

# Magnetization of Thin-Film Permalloy Ellipses used for Programmable Motion of Magnetic Particles

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**Abstract**—Simulations of magnetic microstructure in elliptical Permalloy elements used for controlled motion of magnetic particles are discussed. The saturating field of the elliptical elements was studied with respect to lateral dimensions for one-vortex, cross-tie, diamond and double-diamond states as initial zero-field domain configurations. With aspect ratio of 1:3 the short axis was varied from 125 nm to 1000 nm, whereas the thickness was kept constant at 50 nm.

**Keywords**—Domain structure, magnetization, micromagnetics, Permalloy.

## I. INTRODUCTION

SEPARATION of biomolecules is an important branch of life sciences. Particularly, magnetic separation has become a widely employed technique. Particles with functionalized surfaces bind selectively to targets and can be separated, as a group, from a heterogeneous suspension by applying magnetic fields [1-3]. It is desirable to control the movement and positioning of single magnetic particles, since it opens up the potential for new applications, e.g. relating to nanodispensing or to sophisticated separation of different kinds of targets in a suspension.

A method has recently been reported that enables controlled motion of individual magnetic particles [4]. Fabricated arrays of cylindrical ellipses constitute transport lines. Adjacent elements in a transport line have their long axes rotated an angle of  $90^\circ$  with respect to each other. A junction is formed by connecting two such transport lines perpendicularly. Movement of particles along a transport line is controlled by an external rotating magnetic field. By rotating the field, a micrometer-sized particle made of porous polystyrene filled with iron oxide nanoparticles [5] follows the perimeter of the elements. The sense of rotation, i.e. clockwise or anticlockwise rotation of the field, determines the choice of path at a junction (see Fig. 1).

The crucial part for achieving a programmable movement of magnetic particles is the magnetic microstructure of the

elements and its dependence on magnitude and orientation of the applied field (defined by the angle between the field and the long axis of an element). A single-domain state of an element implies a strong interaction between the element and a particle. However, for certain angle intervals of the applied field, multi-domain states are nucleated [6-7]. If the particle initially sticks to an element that suddenly transforms from a single-domain to multi-domain state, the particle will jump to a neighboring element if this element is in a single-domain state. In order to know for what field amplitude,  $H_s$ , a single-domain state is formed, micromagnetic simulations were carried out using the object oriented micromagnetic framework, OOMMF [8]. Arrays with two different sizes of elliptical elements have been fabricated:  $1 \mu\text{m} \times 3 \mu\text{m} \times 0.05 \mu\text{m}$  and  $2 \mu\text{m} \times 6 \mu\text{m} \times 0.05 \mu\text{m}$ , respectively. The elements were defined using electron beam lithography, thermal evaporation of Permalloy and a lift-off technique. Smaller elements can be fabricated, opening up the possibility for using sub-micrometer sized particles in biomagnetic applications. Here, simulations on smaller elements will be investigated.

## II. THEORETICAL MODEL

Discretization of each ellipse was made into cells with dimensions  $5 \text{ nm} \times 5 \text{ nm} \times 50 \text{ nm}$ . The calculation is performed by integrating the Landau-Lifshitz equation,

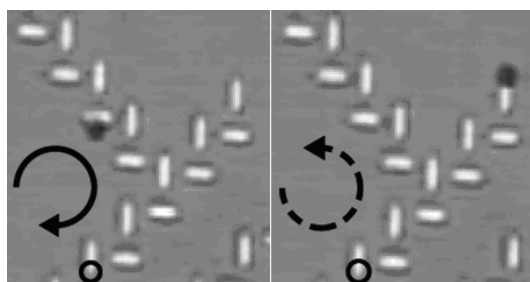


Fig. 1 Two transport lines forming a junction. The arrows indicate the sense of rotation of the applied field. The hollow and solid circles indicate the start and end position of a magnetic particle, respectively. A field rotating clockwise makes the particle go left at the junction, whereas a field rotating anti clockwise makes the particle go straight ahead.

