Asymmetric magnetization splitting in diamond domain structure: Dependence on exchange interaction and anisotropy

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The distributions of magnetization orientation for both Landau and diamond domain structures in nano-rectangles have been investigated by micromagnetic simulation with various exchange coefficient and anisotropy constant. Both symmetric and asymmetric magnetization splitting are found in diamond domain structure, as well as only symmetric magnetization splitting in Landau structure. In the Landau structure, the splitting angle increases with the exchange coefficient but decreases slightly with the anisotropy constant, suggesting that the exchange interaction mainly contributes to the magnetization splitting in Landau structure. However in the diamond structure, the splitting angle increases with the anisotropy constant but decreases with the exchange coefficient, indicating that the magnetization splitting in diamond structure is resulted from magnetic anisotropy.

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I. INTRODUCTION

Magnetic nanostructures is an active study aspect, not only for its high sensitivity function¹ or excitations of magnetic moments for practical application,²,³ but also as good candidates in research on some fundamental and interesting magnetism physics.⁴–⁸ On the other hand, the framework of micromagnetic simulation can describe the magnetization configuration and dynamics in a scale between several tens nm and a few microns.⁴–⁹ Basically there are two ways for micromagnetic calculations. One is based on the integration of the equation, which is the motion of the magnetic moments described by the Landau-Lifshitz-Gilbert (LLG) equation. The other one is to minimize the total magnetic energy. The former is in favor of showing time-dependent evolution of magnetization,¹⁰ while the latter is in a perspective of energy. It shows that the size,¹¹,¹² the aspect ratio¹³,¹⁴ and the thickness¹³,¹⁴ are important parameters over magnetic configuration.⁹ In order to reduce the exchange energy, a uniform magnetization is ideal, but the demagnetization energy would like magnetization parallel to surface or poles counter balance at interface. Meanwhile, magnetic moment favors low anisotropy energy if its magnetization is parallel to the easy direction. If no external field is applied, the magnetization will relax to an equilibrium state, which is the competition and compromise around these three energy items and reach a local minimum energy. No matter spatial dimension differences¹¹–¹⁵ or roughness variety,¹⁶,¹⁷ in a viewpoint of minimum energy, they all act on the local and non-local magnetic energy items.¹⁸

In thin soft elements, the Landau state and the diamond state are well known as typical magnetic flux-closure patterns and prominent candidate of ground state.¹,⁵ In Ref. 4, the magnetization orientation splitting has been observed in the flux-closure domain which means the majority of the magnetization orientation in splitting domain is slightly away from the axis within the rectangle plane, and its roughness dependence has been explained successfully by micromagnetic simulation. However, the magnetization splitting was only reported in the Landau structure and it is symmetric.⁴ In this paper, we report that both symmetric and asymmetric magnetization splitting is investigated in diamond domain structure. From the dependences of the splitting angle on the exchange coefficient and the anisotropy constant, it suggests that the exchange interaction mainly contributes to the magnetization splitting in Landau structure, while that in diamond structure is dominated by magnetic anisotropy.

![Image](349x376 to 423x413)

![Image](349x329 to 423x365)

![Image](461x329 to 534x365)

FIG. 1 (color online) (a) and (b), two initial magnetization states for relaxing to Landau domain structure (c) and diamond domain structure (d), respectively. Blue and red represent two magnetic domains, and the arrows show the magnetization orientation. (e) Dependence of total energy on anisotropy constant $K$. (f) Dependence of total energy on exchange coefficient $A$.

II. MODEL

We made a systematical investigation on the magnetization orientation splitting in both Landau and diamond domain structures in nano-rectangles by OOMMF micromagnetic simulation, based on a model of Standard Problem 1.¹⁹ The dependence of magnetization splitting on exchange coefficient and anisotropy constant were studied. Principle of minimum energy and the symmetry of magnetic microstructure¹⁶,¹⁰ were employed...
to explain the different dependence and distribution features. The simulated sample size is $1000 \times 500 \times 20 \text{ nm}^3$ with cell size no larger than $5 \times 5 \times 5 \text{ nm}^3$. In our simulation, no external magnetic field was applied. The total energy $E$ includes the exchange energy $E_{ex}$, anisotropy energy $E_A$ and demagnetizing energy $E_D$, where

$$ E_{ex} = \int_{V} J_e \left( (\nabla m_x)^2 + (\nabla m_y)^2 + (\nabla m_z)^2 \right) \, dV, $$

$$ E_A = \int_{V} K (\alpha_x \alpha_x \partial_x + \alpha_y \alpha_y \partial_y + \alpha_z \alpha_z \partial_z) \, dV, $$

