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Resin-bonded NdFeB micromagnets for integration into electromagnetic vibration energy harvesters*

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Abstract: A micromachining technique is presented for the fabrication of resin-bonded permanent magnets in the microscale. Magnetic paste is prepared from NdFeB powder and an epoxy resin, filled into lithographically defined photoresist molds or metal molds, and formed into resin-bonded magnets after curing at room temperature. A coercivity of 772.4 kA/m, a remanence of 0.27 T, and a maximum energy product of 22.6 kJ/m^3 have been achieved in an NdFeB disk micromagnet with dimensions of Φ200 μm×70 μm. Based on the developed micro-patterning of resin-bonded magnets, a fully integrated electromagnetic vibration energy harvester has been designed and fabricated. The dimensions of the energy harvester are only 4.5 mm×4.5 mm×1.0 mm, and those of the micromagnet are 1.5 mm×1.5 mm×0.2 mm. This microfabrication technique can be used for producing permanent magnets tens or hundreds of micrometers in size for use in various magnetic devices.

Key words: NdFeB, Micromagnet, Resin-bonded, Electromagnetic vibration energy harvester
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1 Introduction

High-performance permanent magnets play an important role in various magnetic devices, especially magnetic micro-electromechanical systems (MEMS) devices (Cugat *et al*., 2003; Arnold and Wang, 2009). However, there is a significant problem hindering the development of magnetic MEMS devices. Conventional methods for manufacturing permanent magnets are hardly compatible with today's techniques for the microfabrication of MEMS devices. The typical dimensions of the magnet in MEMS devices range from a few micrometers to hundreds of micrometers or even larger, depending on the different applications. The dimensions of bulk magnets cannot be reduced to a few hundred micrometers. Magnetic films obtained using sputtering, electroplating, or other methods have good magnetic properties (Molian and Molian, 2009; Nakano *et al*., 2009; Yang *et al*., 2009; Sun *et al*., 2012), but these methods are limited to film thicknesses of a few micrometers because of their slow deposition rate and large film stress. Thus, a new technique for the microfabrication of micromagnets is required for magnetic MEMS.

Bonded micromagnets (Arnold and Wang, 2009), which are obtained from an unconventional microfabrication technique, are very attractive. In this method, magnetic pastes including polymers/resins/inks and magnetic particles are formed first, and then these composites are filled into various molds to form micromagnets with micrometer-to-millimeter scale features. There have been many studies of bonded micromagnets (Lagorce and Allen, 1997; Dutoit *et al*., 1999; Cho and Ahn, 2003; Wang *et al*., 2008; Walther *et al*., 2009). However, this microfabrication technique is still immature and the magnetic performance of the bonded micromagnets is relatively low, and thus further development is needed.

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In this paper, we present a method to fabricate resin-bonded NdFeB micromagnets at room temperature, and characterize these micromagnets fabricated using this method. Finally, we describe the design and fabrication of a fully integrated electromagnetic vibration energy harvester using the developed NdFeB micromagnets.

2 Experiment

The rare earth NdFeB magnetic powder used in the fabrication of the micromagnets was obtained from Magnequench (Tianjin) Co. (MQFP). Fig. 1a shows a scanning electron microscope (SEM) image of the raw magnetic powder. It is shown that the particles have very irregular shapes and the dimensions of the particles are highly variable. The average size of a raw particle is about 10–40 μm. To obtain fine particles, the raw magnetic powder is milled for 12 h in a mill. An SEM image of the milled powder (Fig. 1b) shows clearly that the particles have become smaller and the particle size distribution is reduced. The average size of the milled particles is about 5–10 μm. After milling, a magnetic paste is prepared by thoroughly mixing the fine magnetic powder into room temperature curable epoxy resin. The optimum proportion by weight of magnetic powder in the magnetic paste is about 90% (Tao *et al*., 2011).

