Symmetry Breaking in Magnetic Vortex Formation near Shaped Boundary of Ferromagnetic Film

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***Abstract*— Micromagnetic modeling of in-plane magnetization distribution near shaped boundary of ferromagnetic film was made by both finite difference and finite element methods. Symmetry breaking of magnetization distributions for two symmetrical field directions was found due to macro-vortex formation and annihilation in opposite phases of rotating external magnetic field. Principal difference of vortex stability was found between smooth and broken boundary shapes. Field margin of vortex stability near smooth boundary exceeds that one for broken line shape by an order of magnitude. Weak stability of vortex state in broken line shaped film is explained by peculiarities of exchange energy near corners caused by magnetostatic spin orientations along angle straight sides.**

***Index Terms*— micromagnetics, magnetization reversal, magnetostatics, garnet films.**

I. Introduction

Control of magnetic vortex formation and its chirality is of significant interest due to potential applications of patterned magnetic films [1]. Rotational symmetry of disk-like film elements significantly complicates creation of definite vortex chirality.

It is known that vortex with definite chirality can be created by in-plane external field in triangular micro ring [2] and/or in odd-sided polygon disk [3] when asymmetry of the film element in relation to external field direction is introduced.

Degeneracy of clockwise (CW) and counterclockwise (CCW) chirality in a magnetic disk was removed also by element cut to form straightened part of the film boundary [4]. Asymmetry effect was optimized empirically and explained briefly in terms of magnetostatic specific interaction along straight boundary part.

Recently breaking of vortex states four-fold degeneracy in permalloy nanodisks was surprisingly revealed and attributed to Dzyaloshinskii-Moriya interaction at the film surface [5].

In general the nature of different vortex stability near straight and curved element boundaries remains unclear.

From the other hand incontrollable instability of magnetization distribution with vortices and anti-vortices formation in macroscopic film disk produces magnetic noise in garnet fluxgate magnetometers [6]. To avoid this effect the peculiarities of vortices behavior should be investigated in more details.

Numerical modeling of magnetization distribution near smooth and broken line shaped boundary of magnetic film was made in the present work. Magnetization distribution in film plane was calculated by both finite difference [7] and finite element [8] methods by minimization of free energy functional with zero crystalline anisotropy.

Natural and simple mechanism of vortex formation symmetry breaking is demonstrated.

II. Object of Modeling Procedure

Periodical sinusoidal, rectangular, triangular (cogged) and circle-like shapes of magnetic film boundary were investigated numerically. Magnetic film has diluted garnet yttrium iron (YIG) magnetization $4\pi M$ = 100 kA/m and exchange constant A = 5 pJ/m and film thickness h = 0.5 μm. Geometry of every boundary type is characterized by the same values of period L= 13 μm and amplitude (half-height) $D/2$ = 4 μm as shown in Fig. 1a.

Cell dimension for finite difference computing procedure was chosen 100x100x500 nm.

Homogeneous external magnetic field H rotates or oscillates along to the line walking round boundary apexes (x-axis) with the amplitude up to maximum value H_{max} = 12 kA/m at which saturation near film boundary was found for every boundary type. Magnetization was calculated every 10 degrees of magnetic field phase beginning from symmetrical state saturated perpendicular to the line walking round apexes. Cartoons were produced to visualize magnetization reversal.

The present paper represents results for sinusoidal and rectangular shaped boundaries.

III. Modeling Results and Discussion

Magnetization distributions for sinusoidal boundary are presented in Fig. 1a,b corresponding to opposite directions along x axis of CW rotating field with amplitude H = 2 kA/m. Fig. 1a represents magnetization distribution after a first quarter of period with preferable magnetization direction along magnetic field vector and absence of vortex formation. Fig. 1b represents magnetization distribution after successive half-period and shows vortex formation with magnetization direction opposite to magnetic field new direction in boundary apex. Vortex disappears after the next half-period so that magnetization distributions repeat in every phase during rotation of external field.

Vortex chirality is determined by the first orientation of magnetic field parallel to the line walking round sinus apexes. So it can possess both CW and CCW orientations in dependence on initial phase and rotational direction of external magnetic field.

