Communications in Physics, Vol. 24, No. 3S1 (2014), pp. 85-89
DOI:10.15625/0868-3166/24/3S1/5225

A SIMPLE PROCESS TO FABRICATE MICRO FLUX SOURCES WITH HIGH MAGNETIC FIELD GRADIENT

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Received 04 April 2014
Accepted for publication 24 August 2014

Abstract. *In this paper, we present a fabrication process to produce the micro-sized magnetic structures based on the hard magnetic powders. Under the magnetic field originated from a micro patterned hard magnetic film, these magnetic powders are magnetically aligned to form arrays of the micro magnets on a polydimethysiloxane (PDMS) substrate. The high magnetic field gradient and stable magnetic flux can be obtained at certain micro-sized area on the surface of the micro magnets. The fabricated structures have been used for trapping iron oxide particles. Generally this fabrication process is simple, low cost and the micro magnets can be used for further applications in biology, medicine and beyond.*

Keywords: magnetic materials, NdFeB, SEM.

I. INTRODUCTION

Cell positioning and separating on surfaces are a challenge in cell biology. For the current diagnostic techniques which require a rapid and controlled spreading of thousands of cells, several methods have been proposed for on-chip cell arraying. One type of approach is based on surface engineering. Self-assembled monolayer [1], micro-fabricated polymer chip [2] and aspiration technique [3] fall into this category. Another approach consists of using a force to drag cells towards the targeted locations. Among the techniques, which present an advantage to enable contactless and chemical-free cell manipulation, there are dielectrophoresis [5] and magnetophoresis. They are widely used in chips combining actuation and sensing capabilities [6–8]. In the magnetophoresis technique, where the thermal problems may arise from the use of laser sources or electrodes, the permanent micro-magnets which can supply a constant magnetic field without energy dissipation or heating, are well suited for biological applications. Indeed, many research groups have demonstrated the application ability the permanent micro-magnets in biotechnology field [3–5]. The most important properties of the micro-magnets are a strong and stable remanent magnetization and a high magnetic field gradient in the small space. Many techniques have been developed to fabricate the permanent micro-magnets such as the electroplating method, the self assemble method, the topographically patterned method, the thermomagnetic patterned method and the magnetic imprinting.

In this paper we present a simple process to fabricate a magnetic trap based on arrays of the micro magnets distributed on the PDMS layer, so-called a composite structure. The micro magnets contain Nd-Fe-B micro-sized particles which are magnetically aligned. This fabrication method may be called as magnetic imprinting which exploits magnetophoresis to fabricate magnetic field sources and is applicable to biological applications.

II. FABRICATION PROCESS AND SIMULATION

The master micro-magnet structure is based on 4 μm-thick Nd-Fe-B film deposited by sputtering onto thermally oxidized Si substrates (see Fig. 1a). After a heat treatment at 750°C, the film was patterned at the micron scale in the out-of-plane direction, as shown in Fig. 1b, using the thermomagnetic patterning technique [9]. In the patterned film each square corresponds to a micro-magnet with the surface area of 100×100 μm^2, as photographed in Fig. 1c. The magnetic analysis, obtained by using a VSM, shows that this film possess a large magnetic hysteresis loop with a coercivity value of about 1.4 T (Fig. 1d). At the close distance (< 30 μm) to the surface of such magnetically patterned films, the intensity of the magnetic field is stronger and the magnetic field gradient is maximal just above the interfaces between the magnetic moment up regions and the magnetic moment down regions (Fig. 1e).