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$$\frac{d\mathbf{M}}{dt} = -\gamma\mathbf{M} \times \mathbf{H}_{\text{eff}} - \frac{\gamma\alpha}{M_s}\mathbf{M} \times (\mathbf{M} \times \mathbf{H}_{\text{eff}}), \quad (1)$$

and solving for the magnetization  $\mathbf{M}$  of each cell. Contributions from exchange interaction, magnetocrystalline anisotropy, demagnetization and Zeeman terms are included in the effective field  $\mathbf{H}_{\text{eff}}$  of each cell.  $\gamma$  is the gyromagnetic ratio and  $\alpha$  is a material-specific damping coefficient. Here,  $\gamma = 2.21 \times 10^5$  m/As and  $\alpha = 0.5$  were used. The saturation magnetization  $M_s$  for Permalloy was set to  $8.6 \times 10^5$  A/m. The exchange coefficient used in the eight-neighbor interpolation of the exchange field was  $A = 1.3 \times 10^{-11}$  J/m. Calculated configurations were considered to be stable when the absolute value of the point-wise normalized torque,  $\mathbf{M} \times \mathbf{H}_{\text{eff}}/M_s^2$ , reached below  $10^{-5}$  for all cells. The anisotropy coefficient for Permalloy has a negligible effect on the magnetization process and was set to zero. The exchange length,  $l_{\text{ex}}$ , corresponding to the smallest length scale of domain formation is defined as  $(2A/\mu_0 M_s^2)^{1/2}$ . With current parameters the exchange length is 5.3 nm, which is in good agreement with the cell size of 5 nm. Too large a cell size would restrain the formation of domains, whereas a too small cell size would not have any influence on domain formation but would result in unnecessarily long computation times.

### III. RESULTS AND DISCUSSION

The magnetization process was studied by successively increasing the applied field along the easy axis, i.e. the long axis, starting from demagnetized states. Demagnetized states were obtained by letting the microstructures relax in zero field. The saturating field,  $H_s$ , was defined to be at 95% saturation of the element, i.e. where the ratio  $M_y/M_s$  has reached 95%.  $M_y$  is the net-magnetization component along the  $y$  axis, which coincides with the long axis of the ellipse.

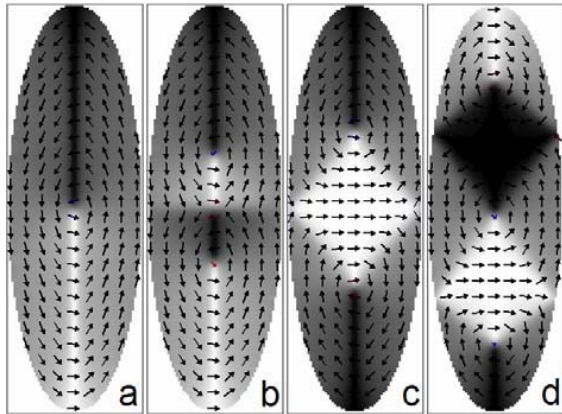


Fig. 2 Initial domain configurations showing a vortex (a), a cross-tie (b), a diamond (c) and a double diamond state (d).

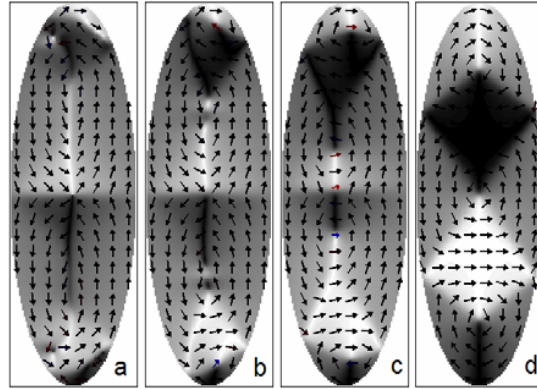


Fig. 3 Temporal evolution of the transformation of a cross-tie (a) into a diamond structure (b) – (d) in zero field for a  $400 \text{ nm} \times 1200 \text{ nm}$  element.

The demagnetized states were obtained by letting initial domain configurations, illustrated in Fig. 2, relax in zero field. Diamond, vortex and double-diamond states are stable as zero field states for the studied range of element dimensions, i.e. short axis,  $a$ , ranging from 125 nm to 1000 nm. The cross-tie state was found to be stable for a  $< 400$  nm, while for larger dimensions the initial cross-tie becomes unstable and transforms into a double-diamond state. In Fig. 3 this transformation is illustrated. Between the cross-tie and the apex a vortex forms on each side, both having anti-clockwise orientations. Under this formation an additional vortex forms in each apex, as illustrated in Fig. 3 (a). The innermost vortices move towards the cross-tie where they combine and form one vortex, shown in Fig. 3 (b-c). The outermost vortex is at a point about  $2/3$  of the distance between the centre and the apex when the structure has equilibrated, as shown in Fig. 3 (d).

