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Manipulation of magnetic particles by patterned arrays of magnetic spin-valve traps

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Abstract

A novel platform for microfluidic manipulation of magnetic particles is discussed. The particles are confined by an array of magnetic spin valves with bistable ferromagnetic "ON" and antiferromagnetic "OFF" net magnetization states. The switchable fringing fields near the spin-valve traps can be used to selectively confine or release particles for transport or sorting. Spin-valve traps may be potentially used as magnetic molecular tweezers or adapted to a low-power magnetic random access memory (MRAM) switching architecture for massively parallel particle sorting applications.

Keywords: Magnetic traps; Magnetic tweezers; Single molecule; Microfluidics; Spin-valve arrays

1. Introduction

Several single-molecule tweezers have been recently developed and are widely used to study information about the behavior of individual biological molecules [1–11]. Tweezers technologies are based on the trapping forces of intense electric or magnetic field gradients. Optical tweezers involve tethering biological molecules to dielectric sphere handles and then capturing the spheres at the focal point of a laser field. Optical tweezers can selectively manipulate a single molecule and manipulate each end of a molecule independently. Despite these strengths, optical manipulation has a relatively low throughput, and force measurements are limited by the laser power and heating effects, the difference between the refractive indices of the object and its surrounding medium, and the object dimensions.

Magnetic tweezers, on the other hand, trap magnetic micro-particles near points of high magnetic field gradients. Due to the magnetic anisotropy inherent in the particles, rotation of the magnetic fields that capture the particles imparts torque to the particle and, consequently, to a biological molecule attached to the particle. This torsional motion can be used to stretch, twist, or uncoil the molecule. In addition, the size of the particle used in magnetic tweezers experiments can be small (<100 nm) compared to micrometer scale particles used in optical tweezers. Currently, single-molecule techniques are limited to studying one molecule at a time, which limits the throughput to typically one molecule per apparatus per day [11]. In the case of magnetic tweezers permanent immobilization of the molecule is necessary—a time-consuming process which further hinders it from being moved for subsequent analysis. The ability to use a microchip-based platform for high-throughput analysis without impairing the mobility of the molecules within a sample and ensuring adequate spacing between trapped molecules is essential in performing thousands of sequential experiments at the single molecule level one at a time or many molecules simultaneously at a rapid rate.

To address some of the limitations of current tweezers techniques, we are developing a novel magnetic tweezers based on a chip-scale microfluidic platform that can trap, measure, manipulate and sort magnetic particles in an array. The platform consists of an array of magnetic spin-valve elements separated from the biological sample by an

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optically transparent thin membrane effectively isolating the electronic or magnetic components from the fluid-bead solution.

2. Experimental

Previous work with spin-valve trapping elements in terms of biological microfluidic applications focuses on their ability to detect the presence of magnetic particles as they attach to locations with specific biological antibodies [12,13]. In contrast, the current platform incorporates spin-valve elements that can be switched between bistable states to provide a local magnetic field gradient sufficiently large enough to trap a magnetic particle that can not only be used for the purpose of investigating conformational dynamics of single biological molecules but can also be used to capture and sort biological molecules for gene sequencing or bio assay applications. We are also interested in applying a global rotating magnetic field in conjunction with the trap confinement fields to apply torsional forces to biological molecules for the purpose of investigating interactions between torsionally strained biopolymers and their surrounding medium. This paper focuses on our results demonstrating the application of a rotating magnetic field to that platform to prove the ability to confine, rotate, and subsequently release an array of trapped magnetic particles using spin valves.

A spin-valve array integrated with a microfluidic platform is illustrated in Fig. 1. The details of the microfabrication process for generating the platform can be found in previous work [14,15]. We made a modification to the magnetic structures in this previous by replacing low-coercivity permalloy traps with permanent magnet spin-valve traps [16–18] on a 200 nm thick silicon nitride support membrane. The spin valves have a six layer composition comprised of 5 nm Ta/15 nm $Ni_{80}Fe_{20}$/5 nm Co/10 nm Cu/5 nm Co/15 nm $Ni_{80}Fe_{20}$/5 nm IrMn/5 nm Ta. The multilayer is patterned using optical lithography to make structures 1 μm wide and 4 μm long with variable spacing depending on the length of the molecule to be studied. The first layer of tantalum promotes adhesion of the structure to the surface and the last layer of tantalum acts as a barrier to oxidation. The cobalt layer acts as a diffusion barrier between the permalloy ($Ni_{80}Fe_{20}$) and the Cu spacer layer. The IrMn layer pins the magnetization of the adjacent permalloy layer. The layers were sputter deposited in a 20 mT field applied along the long axis of the spin-valve element.

