keep the device dimension, miniaturizing a magnet pitch and narrowing a gap are required simultaneously. The calculated value of the magnet pitch and gap vs. \( c_e \) is shown in
The magnet pitch has an optimal value $P_{\text{opt}}$ that can generate maximum power, and $P_{\text{opt}}$ is also proportional to the gap. In previous work, the previous work has $W$ and $L$ of 10 mm, $\Delta B$ of 0.09 T, $P$ of 140 $\mu$m, $\rho$ of $2.21 \times 10^8$ $\Omega$m and $S$ of $20 \times 6$ $\mu$m$^2$, therefore $c_e$ is estimated to $7.1 \times 10^{-6}$. The motion of coil mass on VDRG model is following equation:

$$m \ddot{x}(t) + (c_e + c_m) \dot{x}(t) + kx(t) = -m \omega^2 \dot{y}(t)$$

(2)

where $k$ and $y$ are mechanical spring constant and position of external vibration, respectively. The generated power is calculated by following equation:

$$\text{Power}(t) = c_e \dot{x}(t)^2$$

(3)

where $\dot{x}$ is vibration velocity of coil mass. Assuming the applied vibration of 100 Hz, 300 $\mu$m$_{\text{p-p}}$, designed harvesters with 30 $\mu$m, 20 $\mu$m and 10 $\mu$m gap can generate 0.009 $\mu$W, 0.026 $\mu$W and 0.12 $\mu$W in the estimation.

$$
\begin{align*}
\text{Cross-section area} & : S \\
\text{Resistivity} & : \rho
\end{align*}
$$

3. Fabrication of narrow gap device

3.1. Improvement of internal stress

As mentioned previously, the narrow gap the larger generated power. In order to narrow the gap, the biggest problem is a curvature distortion of the Si substrate with magnet film. Our 15 $\mu$m NdFeB/Ta multilayer film shows maximum radius of curvature 5.00 m i.e. it has residual stress of 144 MPa after
600 °C annealing (Fig. 7a). The 200 μm camber on 4 inch Si wafer that caused by the residual stress is a serious obstacle for MEMS fabrication. A deposition at room temperature and applying high temperature post-annealing could control the residual stress, however the magnetic characteristic was extremely declined. There also is the optimum combination of gas and pressure for sputtering. Thus, we try to deposit the magnetic film on opposite side of the Si wafer for compensating the curvature distortion. By depositing the similar magnetic film of 10 layers on the reverse surface, the distortion is compensated from 5.00 m to 57.9 m curvature radius. The residual stress is successfully reduced from 144 MPa to 9.4 MPa (Fig. 7b).

(a) Sputtering magnet on corrugate Si side. The magnet is 15 μm thickness and 40 layers at 600 °C.

(b) Sputtering magnet on both-side. The magnet are 15 μm thickness and 40 layers at 600 °C on corrugate side and 4 μm thickness and 10 layers at 600 °C on back side.

Figure 7. Surface profile of corrugate shaped magnet

Regarding the coil wafer, there is no distortion because thin Au/Cr is deposited at room temperature and 6 μm thickness Au coil line was electroplated, though (Fig. 8). From the measured curvature radius of magnet and coil wafer, we confirmed to narrow the gap to 20 μm for MEMS batch fabrication with 4 inch wafer.

Figure 8. Surface profile of serpentine coil

3.2. Fabrication of harvester with narrow gap

We fabricated the prototype of harvester with 20 μm gap (Fig. 9a) from the result of reducing the residual stress. The Au coil line was fabricated on the Si mass-spring wafer by Au electroplating and deep-RIE (MCU-21-090; Sumitomo Precision Product Co.,) (Fig. 9b). The NdFeB/Ta multilayer (40 layers) is sputtered on miniaturized corrugate shaped Si surface and additional 10 layers are sputtered on the back side for compensation (Fig. 9c). In order to regulate the gap to 20 μm, a negative type photo resist (KMPR; Nippon Kayaku Co.,) was used for spacer. The mass-spring structure is not packaged for optical measurement from the bottom side. We measured the displacement of coil mass during changing vibration frequency with sweeping up condition by using laser Doppler vibrometer (MLD-103A; Neoark Co.,). The frequency response of mass vibration amplitude and phase at 0.03 G
(G: gravitational acceleration) and 0.07 G of applied acceleration are shown in Fig. 10. The measured resonant frequency and mechanical Q-value are 215 Hz and 715, respectively. The larger acceleration causes a collision over the maximum travel range of 180 μm, however we confirmed that the 20 μm narrow gap device could vibrate with high Q-factor.

4. Conclusion
We demonstrated the improvement method of curvature radius of the NdFeB/Ta sputtered wafer. During high temperature annealing for sufficient magnetic performance, the magnet film has large curvature distortion. By applying the additional sputtering on the Si back side, we could reduce the residual stress from 144 MPa to 9.4 MPa. In addition the electromagnetic harvester with 20 μm narrow gap was successfully fabricated and cleared the vibration test.

5. References
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