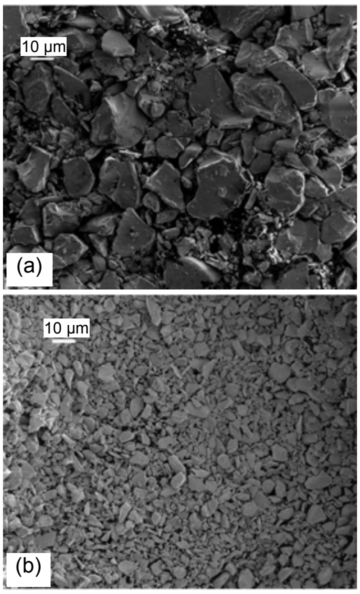

Fig. 1 SEM images of raw NdFeB powder (a) and fine NdFeB powder after milling for 12 h (b)

The next step is the micro-patterning of the NdFeB magnets. The main fabrication process of micro-patterning is sketched in Fig. 2. First, 200-nm Cr/Cu film is sputtered on the glass wafer for electroplating. Then, a thick photoresist is spincoated and patterned by photolithography. The thickness of the photoresist depends on the type of photoresist and can cover a big range. A Cu mold with a certain thickness is electroplated. After electroplating, the photoresist is stripped using acetone. An optical image of the electroplated Cu mold on glass substrate is shown in Fig. 3a. The magnetic paste is then filled into the Cu molds by compression with a metal squeezer and the extra paste is removed. Then the micromagnets are fully cured at room temperature for 24 h. After curing, the paste residues are etched using oxygen reactive ion etching (RIE) and the surface is polished. Finally, the Cu mold is removed either by peeling or with specific copper etching solutions, leaving the NdFeB micromagnets on the glass substrate.

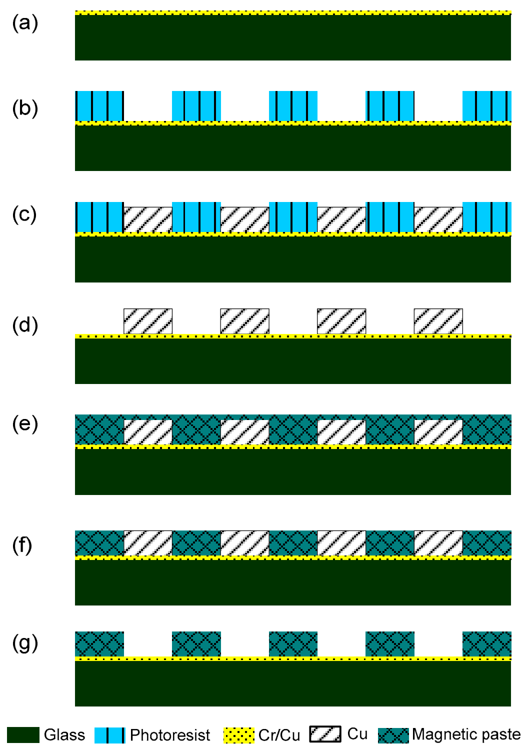

Fig. 2 Fabrication process for resin-bonded NdFeB micro magnets

(a) Sputtering Cr/Cu seed layer; (b) Photoresist patterning; (c) Electroplating copper mold; (d) Stripping photoresist; (e) Filling the Cu mold; (f) Removing the paste residues; (g) Removing the Cu mold