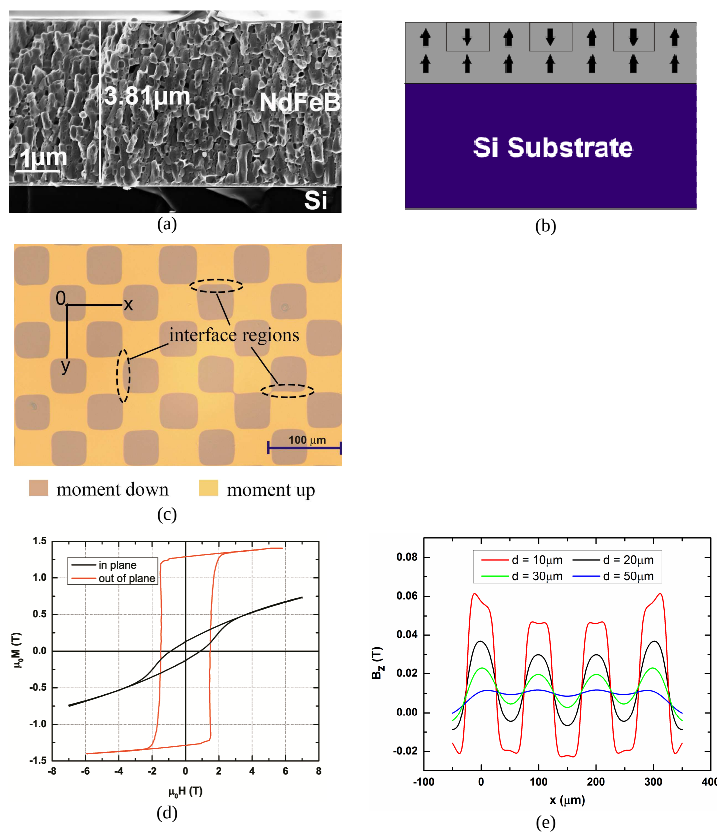


Fig. 1. a) SEM image of Nd-Fe-B film; (b) Magnetic structure of patterned film; (c) Surface image of patterned film; (d) M(H) plots of the patterned film; (e) Out-of-plane magnetic intensity B_z(T) at given distances as a function of x

For fabrication process, firstly, a layer of photoresist was covered on patterned film by spin coating followed by a soft baking to produce a hard photoresist layer. Then the Nd-Fe-B powders were put on the photoresist layer, and gently clean by dried air which favours the movement of powders to the regions of highest stray magnetic field strength, i.e. at the interfaces between oppositely magnetised micro-magnets, and remove non-trapped powders. Thanks to this modulated stray magnetic field of the patterned film, these Nd-Fe-B particles will be magnetophoretically controlled and therefore spatially distributed on the surface of the photoresist and reflected with the same structure as the patterned film. The Nd-Fe-B based powders used in this study were commercial powders, having average diameter of 5 μm and being composed of randomly oriented nano-crystals (Fig. 2). Next, the PDMS solution was poured onto the as-produced powders and soft baked. Finally the PDMS layer was pulled out from the patterned film to obtain a PDMS substrate with Nd-Fe-B squares in it which is called a composite structure (Fig. 3a). The magnetic powder aggregates have a depth from 5 μm to 10 μm and width from 5 to 20 μm, and they are separated by a distance of about 100 μm, which corresponds to the width of the micro-magnets in the patterned film. After fabrication, the composite structure was magnetized in an external magnetic field to obtain a completed magnetic trap with out-of-plane orientation (Fig. 3b).

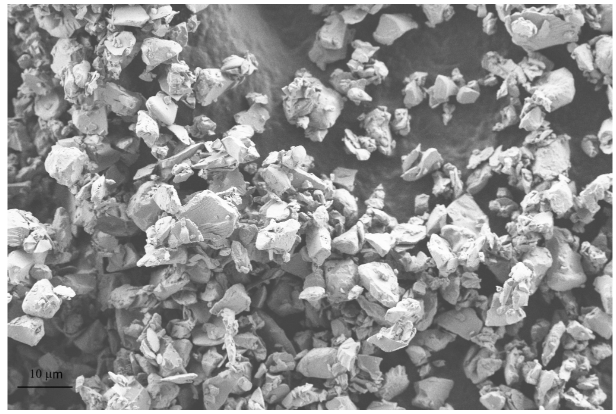
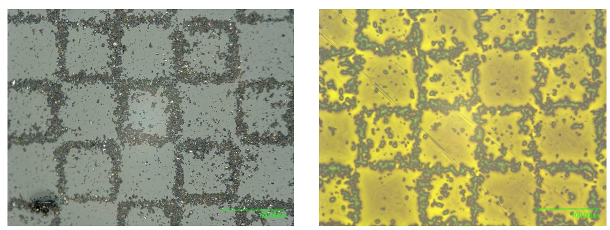


Fig. 2. SEM image of Nd-Fe-B particles.



(a) (b)

Fig. 3. Plan-view optical image of a composite (a), and magnetic structure of a composite (b).

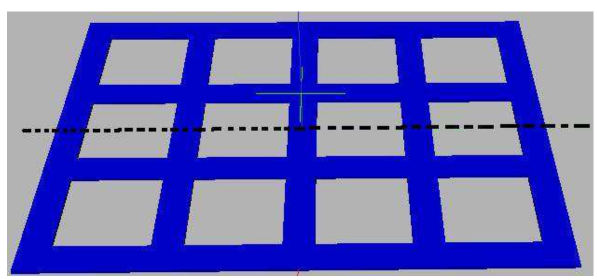


Fig. 4. A model of the composite structure with Nd-Fe-B magnets (dark lines), the distance between two Nd-Fe-B lines is 100 μm. The black dash-line is a scanning line in the x axis from left to right at arbitrary height on the model.

Besides experiments, we also calculate the stray magnetic field and its distribution on the surface of the micro-magnets. Assuming that Nd-Fe-B lines are rectangular parallelepipeds (see Fig. 4), by using a software we can simulate z-component (B_z) of magnetic field induction at different distance above the composite structure. The obtained results are presented in Tables 1 and 2 for different thickness of Nd-Fe-B of 7.5 and 10 μm, respectively.