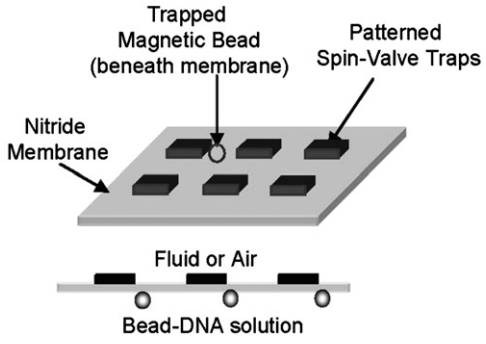

Fig. 1. Magnetic trap array patterned on a thin silicon nitride membrane showing magnetic beads trapped below the membrane in fluid.

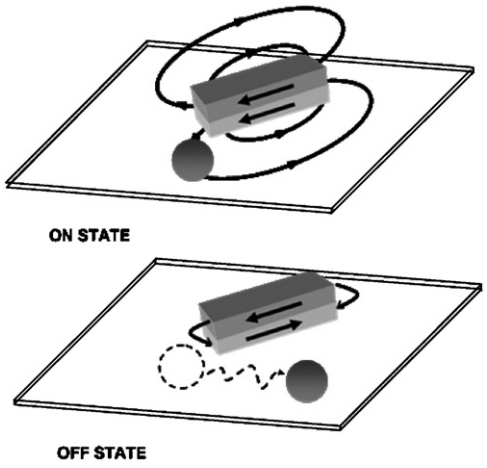

Fig. 2. "ON" and "OFF" states of a spin-valve trap showing magnetic bead release as the field lines collapse to the ends of the spin-valve structure.

The spin-valve elements exhibit a bistable magnetic structure that is either in the ferromagnetic "ON" or the antiferromagnetic "OFF" state in the absence of an applied magnetic field. In the "ON" state, the free layer in the element is aligned with the pinned layer, thereby producing a magnetic field gradient that is strongest near the ends of the elements below the membrane. In this state, the particles are trapped in the high magnetic field gradients near the ends of each spin-valve element. In the "OFF" state, the spins in the free layer are aligned antiparallel to the spins in the pinned layer. The fields from each layer cancel one another (since the permalloy layers have equal magnetic moments and the spin valve is "balanced") and will release a trapped particle in the "OFF" state leaving the element essentially non-magnetic in nature. In this case, particles would not be attracted to the element and would be free to seek out the closest magnetic field gradient (Fig. 2).

3. Results

The magnetoresistance curve for a single spin valve is shown in Fig. 3. The coercivity of the spin-valve elements is 3.5 mT, however, since the curve is not symmetric about zero, the minimum external magnetic field that will switch the trap from a ferromagnetic "ON" state to the antiferromagnetic "OFF" state is −1.5 mT. A field of +2.0 mT is necessary to reverse the state. This establishes the maximum field that can be applied to rotate the particles without switching the magnetic state of the

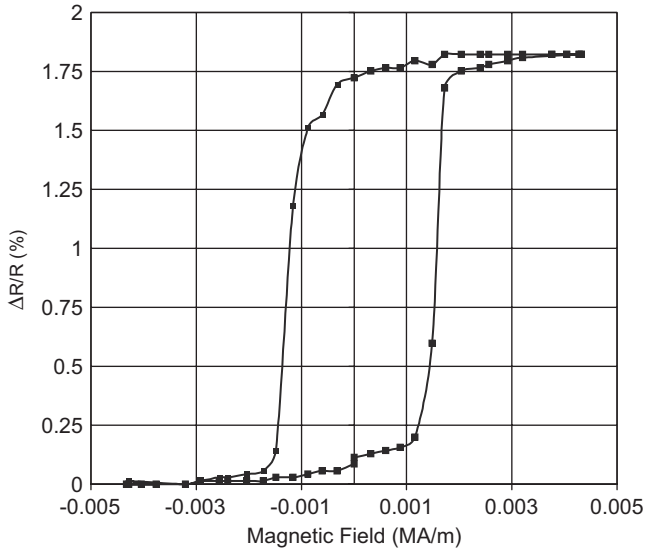

Fig. 3. Magnetoresistance ($\Delta R/R$) versus applied field curve of a single spin-valve element showing the bi-stable state at zero applied magnetic field.

