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A giant magnetoresistance ring-sensor based microsystem for magnetic bead manipulation and detection

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In this paper a novel spin valve giant magnetoresistance (GMR) ring-sensor integrated with a microstructure is proposed for concentrating, trapping, and detecting superparamagnetic beads (SPBs). Taking advantage of the fact that SPBs can be manipulated by an external magnetic field, a unique arrangement of conducting microrings is utilized to manipulate the SPBs toward the GMR sensing area in order to increase the reliability of detection. The microrings are arranged and activated in such a manner so as to enable the detection of minute concentrations of SPBs in a sample. Precise manipulation is achieved by applying current sequentially to the microrings. The fabricated ring-shaped GMR element is located underneath the innermost ring and has a magnetoresistance of approximately 5.9%. By the performed experiments it was shown that SPBs could be successfully manipulated toward the GMR sensing zone. © 2011 American Institute of Physics. [doi:10.1063/1.3536822]

Superparamagnetic beads (SPBs) are increasingly being used to tag biological entities for biomolecular recognition purposes.¹ SPBs can be magnetized by an external magnetic field enabling their controlled manipulation like concentration, separation, and transportation as well as their detection by means of magnetic sensors.² Another distinct advantage of SPBs is that they lose their magnetization when the external field is removed, which prevents them from agglomerating. However, understanding the potential risks associated with exposure to these SPBs and the effect of the range of surface coatings used for functionality is crucial.³

Several types of microelectromagnets have been fabricated to trap SPBs in microfluidic channels.^{4,5} Alternatively, permanent magnetic microstructures could be employed to manipulate SPBs,^{6,7} but microelectromagnets are easier and cheaper to fabricate. Furthermore, microelectromagnets can be used to produce a magnetic field in various waveforms over a wide frequency band. Giant magnetoresistance (GMR) sensors have been widely used to detect SPBs in magnetic microsystems because they are sensitive to low-magnetic fields, compact in size, can be fabricated in a large scale and easily integrated with existing semiconductor electronics.⁸ Rectangular,^{8–10} meander,¹¹ horseshoe,¹² and spiral¹³ shaped GMR sensors have been used with tapered current lines, large external electromagnets, complementary GMR sensor bound biomolecules as well as various combinations of these, to trap and detect biomolecular tagged SPBs. Given that only a few biomolecular tagged SPBs are used in magnetic microsystems, tapered current lines, large external electromagnets, and complementary labels do not allow precise control and manipulation of SPBs. Furthermore, binding complementary molecules to the sensor is

time consuming, expensive and might cause complications if not bound properly. Moreover, the complementary biomolecules lack long-term stability.

The magnetic microsystem proposed in this paper includes a simple ring type structure, which is easy and cheap to fabricate. The number of rings needed for precise manipulation depends on the size of the microfluidic channel. The novel process of attracting, trapping and guiding SPBs has great potential to enable a high detection rate by the integrated GMR sensor, since the SPBs are transported in such a manner that they are trapped directly above the sensing elements. The motivation for designing and fabricating a ring shaped GMR sensor rather than a common rectangular or meander structure is to detect and estimate a large majority of SPBs confined to the periphery of the conducting microrings. Hence, apart from the fact the proposed magnetic microsystem is simple, its precise manipulation combined with accurate sensing offers an additional advantage regarding the seamless integration to a microfluidic lab-on-a-chip device, paving the way for rapid and reliable diagnosis of diseases.

The force on a SPB can be expressed by the following equation:¹⁴

$$\vec{F}_b = \frac{V_b \Delta\chi}{\mu_0} (B \cdot \nabla) B, \quad (1)$$

where V_b is the volume of the SPB, $\Delta\chi$ is the difference between the magnetic susceptibility of the SPB χ_b and its surrounding medium χ_m , μ_0 is the permeability of vacuum ($1.25 \times 10^{-6} \text{ N} \cdot \text{A}^{-2}$), and B is the magnetic field in Tesla.

The schematic of the proposed GMR ring-sensor based microsystem is shown in Fig. 1. Two GMR sensing elements are located under the innermost conducting microring. The GMR sensing elements are separated from the microrings by a thin Si_3N_4 passivation layer. Switching current to different microrings changes the location of the magnetic field maxima.

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FIG. 1. (Color online) Schematic of GMR ring-sensor based microsystem.

The SPBs follow these maxima all the way toward the active GMR sensing elements. Once the SPBs are concentrated to the GMR sensing area, the very magnetic field that is holding and trapping the SPBs is used to align the magnetic moments of the SPBs, thus producing a measurable fringing magnetic field for the GMR sensing elements.

A 2D finite element model was developed with COMSOL, Inc as shown in Fig. 2, to obtain the magnetic field distribution at the surface of the microrings. Aluminum (Al) was used as the material for the microrings with a conductivity of 3.77×10^6 S/m. The width and height of the microrings were 4 and 0.5 μm , respectively. An external current density of 5×10^6 A/m² was applied to the microrings sequentially. The change in axial, radial and magnitude of magnetic field with respect to radial distance from the surface of the coils is shown in Fig. 3(a). Corresponding force calculations were obtained using Eq. (1) for a 1 μm radius magnetic bead (Micromod®) with $\chi_b = 0.22$.¹¹ Assuming the surrounding medium is water, $\Delta\chi$ can be approximated as χ_b , since $\chi_b \gg \chi_m$. It can be seen from Fig. 3(b) that forces up to 150 pN can be obtained at the surface of the microrings. The strongest opposing force to manipulation of SPBs is the hydrodynamic force. However, this opposing hydrodynamic force can be controlled by adjusting the velocity of the microfluidic medium.¹⁵

FIG. 2. 2D finite element analysis of conducting microrings.