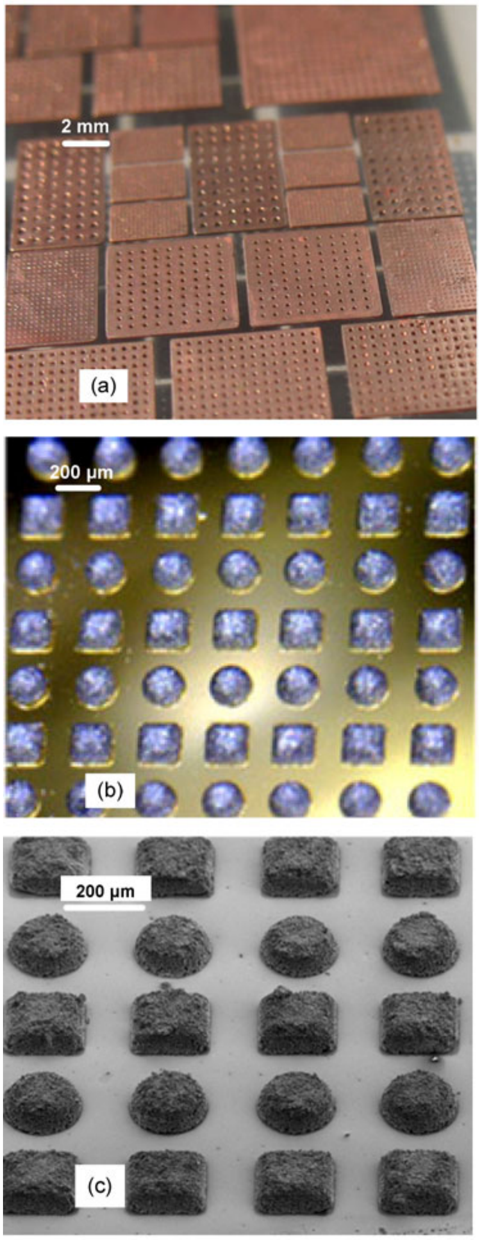

Fig. 3 Optical image of the Cu mold (a), optical image of the micromagnet array (b), and SEM image of the micromagnet array (c)

An optical image and an SEM image of an array of the NdFeB micromagnets with different shapes are given in Figs. 3b and 3c, respectively. The dimensions of the disk micromagnet are Φ200 μm×70 μm and those of the rectangular micromagnet are 200 μm ×200 μm×70 μm. For characterization, the micromagnet array was placed in a pulse magnetizer and magnetized in the in-plane or out-plane direction using a pulse magnetic field of 3.7 T.

3 Characterization

The microfabricated NdFeB micromagnets were characterized using a vibrating sample magnetometer (VSM) (Lake Shore Cryotronics, 7400 Series). A typical magnetic hysteresis loop of the resin-bonded NdFeB micromagnets tested using the VSM at room temperature is given in Fig. 4. The micromagnet had a coercivity of 772.4 kA/m, a remanence of 0.27 T, and a maximum energy product of 22.6 kJ/m^3. The magnetic properties of the fabricated micromagnet are better than those of other bonded NdFeB micromagnets (Wang *et al*., 2008; Arnold and Wang, 2009). So our method for fabricating NdFeB micromagnets is feasible.

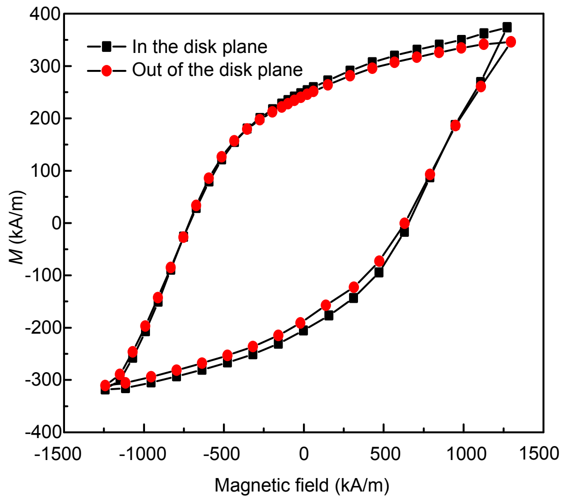

Fig. 4 Demagnetization curves of a resin-bonded NdFeB micromagnet

The adhesive strength of the resin-bonded NdFeB micromagnets was evaluated using a bonding tester (PTR-1101, RHESCA, JAPAN). A shear stress sensor was used to push the micromagnet in a horizontal direction. The tested shear stress from the sensor versus the displacement of the sensor is given in Fig. 5. The stress sensor moved freely in the range of 0–0.13 mm. The sensor then met the micromagnet and started to push it. During the pushing, the shear stress applied on the micromagnet increased, quickly reaching a maximum, and then dropped rapidly. The decrease in the shear stress indicates that the micromagnets had started to be peeled away. So the maximal shear stress is the adhesive strength of the micromagnet, and that was about 33 MPa.

