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Domain structure and force analysis of micromagnetic patterns for bio-functionalized bead actuation

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2016
Domain structure and force analysis of micromagnetic patterns for bio-functionalized bead actuation

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A thesis submitted to the faculty of DGIST in partial fulfillment of the requirements for the degree of Master of Science in the Department of Emerging Materials Science. The study was conducted in accordance with Code of Research Ethics¹).

12. 02. 2015

Approved by
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¹) Declaration of Ethical Conduct in Research: I, as a graduate student of DGIST, hereby declare that I have not committed any acts that may damage the credibility of my research. These include, but are not limited to: falsification, thesis written by someone else, distortion of research findings or plagiarism. I affirm that my thesis contains honest conclusions based on my own careful research under the guidance of my thesis advisor.
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Master of Science.

12. 02. 2015

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Abstract

One of the important items for the determination of the macroscopic behavior of the thin magnetic film is the arrangement of magnetic domains as a function of an applied external field. These domain structures of the magnetic thin films are observed by the Magnetic transmission x-ray microscopy. The magnetic transmission x-ray microscopy is a novel technique to image element specifically magnetic domain structures. As the element-specific magnetic contrast which is due to x-ray magnetic circular dichroism scales with the projection of the magnetization onto the photon propagation direction both out-of-plane and in-plane magnetic domain structures can be studied. While observing the domain structures, enhance magnetic contrast and eliminates non-magnetic background so that, each image was normalized to a reference image taken at saturation state. Using magnetic transmission x-ray microscopy, we characterized the domain structure of the magnetic patterns including half disk and full disk and observed the vortex state of the magnetic pattern in demagnetized state. The change in vortex state for the magnetic patterns by changing the applied filed is also measured by x-ray microscopy. Furthermore, the demagnetized states for the full disk micro-magnet were determined by OOMMF simulation which is good agreement with the magnetic domain structure measured by X-ray microscopy.

In addition, the non-linear dynamics of superparamagnetic beads moving around the periphery of patterned magnetic disks in the presence of an in-plane rotating magnetic field was studied here. Two different dynamical regimes are observed in experiments, including (1) phase-locked motion at maximum driving frequencies, (2) phase-slipping motion above a first critical frequency $f_{c1}$.

The force calculations, Phase-locked and Phase-slipping angles are calculated by the superparamagnetic bead around a disk micro-magnet under an applied in-plane rotating field in
clockwise direction. Due to the magnetic field gradient produced by the micro-magnets, the beads can be trapped at the location of high induced field. Under the rotating field, there could be a phase lag of bead from the field direction, and the schematics for governing forces on a moving bead are discussed.

**Keywords**

Magnetic domain, X-ray microscopy, Phase-locked angle, Phase-slipping angle
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I. Introduction

Controlling the transport of micron and sub-micron diameter colloidal beads as carriers in aqueous fluids is of great interest for myriad biological applications. Several techniques have been developed to control bead motion, based on optical tweezers [1-3], electromagnetic tweezers [4,5], dielectrophoresis [6,7], acoustic traps [8,9] and on-chip micromagnets. [10-15] In particular, the ability to control large number of beads in parallel, by employing an external field and magnetizable features patterned in substrates, shows high potential for remotely organizing single particles on on-chip.

Many applications require the ability to separate colloidal components based on size or some other physical or chemical property. Hence, there has been great interest in exploiting the non-linear dynamics of bead motion in translating potential energy landscapes. The separation mechanism is typically based on tailoring the balance between the applied force and hydrodynamic resistance for different sized particles. This approach has been studied previously in colloidal suspensions interacting with arrays of optical traps [16,17], or in periodic magnetization patterns exposed to a time-varying magnetic field. [10-14,18-22]

Magnetic separation, in particular, has notable advantages including its biocompatibility, absence of magnetic shielding from the environment, the wide selection of commercially available magnetic beads, and finally its ability to apply strong forces remotely to colloidal particles without significant heating or other deleterious effects.

There have been several prior studies of magnetic bead motion through periodic potential energy landscapes. In one example, micron sized beads have been sorted in a quasi-1D potential energy landscape induced by an array of ferromagnetic disks exposed to a magnetic field rotating in the xz-plane. [21–23] In another example, magnetic beads are transported through a 2-D energy landscape induced by a hexagonal array of cylindrical magnetic “bubble” domains in uniaxial ferrite garnet films exposed to a conical magnetic field profile. [24–26]
The non-linear dynamics of bead motion through periodic lattices has also been studied both theoretically and experimentally. [21,27] Prior theoretical investigations were motivated by the experimental discovery of a third dynamical regime [14], in which magnetic beads were observed to enter into closed orbits, exhibiting effectively zero time-averaged translational motion across the substrate. This “phase-insulated” state is not predicted by the classical dynamics of synchronization behavior in a monochromatic non-uniform oscillator [28], which spurred the development of new theoretical models to understand this dynamical regime for its potential in high resolution magnetic separation.

Simulations first showed that the inclusion of multiple interacting oscillators was found to adequately predict the phase-insulated state, as well as the onset of quasi-periodic velocity states, resembling a “devil’s staircase”. [21] These predictions were later confirmed in experiments [27], which showed clear quasi-periodic phase locking behavior, as well as the existence of the phase-insulated state above a critical frequency. However, it is far from clear whether the phase-insulated regime exists just in this previously studied system, or whether these dynamics are universally present in other types of non-linear dynamical systems.

The goal of this thesis is to demonstrate magnetic property of domain structure for bead actuation and another example of this non-linear dynamic behavior in a system of magnetic beads exposed to an array of patterned disks of soft permalloy (Ni$_{80}$Fe$_{20}$), which are driven by an in-plane rotating field. Unlike prior studies, in which the magnetic beads experience strongly varying magnetic field profiles during translational motion, we investigate a system in which the magnetic field profile is weakly-varying, and in some cases quasi-static, within the translating reference frame of the bead. Even in this system, we show the existence of phase-locked and phase-slipping regimes.
The thesis - containing 5 chapters - is organized as follows:

**Chapter 1** includes motivation behind this thesis work, general introduction to bead manipulation systems on magnetic patterns and the importance of bead dynamic analysis on the magnetic patterns.

**Chapter 2** presents theoretical background of magnetic anisotropy and magnetic domain structures. demonstrates OOMMF simulation for magnetic domain structures and Maxwell simulation for magnetic force. These materials have been an integral part of this thesis work.

**Chapter 3** explains the experimental section of this thesis work. Photolithography, electron beam lithography and sputtering technique for patterning the magnetophoretic pathways on silicon substrate have been discussed. Electron beam lithography and sputtering technique for patterning on silicon nitride membrane have been discussed. X-ray microscope is used to characterize domain structures in the magnetic patterns. Experimental setup for bead dynamic analysis is also presented.

**Chapter 4** reports the results and discussion of magnetic domain structures and how to calculate between magnetic field direction and bead position for moving bead along to micro-magnetic patterns.

**Chapter 5** focuses on conclusive remarks of this thesis work.
Ⅱ. Theoretical background

2.1. Magnetic anisotropy

One factor which may strongly affect the shape of the $M, H$ (or $B, H$) curve, or the shape of the hysteresis loop, is magnetic anisotropy. This term simply means that the magnetic properties depend on the direction in which they are measured. This general subject is of considerable practical interest, because anisotropy is exploited in the design of most magnetic materials of commercial importance. A thorough knowledge of anisotropy is thus important for an understanding of these materials. There are several kinds of anisotropy: [29]

1) Crystal anisotropy, formally called magnetocrystalline anisotropy.