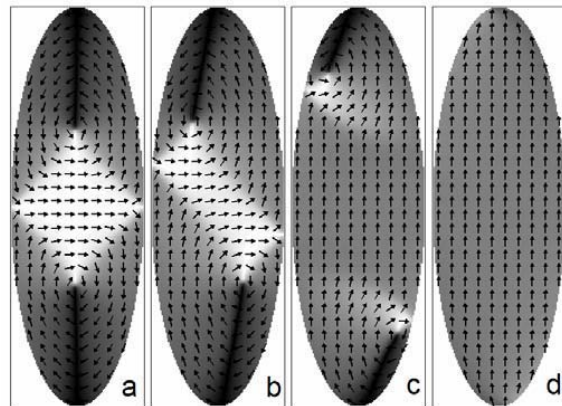


Fig. 4 Magnetization process of a diamond state with lateral dimension  $500 \text{ nm} \times 1500 \text{ nm}$ . (a) shows the demagnetized state in zero field, (b) and (c) show the domain configuration at fields of 13 mT and 19 mT, respectively. In (d) a 25 mT field has been applied.

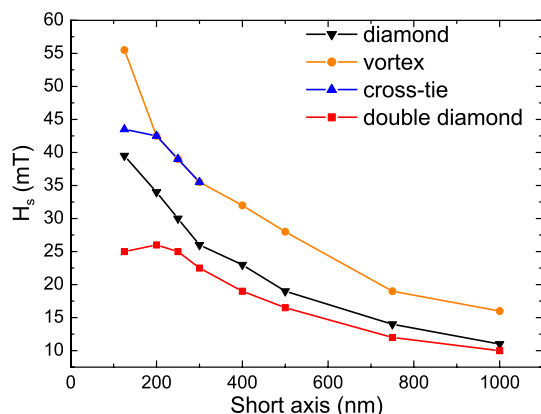


Fig. 5 Saturating field as a function of short axis. The cross-tie state is only stable for small ellipses. For  $a = 400$  nm the state develops into a double diamond state.

The magnetization process towards saturation of a diamond state is illustrated in Fig. 4. As the applied field is increased the vortices are driven out towards the apices of the structure. A 19 mT field is required to saturate a  $500 \text{ nm} \times 1500 \text{ nm}$  ellipse.

TABLE I  
TOTAL ENERGY FOR DEMAGNETIZED STATES

Area (nm <sup>2</sup> )	Energy (J/m <sup>3</sup> )			
	diamond	vortex	cross-tie	double diamond
125x375	38000	43000	43000	43000
200x600	21000	25000	24000	23000
250x750	16000	19000	18000	17000
300x900	13000	15000	15000	14000
400x1200	9200	11000	-	9500
500x1500	7100	8600	-	7200
750x2250	4400	5500	-	4400
1000x3000	3200	4000	-	3100

Total energies for demagnetized states of different initial states are presented in Table 1. The diamond state lies lower in energy than the vortex state for all sizes. Moreover, the vortex state requires higher applied fields to reach magnetic saturation. An explanation to this is that saturation of a vortex state occurs as the central vortex is driven out to the rim where it is annihilated. A diamond state has two vortices that initially lie closer to the rim. A comparison between saturating fields of different initial states is presented in Fig. 5. A vortex state requires highest magnetic fields to saturate. A double-diamond state is most easily saturated and for  $a = 125$  nm  $H_s$  is 25 mT, which can be compared with 55.5 mT for a vortex states. As can be seen, the saturating field increases with decreasing axis length. However, a double-diamond state seems to saturates at a lower field for  $a = 125$  nm than for  $a = 200$  nm. The saturating field for the cross-tie state coincides with that of a vortex state for  $a = 200$  nm to  $a = 300$  nm. At larger dimensions, the relative distance between saturating

fields for different states decreases. For  $a = 1000$  nm, diamond and double-diamond states saturate at approximately the same applied fields, 11 mT and 10 mT, respectively.

#### IV. CONCLUSION

The separation method described here is dependent on elements that can exhibit a magnetic structure alternating between a single domain and a multi-domain state as the applied field is rotated. We know from experiments [6] that the domain configuration of a specific element can be different as the field has been rotated one cycle. So, even though an applied field is sufficiently large, initially, to saturate an element it could be insufficiently large for saturation as the field has been rotated into another multi-domain state. By choosing a sufficiently large applied field this problem can be avoided. The magnitude of such a field is suggested by the saturation curve for a vortex state in Fig. 5, since this state requires the highest fields for saturation.

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