$$ E_D = -\frac{1}{2} \int_{V} M H \, dV. $$

In the simulation, the minimization of total energy is performed by using the conjugate gradient method with no preconditioning, by locating local minimum in the energy surface. The parameters of permalloy are used here as reference. The magnetization $M$ is $8.6 \times 10^5 \text{ A/m}$, the exchange coefficient $A$ between cells varies from $9 \times 10^{12} \text{ J/m}$ to $2.3 \times 10^{13} \text{ J/m}$, and the anisotropy constant $K$ between $-900 \text{ J/m}^3$ and $900 \text{ J/m}^3$, respectively. Different magnetization configurations are chosen as the initial state without considering the thermal activation. Then, it converges to a minimum energy state confined by the local energy barrier. For an initial magnetization state described in Fig. 1(a), it relaxes to the Landau state as shown in Fig. 1(c); while a diamond state will form in the case of an initial state in Fig. 1(b), as shown in Fig. 1(d). The up direction of the short axis of the rectangle is defined as $0^\circ$ direction. Positive anisotropy constant $K$ means the magnetization prefers in $90^\circ$ or $270^\circ$, i.e. the long axis. Either the diamond structure or the Landau structure is converged to, although the total energy of each differs for different $A$ and $K$. The dependence of the total energy on $A$ and $K$ is shown in Fig. 1(e) and Fig. 1(f) respectively. It is found that mostly the lower total energy prefers the diamond structure as $K$ changes. This is similar to the results in the literatures. However, the lower energy favors the Landau structure as $A$ larger than $1.5 \times 10^{13} \text{ J/m}$.

### III. LANDAU DOMAIN STRUCTURE

Figure 2(a) shows a typical distribution curve of magnetization orientation as a function of the magnetization angle $\theta$ in Landau domain structure. The proportion density $P$ is calculated as the count in a step of $1.2^\circ$ over the total cell amount. The distribution curve of magnetization orientation show a minimal period of $180^\circ$, corresponding to the centro-symmetry in Landau domain structure. Four main peaks $P_1$, $P_2$, $P_3$ and $P_4$ correspond to four different magnetization orientations in domain C, B, A and D respectively. The dependence of magnetization distribution on $\theta$ in Landau domain structure. The splitting angle $\Delta \theta$ between $P_{2L}$ and $P_{2R}$. (c) $P_2$ ($P_4$) splits to two symmetric peaks $P_{2L}$ and $P_{2R}$ ($P_{4L}$ and $P_{4R}$) with a valley $V_2$ ($V_4$), which correspond to the magnetization orientations in domain B (D) aligning with the long edges. $V_{23}$ is the valley between $P_2$ and $P_3$, which locates in the $90^\circ$ wall between domain A and B.

**FIG. 2 (color online)** For Landau domain structure: (a) the distribution curve of magnetization orientation as a function of the magnetization angle $\theta$. (b) the distribution curves of $P_1$ for $K = -900$, 0 and $900 \text{ J/m}^3$, as $A = 1.3 \times 10^{13} \text{ J/m}$, and those of $P_2$ are shown in Fig. 2(c). The splitting angle $\Delta \theta$ between $P_{2L}$ and $P_{2R}$ defined by the half depth of the valley is about $9.5^\circ$ (see Fig. 2(c)). (d) Dependence of the proportion densities on $K$ for $P_1$, $P_2$ and $V_2$. (e) Dependence of the splitting angle $\Delta \theta$ on $K$ for $P_2$.
symmetric peaks \( P \) interesting that the magnetization splitting can be found in anisotropy constant. It suggests the exchange interaction increases from \( 8^\circ \) to \( 11^\circ \) with \( A \) from \( 9 \times 10^{12} \) J/m\(^2\) to \( 2.3 \times 10^{13} \) J/m\(^2\), indicating much more influence than the anisotropy constant. It suggests the exchange interaction mainly contributes to the magnetization splitting in Landau structure.