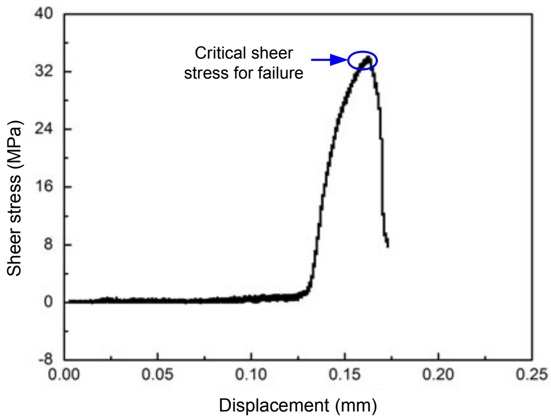

Fig. 5 Shear stress of the micromagnet vs. displacement of the sensor

4 Application

The vibration energy harvesting technique has attracted much interest in the MEMS field in recent decades. The electromagnetic transduction mechanism has been widely used to convert vibration energy into electrical energy. Because almost all the magnets in electromagnetic vibration energy harvesters are bulk manufactured and manually assembled into the device, electromagnetic vibration energy harvesters cannot be microfabricated totally using the MEMS technique. In our previous work (Wang *et al.*, 2012), several vibration energy harvesters with bulk magnets were designed, fabricated, and characterized. In this work, a fully integrated electromagnetic vibration energy harvester was designed and fabricated using the above microfabrication technique of resin-bonded NdFeB micromagnets. This electromagnetic vibration energy harvester includes a planar micro coil, a planar nickel spring, and a resin-bonded NdFeB micromagnet. The resin-bonded NdFeB micromagnet is located on the center of the planar spring and is over the coil. When an external vibration is applied to the device, the micromagnet will move up and down relative to the coil. The relative movement between the magnet and the coil can result in a change in the magnetic flux in the coil and an induced voltage can be generated in the coil, according to Faraday's law. An optical image of the fully integrated energy harvester array is given in Fig. 6. The dimensions of the micromagnet are 1.5 mm×1.5 mm×0.2 mm. The volume of that smaller energy harvester is about 20 mm^3. This fabricated integrated energy harvester is one of the smallest electromagnetic vibration energy harvesters compared with other energy harvesters with integrated magnets (Wang and Arnold, 2009; Zhang *et al.*, 2011). The characterization of this fully integrated vibration energy harvester is ongoing.

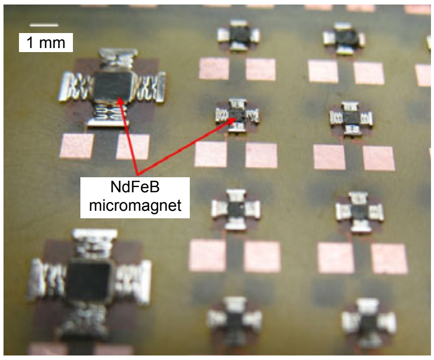

Fig. 6 Optical image of the fully integrated electromagnetic vibration energy harvesters with different dimensions

5 Conclusions

In this work, a microfabrication technique has been developed for resin-bonded NdFeB micromagnets in the microscale, and the micromagnets have been applied to electromagnetic vibration energy harvesters. Using this fabrication method, a coercivity of 772.4 kA/m, a remanence of 0.27 T, and a maximum energy product of 22.6 kJ/m^3 have been achieved in an NdFeB disk micromagnet with dimensions of Φ200 μm×70 μm. Moreover, test results showed that the adhesive strength of the micromagnet was above 30 MPa. A fully integrated electromagnetic vibration energy harvester with a resin-bonded NdFeB micromagnet and dimensions of 4.5 mm ×4.5 mm×1.0 mm has been fabricated. The characterization of this fully integrated energy harvester is ongoing. The developed resin-bonded micromagnets can be used in various magnetic MEMS devices.

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