FIG. 3. (Color online) Numerical results. (a) Magnetic field distribution on the surface of rings with different radii and (b) Corresponding magnetic force applied on a superparamagnetic bead.

The bottom spin valve type GMR sensing elements utilized for the presented experiments were fabricated at the Austrian Institute of Technology (AIT). MnIr was used as the antiferromagnetic material to pin the NiFe layer (hard layer) in a transverse magnetic field H_{fc} , while the CoFe layer (soft layer) is free to move in the presence of an external magnetic field.

The patterned spin valve GMR sensing elements were covered with a 100 nm Si_3N_4 passivation layer, except from the parts of the connection/bonding pads, in order to protect the sensor from corrosion. Next, 500 nm thick Al microrings were fabricated on top of the spin valve elements, utilizing photolithography and lift-off techniques. The microring structure was designed with a radius of 10 μm for the innermost microring and a distance of 5 μm apart for repeating adjacent microrings. The width of the rings was set at 4 μm .

The GMR sensing elements are shown in Fig. 4(a). The sensing element was characterized for a magnetic field range of -120 to 120 Oe. The maximum magnetoresistance is 5.9% as shown in Fig. 4(b) at a dc bias current of 5 mA. The linear region sensitivity is between 10 and 30 Oe.

Iron oxide (Fe_3O_4) based SPBs with radius 1 μm and density 1.1 g/cm³ from Micromod® were used for experimentation. SPBs were pumped into the microring area. At first, when no external magnetic field was present, the SPBs simply flowed over the microring structure as shown in Fig. 5(a). A sinusoidal peak current of 50 mA was then applied by a waveform generator (Agilent 33220A) to the outermost microring to generate a time varying magnetic field. The SPBs were attracted toward the field maxima and hence trapped on the border of the rings as shown in Fig. 5(b). This verified the results obtained by the numerical analysis which showed that the magnetic field and

FIG. 4. GMR ring-sensor. (a) SEM image of fabricated GMR ring-sensor, and (b) magnetoresistance curve when applied magnetic field is parallel to H_{fc} .

gradients are highest at the edge of the conducting rings. Current is then switched from the outermost ring to the adjacent, second ring. The SPBs now moved away from the outermost ring toward the second ring as shown in Fig. 5(c). Finally, current was applied to the innermost ring and the SPBs were successfully transported to the GMR sensing zone as shown in Fig. 5(d).

FIG. 5. (Color online) Experimental results – Attracting, trapping, and transporting superparamagnetic beads toward the GMR sensing zone. (a) No current applied, (b) current applied to outermost ring, (c) current applied to second/middle ring and (d) current applied to innermost ring.

A GMR ring-sensor based microsystem was designed and fabricated to manipulate SPBs toward a region of interest in a microfluidic system. Numerical analysis was performed to study the magnetic field magnitude and gradient distributions from these structures. The results revealed that SPBs can be moved by switching current between the different microrings. Ring-shaped spin valve GMR sensing elements were designed, fabricated and characterized in order to detect SPBs. The experimental results showed that SPBs can be successfully attracted, trapped and transported toward the GMR sensing zone.

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- ¹D. L. Graham *et al.*, *Trends in Biotech.* **22**, 455 (2004).
- ²Q. A. Pankhurst *et al.*, *J. Phys. D: Appl. Phys.* **36**, R167 (2003).
- ³N. Singh *et al.*, *Nano Reviews*, **1**:5358 (2010).
- ⁴Q. Ramadan *et al.*, *Microfluid. Nanofluid.* **6**, 53 (2009).
- ⁵R. Fulcrand *et al.*, *J. Micromech. Microeng.* **19**, 105019 (2009).
- ⁶R. S. Conroy *et al.*, *J. Appl. Phys. Lett.* **93**, 203901 (2008).
- ⁷A. Winkleman *et al.*, *J. Appl. Phys. Lett.* **85**, 2411 (2004).
- ⁸S. X. Wang and G. Li, *IEEE. Trans. Mag.* **44**, 1687 (2008).
- ⁹D. L. Graham *et al.*, *Sens. Act B* **107**, 936 (2005).
- ¹⁰B. M. de Boer *et al.*, *Biosens. Bioelec.* **22**, 2366 (2007).
- ¹¹P. P. Freitas *et al.*, in *Magneto-electronics*, edited by M. Johnson (Academic, New York, 2004).
- ¹²H. A. Ferreira *et al.*, *IEEE. Trans. Mag.* **41**, 4140 (2005).
- ¹³J. Schotter *et al.*, *IEEE. Trans. Mag.* **38**, 3365 (2002).
- ¹⁴N. Pamme, *Lab. Chip* **6**, 24 (2006).
- ¹⁵C. Liu *et al.*, *J. Appl. Phys.* **105**, 102014 (2009).