Skyrmion-like states in multilayer exchange coupled ferromagnetic nanostructures with distinct anisotropy directions

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Abstract We report the experimental observation of magnetic skyrmion-like states in patterned ferromagnetic nanostructures consisting of perpendicular magnetized Co/Pt multilayer film exchange coupled with Co nanodisks in vortex state. The magnetic force microscopy and micromagnetic simulations show that depending on the magnitude of Co/Pt perpendicular anisotropy in these systems two different modes of skyrmion formation are realized.

Magnetic skyrmion is a localized spin configuration demonstrating unusual topological and transport properties [1]. This state was predicted theoretically as the effect of Dzialoshinskii-Moriya interaction in crystals without an inversion center [2-4]. Experimentally the skyrmion lattices were observed in some crystals (MnSi, FeGe and other) at low temperatures [5-7]. Now one of actual problem is to expand the class of magnetic materials suitable for realization of skyrmions stable at room temperature. Recently the formation of skyrmion-like states induced by magnetic vortex in artificial ferromagnetic nanostructures was considered theoretically in Ref. [8]. In current letter we present the experimental realization of skyrmion-like states in Co/Pt multilayer films exchange coupled with Co nanodisks (Co/Pt-Co disk nanostructures).

The initial thin film structures [Co (0.5 nm) / Pt (1 nm)]5 (denoted further as Co/Pt) and [Co (0.5 nm) / Pt (1 nm)]5 / Co (denoted further as Co/Pt-Co) was grown by DC magnetron sputtering on Si substrate with Ta (10 nm) / Pt (10 nm) buffer layer. The magnetic properties of Co/Pt and Co/Pt-Co thin film structures were investigated by magneto-optical Kerr effect (MOKE) and ferromagnetic resonance (FMR) methods. In experiments we used two Co/Pt structures differing by coercivity. First structure (structure I) had the coercive field \( H_cI = 130 \text{ Oe} \) and saturation field \( H_sI = 210 \text{ Oe} \), while the second one (structure II) had coercive field \( H_cII = 180 \text{ Oe} \) and saturation field \( H_sII = 300 \text{ Oe} \). The corresponding hysteresis curves are presented in Fig. 1a.

Covering Co/Pt structures by Co layer with thickness \( t_{co} < 1.5 \text{ nm} \) led to narrowing hysteresis loop and for \( t_{co} > 1.5 \text{ nm} \) we registered the anhysteretic magnetization curves. For example, normalized MOKE remagnetization loop for the structure I covered by 20 nm Co upper layer is presented in Fig. 1b. The FMR measurements showed that Co/Pt-Co thin film structures consist of two coupled effective oscillators Co/Pt (easy axis anisotropy) and Co (easy plane anisotropy) with surface energy of exchange interaction \( J = 1.9 \times 10^{-3} \text{ J/m}^2 \) and we believe that anhysteretic behavior of these structures with \( t_{co} >1.5 \text{ nm} \) shows that easy plane anisotropy is dominant.

Removing Co coating layer by ion etching with ion energy 200 eV does not destroy Co/Pt multilayer structure. The hysteresis loop for Co/Pt multilayer film after 20 nm Co coating removal is presented in Fig. 1c.

The Co/Pt-Co disk nanostructures with array of circle nanodisks (disk diameter 200 nm, thickness 20 nm, period 400 nm) were fabricated by electron beam lithography and ion etching (ion energy 200 eV, ion beam current 5 mA) of structures I and II with 20 nm Co upper layer.

The magnetic states and the magnetization reversal effects in these nanostructures were studied using a vacuum multimode magnetic force microscope (MFM)

![Fig. 1](image-url)
“Solver-HV”, which was equipped with dc electromagnets. The MFM measurements were performed in two-pass mode with relief extraction.

The MFM probe was magnetized along the axis so that its magnetic moment was directed towards the sample. The phase shift of cantilever oscillations under the gradient of the magnetic force was registered to obtain the MFM contrast [9]. All measurements were performed in a vacuum of 10⁻⁴ Torr, which improved the MFM signal due to an increase in the cantilever quality factor.

