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# MONOLITHIC INTEGRATION OF THICK NDFEB MICRO-MAGNETS INTO MEMS: APPLICATION TO ELECTROMAGNETIC ENERGY HARVESTING

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## ABSTRACT

This paper presents a fabrication process for patterning 50 $\mu\text{m}$  thick rare-earth micro-magnets on a free-standing silicon resonator integrated into an electromagnetic energy harvester. Patterning of the micro-magnet arrays on a millimeter-scale surface is achieved by sputtering a NdFeB film onto a silicon substrate with etched features, through a shadow-mask. The use of a pre-patterned silicon substrate reduces the build-up of stress within the NdFeB layer, thus preventing delamination, while defining the in-plane dimensions of the micro-magnets. As a proof-of-concept, a fabrication process is implemented to integrate the micro-magnet array into an energy harvester that exhibits a normalized power density of  $\approx 0.8 \times 10^{-3}$  kg.s.m<sup>-3</sup> for a device volume of  $\approx 300 \text{mm}^3$ , which is comparable to state-of-the-art MEMS electromagnetic harvesters. This patterning approach is foreseen to facilitate the integration of high-performance magnets into MEMS.

## KEYWORDS

NdFeB, Permanent magnet, Energy harvester, Resonator, Micromachining, Integration.

## INTRODUCTION

Electromagnetic MEMS used as actuators [1], sensors [2], or energy harvesters [3], call for high-performance permanent magnetic field sources to produce large static magnetic fields at specific locations. These magnetic fields, which quickly decay with increasing distance from the magnet, depend on the magnet's shape and remanence.

Various approaches have been proposed for the monolithic integration of magnets into MEMS [4], including sputtering of rare-earth compounds with excellent magnetic properties (remanence and coercivity) but that display limited film thickness [5], electrodeposition of thicker films of rare earth free magnetic alloys but with poorer magnetic properties [6], and the use of magnetic powder either diluted in a polymer matrix that results in a limited magnetic volume fraction [7], or assembled by capillary forces and magnetophoresis, an approach currently limited to in-plane magnetization [8]. Hence, no high performance microfabricated magnets exhibiting large thickness, and freedom in the choice of magnetization direction have been integrated into prototypes.

The work presented here builds on a recently proposed strategy for thick rare-earth micro-magnet fabrication [9]. This strategy consists in creating topographic features in the substrate onto which the NdFeB layer is to be deposited to reduce the build-up of stress and to avoid layer delamination, which is the main limitation for depositing NdFeB thick-films. Here we demonstrate the integration of such NdFeB magnets into a vibrating mass used in an electromagnetic MEMS vibration energy harvester (consisting of a magnetic mass vibrating in front of a coil). This is a class of harvester that has been identified as a promising answer for the future needs of IoT but for which one of the main issues is a lack of high-performance micro-magnets [3].

We have combined the substrate pre-patterning strategy with the use of a shadow mask to selectively deposit an array of magnets onto a silicon substrate that undergoes additional process steps to fabricate a MEMS resonator. The proof-of-concept device, an in-plane vibration electromagnetic energy harvester, the design of which was inspired by the work of Han et al. [10], is then obtained by transferring this resonator onto a substrate hosting a planar inductor. The fabricated device outputs 3nW through a 1k $\Omega$  load resistance for a mass displacement of 110 $\mu\text{m}$ , corresponding to a  $\approx 0.9\text{g}$  acceleration.

## DESIGN AND FABRICATION

The fabrication process developed for the integration of NdFeB micro-magnets into a MEMS energy harvester is depicted in figure 1. It includes the fabrication of the MEMS resonator hosting the array of micro-magnets, the fabrication of a copper coil on a silicon substrate and the bonding of both substrates using an adhesive layer that acts as a spacer to provide a controlled gap between the moving magnets and the coil.