2) Stress anisotropy.

3) Shape anisotropy.

4) Induced magnetic anisotropy

2.1.1. Magnetocrystalline Anisotropy

Magnetocrystalline anisotropy is an intrinsic property of a ferromagnet, independent of grain size and shape. It can be most easily seen by measuring magnetization curves along different crystal directions. Crystal anisotropy may therefore be regarded as a force which tends to hold the magnetization in certain equivalent crystallographic directions in a crystal. Because the applied field must do work against the anisotropy force to turn the magnetization vector away from an easy direction, there must be energy stored in any crystal in which $M_s$ points in a noneasy direction. This is called the crystal anisotropy energy $E$. The Russian physicist Akulov showed in 1929 that $E$ can be expressed in terms of a series expansion of the direction cosines of $M_s$ relative to the crystal axes. In a cubic crystal, let $M_s$ make angles $a, b, c$ with the crystal axes, and let $\alpha_1, \alpha_2, \alpha_3$ be the cosines of
these angles, which are called direction cosines. Then

\[ E = K_0 + K_1 (\alpha_1^2 \alpha_2^2 + \alpha_2^2 \alpha_3^2 + \alpha_3^2 \alpha_1^2) + K_2 (\alpha_1^2 \alpha_2^2 \alpha_3^2) + \cdots \]  

(2-1)

Where \( K_0, K_1, K_2, \ldots \) are constants for a particular material at a particular temperature and are expressed in \( \text{erg/cm}^3 \) (cgs) or \( \text{J/m}^3 \) (SI). Higher powers are generally not needed, and sometimes \( K_2 \) is so small that the term involving it can be neglected. The first term, \( K_0 \), is independent of angle and is usually ignored, because normally we are interested only in the change in the energy \( E \) when the \( M_s \) vector rotates from one direction to another.

Magnetocrystalline anisotropy is the energy necessary to deflect the magnetic moment in a single crystal from the easy to the hard direction. The easy and hard directions arise from the interaction of the spin magnetic moment with the crystal lattice (spin-orbit coupling). Crystal anisotropy is due mainly to spin-orbit coupling. There is also a coupling between the spin and the orbital motion of each electron. When an external field tries to reorient the spin of an electron, the orbit of that electron also tends to be reoriented. But the orbit is strongly coupled to the lattice and therefore resists the attempt to rotate the spin axis. The energy required to rotate the spin system of a domain away from the easy direction, which we call the anisotropy energy, is just the energy required to overcome the spin–orbit coupling. This coupling is relatively weak, because fields of a few hundred oersteds or a few tens of kilamps per meter are usually strong enough to rotate the spins.

Suppose a single crystal with cubic structure is cut in the form of a disk parallel to a plane of the form \{110\}. This specimen will then have directions of the form \(<100>\), \(<110>\), and \(<111>\) as diameters, as shown in Fig. 2-1 for the plane (110). Measurements of magnetization curves along these diameters, in the plane of the disk, will then give information about three important crystallographic directions. The results for iron, which has a body-centered cubic structure, are shown in Fig. 2-2 (a), and those for nickel (face-centered cubic), in Fig. 2-2 (b).
Figure 2-1. The three principal crystallographic directions in the (110) plane of a cubic material. [29]

For iron these measurements show that saturation can be achieved with quite low fields, of the order of a few tens of oersteds at most, in the <100> direction, which is accordingly called the “easy direction” of magnetization. In nickel, Fig. 2-2 (b) shows that the direction of easy magnetization is of the form <111>. This tells us something about domains in iron in the demagnetized state. As will become clear later, a domain wall separating two domains in a crystal can be moved by a small applied field. Continued application of the field eliminates all but the favored domain, and the crystal is now saturated. This has been accomplished simply by applying the low field required for domain wall motion. We conclude that our postulated domain structure is basically correct and, more generally, that the direction of easy magnetization of a crystal is the direction of spontaneous domain magnetization in the demagnetized state. [29]
Figure 2-2. Magnetization curves for single crystals of iron (a) and nickel (b). [29]
2.1.2. Stress Anisotropy

In addition to magnetocrystalline anisotropy, there is another effect related to spin-orbit coupling called magnetostriction. Magnetostriction arises from the strain dependence of the anisotropy constants. Upon magnetization, a previously demagnetized crystal experiences a strain that can be measured as a function of applied field along the principal crystallographic axes. A magnetic material will therefore change its dimension when magnetized.

The inverse effect, or the change of magnetization with stress also occurs. A uniaxial stress can produce a unique easy axis of magnetization if the stress is sufficient to overcome all other anisotropies. The magnitude of the stress anisotropy is described by two more empirical constants known as the magnetostriction constants ($\lambda_{111}$ and $\lambda_{100}$) and the level of stress.

The magnetostriction constants are given in Fig. 2-3. The value of $\lambda_{100}$ is zero at two compositions, near 46 and 83% Ni, while $\lambda_{111}$ is zero at about 80%. Note also that the magnetostriction becomes isotropic ($\lambda_{111} = \lambda_{100}$) near 60 and 86% Ni. We expect high permeability when $K$ and $\lambda$ are small. A low value of $K$ decreases domain-wall energy and increases domain wall thickness, so that inclusions become less effective hindrances to wall motion. A low value of $\lambda$ means that microstress becomes similarly less effective. Fig. 2-3 shows that both $K_1$ and $\lambda_{111}$ are near zero just below 80% Ni, and $\lambda_{100}$ is not very large. The maxima in $\mu$ near 50 and 80% Ni are due to near-zero values of $\lambda$. Note that it is the value of $\lambda$ in the easy direction of magnetization that determines the effect of microstress on wall motion; near 50% Ni, the value of $K_1$ is positive, $<100>$ are easy directions, and $\lambda_{100}$ is zero; at 80% Ni the value of $K_1$ is negative, $<111>$ are easy directions, and $\lambda_{111}$ is zero. [30]
2.1.3. Shape Anisotropy

The shape anisotropy results from the demagnetising fields which occur within a magnetised material. A magnetized body will produce magnetic charges or poles at the surface. This surface charge distribution, acting in isolation, is itself another source of a magnetic field, called the demagnetizing field. It is called the demagnetizing field because it acts in opposition to the magnetization that produces it.