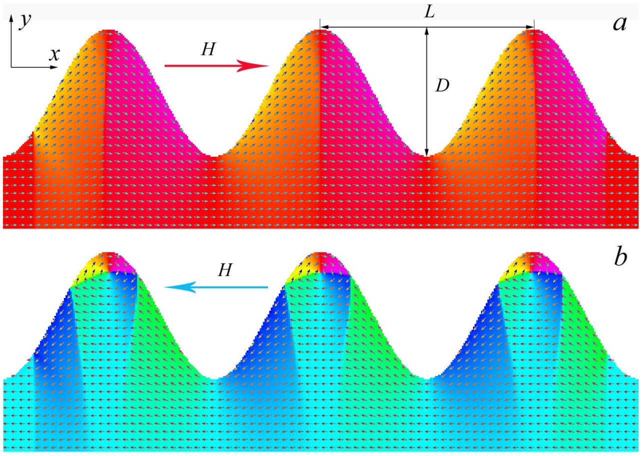

Fig. 1. Magnetization distributions near sinusoidal boundary in external magnetic field with intensity H =2 kA/m, a – initial field direction, b – opposite field direction

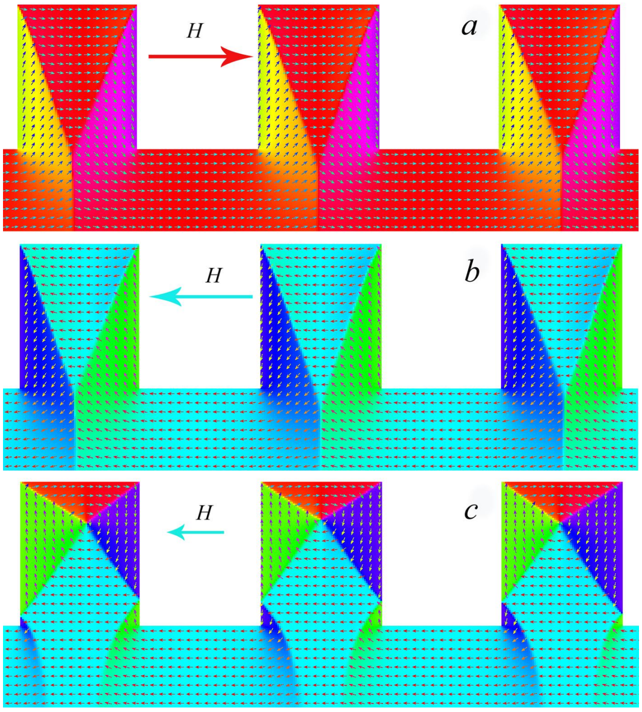

Fig. 2. Magnetization distributions near rectangular boundary in external magnetic field, a – initial field direction, b, c – opposite field direction. Field intensities: a, b - H = 2 kA/m, c - H = 1 kA/m

An extremely high stability of vortex formation and annihilation repeating process in wide range of external field amplitude and geometrical dimensions of shaped boundary was found. Vortex formation occurs up to magnetic field amplitude H = 12 kA/m where apexes are saturated. Proportional size enhancement or shape variations don't lead to appreciate change of magnetization reversal features until boundary curve remains smooth.

Highly different situation takes place for broken line film boundary. Fig. 2a,b shows magnetization distributions in the vicinity of rectangular boundary in the same conditions. No vortices with magnetization opposite to the direction of external field are seen here. Magnetization distributions for two opposite field directions along x axis are symmetrical this case despite of film magnetic state is far from saturation.

Destruction of the seed with reverse magnetization (which is responsible for vortex formation) begins from right angles of rectangular boundary. Spins located at the corners suffer exchange interaction with two kinds of spins located along rectangular mutually perpendicular adjacent sides. Equilibrium direction of corner spins is inclined with respect to x and y axes by $\pi/4$ in zero field. Therefore spins at the corners possess high freedom for rotation in external field and play as initiator for magnetization reversal along straight boundary. Vortices with reverse magnetized apexes shown in Fig. 2c were found only in narrow margin of low external field values $H \leq 1$ kA/m.

Calculation made for circular and triangular boundaries shows symmetry breaking of magnetization distribution analogues to that one for sinusoidal and rectangular boundaries accordingly. Circular shape produces also multi-vortex states in particular phases of rotating field. Vortex size is restricted then not only by film edge but by neighboring vortices as well.

Thus symmetry breaking of magnetization distributions near shaped film boundary is caused by vortex formation due to conservation of stable seed magnetized reverse to external field direction. Seed stability is sharply weakened by angles in film boundary shape due to exchange interaction of corner spins with neighbors aligned along mutually perpendicular straight sides due to magnetostatic interaction with film edge.

Control of magnetization distribution in film sensitive element by geometry of film boundary can be used for signal/noise ratio enhancement in two dimensional fluxgate magnetometers with excitation by rotating field.

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