First, 50 $\mu\text{m}$  deep patterns were etched into a silicon substrate by deep reactive ion etching (DRIE) using a 15 $\mu\text{m}$  thick AZ 15 nXT photoresist layer to define the in-plane dimensions of the individual micro-magnets (500 $\mu\text{m} \times 500\mu\text{m}$ ) and at the same time to relieve the stress in the magnetic layer. The latter was deposited at room temperature via triode sputtering, through a shadow mask machined from a 1mm thick sheet of Mo. A 100nm Ti adhesion layer was sputtered before depositing the NdFeB

magnet, that was subsequently capped with a 100nm Ti layer to protect it from oxidation. Fabrication of the resonator (frame and springs) and chip individualization were then carried out by etching through the silicon wafer by DRIE using a 100 $\mu$ m thick WBR2100 photoresist layer deposited under vacuum using a nanonex press (5 min, 65°C, 30 PSI) to ensure the conformal coating of the photoresist on the topographic features of the magnets. The central mass of the resonator is 4.3mm wide, 6.4mm long and 525 $\mu$ m thick and hosts a 7 $\times$ 11 array of 500 $\mu$ m $\times$ 500 $\mu$ m micro-magnets spaced 50 $\mu$ m apart (figure 2.1). Annealing of the micro-magnets was conducted at 600°C during 1min to crystallize the high anisotropy Nd<sub>2</sub>Fe<sub>14</sub>B phase. The micro-magnets were then magnetized in the out-of-plane direction under a field of 7T.

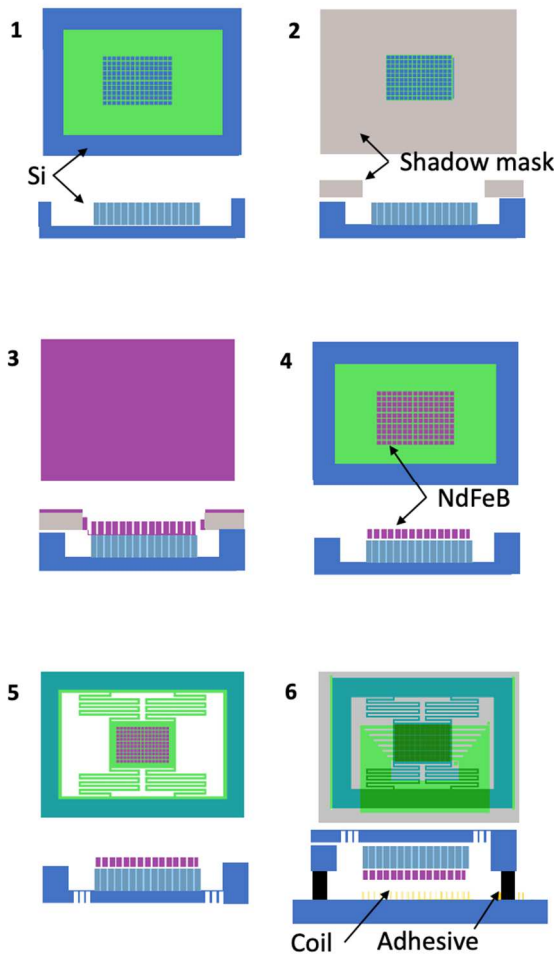


Figure 1: Fabrication process for integrating an array of thick NdFeB micro-magnets into a MEMS energy harvester. (1) DRIE of the silicon substrate to create 50 $\mu$ m deep topographical features to define the in-plane dimensions of individual micro-magnets and at the same time to relieve stress in the magnetic layer. (2) Alignment of a Mo shadow mask using the wafer flat. (3) Deposition of a 50 $\mu$ m thick NdFeB layer by triode sputtering through the shadow mask. (4) Patterned magnet array after shadow mask removal. (5) DRIE of the silicon substrate to release the vibrating mass and to dice the wafer. Magnetization of the NdFeB magnets is conducted at the chip level. (6) Bonding of the vibrating mass to a silicon substrate with integrated coils using a polymer adhesive.