The shape of the sample has the effect of creating directions in which it is easier to magnetise the sample, and this is governed by the demagnetising field, \( H_d \), which, in the material, points in the opposite direction to the magnetisation and the applied field. For
instance, a smaller field is required to magnetise a long cylindrical magnetic rod along its length, because of the smaller demagnetising field, compared to the magnetic field required to magnetise the rod along a diameter. If one thinks in terms of magnetic poles, the strength of the demagnetising field depends upon the separation between these opposite magnetic poles. The poles generated at the ends of a rod are much further apart, giving rise to a small demagnetising field, whereas the magnetic poles will be much closer together when the rod is magnetised across its diameter, thus producing a larger demagnetising field. The demagnetising field depends solely on the magnetisation and the demagnetising factor, and is expressed as

\[ H_d = -N_d M \]  

(2-2)

where \( N_d (0<N_d<1) \) is the demagnetising factor which is shape dependent, and \( M \) is the magnetisation. The \( N_d \) term is calculated solely from the geometry of the sample and can only be calculated exactly for an ellipsoid. The energy associated with this demagnetising field can be expressed as follows, and is referred to as the magnetostatic energy density.

\[ E = \frac{1}{2} \mu_0 N_d M^2 \]  

(2-3)

The shape anisotropy has an obvious importance in thin films, since there is a significant shape anisotropy because of the thickness of the film. It is well known that the magnetisation usually lies in-plane for a film in the absence of any crystal anisotropy or any other anisotropy which would cause the magnetisation to lie out of plane. In general, a thin film can be approximated by a flat ellipsoid or an oblate spheroid; this allows one to determine approximately the demagnetising factors for a thin film system. The demagnetising factor for an oblate spheroid [Craik (1995)] with the magnetisation in the plane of the film is given by

\[ N_d = \frac{1}{2} \left[ \frac{q^2}{(q^2-1)^{1/2}} \sin^{-1} \left( \frac{\sqrt{q^2-1}}{q} \right) - \frac{1}{q^2-1} \right], \quad q = \frac{d}{t} \]  

(2-4)

where \( q \) is the ratio of the of the diameter \( d \) of the spheroid to its thickness \( t \). This is a
reasonable approximation for the films which were typically investigated in this thesis; the films were generally either rectangular (mainly square), or circular. Essentially, the in-plane demagnetising factor is equal to zero and the demagnetising factor perpendicular to the plane of the film is therefore equal to one (Nx+Ny+Nz=1). Hence the easy-axis is in the plane of the film, whilst the hard axis is perpendicular to the plane of the film. This means that any competing anisotropy, or an applied field, must overcome the demagnetising field which is equal to the magnetisation $M$ (Eq. 2-2), in order to rotate the magnetisation out of the plane of the film. It is therefore important to be aware of the shape anisotropy in the design process of thin film sensors in situations where the x-y dimensions of the film approach the thickness of the film, since the in-plane demagnetising field will no longer be negligible.

For example, take a long thin ellipse shaped pattern. The demagnetizing field will be less if the magnetization is along the long axis than if is along one of the short axes. This produces an easy axis of magnetization along the long axis. A sphere in shown Fig. 2-4, on the other hand, has no shape anisotropy. The magnitude of shape anisotropy is dependent on the saturation magnetization. [31-34]
2.1.4. Induced magnetic anisotropy

The induced anisotropy is described by the energy relation

$$E = K_u \sin^2 \theta \quad (2-5)$$

where $\theta$ is the angle between $M_s$ and the easy axis, which is the direction of the applied field during deposition. The value of $K_u$ is generally of the order of $1000 − 3000 \text{ erg/cm}^3$ or $100 − 300 \text{ J/m}^3$ for 80 permalloy, which is similar to the value observed for magnetically annealed bulk alloys. [29,35]
2.2. Magnetic domain

A remarkable property of ferromagnetic materials is not so much that they have a spontaneous magnetization, but rather that their magnetization can be influenced by the application of very low magnetic fields.

What allows this to occur is the fact that the sample is actually composed of small regions called magnetic domains, within each of which the local magnetization is saturated but not necessarily parallel. Domains are small (1-100's microns), but much larger than atomic distances. The existence of domains is hinted at by the observation that some magnetic properties, and in particular, coercivity and remanence vary greatly with grain size. This is best illustrated in the figure below, which shows the variation of $H_c$ with grain size.

![Figure 2-5. Variation of intrinsic coercivity $H_c$ with particle diameter D (schematic) [29]](image)

Single-domain, below a critical diameter $D_s$ the particles become single domains, and in this size range the coercivity reaches a maximum. Particles of size $D_s$ and smaller change
their magnetization by spin rotation, but more than one mechanism of rotation can be involved. Multi-domain, magnetization changes by domain wall motion. The maximum coercivity for a given material occurs within its single-domain range. For larger grain sizes, coercivity decreases as the grain subdivides into domains. For smaller grain sizes, coercivity again decreases, but this time due to the randomizing effects of thermal energy. [29]

Domains constitute a fundamental concept in magnetism. A ferro- or ferrimagnetic material may be generally defined as one that possesses a spontaneous magnetization, $M_s$, dependent on temperature, but only slightly dependent on applied field.

Suppose it is uniformly magnetized, and hence a single domain. Surface charges will form on the ends due to the magnetization and are themselves a second source of a magnetic field (the demagnetizing field). The energy associated with the surface charge distribution is called the magnetostatic energy. It is just the volume integral of the field over all space. The magnetostatic energy can be approximately halved if the magnetization splits into two domains magnetized in opposite directions. This brings (+) and (-) charges closer together, thus decreasing the spatial extent of the demagnetizing field. This subdivision into more and more domains cannot continue indefinitely because the transition region between domains (called a domain wall) requires energy to be produced and maintained. Eventually an equilibrium number of domains will be reached for a given particle size. Domain walls are interfaces between regions in which the magnetization has different directions. Within the wall, the magnetization must change direction from that in one domain to that in the other domain. Domain walls have a finite width that is determined principally by exchange and magnetocrystalline energy.

Let's consider a domain wall in which the magnetization changes by 180°. The change in magnetization within the wall can be gradual as in Fig. 2-6 (a) or abrupt as in (b).
Figure 2-6. (a) Structure of a 180° domain wall. (b) Hypothetical 180° domain wall of zero thickness. [29]
The exchange energy acts to keep spins parallel and can be kept small if the 180° rotation takes place gradually, over many atomic units. Therefore, the exchange energy is small in Fig. 2-6 (a) but large in Fig. 2-6 (b). However, the spins within the wall are no longer aligned along an easy axis of magnetization. This produces an anisotropy energy, which is high in Fig. 2-6 (a) but low in Fig. 2-6 (b). The exchange energy tends to make the wall as wide as possible whereas the anisotropy tends to make the wall as thin as possible. As a result of this competition between exchange and anisotropy energies, the domain wall has a finite width (on the order of 100 nm) and surface energy. [29]

To calculate the energy and structure of a domain wall, we assume a fairly thick wall and use a continuum model rather than a model of individual atoms. In particular, we replace the exchange energy for a pair of atoms of the same spin \( S \)

\[
E_{ex} = -2JS^2 \cos \phi_{ij}
\]  

(2-6)

with a continuum expression

\[
E_{ex} = -2A \cos \frac{d\phi}{dx}
\]  

(2-7)

where \( A = nS^2/\alpha \) is called the exchange stiffness or the exchange constant. Here \( n \) is the number of atoms per unit cell, and \( \alpha \) is the lattice parameter. The exchange stiffness \( A \) has units of J/m or erg/cm, and may be regarded as a macroscopic equivalent of the exchange energy \( J \). The quantity \( df/dx \) represents the rate at which the direction of local magnetization rotates with position in the wall. The series expansion of \( \cos \phi \) is

\[
\cos \phi = 1 - \frac{\phi^2}{2} + \frac{\phi^4}{24} - \cdots
\]  

(2-8)

Dropping the terms in \( \phi^4 \) and higher powers because \( \phi \) is assumed to be small,

\[
E_{ex} = -2A + A \left( \frac{d\phi}{dx} \right)^2
\]  

