Extended Abstracts of the 2005 International Conference on Solid State Devices and Materials, Kobe, 2005, pp.90-91

D-2-4

Magnetic capture of a single magnetic nanoparticle using nano-electromagnets

H. K. Kim[1], S. H. Hong[1], S. W. Hwang[1,2], J. S. Hwang[2], D. Ahn[2], S. Seong[3] and T. H. Park[3]

[1]Department of Electronics and Computer Engineering, Korea University
5-1, Anam, Sungbuk, Seoul 136-701, Korea
Phone: +82-2-3290-3241 E-mail: swhwang@korea.ac.kr
[2]Institute of Quantum Information Processing and Systems, University of Seoul
90 Jeonnong, Dongdaemun, Seoul 130-743, Korea
[3]School of Chemical Engineering, Seoul National University
San 56-1, Shilim, Kwanak, Seoul 151-742, Korea

1. Introduction

Recently, controlled manipulation of nanoparticles becomes an important issue due to its wide application in nano, bio-medical, chemistry, and electronics field. Several groups have performed the magnetic manipulation of various magnetic objects [1], but the manipulation of individual magnetic materials in a *nanometer* scale has not been demonstrated yet. In this work, we demonstrate the capture of magnetic nanoparticles using nano-electromagnets. We use serpentine-shaped nano-electromagnets, whose size and shape are adequate for capturing a single magnetic nanoparticle. The ***B*** pattern is analyzed by an electromagnetic simulator using finite element method.

2. Experiments

A magnetotactic bacterium, *magnetospirillum magneticum* AMB-1 (ATCC 700264), is used for bacterial magnetite production. The magnetite nanoparticle is extracted from this magnetotactic bacterium and their diameter is approximately 50 nm. These magnetic nanoparticles typically have the magnetic moment of ~ 6×10^{-17} Am^2 [2]. The nano-electromagnet is fabricated on a Si/SiO_2 substrate by a conventional electron beam lithography and lift-off process. As shown in Fig. 1, a droplet of the solution containing magnetic nanoparticles is dropped onto the nano-electromagnet. The DC current (I_{DC}) is supplied to the nano-electromagnet, then the ***B*** generated from the nano-electromagnet captures magnetic nanoparticles. Finally, the solution is removed by a N_2 blow dry. The captured particles survive during the blow dry if the current flow through the nano-electromagnet is maintained.

3. Results and Discussion

Capture of single magnetic nanoparticle

Successful captures of magnetic nanoparticles at the expected capture spots are demonstrated in Fig. 2(a). The value of I_{DC} is 10 mA. Figure 2(b) shows that a smaller nano-electromagnet can capture the particle at a smaller I_{DC} of 4.5 mA. It suggests that the gradient of B (∇B) is important. The gradient becomes larger in a smaller magnet.

Simulation of magnetic field pattern

Figure 3(a)-(c) show the magnitude of magnetic field (B) pattern at the *xy*, *yz*, *zx* planes respectively. Figure 3(d) shows $|\nabla B|$ at the *xy* plane. The maximum B spots with ~ 35 mT are shown at the corners of the nano-electromagnet and the maximum $|\nabla B|$ also exists at those spots. Figures 4(a) and 4(b) show the variations of B and $|\nabla B|$ as a function of the distance (z) from the surface of the magnet, respectively. They rapidly decrease away from the magnet surface.

Forces on magnetic particles

The force $\boldsymbol{F}_{\mathrm{mag}}$ on the individual particle due to the external magnetic field can be written by $\boldsymbol{F}_{\mathrm{mag}} = m\nabla B$, where m is the magnetic moment of the particle. We obtained the gradient value of ~ 4×10^5 T/m around the maximum B spots from simulation. Then, the force on the particle is ~ 24 pN. The maximum diffusional force per particle due to thermal Brownian motion is ~ 80 fN at room temperature. In Fig. 4(b), this diffusion limit (magnetic force = diffusion force) is denoted by the dashed horizontal line. The average interparticle distance estimated from the particle solution is ~ 600 nm and is denoted by the vertical line in the figure. The crossing point of these two lines is within a factor of 2~3 from the simulated ∇B curve. The force on the particle due to gravity is very weak (~ 3 aN) in comparison with the forces above. The results of Fig. 4(b) clearly demonstrate that there is only a single particle in the vicinity of the magnet where ***B*** is large enough to pull the particle.

4. Conclusions

We demonstrate the manipulation of magnetic nanoparticles in a *single* particle level using the nano-electromagnets. Only a single magnetic nanoparticle is captured at the maximum $|\nabla B|$ spots around the electromagnet. Our experiment is in the regime in which we can have a crossover between the magnetic force and the diffusion force within the average interparticle distance.

Acknowledgements

This work was supported by the Korean Ministry of Science and Technology through the Creative Research Initiative Program under Contract No. R16-1998-009-01001-0. The work at Korea University was supported by the Brain Korea 21 Project in 2004.

References

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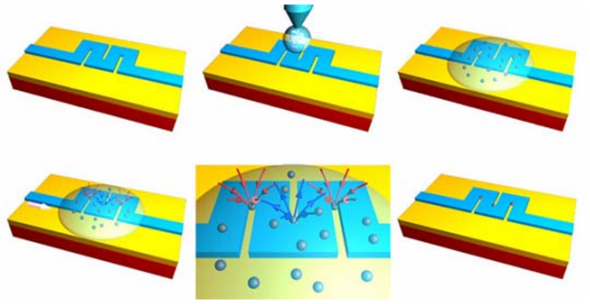

Fig.1 Schematic of capture process.