IV. DIAMOND DOMAIN STRUCTURE

Next, we show the results in diamond domain structure. Figure 4(a) shows a typical distribution curve of magnetization orientation as a function of the magnetization angle \( \theta \) the in diamond domain structure. The distribution curve exhibits four main peaks \( P_1, P_2, P_3 \) and \( P_4 \) in a period of \( 360^\circ \), where show the symmetry to the short axis in diamond structure (see Fig. 1(d)). It is interesting that the magnetization splitting can be found in \( P_1, P_2, P_3 \) and \( P_4 \). As shown in Fig. 4(b), \( P_1 \) splits to two symmetric peaks \( P_{1L} \) and \( P_{1R} \), corresponding to the magnetization orientation in domain E and H in Fig. 1(d). However, \( P_2 \) whose magnetization around the \( 90^\circ \) axis, splits to two asymmetric peaks \( P_{2L} \) and \( P_{2R} \), shown in Fig. 4(c). This asymmetry of the splitting could be explained by the different neighbor domains. For example, the splitting of \( P_2 \) describes the magnetization orientation of domain G and J. They both have a same neighbor domain \( K \) that show no splitting and locate in the center of rectangle. The other neighbor of domain \( G \) is domain \( H \), while that of domain \( J \) is domain \( E \) respectively. It is noticed that the size, shape and boundary conditions of domain \( E \) are different from domain \( K \) and thus, the magnetization distribution in domain can be different due to the competition of the exchange and dipolar interactions.

FIG. 3 (color online) For Landau domain structure, the distribution curves of of \( P_1 \) (a), \( V_{12} \) (b), \( P_2 \) and \( V_2 \) (c) for \( A = 9 \times 10^{12}, 15 \times 10^{12} \) and \( 23 \times 10^{12} \) J/m, as \( K = 500 \) J/m\(^2\). (d) Dependence of \( \Delta \theta \) on \( A \) for \( P_2 \). (e) Dependence of the proportion densities on \( A \) for \( P_1, P_{2L}(P_{2R}) \), and \( V_2 \).

It can be seen from Fig. 4(d) that the proportion densities of \( P_{2L}, P_{2R} \), \( V_1 \) and \( P_3 \) decrease as the anisotropy constant \( K \) increases. However, the proportion densities of \( P_{2L}, P_{2R} \) and \( V_2 \) increase with \( K \). This is due to the conservation of the total magnetization in the domain, i.e. wherever the magnetization of \( P_1 \) and \( P_3 \) gain, there must be partly a loss in that of \( P_2 \) and \( P_4 \). The magnetization favors aligning around the long axis as \( K \) increases. The splitting angle \( \Delta \theta \) of \( P_1 \) varies a little bit with \( K \), as shown in Fig. 4(e), while that of \( P_2 \) increase with \( K \).

FIG. 4 (color online) For diamond domain structure: (a) the distribution curve of magnetization orientation as a function of the mangetization angle \( \theta \). (b) the distribution curves of \( P_1 \) for \( K = -900, 0 \) and 900 J/m\(^2\), as \( A = 1.3 \times 10^{13} \) J/m. (c) the distribution curves of \( P_2 \) for \( K = -900, 0 \) and 900 J/m\(^2\), as \( A = 1.3 \times 10^{13} \) J/m. (d) Dependence of the proportion densities on \( K \). (e) Dependence of the \( \Delta \theta \) on \( K \) for \( P_1 \) and \( P_2 \).
sides of the domain wall and makes the domains less
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due to the change of volume charges created by the 180
magnetization splitting in Landau structure. In the Landau
coefficient and anisotropy constant. Both symmetric and
micromagnetic simulation with various exchange
structures in nano-rectangles have been investigated by
structure is resulted from magnetic anisotropy.

In summary, the distributions of magnetization
angle as increasing A, as shown in Fig. 5(e). As the
exchange coefficient increases, sharp direction changes of
neighbor magnetic moment are not allowed in the 90°
domain wall region. This consumes the domains at both
sides of the domain wall and makes the domains less
magnetic moment. It can be seen from Fig. 5(d), Δθ for
both P_1 and P_2 decrease with increasing A. This may be
due to the change of volume charges created by the 180°
Néel wall along the center, and the decrease of the net
magnetization in every domain as A increases. Due to the
splitting angle decreases with increasing the exchange
coefficient but increases with the anisotropy constant, we
suggest that the magnetization splitting in diamond
structure is resulted from magnetic anisotropy.

V. SUMMARY

In summary, the distributions of magnetization
orientation for both Landau and diamond domain
structures in nano-rectangles have been investigated by
micromagnetic simulation with various exchange
coefficient and anisotropy constant. Both symmetric and
asymmetric magnetization splitting are found in diamond
domain structure, as well as only symmetric magnetization splitting in Landau structure. In the Landau
structure, the splitting angle Δθ increases with the
exchange coefficient A but decreases slightly with the
anisotropy constant K, suggesting that the exchange
interaction mainly contributes to the magnetization
splitting in Landau structure. However in the diamond
structure, the splitting angle Δθ increases with the
anisotropy constant K but decreases with the exchange
coefficient A, indicating that the magnetization splitting in
diamond structure is resulted from magnetic anisotropy.

These results can extend the understanding of the
magnetic domain microstructures. We expect the
magnetization splitting in diamond domain structure
could be observed in the future experiment.

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