(2-9)

The first term is independent of angle and can therefore be dropped. The extra exchange
energy existing within the wall is given by the second term

\[ E_{ex} = A \left( \frac{d\phi}{dx} \right)^2 \quad (2-10) \]

The anisotropy energy is given in the general case by

\[ E_k = g(\phi) \quad (2-11) \]

where \( \phi \) is measured from the easy axis. For uniaxial anisotropy, \( g(\phi) = K_u \sin^2 \phi \), and for cubic anisotropy with magnetization confined to a \{100\} plane, \( g(\phi) = K_1 \sin^2 \phi \cos^2 \phi \). The wall energy is given by the sum of the exchange and anisotropy energies, integrated over the thickness of the wall:

\[ \gamma_{wall} = \gamma_{ex} + \gamma_K = \int_{-\infty}^{\infty} \left[ A \left( \frac{d\phi}{dx} \right)^2 + g(\phi) \right] dx \quad (2-12) \]

When the thickness of a sample becomes comparable to the thickness of the domain wall, the energy associated with the free poles that arise where a Bloch wall meets the surface (Fig. 2-7) becomes significant. This can lead to a change in wall structure, with the magnetization rotating in the plane of the sample rather than in the plane of the wall (Fig. 2-8). This creates free poles on the wall, since the normal component of magnetization in the wall is no longer constant, but nevertheless gives a lower overall energy. This kind of wall is called a Neel wall, and the term Bloch wall is now reserved for the normal wall structure in Fig. 2-7. There are also calculations and evidence to show that the spin variation in a Bloch wall is modified where the wall meets the surface of the sample. [36]
A typical Bloch wall in a 100nm thickness Permalloy film is shown in Fig. 2-9. The asymmetric feature can be clearly seen from the distribution of the easy-axis component of magnetizations. This asymmetric Bloch wall consists of Neel-like walls at the film surfaces and Bloch-like wall at the film center. The deviation of the finite-thickness film magnetization profiles from those for the bulk materials comes from the magnetostatic coupling interaction between the two opposite film surfaces, resulting in an energetically favorable Aux-closure single vortex. [37]
Figure 2-9. A typical asymmetric Bloch domain wall in a 100nm-thickness Permalloy film. Uniaxial crystalline anisotropy easy axis is along z. Film plane is parallel to the x-z plane. Upper graph shows the magnetization vector projections in the x-y plane; lower graph shows the distribution of the z component of magnetizations. [37]

In the Fig. 2-10 is compared with a simple onedimensional variational approximation. This 1D prediction only shows a qualitative trend rather than a quantitative result. By comparing the energy, it is seen that a 1D Neel wall is more favorable than a Bloch wall at small saturation magnetization values. [37]

In the Fig. 2-11 shown a Neel wall occurs. In this case, the magnetization reverses its direction along the x direction over a distance larger than the film thickness, hence the exchange energy is reduced compared to the vortex wall, where the magnetization reverses direction across the film thickness; the magnetization divergence in the Neel wall replaces the flux closure in the vortex wall, hence the magnetostatic energy is increased. Since M, is sufficiently small, the decrease in the exchange energy more than compensates for the increase in the magnetostatic energy, resulting in an energetically more favorable Neel wall.
Figure 2-10. Wall energy per unit area vs saturation magnetization in a 100 nm thickness film, with the same parameters as Permalloy except $M_s$. [37]

Figure 2-11. Neel wall structure in a 100 nm thickness film with $M_{s_1} = 200$ emu/cm$^3$. Arrows inside the frame show x-y projections of magnetization; top and bottom vectors show the x-z projections of the upper and lower film surface magnetizations. [37]

2.3. Micromagnetic simulation (OOMMF)

The Object Oriented Micro-Magnetic Framework (OOMMF) is a portable, extensible public domain micro-magnetics program developed by scientists in the National Institute of Standards and Technology (NIST), in order to determine the equilibrium configuration of the magnetization in ferromagnets or the dynamic response of magnetic moments.
OOMMF is written in C++ as a good agreement in accordance with the availability, functionality and portability. In order to allow the programming code to run on a wide variety of systems, the writing interface and glue code in Tcl/Tk so that OOMMF operates across a wide range of Unix platforms, Windows, Windows NT, Windows 9X and Mac OS X. Tcl/Tk must be installed before installing OOMMF software.

The code may be mutated at three definite levels. At the first level, individual programs communicate through the well-defined TCP/IP network sockets. From the user interface, one may combine these modules in distinct forms and we can add the new modules delivering the same protocol. The second level of mutation is at Tcl/Tk script level. These Tcl/ Tk scripts allowed by some modules and the scripts can be imported and executed at run time. The first level scripts are easy to modify or replace.

And at the third level, the C++ source is provided and which can be modified.

Two shell programs were included for the installation of Tcl/Tk. The first shell program referred as “tclsh” and the second shell program refered as “wish”.

In the present study, we studied magnetic domain structures. Micro-magnetic simulations were performed using OOMMF simulations. The OOMMF 2D micro magnetic computation engine capable of solving the problems using the application called “mmSolve2D”.

The application mmSolve2D integrates with the “Landau-Lifshitz equation” defined by the rate of change of the dynamical field $M$ (magnetization) is governed by a non-linear equation of motion having non-trivial index structure.
\[
\frac{dM}{dt} = - |\mathcal{Y}| M \times H_{\text{eff}} - \frac{|\mathcal{Y}| \alpha}{M_S} M \times (M \times H_{\text{eff}}) \tag{2-13}
\]

Where

\[M\] is the magnetization

\[H_{\text{eff}}\] is the effective field

\[\mathcal{Y}\] is the Landau–Lifshitz gyromagnetic ratio \(\left(\frac{m}{A_s}\right)\)

\[\alpha\] is the damping coefficient

The effective field is given by

\[H_{\text{eff}} = - \mu_0^{-1} \frac{\partial E}{\partial M} \tag{2-14}\]

“\(E\)” is an average energy density which is a function of “\(M\)”.

The “Landau-Lifshitz equation” gives rise to conservation-law \(\frac{dM_s}{dt} = 0\) which is essential but in some cases it can be neglected because of the numerical approximation errors.

The effective field \(H_{\text{eff}}\) governs with the various fields anisotropy, exchange, self-magnetostatics (demagnetization) and applied field (Zeeman) terms.

The applied field (Zeeman) energy and anisotropy can be calculated by assuming magnetization in each cell as constant. The exchange energy can be calculated by using the eight-neighbor bilinear interpolation with Neumann boundary conditions.

The self-magnetostatic field can be calculated by the convolution of the magnetization against a kernel that describes the cell to cell magnetostatics interaction. The convolution is evaluated using Fourier transform techniques.
2.4. Magnetic force simulation (Ansys, Maxwell)

Maxwell is a software package for low-frequency electromagnetic field simulation. Maxwell can be used to design 3-D/2-D structures, such as motors, actuators, transformers and other electromagnetic and electromechanical devices. Maxwell uses the Ansoft-pioneered automatic adaptive meshing capability which automatically creates and refines the finite element mesh as the solution converges, streamlining the solution process and making the software very easy to use.

