Domain structures and domain wall pinning in arrays of elliptical NiFe nanoelements

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Stable domain patterns in a chain of NiFe nanoelements have been investigated using finite element micromagnetic simulations. The solution of the Landau-Lifshitz-Gilbert equation provides the hysteresis curves as well as the dynamic response of the system subject to an external field. We have studied elliptical elements with a long axis of 165 nm, a short axis of 55 nm and a thickness of 10 nm. Due to the shape anisotropy and magnetostatic interactions neighboring elements spontaneously align their magnetization antiparallel, if the magnetization of the elements was initially parallel to the short axis. If the initial magnetization is antiparallel, the magnetostatic stray field stabilizes this configuration. If the elements are in contact with each other, the effect of domain wall magnetoresistance can be used for applications. Chains of six elliptic elements with contact faces have been investigated. For sufficiently small contact faces, the antiparallel domain pattern is maintained, even though there is exchange coupling between neighboring elements. For small contact faces the stability of the antiparallel pattern is shown and a switching field of 48 kA/m has been obtained. The switching fields can be tailored by the shape and size of the elements. [DOI: 10.1063/1.1447177]

Magnetic nanoparticles have seen growing interest in recent years due to advances in fabrication, observation,[1] and computational techniques.[2] Since the typical size of these particles approaches the magnetic domain wall width (nm$-\mu$m range) different effects appear and can be exploited for applications. Transport phenomena and magnetoresistive effects in particular are intensively studied. In experiments different magnetic domain configurations and domain walls have been found to influence magnetoresistive effects.[3–6]

In this work magnetic nanoparticles of permalloy ($Ni_{80}Fe_{20}$) have been investigated. We have assumed a saturation polarization of $J_s = 1\,T$, an exchange constant $A = 13$ pJ/m, and zero magnetocrystalline anisotropy. Three dimensional (3D) dynamic micromagnetic simulations based on the Gilbert equation of motion of the magnetization[7] have been carried out to study the magnetic reversal processes and domain configurations in single particles, arrays of isolated particles, connected particles with contact faces of different size and connected particles of different size.

The magnetic domain wall width in permalloy is approximately as large as the long axis of the particles, but effects of the magnetostatic stray field and small contact faces can stabilize certain domain configurations. The remaining "domain walls" can be used to investigate magnetoresistive effects. The elliptic permalloy particles have a long axis of 165 nm, a short axis of 55 nm, and a thickness of 10 nm.

When a single ellipsoidal particle is initially magnetized parallel to its long axis, which is also the remanent state due to the shape anisotropy, it requires an (antiparallel) external field of 239 kA/m to reverse its magnetization. The particle exhibits a very inhomogeneous magnetization reversal process, but due to its small size and the soft magnetic material, which have been assumed, it is a single domain particle.

The behavior of a chain of six isolated ellipsoidal nanoparticles (Fig. 2), which are separated by a gap of 5 nm, is strongly influenced by the magnetostatic stray field. The demagnetization curves are given in Fig. 1. The external field is parallel to the long axis of the ellipsoids. If the particles are initially magnetized parallel to each other and the long axis of the ellipsoids, the magnetization reversal occurs at an external field of 72 kA/m. However, if the magnetization of each particle is initially antiparallel to that of its neighbors, that particle at one end of the chain, whose magnetization is antiparallel to the external field, reverses at 87 kA/m. The two other particles inside the chain, whose magnetization is antiparallel to the external field, reverse at 104 kA/m. Thus, the stray field stabilizes the antiparallel magnetized particles and increases the switching field by 44%. A snapshot of the magnetization reversal process is given in Fig. 2.

In order to study the influence of the shape of the nanoparticles another set with rectangular shape has been created. Each particle is a hexahedron with 165 nm$\times$55 nm$\times$10 nm

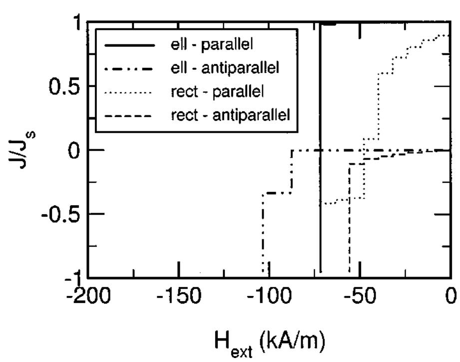

FIG. 1. Demagnetization curves for a chain of ellipsoidal and rectangular particles with parallel and antiparallel initial magnetization.

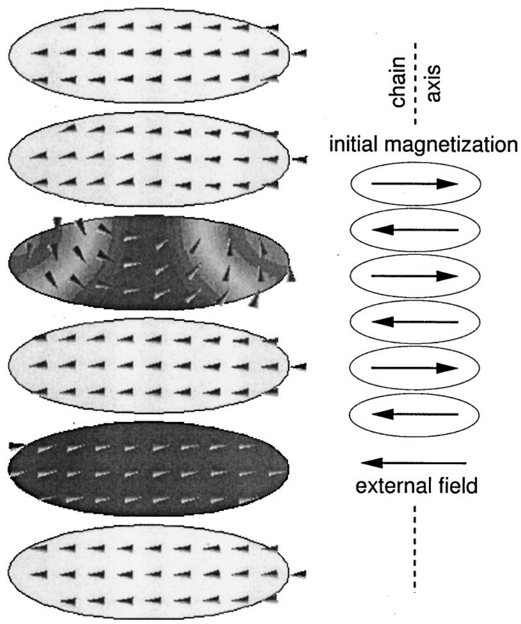

FIG. 2. Snapshot of the magnetization reversal process of a chain of six ellipsoidal particles with initially antiparallel magnetization.

edge length. The particles are separated by 5 nm. The demagnetization curve for parallel and antiparallel alignment and in comparison with ellipsoidal particles is given in Fig. 1.