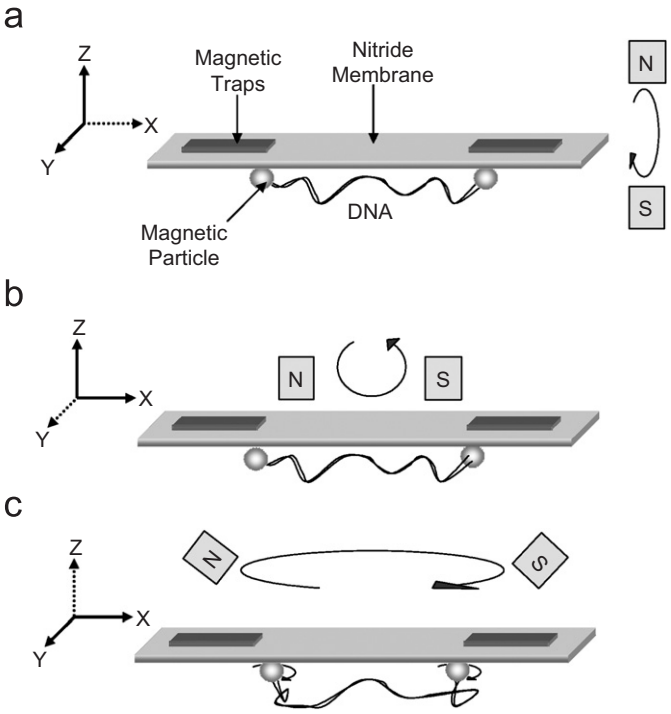

Fig. 4. Rotational configurations for single molecule manipulation.

spin-valve elements. In the "ON" state, a global magnetic field of sufficient strength to rotate the particle, but of insufficient strength to change the moment of the spin-valve element, can be applied to provide torsional/rotational manipulation to a molecule attached to the trapped magnetic particle.

Fig. 4 depicts the experimental geometries for the application of the rotational field. The rotation of the magnetic field can be about the x-, y- or z-axis. Since the direction of rotation (clockwise or counterclockwise) is the same for all particles, rotation about the y- and x-axis will not allow for the application of torque to biological molecules. For the x-axis, the entire molecule will rotate about a fixed point. About the y-axis, it is possible for the bead position to flip to alleviate the any applied torsional force. For rotation about the z-axis, torsional force can be applied to the DNA. For this geometry, we note that the attachment points of the molecule to the magnetic particle point must both point away from the nitride surface. For these experiments, a rotational field of approximately 1.2 mT with a 3 mT/cm magnetic field gradient is sufficient to rotate the particles in the trap. The small magnitude of the rotational field has a negligible effect on the trap magnetization state since the minimum field required to flip the state of the spin valve is 1.5 mT. Fig. 5 is a video sequence of a strand of magnetic particles confined by the field gradient produced by a spin-valve trap during rotation of the magnets about the platform. 2.8 μm diameter polystyrene spheres embedded with iron and iron oxide particles ($M \approx 1 \times 10^4$ A/m) were used. To visually demonstrate the rotation of the magnetic particles, we used a strand of particles instead of a single particle. The length of the strand consists of four particles, the first of which is trapped in the field gradient to the right of the trap. As the

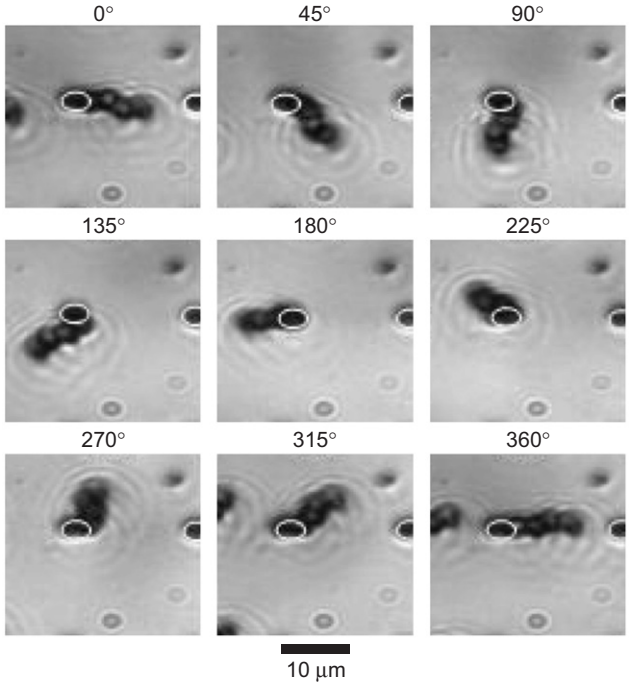

Fig. 5. Video micrographs showing the rotation of a strand of magnetic particles while trapped at the edge of a single spin-valve element (highlighted by the white ellipses).