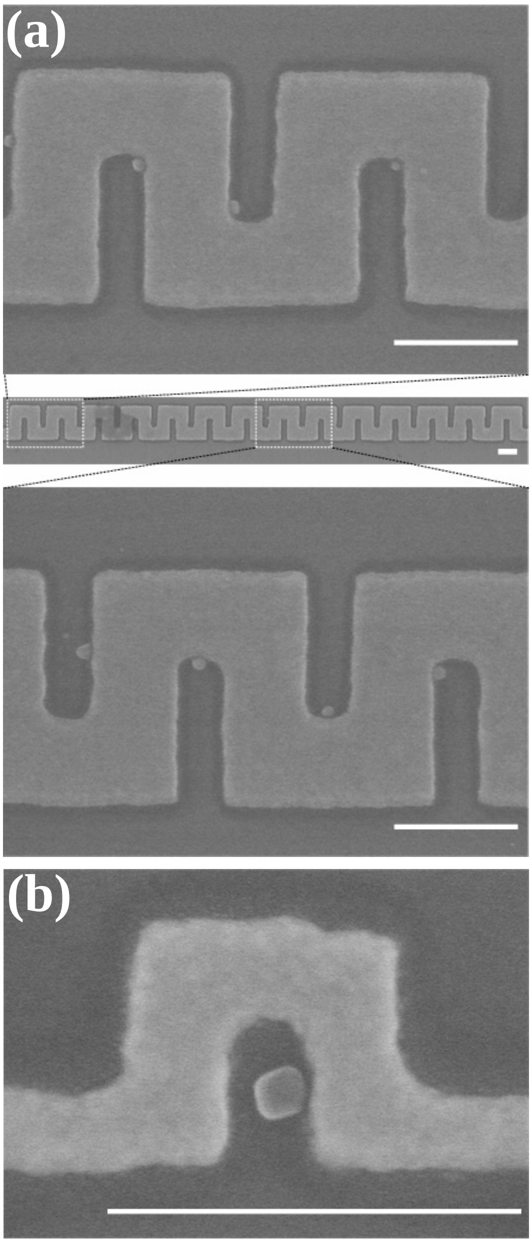

Fig. 2 (a) SEM image of the nano-electromagnet with the captured nanoparticles. (b) Capture of a single magnetic nanoparticle using a smaller nano-electromagnet. All the scale bars denote 500 nm.

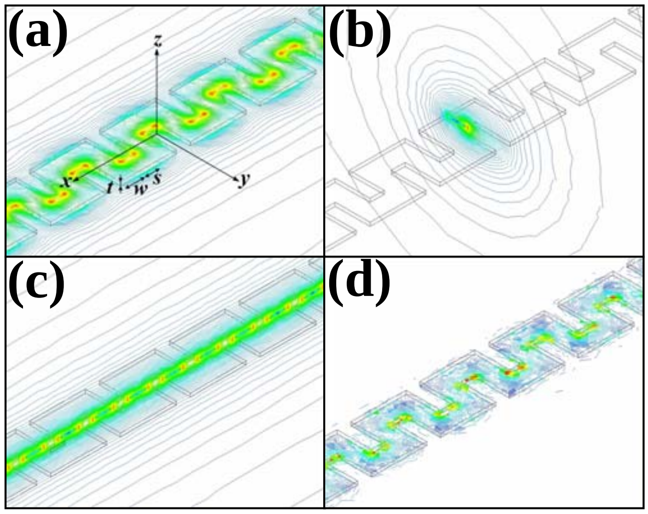

Fig. 3 (a)-(c) Simulated magnetic field (*B*) patterns at *xy*, *yz*, *zx* planes, respectively. (d) $|\nabla B|$ pattern at the *xy* plane.

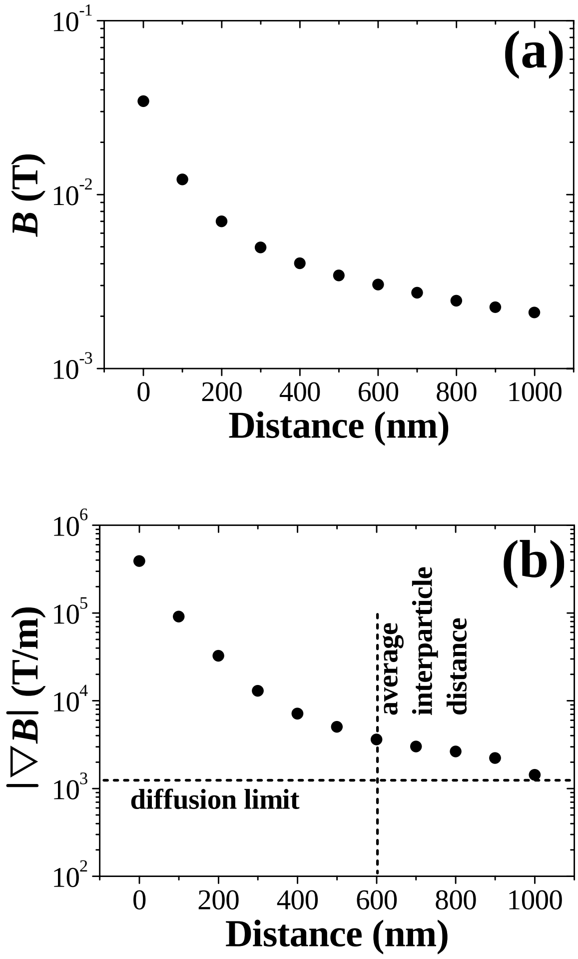

Fig. 4 (a) Variations of *B* as a function of the distance (*z*) from the surface of the magnet. (b) Variations of $|\nabla B|$ as a function of the distance (*z*)