Due to the inhomogeneous magnetization of the rectangular particles in equilibrium, the chain of rectangular particles is not as stable as that of ellipsoidal particles. Thus, the magnetization is reduced already for small external fields and the switching fields are considerably lower. The switching field is 56 kA/m for antiparallel initial magnetization. The demagnetization curve of the initially parallel magnetized particles shows a plateau at $J/J_s = -0.38$, which is again caused by the stabilizing effect of the outer particles, which have already switched. In contrast to the ellipsoidal particles, which reverse their magnetization almost at the same time, the rectangular particles do so consecutively. Thus, a stabilized antiparallel pattern is formed.

If the initial magnetization of the particles is parallel to the axis of the chain and the short axis of the ellipsoids, the behavior in zero field is also dominated by the magnetostatic stray field. The demagnetization curves for ellipsoidal and rectangular particles are given in Fig. 3. The inhomogeneity of the magnetization distribution in the rectangular particles causes again the "rounded" demagnetization curve. The magnetization of the particles at the end of the chain tries to align parallel to the long axis. As soon as the symmetry of this metastable state breaks, the stray field leads to an antiparallel alignment of the magnetization of the neighboring particles. By chance the particles at the end of the chain choose one or the other direction but in any case the stray field causes the antiparallel alignment of the neighboring particle. Since the particles at the end of the chain chose the same direction, the magnetization of those in the center is parallel.

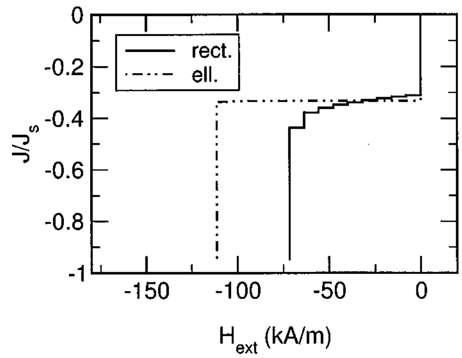

FIG. 3. Demagnetization curves for a chain of six particles with the initial magnetization parallel to the chain axis.

Finally the influence of contact faces, which is necessary for electrical contact in magnetoresistance (MR) experiments, between the particles has been investigated. This contact causes exchange coupling of the magnetization of the particles and has a strong influence on the domain patterns.

First, a rather large contact face of 50 nm×10 nm between the ellipsoidal particles was assumed. The demagnetization curves in Fig. 4 show that the switching field of the particles with initially parallel magnetization is reduced by more than 50%. For the particles with initially antiparallel magnetization we find a different behavior: The exchange coupling of the particles overrides the shape anisotropy and causes the formation of domains which extend over several particles.

If we reduce the size of the contact faces to 10 nm ×10 nm we can "pin" the domain walls between particles with antiparallel magnetization at the contact faces. The demagnetization curves for this small contact faces are given in Fig. 5. If the particles are initially magnetized parallel to the chain axis, the exchange coupling is still strong enough to suppress the spontaneous formation of the antiparallel pattern. When the external field is switched on, the magnetization of the inner particles rotates homogeneously in the direction of the external field.

In summary, we have studied magnetization reversal processes of permalloy nanoparticles of ellipsoidal and rectangular shape by 3D dynamic finite element micromagnetic simulations. The results show the strong influence of the

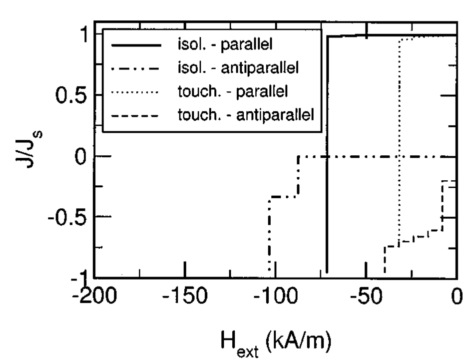

FIG. 4. Demagnetization curves for a chain of ellipsoidal particles with ("touch." 50 nm×10 nm) and without ("isol.") contact faces with parallel and antiparallel initial magnetization.

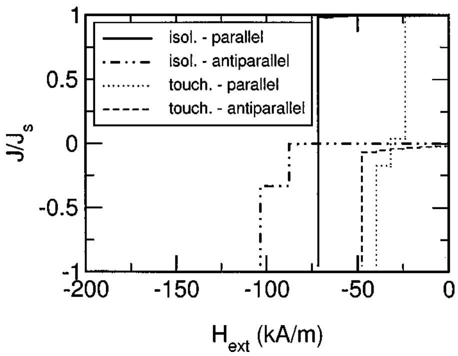

FIG. 5. Demagnetization curves for a chain of ellipsoidal particles with (“touch.” 10 nm×10 nm) and without (“isol.”) contact faces with parallel and antiparallel initial magnetization.

shape and the demagnetizing field on the behavior of the particles. Even without magnetocrystalline anisotropy stable domain configurations with the magnetization perpendicular to the axis of a chain of particles can be obtained. The shape anisotropy and demagnetizing field lead to a spontaneous antiparallel alignment of the magnetization of neighboring particles. If the particles have very small contact faces a stable antiferromagnetic configuration is found in spite of exchange coupling. This effect can be used in experiments to study MR effects in nanoparticles of materials without magnetocrystalline anisotropy.

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