Here, Maxwell 3D software (version 12.2, Ansoft) was employed for finite element method (FEM) simulations, which used experimentally derived material constitutive relationships to model the magnetic field distribution over micro-magnets (Ni_{80}Fe_{20}) for calculating the magnetic forces on superparamagnetic beads. Specifically, we used the experimentally measured magnetization hysteresis curve of thin permalloy film with 100-nm thickness, from which we obtained the saturation magnetization and coercivity value of 668 emu/cc and 190 A/m, respectively.

An example of the finite element mesh on the surface of a disk micro-magnet, and the induced field contour around the disk under an applied field are shown in Fig. 2-12 (a) and (b), respectively. Translocation of magnetic beads is due to functional field and its gradients around micro-magnets. Eq. (2-15) is the relationship for magnetic forces acting on a magnetic bead around a disk micro-magnet under an applied magnetic field.

\[
\bar{F} = \frac{\chi_f V}{2\mu_o} \nabla(\bar{B} \cdot \bar{B}) = F_\rho \hat{\rho} + F_\phi \hat{\phi}
\]

with \( F_\rho = \frac{\chi_f V}{\mu_o} \left( B_\rho \frac{\partial B_\rho}{\partial \rho} + B_\phi \frac{\partial B_\phi}{\partial \rho} \right) \),

\( F_\phi = \frac{\chi_f V}{\mu_o} \frac{1}{\rho} \left( B_\rho \frac{\partial B_\rho}{\partial \phi} + B_\phi \frac{\partial B_\phi}{\partial \phi} \right) \)  \( \ldots \tag{2-15} \)
Here, \( V \) is the volume of the bead (\( m^3 \)), \( \chi_v \) is the magnetic volume susceptibility of the bead (the magnetization of the surrounding medium is neglected), \( \mu_0 \) is the permeability of vacuum (\( 4\pi \times 10^{-7} \text{ N/A}^2 \)), and \( B_r, B_{\phi} \) are the radial and rotational components of the magnetic flux (T).

**Figure 2-12.** (a) A finite element mesh for simulation, (b) The induced field contour around a full disk under an applied magnetic field.
### III. Experiment

#### 3.1. Fabrication of pattern

**3.1.1. Photolithography**

Fig. 3-1 shows the photolithography processes, all the steps have been performed in the clean room. Photolithography is a process which is extensively employed to transfer a predefined pattern from a photo mask onto a substrate surface.

**3.1.1.1. Photolithography process**

The process to make a pattern and photoresist is as follows:

i. Primers form bonds with surface and produce a polar surface.

ii. Wafer is held on a spinner chuck by vacuum and resist is coated to uniform thickness by spin coating.

iii. Evaporate the solvent from the resist after spin coating.

iv. For simple contact, proximity, and projection systems, the mask is the same size and scale as the printed wafer pattern.

v. Uniform UV exposure illumination. Deep ultraviolet (DUV) light with wavelengths of 250 and 190 nm are utilized. This allows feature sizes down to 50 nm. The current commercial standard for photolithographic system is 193 nm DUV.

vi. Developer has to be Metal Ion Free (MIF) or if alternatively metal ion containing (MIC) developers can be used. Most MIF developers are ready-to-use solutions, while typical MIC developers are supplied as concentrate which has to be diluted before use.

vii. Hard bake removes any remaining traces of the coating solvent or developer. [38]
3.1.1.2. Photoresist

PR (photoresist) components are Phenol formaldehyde resin (polymer), sensitizer (PAC or PAG) and cross linking agent. Phenol formaldehyde resins include synthetic thermosetting resins, that can be obtained by the reaction of phenols with formaldehyde. There are two kinds of sensitizer, i) PAC (Photo Active Compound) is positive PR, ii) PAG (Photo Acid Generator) is negative PR. The negative photoresist material will become hardened and could not be dissolved and washed away in developer solvents when exposed to the ultraviolet light. While positive photoresist is initially insoluble, but degrades upon exposure to radiation. Both positive and negative resists are widely used in microcircuit technology today. [38]

3.1.1.3. Mask aligner

A mask aligner system is to align the mask and to expose the UV light to the photoresists. With UV radiation, it was limited by a consequence of basic physics. In any single wavelength optical system, the minimum feature size is given by:
\[ W_{\text{min}} \sim (\lambda g)^{1/2} \quad (3-1) \]

(W\text{min}: minimum feature size, \( \lambda \): the illumination wavelength, \( g \): the gap between the mask and substrate)

Spatial resolution using UV exposure at I-line (365nm) wavelength is beam intensity 20 mW/cm\(^2\). From this equation, it was shown that the minimum feature size can be reduced by operation at shorter wavelengths of UV or minimizing the gap between sensor surface and the mask.

![Figure 3-2. Mask aligner in our lab](image)

The mask aligner (MDA-400S) system is used as an UV Supply that is shown in Fig. 3-2. Its parameters are summarized as follows:

- UV source: I-line (365 nm)
- Exposure methods: proximity, soft, hard vacuum (vacuum contact force is adjustable) contacts
- Mask size: interchangeable up to 7 x 7 inch

- Substrate size for a top side alignment: 6 inch diameter

- Uniform beam size: 6.25 x 6.25 inch, Beam uniformity < ±5%

The aligner is exclusively intended for use as an alignment and exposure device for substrates used in Semiconductor and Microsystems Technology. [38]

3.1.2. Electron beam lithography

![Schematic of electron beam direct write system](image)

**Figure 3-3.** Schematic of electron beam direct write system [39]

3.1.2.1. Electron beam lithography process

E-beam Lithography is a process used in nanofabrication. It focuses electron beam to
draw nano size pattern on a substrate covered with an electron beam resist.

The process to make a pattern is as follows:

i. Application of E-beam resist

First step is resist liquid drop on the substrate up to covered whole area. After Spin coating start at 3000rpm/60sec. E-beam resist is electron sensitive material. It makes film on the silicon nitride membrane surface by spin coating. Control of the resist film thickness by spinning speed of spin coater.

ii. Soft baking

The substrate baked on 170°C hotplate at 5 min to evaporate solvent and curing it.

iii. Exposure

Fig. 3-3 shows that e-beam resist chemically reacts with electron beam energy. E-beam exposes energy controlled by dose quantity. If E-beam dose is not enough or over Pattern quality will decrease. E-beam draw predesigned pattern.