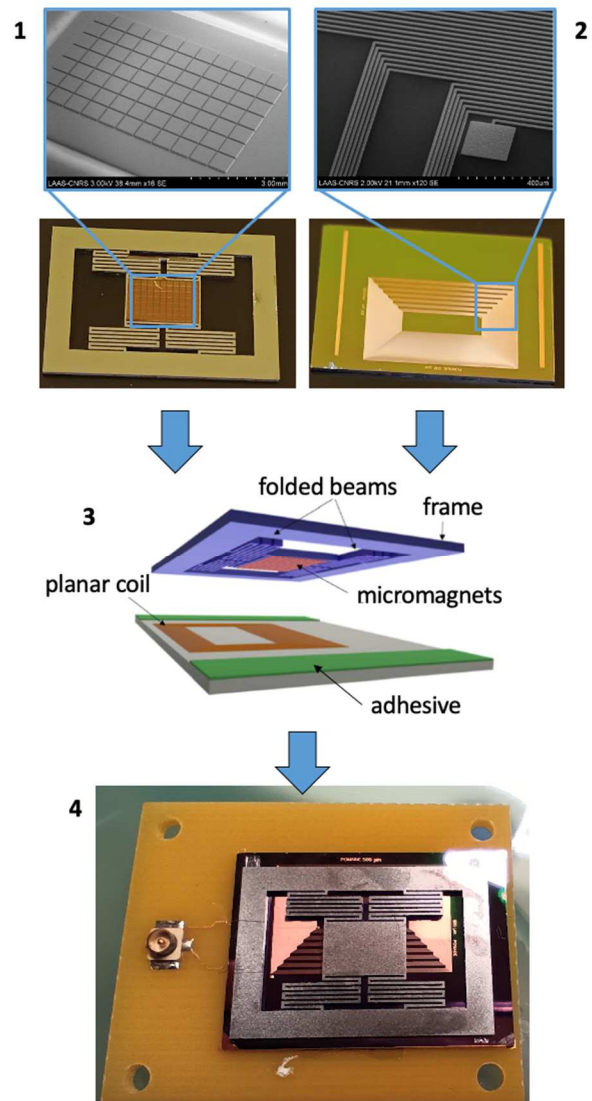


Figure 2: Schematics and photographs of the fabricated energy harvester. SEM and optical pictures of (1) the silicon vibrating mass hosting the array of micro-magnets and (2) the microfabricated coil on a silicon substrate. (3) Schematics of the assembly process. (4) Picture of a packaged electromagnetic energy harvester.

Coils were electroplated onto another 100mm standard silicon wafer coated with 200nm of silicon dioxide. To this end, a 100nm/200nm Ti/Cu seed layer was first sputtered and a 20 $\mu$ m thick electroplating mold was made with AZ 40 XT photoresist. After electroplating a 6 $\mu$ m thick copper layer using a plating equipment from Yamamoto-MS, the mold was removed and the seed layer was etched. The metal was then annealed at 250°C under N<sub>2</sub> for 20min, resulting in a total coil resistance of  $\approx$ 1k $\Omega$  for 7 $\times$ 16 turns (each row of 11 magnets was designed to be centered onto 16 turns of the coil [11]). Then, the substrate was diced into chips (figure 2.2).

The suspended mass with integrated micro-magnets was attached to the silicon substrate with the patterned coil via two layers of manually cut 50 $\mu$ m thick tesa 61210 adhesive tape. Due to the use of the 100 $\mu$ m thick adhesive spacer, the magnets were positioned  $\approx$ 44 $\mu$ m above the top surface of the coil. The chips were aligned and bonded

(1kg, 2 min, room temperature) by means of a SET-FC 150 equipment to create the in-plane vibrating electromagnetic energy harvester (figure 2.3). Finally, the energy harvester was glued onto a PCB and wire bonding was used to electrically connect the chip to the PCB (figure 2.4).

## RESULTS AND DISCUSSION

The patterned micro-magnets (figure 3) were characterized using a vibrating-sample magnetometer, and displayed a remanence ratio of 0.57 (*i.e.* remanence  $\approx 0.7T$ ) and a coercivity of 2.3T.