magnetic field is rotated, the line of particles follows the field. For angles of 135–270°, the length of the strand of magnetic particles appears shorter. This is due to the fact that the trapped particle remains in its initial location

(at one end of the spin valve element) and the strand of particles overlap the spin-valve trap and are obscured by it. In contrast, in a permalloy trap the particle would migrate from one end to the other with field rotation.

4. Summary

We have demonstrated that bistable spin-valve elements, in the absence of externally applied magnetic fields, are capable of confining magnetic particles. We are able to rotate magnetic particles while they are confined to a specific location with the application of a rotating magnetic field—a promising indication that we will be able to apply torsional forces to arrays of DNA molecules. Our results show the potential for high-throughput and low power consumption measurement and control of biological processes on a single molecule level. Trapping forces greater than 100 pN have been estimated based on micromagnetic modeling [14,15] for permalloy traps with similar dimensions. These forces are sufficient for changing the confirmation of nucleic acids or proteins. The magnetization of the spin-valve elements may be individually switched by applying the magnetic fields locally to the each individual element using a matrix addressable array of orthogonal wires similar to a magnetic random access memory (MRAM) chip. Spin-valve-based micofluidic MRAMs would use zero power in the quiescent states between switching pulses making it an interesting alternative to other kinds of matrix addressable microfluidic traps currently being developed [19,20].

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References

[1] S. Nie, R. Zare, Annu. Rev. Biophys. Biomol. Struct. 26 (1997) 567.
[2] S. Scheuring, D. Fotiadis, C. Möller, et al., Single Mol. 2 (2001) 59.
[3] R.B. Best, D.J. Brockwell, J.L. Toca-Herrera, et al., Anal. Chim. Acta 479 (2003) 87.
[4] E. Evans, K. Ritchie, R. Merkel, Biophys. J. 68 (1995) 2580.
[5] A. Meller, L. Nivon, D. Branton, Phys. Rev. Lett. 86 (2001) 3435.
[6] J.E. Molloy, M.J. Padgett, Contemp. Phys. 43 (2002) 241.
[7] C. Gosse, V. Croquette, Biophys. J. 82 (2002) 3314.
[8] C. Haber, D. Wirtz, Rev. Sci. Instrum. 71 (2000) 4561.
[9] S.J. Koch, M.D. Wang, Phys. Rev. Lett. 98 (2003) 027103.
[10] C. Bustamante, J.C. Macosko, G.J.L. Wuite, Nat. Rev. Mol. Cell Bio. 1 (2000) 130.
[11] F. Assi, R. Jenks, J. Yang, et al., J. Appl. Phys. 92 (2002) 5584.
[12] L. Lagae, R. Wirix-Speetjens, J. Das, et al., J. Appl. Phys. 91 (2002) 7445.
[13] G.X. Li, V. Joshi, R.L. White, et al., J. Appl. Phys. 93 (2003) 7557.
[14] E. Mirowski, J. Moreland, S.E. Russek, et al., Appl. Phys. Lett. 84 (2004) 1786.
[15] E. Mirowski, J. Moreland, A. Zhang, et al., Appl. Phys. Lett. 86 (2005) 243901.
[16] S.E. Russek, J.O. Oti, Y.K. Kim, J. Magn. Magn. Mater. 199 (1999) 6.
[17] S. Kaka, S.E. Russek, J. App. Phys. 87 (2000) 6391.
[18] S.E. Russek, R.D. McMichael, M.J. Donahue, Top. Appl. Phys. 87 (2003) 93.
[19] H. Lee, A.M. Purdon, R.M. Westervelt, IEEE Trans. Magn. 40 (2004) 2991.
[20] P.Y. Chiou, A.T. Ohta, M.C. Wu, Nature 436 (2005) 370.