- Electron beam energy : 20kV
- Aperture size : 30um
- Step size : 20nm
- Area dose : 300
- Mode: Longitudinal mender

iv. Developing

The substrate developed 45 seconds and rinsed 1 minute.
3.1.3. Sputtering

Sputtering is a deposition technique, in which a solid target material is bombarded with energetic ions (approximately 100 eV or more). This bombardment causes a cascade of collisions in the target material's surface. These multiple collisions eject (or sputter) atoms from the surface into the gas phase. These atoms are then directed towards the target substrate to form a thin film. The number of atoms ejected from the surface per incident ion is called the sputter yield. The ions for the sputtering process are produced by plasma which is generated above the target material. The atoms sputtered from the surface of the target enter the plasma where they are excited and emit photons. [38]

3.1.3.1. Diode sputtering

A conventional diode plasma (or DC sputter) is simply a diode, which consists of an anode and a cathode inside a vacuum system shown in Fig. 3-4 (a). Applying the right voltage across the electrodes, insert a suitable gas pressure in to the vacuum chamber, the gas breakdowns into plasma. Near the cathode a dark space with a very large electric field is formed as shown in Fig. 3-4 (b). Ions are accelerated rapidly across this dark region and strike the cathode. These collisions cause sputtering of the target material. Some electrons, known as secondary electrons, are also emitted from the surface and then accelerate back across the dark region, gaining significant energy. This energy is used, through collisions with gas atoms, to form more ions to sustain the plasma. The sputtering gas can be inert, such as argon. In this case, the deposited thin film’s composition is the same as the target (perhaps with different crystal structure). Reactive sputtering takes place when the deposited film is formed by chemical reaction between the target material and a gas, which is introduced into the vacuum chamber. Oxide and nitride films can also be fabricated in this way. However, the deposition rate can be very different. The deposition rate depends on parameters such as the softness of the target, the target to substrate distance, the power
applied and the energy applied to the target. The applied energy can be in a range of several Watts to a few thousands of Watts depending on the area of the target and the deposition rate required. The deposition rate can be as small as several nanometers to several micrometers per hour. [40]

![Diagram of a simple diode sputtering system and formation of the dark and plasma regions above the target's surface.](image)

**Figure 3-4.** (a) Schematic diagram of a simple diode sputtering system and (b) formation of the dark and plasma regions above the target's surface. [39]

### 3.1.3.2. Magnetron sputtering

Magnetic fields can also be applied to the plasma region in order to improve the sputtering performance. For instance, a static magnetic field at the surface of the sputtering target can be produced by a permanent magnet (magnetron). The magnetic field generated is parallel to the cathode (the target) surface shown in Fig. 3-5. This magnetic field forces the secondary electrons to move perpendicular to both the electric field (normal to the surface) and the magnetic field (parallel to the surface). As a result, these secondary electrons are trapped in a region close to the target. These electrons eventually lose their kinetic energy through collisions with gas atoms causing ionization, or with other electrons, which generates heat. This results in dense plasma near the target, which increases the deposition rate as it enhances the ionization of sputtering gas. However, this plasma does not affect the ejected
atoms, as they have a neutral charge and are unaffected by the magnetic field. The magnetron requires cooling because of the heat generated by the energetic collisions around the target. Through sputtering not only is it possible to deposit films with nano sized features, but it is also possible to tailor these features. This can be achieved by adjusting various sputtering parameters such as: the sputtering power, sputtering gas, the magnetron, and temperature. Furthermore, crystal structure and surface morphology of the films also depends on the substrates on which they are deposited. [40]

**Figure 3-5.** The magnetic field configuration for a circular planar magnetron cathode [39].

3.2. Domain Measurement

3.2.1. X-ray microscopy

The schematic (Fig. 3-6) is shown here were collected using a conventional transmission X-ray microscope (XM-1). The specimen is fully hydrated and positioned between two thin
(100 nm) low-absorption silicon nitride membranes then examined using photon energies just below the oxygen edge, i.e. 517 eV (corresponding to a wavelength of $\lambda = 2.4$ nm). The flux images with 1000 x 1000 pixels, 1000 photons/pixel recorded in 3 s at 517 eV with 0.2% BW (ALS at 1.9 GeV, 400 mA). Images were focused using Fresnel zone plates as the condenser and objective lenses. The spatial resolution is largely determined by the width of the outermost zone of the objective zone plate and is on the order of 25±10 nm, depending on the zone plate used, the sample contrast, and the attainable signal-to-noise ratio. The magnified image is recorded on a Peltier-cooled, backilluminated, 2048X2048-pixel X-ray CCD camera. Various fast electronic pulses for spin dynamics, fast sampling oscilloscope, polarization selecting aperture. [41,42]

Figure 3-6. Schematic of X-ray microscopy [41]

The samples were arrays of a few permalloy (Ni$_{80}$Fe$_{20}$, hereafter NiFe) disks, with thickness 100nm and radius between 1 and 15 um. The structures were defined by electron-beam lithography and subsequent electron-beam evaporation of NiFe onto 100-nm-thick Silicon Nitride membranes to allow for sufficient x-ray transmission. The vortex-core profiles
were computed through 3D micromagnetic simulations using the public OOMMF code. [41,42]

### 3.3. Magnetic actuation

In this system, two convex shaped ferrite cores wound with copper wires are arranged perpendicular to each other as quadrupole configuration to generate rotating magnetic field. Fig. 3-7 shows block diagram of the computer controlled electromagnet for the generation of rotating magnetic field. Using Lab view software two sinusoidal signals (sine and cosine) with 90° phase difference are connected to the copper wires wound on ferrite cores for the generation of the rotating magnetic field. By adjusting the amplitude and frequency of the sinusoidal waves the field intensity and rotational speed of the magnetic field can be controlled by the computer software. [43]

**Figure 3-7.** Block diagram of the computer controlled electromagnet for rotating magnetic field. [43]
Fig. 3-8 shows the experimental setup for the motion of bead magnetic carriers using computer controlled electromagnets. The patterned sample was kept at the center of the convex shape-ferrite cores for focusing the external rotating magnetic field on to the pattern sample.

In order to decrease the vibration of camera and creates the homogenous rotating magnetic field, a modified electromagnet system has developed (Fig. 3-8) i.e., independent the electromagnet system from the microscope body – to decrease the vibration of camera and to produce homogeneous rotating magnetic field – concave iron cores used near patterned sample. [43]

![Experimental setup of modified electromagnet system. Inset represents high resolution photo of the bead actuation.](image-url)
These concave iron cores produces more homogeneous rotating magnetic field, it was find out by the magnetic simulation data (Fig. 3-9). Fig. 3-9(a) shows the generating rotating magnetic field at the 1.2 cm working area (square in Fig. 3-9 (b)) is more homogenous than the above used electromagnetic system. [43]

Figure 3-9. (a) The generation of magnetic field from concave shape ferrite cores along the x-axis at the 1.2 cm working area (square) obtained by Maxwell simulation software and (b) the configuration of concave shape iron cores. [43]

3.4. Magnetic beads characterization and conjugation of Atto-520 biotin

Streptavidin magnetic bead with 2.8 μm diameter was used for the experimental purpose. The scanning electron microscope image of the magnetic beads is shown in Fig. xxx. The streptavidin magnetic beads are coated with fluorescent atto-520 biotin. To load the fluorescent-labeled Atto-520 biotin with streptavidin magnetic beads, we put 5 μL of streptavidin-coated magnetic bead solution in a clean eppendorf tube. The bead solution was washed three times with phosphate-buffered saline (PBS) at a pH of 7.4 to remove the preservatives. The supernatant of the solution was removed using a micropipette by collecting the magnetic beads at the bottom of the eppendorf tube using a permanent magnet and re-suspending them in 90 μL of 0.1 M PBS buffer. 1 mg of Atto-520 biotin was
diluted in 200 μL of ethanol. The fluorescent concentration of the Atto-520 biotin was calculated to be 6.4 mM. Then, 5 μL of diluted Atto-520 was mixed with the 90 μL of magnetic bead solution and the solution was continuously stirred for 2 h at room temperature for completion of the streptavidin–biotin conjugation. Finally, the solution was further washed with PBS buffer several times to remove the biotin surplus by means of magnetic separation. The loading of the fluorescence-labeled biotin on the streptavidin magnetic beads was confirmed using a confocal microscope. The optical image of the magnetic beads and the corresponding fluorescence image exhibiting fluorescence are shown in Fig. 1(a) and (b), respectively. As shown in Fig. 1(b) the fluorescence on magnetic beads display uniformly, it reveals that both streptavidin coating and fluorescent-labeled Atto-520 biotin interaction with streptavidin were occurred homogeneously over entire surface of the magnetic beads. The measured fluorescence intensity on a group of five magnetic beads shown in Fig. 1(c) has same magnitude. [11]