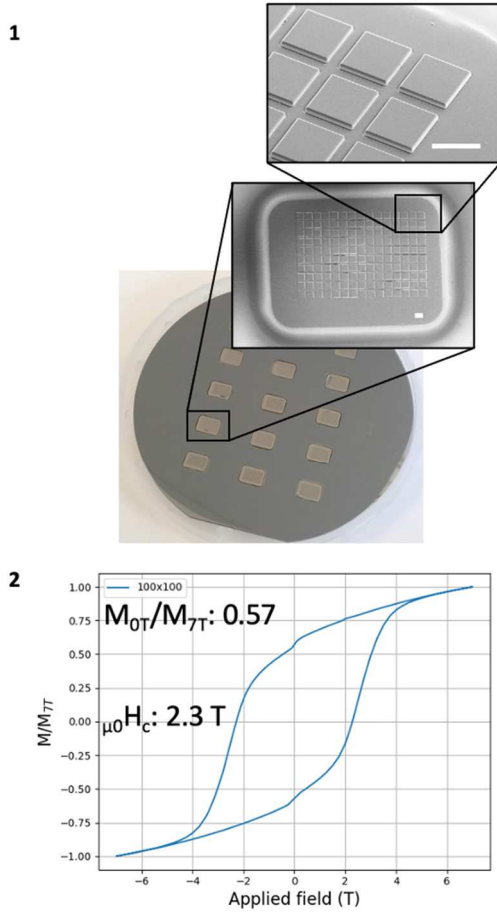


Figure 3: (1) Optical picture of the shadow mask and the 100mm diameter silicon wafer after NdFeB layer deposition and SEM pictures of the deposited array of micro-magnets (scale bars=500 $\mu$ m). (2) Hysteresis curve measured using a vibrating-sample magnetometer.

The energy harvester was then characterized by mounting the PCB onto a 4810 mini-shaker from Brüel & Kjaer (figure 4.1). Displacement of the shaker (for the evaluation of the acceleration) and the MEMS resonator were both measured using an IFS2407-3 confocal microscope from micro-epsilon and the voltage induced in the coil (the electromotive force  $e$ ) was measured with a NI data acquisition card (NI USB-6363), where:

$$e(t) = - \sum_i \frac{d\phi_i}{dt} = - \sum_i \frac{d\phi_i}{dx} \cdot \frac{dx}{dt} \quad (1)$$

with  $\Phi_i$ , the magnetic flux induced by the magnet array in

the coil turn  $i$  and  $x$ , the lateral displacement of the magnet array above the coil induced by the shaker.

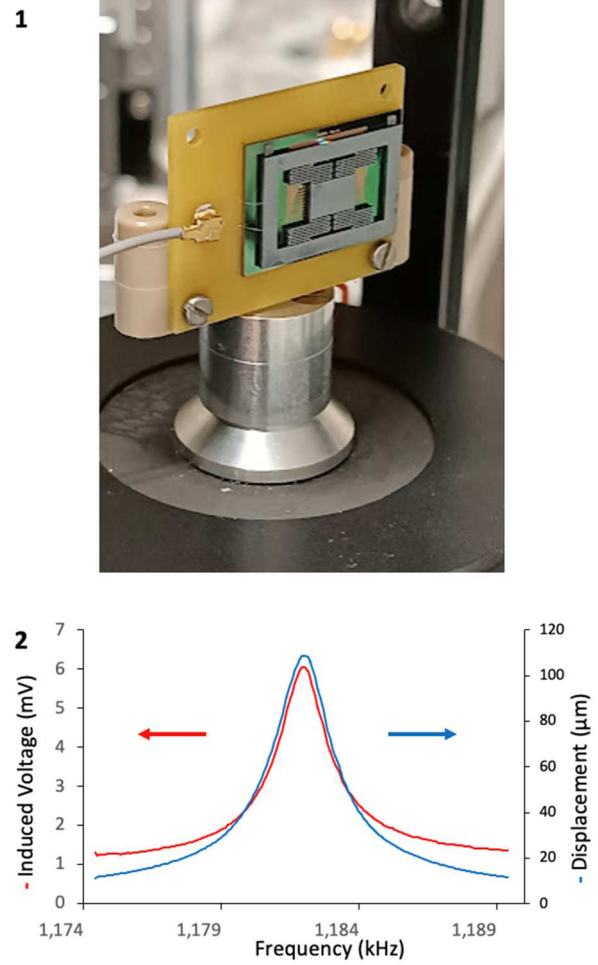


Figure 4: (1) Optical picture of the energy harvester mounted on a shaker. (2) Resonant frequency of the vibrating mass under 0.9g excitation (blue: vibration amplitude of the mass measured optically; red: peak of the coil output voltage).