The experiments were carried out in the following scenario. At the first stage the samples were magnetized in an external magnetic field \( H_0 = 10 \) kOe, so that the magnetization direction coincided with the direction of the outward normal to the sample surface. Then at the second stage the reversed magnetic field \( H_R \) was applied with amplitude near \( H_c \) of Co/Pt and remagnetization effect was registered.

We observed experimentally that in Co/Pt-Co\(_{\text{disk}}\) systems two different modes of magnetization switching were implemented depending on the parameters of Co/Pt multilayer structure. For structure I the remagnetization effect was observed in the field 240 Oe greater than the saturation field (\( H_s > H_{cI} \)). The MFM images of the initial state and state after remagnetization for structure I are presented in Fig. 2a,b. A characteristic feature of MFM image presented in Fig. 2a is a narrow bright spot in the center of the disk. After magnetization switching the MFM image was changed dramatically and we observed the broad bright spot in the MFM contrast distribution indicating a change in magnetic structure of the sample (Fig. 2b).

On the other hand, the remagnetization of structure II has some difference. The switching effect was observed in the field 170 Oe lower than the coercive field (\( H_R < H_{cII} \)). Typical MFM images of structure II before and after remagnetization are shown in Fig. 3 a,b. In this case we observed the appearance of broad dark spot in the MFM contrast distribution over the disk (Fig. 3b).

To explain observed effects we supposed that remagnetization of structure I is connected with remagnetizing the peripheral region of the Co/Pt film (outside the Co disk), while remagnetization of structure II is caused by reorientation of magnetization in central part of Co disk and underlying Co/Pt area. It is known that in free Co disk with such dimensions the vortex state is realized [10]. So we assume that after initial magnetizing both Co disk and exchange coupled underlining region of Co/Pt have vortex distribution of magnetization [8] (see Fig. 2c and Fig. 3c). In this case the MFM registered lateral scale of non-homogeneity for Z component of stray field is defined by total thickness of Co/Pt-Co\(_{\text{disk}}\) structure, which is equal about 28 nm. The remagnetization in structure I is accompanied by reorientation of magnetization in Co/Pt out of Co disk. In this case magnetization in central and peripheral parts has opposite orientation and the characteristic scale of stray field localization is defined by disk diameter (about 200 nm). These changes of stray field localization lead to the observed effect of MFM contrast broadening. The remagnetization effect in structure II is defined by reorientation of central part of Co disk and underlying Co/Pt. In this case the distribution of magnetization (Fig. 3d) coincides with

![Fig. 2](image1.png)

![Fig. 3](image2.png)
200 × 20 nm. The calculations were carried out for the experimental pictures (Fig. 2a and Fig. 3a). (Fig. 2e and Fig. 3e), which agrees qualitatively with the state has the narrow bright spot in the center of the disk area. As a consequence the model MFM image of this magnetization both for Co disk and for Co/Pt underlying appearance of significant Z component in vortex shell with distinct anisotropy directions leads to the of magnetization. Interlayer interaction of two materials directly under the disk have the vortex-like distribution for structure I (Fig. 2d) but has opposite distribution in Co disk and underplaying Co/Pt retained the direction of magnetization, while the peripheral region of the Co/Pt film (outside the disk) taken the opposite magnetization. So, the formation of skyrmion-like state in the Co/Pt layer, similar to that described in [8] was observed. The structure II demonstrated some different micromagnetic behavior. Increasing the perpendicular anisotropy of the Co/Pt layer led to the stabilization of the peripheral area and the magnetic state switching was observed at 280 Oe by changing magnetization direction in the vortex core region. In this case the skyrmion-like state but with opposite orientation (in comparison with structure I) is formed. As a result the corresponding MFM image has the opposite contrast in the central region of Co disk (Fig. 3f), which agrees qualitatively with the experimental data.

Thus, magnetic force microscopy and micromagnetic simulations show that in patterned systems Co/Pt-Co disk the skyrmion-like states are realized. Depending on the Co/Pt coercivity, associated with the magnitude of perpendicular anisotropy, two different modes of skyrmion formation were demonstrated.

Such structures with well-controlled skyrmion-like distribution of magnetization are very promising for fundamental studies of spin-dependent transport peculiarities and magnetodynamic phenomena specific to strongly inhomogeneous magnetic systems.

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