![Figure 3-10](image)

**Figure 3-10.** (a) Optical image of Atto-520 biotin–streptavidin magnetic beads. (b) Confocal image of the magnetic beads exhibiting fluorescent signal. (c) Measured fluorescence intensity of a group of five Atto-520 biotin–streptavidin magnetic beads. [11]
IV. Result & Discussion

4.1. Magnetic Domain

In our study, we observe the magnetic domain structures theoretically and experimentally. Magnetic transmission x-ray microscopy is a novel technique to image element specifically magnetic domain structures. A lateral resolution is provided by the Fresnel zone plates used as optical elements in soft x-ray microscopy. As the element-specific magnetic contrast which is due to x-ray magnetic circular dichroism scales with the projection of the magnetization onto the photon propagation direction both out-of-plane and in-plane magnetic domain structures can be studied. We used SiN membranes having low stress Silicon Nitride windows (5mm x 5mm x 100nm thickness and frame: 10mm x 10mm x 200um thickness Silicon) used to study the domain structures in X-ray transmission microscopy. High-quality micro magnetic patterns have been fabricated by electron-beam lithography on SiN membranes. After preparing the pattern, the SiN membrane sputtered with the ferromagnetic transition metals NiFe. Then finally a lift-off process is carried out. The designed structures are suitable for investigation of their domain structures in a proper way. While observing the domain structures, enhance magnetic contrast and eliminate non-magnetic background so that, each image was normalized to a reference image taken at saturation state. Finally experimentally observed domain structures are exactly matched with the theoretically obtained domain structures.

As described the demagnetized states for the full disk micro-magnet have a good agreement with the magnetic domain structure measured by X-Ray Microscopy presented in Fig. 4-1. The demagnetized states for the full disk micro-magnet are shown by OOMMF simulation in Fig. 4-2. They were obtained by using randomized cell magnetizations as an initial configuration which relaxes in zero fields. The vortex state is obtained in the demagnetized state. In the vortex state, shown in Fig. 4-2 (a), the moments are arranged in
a closed loop around the center of the full disk micro-magnet under the applied of 5 mT. With increasing the magnetic field to 10 mT along the x-axis, the vortex is moving away to the frontier and the moments turn to the field direction more (see Fig. 4-2 (b)). Application of 20 mT field along the x-axis is found to be sufficient to saturate the full disk micro-magnet along the field direction. Very small number of unsaturated spins was observed near the edges due to edge defects as shown in Fig. 4-2 (c).

Figure 4-1. Magnetic domain structure in disk of geometric micro-magnets measured by X-Ray Microscopy.

Figure 4-2. Magnetic configuration of a full-disk micro-magnet under magnetic fields of 5, 10 and 20 mT, as OOMMF simulation.

As described the demagnetized states for the half disk and T-junction micro-magnet have a good agreement with the magnetic domain structure measured by X-Ray Microscopy
presented in Fig. 4-3. They are obtained an initial configuration by using saturation magnetization. Then decrease the magnetic field that direction only x axis. Likewise full disk micro-magnet, half disk magnetic domain structure is obtained the vortex state (see Fig. 4-3 (a)-(f)). The vortex state is obtained in the demagnetized state. We used to the T-junction micro magnetic patterns on cell experiment. T-junction micro pattern is arranged serial by half disk micro pattern. T-junction magnetic domain structures are similar to half disk magnetic domain structures. (see Fig. 4-3 (h)-(l)) Later, we will do the OOMMF simulation how much matching well.
4.2. Force calculation and phase lag of magnetic beads

In order to understand underlying physics of the bead motion, let’s consider the governing forces on bead. Due to the magnetic field gradient produced by the micromagnets, the beads can be trapped at the location of high induced field. Under the rotating field, there could be a phase lag of bead from the field direction, and the schematics for governing forces on a moving bead are presented in Fig. 4-4. Here, three dimensional forces on moving bead consist of rotational force ($F_\phi$), radial force ($F_\rho$), and drag force ($F_D$) given by the sum of friction force ($F_f$) and viscous force ($F_{vis}$) for a moving bead. The $F_{vis}$ force is given by:

$$\bar{F}_D = 6\pi \eta a \bar{v}, \quad (4-1)$$
where $\eta$ is the viscosity of water, and $\bar{v}$ is the instantaneous velocity of a particle with radius $a$.

Figure 4-4. Schematics of parameters on a superparamagnetic bead around a disk micro-magnet under an applied in-plane rotating field in clockwise direction [44].

In the FEM simulations, the bead was approximated as a point with a distance of 1.4 $\mu$m from the disk edge to the point. Fig. 4-5 (a) shows the components of magnetic fields in both radial and rotational directions, $B_\rho$ and $B_\phi$ as function of rotational angle for the disk of 5 $\mu$m radius. Here, it is noted that $B_\rho$, $B_\phi$ show the symmetric and asymmetric curves for the parameter of angle $\phi$ with maximum 85 Gs.

Magnetic forces were obtained from the digital differentiation of eq. (4-1), using the simulated magnetic field components, $B_\rho$ and $B_\phi$ around the disk of 5 $\mu$m radius. As shown in Fig. 4-5 (b), the radial and rotational forces have $\sin(\phi)$ function with 50 pN magnitude, and $\cos(\phi)$ function with 31 pN magnitude, respectively. The maximum value of the rotational force $F_\phi$ is given at $\phi = \pi/4$. It indicates that the bead is forced to the place at the $\phi = 0$, i.e., the field direction because of negative force for $\phi > 0$ tends to reduce the angle of bead position, whereas the positive force for $\phi < 0$ increases the angle. Here, it is noted that there is a positive value of the radial force, $F_\rho$, for the angle range of 65°–115°, which indicate the
existence of the repulsive force between the bead and the disk.
Figure 4-5. Simulated magnetic field (a), and magnetic forces (b) on a Dynabeads M-280 superparamagnetic bead around a disk of 5 µm radius under an applied field of 50 Oe (ρ: radial direction, ϕ: rotational direction). (c) Trajectory analysis by magnetic forces. (d) Bead trajectory on the magnetic pattern. [45]

The two regimes of bead motion observed in experiments are shown in Fig. 4-6, when exposed to a 2 mT rotating external field applied at different frequencies. At a driving frequency of 0.8 Hz, which is below the critical frequency, \( f_c \), the bead rotates synchronously around the perimeter of the micro-magnet with a fixed phase lag between the instantaneous bead position and the external field direction (see Fig. 4-6 (a)-(d)). This dynamic mode is known as the “phase-locked” regime, because the bead’s phase lag is locked in time.