The resonant frequency and quality factor of the fabricated MEMS resonator was measured to be 1.18kHz and  $\approx 660$ , respectively. The vibrating mass displacement and induced voltage were recorded at resonance (figure 4.2), where a peak in both displacement and voltage was observed at the MEMS resonant frequency. The induced voltage as a function of time reflected the sinusoidal excitation signal fed to the shaker (figure 5.1) and the electromotive force increased linearly with vibration amplitude  $A_0$  (figure 5.2, for 3 tested devices), as expected from (1), with  $v(t) = dx/dt = A_0\omega \cdot \cos(\omega t)$ , where 7mV was delivered for a 120 $\mu$ m MEMS displacement, which corresponds to a 1g acceleration. The maximum power of 3nW at  $\approx 0.9g$  was obtained for a load resistance of 1k $\Omega$ , the value of the coil resistance (figure 5.3). This harvester exhibits a normalized power density (output power of the device normalized with respect to the input acceleration level and volume of the device, *i.e.*,  $\approx 300\text{mm}^3$ ), of  $\approx 0.8 \times 10^{-3} \text{ kg.s.m}^{-3}$ , which is comparable to state-of-the-art MEMS electromagnetic harvesters [3].



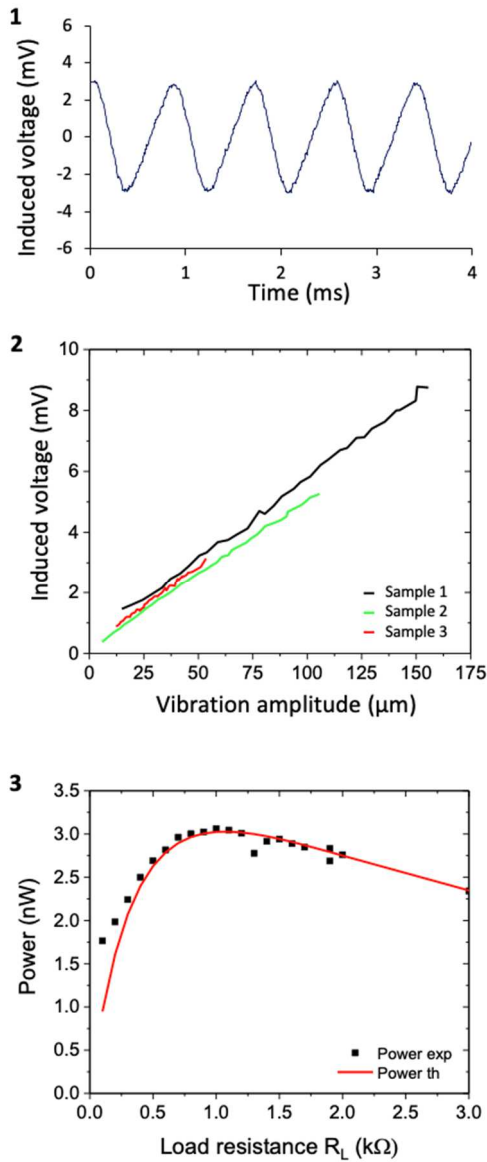


Figure 5: (1) Output voltage delivered by the energy harvester under 0.5g. (2) Output peak voltage of 3 fabricated energy harvesters as a function of the amplitude of the vibrating mass. (3) Output power delivered by the MEMS energy harvester as a function of load resistance (for 110 $\mu$ m vibration amplitude of the mass, corresponding to  $\approx 0.9g$  acceleration).

## CONCLUSION

A fabrication process for integrating 50 $\mu$ m-thick NdFeB micro-magnets into MEMS was presented. The magnet integration strategy relies on the sputtering of NdFeB through a shadow mask onto a topographically patterned silicon substrate. As a proof-of-concept device, we proposed a MEMS energy harvester consisting of a silicon resonator with integrated magnets vibrating in front of a microfabricated copper coil. The energy harvester exhibits a normalized power density of  $\approx 0.8 \times 10^{-3}$  kg.s $^{-3}$  and delivers 3nW at  $\approx 0.9g$ . Improvement of the device performance can be expected by decreasing the coil resistance and increasing the remanence of the micro-magnets by depositing them at elevated temperature to induce out-of-plane texture [5,9].

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