After the fabrication process, we used a Hall probe to measurement the magnetic field in proximity region above the surface of the composite structure. In Fig. 5 we represent the profile of the out-of-plane magnetic field of the composite structure which was obtained for an active area of 10×10 μm^2 at the height of 30 ± 5 μm above the surface of the PDMS containing the Nd-Fe-B lines. This result shows that the amplitude of the magnetic field produced by Nd-Fe-B lines increases from left to right following the scanning line (peak-to-peak field values in the range 4 - 14 mT). It may be caused by gradually increase of the width and thickness of Nd-Fe-B lines in the PDMS or by non-uniform distance from the surface of trap to the Hall probe along the scanning line. Moreover, the measured profiles have a vertical off-set because the scan line was not at center line of the trap and outside regions did not belong to the composite structure.

From the results presented in Tabs. 1-2 and Fig. 5, one can see that the experimental results are well agreed with simulation results at the distances of 25 μm above the trap in Table 1 and 30 μm above the trap in Table 2. Here, there is a difference between the calculated and measured values, as well as, the inhomogeneity in the stray field produced by the composite structure because of the real shape of Nd-Fe-B lines in PDMS, local variations in the size and packing fraction of the hard magnetic powder and because of distance error between the Hall probe and the structure surface. Based on the measured magnetic field values, the magnetic field gradient along the z axis of the composite structure was estimated about 500 T/m These results show that the composite structure represent a micro flux source with high magnetic field gradient, which can be used for trapping magnetic micro-particles and magnetic objects, including bio-objects.

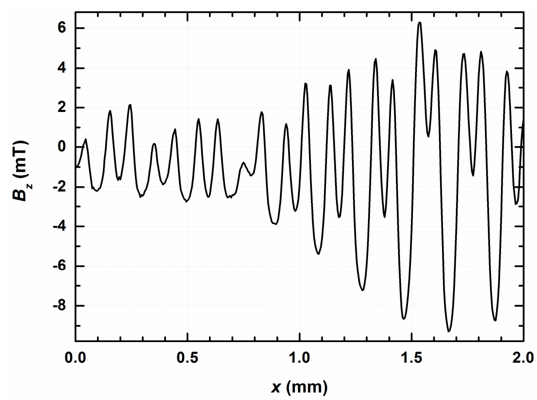


Fig. 5. Profile of the out-of-plane magnetic field component of the composite structure, measured by Hall probe.

Table 1. Calculated results of B_z with Nd-Fe-B magnet thickness of 7.5 μm.

Distance above PDMS (μm)	Width of Nd-Fe-B lines (μm)	B_{zmax} (mT)	B_{zmin} (mT)	B_z^{p-p} (mT)
25	5	2.2	-1.7	3.9
	10	4.2	-3.5	7.7
	15	4.8	-4.0	8.8
	20	6.0	-5.2	11.2
30	5	1.4	-1.3	2.7
	10	2.8	-2.5	5.3
	15	3.3	-2.8	6.1
	20	4.2	-3.6	7.8
35	5	1.1	-0.8	1.9
	10	2.1	-1.7	3.8
	15	2.5	-1.8	4.3
	20	3.2	-2.4	5.6

Table 2. Calculated results of B_z with Nd-Fe-B magnet thickness of 10 μm.

Distance above PDMS (μm)	Width of Nd-Fe-B lines (μm)	B_{zmax} (mT)	B_{zmin} (mT)	B_z^{p-p} (mT)
25	5	3.3	-2.8	6.1
	10	6.5	-5.3	11.8
	15	7.5	-6.2	13.7
	20	9.4	-8.0	17.4
30	5	2.3	-2.0	4.3
	10	4.5	-3.8	8.1
	15	5.2	-4.5	9.7
	20	6.7	-5.6	12.3
35	5	1.7	-1.3	3.0
	10	3.4	-2.5	5.9
	15	4.0	-2.8	6.8
	20	5.1	-3.5	8.6

III. CONCLUSIONS

We have presented a simple technique for fabrication of the micro magnetic structures with high magnetic field and strong gradient flux. The structures compose of micro-sized magnets embedded in the PDMS matrix. The magnetic response of the structure depends on the size, spatial distribution as well as the intrinsic properties of the magnetic particles. The use of a transparent background PDMS allows clear observation of the effect of stray magnetic field of micro magnetic structures on studied objects for on-chip or off-chip applications. Furthermore, by using a biocompatible background, we can make the structures ideally suited for bio-medical applications such as diagnosis, quick test, etc

ACKNOWLEDGEMENT

This work has been supported by Vietnam National University and University of Engineering and Technology, under projects no. CN.14.11 and QG.14.03.

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