Available online at www.sciencedirect.com
ScienceDirect
Journal of Magnetism and Magnetic Materials 311 (2007) 401–404
Journal of magnetism and magnetic materials
www.elsevier.com/locate/jmmm

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

Elizabeth Mirowski[a], John Moreland[a,*], Stephen Russek[a], Michael Donahue[b], Kuangwen Hsieh[a]

[a]*Electronics and Electrical Engineering Laboratory, National Institute of Standards and Technology, Boulder, CO 80305, USA*
[b]*Information Technology Laboratory, National Institute of Standards and Technology, Gaithersburg, MD 20899, USA*

Available online 20 December 2006

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

*Corresponding author. Tel.: +303 497 3641; fax: +303 497 3725.
E-mail address: moreland@boulder.nist.gov (J. Moreland).

0304-8853/$ - see front matter © 2006 Elsevier B.V. All rights reserved.
doi:10.1016/j.jmmm.2006.11.202

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.

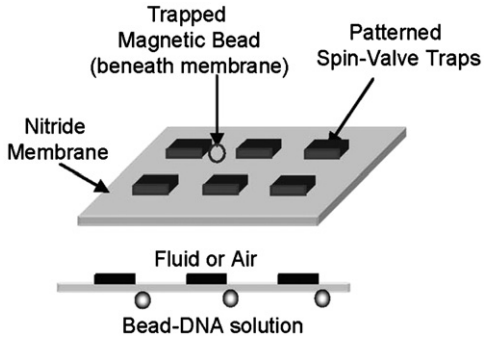

Fig. 1. Magnetic trap array patterned on a thin silicon nitride membrane showing magnetic beads trapped below the membrane in fluid.

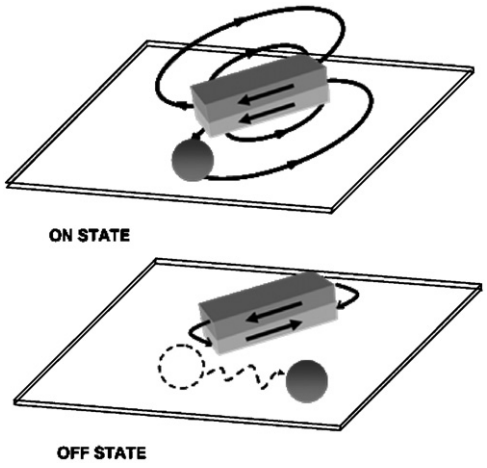

Fig. 2. "ON" and "OFF" states of a spin-valve trap showing magnetic bead release as the field lines collapse to the ends of the spin-valve structure.

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