Phase locked motion results from the balance between the rotational force \( (F_\phi) \), and the drag force \( (F_D) \). As the rotating frequency is increased, the higher bead velocity causes it to experience a stronger viscous fluid drag, which increases the bead phase lag. When the bead phase lag reaches the critical condition of 45°, the bead can no longer remain in the phase-locked state. [45]
At a driving frequency of 1.2 Hz, which is above the critical frequency, $f_c$, the bead enters the “phase-slipping regime”, which is described as such because the phase difference between the external field direction and the bead position can no longer be constant. Experimental images of the phase-slipping motion are shown in Fig. 4-6 (e)–(h).

![Image](image.png)

**Figure 4-6.** Optical images of two different phase regimes of a 2.8-µm diameter bead moving around a 10-µm diameter micro-magnet disk exposed to a $H_{app} = 2$ mT in-plane rotating magnetic field. Red arrows represent the instantaneous phase angle of the external field. For panels (a)–(d) the bead is phase-locked with the external field at a driving frequency of 0.8 Hz. In panels (e)–(h) the bead undergoes phase-slipping motion at a driving frequency of 1.2 Hz. [44]

### 4.3. Method of magnetic field calculation and beads actuation

M-280 'Dynabeads' have different magnetic moments. Select the different beads depending on their critical frequencies at the constant magnetic field of 2 mT. Critical frequency refers to the jumping motion of the bead for each cycle along the trajectory. At the phase slipping regions, the bead jumping occurs. So in order to measure the phase-locked angle, we lower the frequency of the bead to prevent the jumping motion. We measure the angle between the field direction and the bead position from the captured images using the high speed camera. This high speed camera captures the videos in the form of images because it’s difficult to see the bead motion when it moves with the high speed. Prior to
capture the bead motion using the high-speed camera, the camera sets 360 frames/1 s so that it’s easy to calculate magnetic field direction and bead position. The difference of the angle from one frame to another frame is calculated as follows depending on the driving frequency. For example if the driving frequency is 1.5 Hz gives 0.6 s/1cycle so it corresponds to 240 frames/1cycle because already we set the camera as 360 frames/1 s. So then it gives 1cycle = 360 degrees that is the complete circular magnetic path. And so finally 1 frame refers to 1.5 degree (1.5 degree/1frame) along the magnetic field direction.

![Figure 4-7](image)

**Figure 4-7.** Disk pattern (yellow) size is 10um, bead(brown) size is 2.8um. Black dot is magnetic field starting point. Overlap bead for measuring the angle. (a) Maximum phase-locked angle, (b) Jumping angle in phase-slipping region.

The measurement of the maximum phase-locked angle along the magnetic field direction is calculated by the bead position from the 360 frames/1 s (Fig. 4-7(a)). The measurement of the phase-slipping angle along the magnetic field direction is calculated by observing starting point of the bead by the naked eyes (Fig. 4-7(b)). On the basis of this calculation, measure angle between magnetic field direction and bead.
We already calculated the maximum angle of phase-locked and the jumping angle of phase-slipping region. By comparing theoretical data with experimental data, simulation value (Fig. 4-5 (b)) shows the maximum angle of phase-locked is 45 degree. Experimental average value (Fig. 4-8) shows around 48 degree. That is similar to theoretical value. By comparing theoretical data with experimental data, simulation value (Fig. 4-5 (b)) shows the jumping angle of phase-slipping region is around 75~115 degree. Experimental average value (Fig. 4-9) shows around 85 degree. That is contained the phase-slipping region.

**Figure 4-8.** Maximum angle of phase-locked region
Figure 4-9. Jumping angle of phase-slipping region

Mean: 85.4°
V. Conclusion

Magnetic transmission x-ray microscopy is a novel technique to image element specifically magnetic domain structures. A lateral resolution is provided by the Fresnel zone plates used as optical elements in soft x-ray microscopy. As the element-specific magnetic contrast which is due to x-ray magnetic circular dichroism scales with the projection of the magnetization onto the photon propagation direction both out-of-plane and in-plane magnetic domain structures can be studied. We used SiN membranes having low stress Silicon Nitride windows used to study the domain structures in X-ray transmission microscopy. While observing the domain structures, enhance magnetic contrast and eliminate non-magnetic background so that, each image was normalized to a reference image taken at saturation state. The observed domain structures are exactly matched with the OOMMF simulation obtained domain structures.

The non-linear dynamics of superparamagnetic beads moving around the periphery of patterned magnetic disks in the presence of an in-plane rotating magnetic field. Two different dynamical regimes are observed in experiments, including (1) phase-locked motion at maximum driving frequencies, (2) phase-slipping motion above a first critical frequency $f_{c1}$.

The force calculations, Phase-locked and Phase-slipping angles are calculated by the superparamagnetic bead around a disk micro-magnet under an applied in-plane rotating field in clockwise direction. In order to understand underlying physics of the bead motion, consider the governing forces on bead. In the FEM simulation, three dimensional forces on moving bead consist of rotational force ($F_\phi$), radial force ($F_\rho$), and drag force ($F_D$) given by the sum of friction force ($F_f$) and viscous force ($F_{visc}$) for a moving bead. Due to the magnetic field gradient produced by the micro-magnets, the beads can be trapped at the location of high induced field. Under the rotating field, there could be a phase lag of bead from the field direction, and the schematics for governing forces on a moving bead are discussed.
M-280 'Dynabeads' have different magnetic moments. Select the different beads depending on their critical frequencies at the constant magnetic field of 2 mT. We already calculated the maximum angle of phase-locked and the jumping angle of phase-slipping region. By comparing theoretical data with experimental data, the maximum angle of phase-locked region simulation value is 45 degree. Experimental average value is around 48 degree. That is similar to theoretical value. And the jumping angle of phase-slipping region simulation value is around 75~115 degree. Experimental average value is around 85 degree. That is contained the phase-slipping region.
References


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세포 운반 비드의 힘 분석과 마이크로 패턴의 자구 모양 관측

본 논문은 최근 수성 유체 속에서 콜로이드 비드의 이동을 제어하는 무수한 바이오 응용에서 특히, 외부의 필드와 자성 패턴에서 비드 움직임을 제어하는 것을 다룬다. 바이오 세포를 운반하는 자성 비드의 움직이는 힘을 Maxwell 소프트웨어로 계산하였고 자기장과 주파수를 높였을 때 달라지는 비드의 움직임을 세 가지 구역으로 나누고 정의하였다. 첫 번째, 낮은 주파수를 주었을 때 비드가 패턴을 따라 잘 움직이는 구역을 phase-locked이라고 정의하였고 두 번째, 임계 주파수보다 높은 주파수를 주었을 때 비드가 패턴에서 점프하는 구역을 phase-slipping이라고 정의하였고 세 번째, 임계 주파수보다 훨씬 높은 주파수를 주었을 때 비드가 움직이지 않는 구역을 phase-insulated라고 정의하였다. 본 논문은 이 중 비드의 임계 주파수를 파악하고 phase-locked최대각도와 phase-slipping구역의 점핑 각도를 실험하였다. 또한, 비드가 움직이는 자기 패턴의 자기적 특성 분석을 위해 X-ray 마이크로스코프로 자구 모양을 관측하였고 OOMMF 시뮬레이션과 굉장히 유사함을 확인하였다.

핵심어: Phase-locked, Phase-slipping, Maxwell 시뮬레이션, 자구, X-ray 마이크로스코프, OOMMF 시뮬레이션