Evolution and propagation of magnetic vortices in chains of Permalloy nanospheres

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Magnetization reversal in a chain of Permalloy $Fe_{0.2}Ni_{0.8}$ spheres, whose diameters of 40–60 nm are large enough to support vortex structures, is investigated using micromagnetic modeling based on the Landau-Lifshitz-Gilbert equations. The emphasis is on a chain of two spheres with fields applied along and perpendicular to the axis of rotational symmetry. Magnetization processes and critical fields are given for (1) inversion symmetry, with opposite senses of vortex rotation in the two spheres, and (2) a more uniform curling mode, with the sense of rotation the same in both spheres. Symmetry breaking perturbations are shown to be important in the nucleation of changes from one magnetic configuration to the next. As the geometry is approximated by cubic grid cells, whose centers lie within the boundaries of the ideally smooth surfaces, the critical fields are influenced by the grid size. The results for two spheres are generalized in the description of a chain of n spheres, in which at least 2^n symmetry states can be selected by the application of inhomogeneous fields. [DOI: 10.1063/1.2171957]

The treatment by Jacobs and Bean[1] of magnetization reversal in a chain of spheres addressed the problem that, in the first studies of the magnetic properties of elongated ellipsoids, which had sufficiently small diameters for single domain behavior, observed coercive fields were far lower than those theoretically predicted. At that time attempts were being made to create practical permanent magnets based on shape anisotropy. Their paper, cited more than 300 times, applies to uniformly magnetized spheres in chains with diameters generally of less than 20 nm. For diameters greater than 40 nm with a magnetically soft material, such as Permalloy, the spheres in the chain are not uniformly magnetized. We use micromagnetic simulations[2] employing the Landau-Liftshitz-Gilbert (LLG) equations of motion to investigate several key aspects of vortex motion in the reversal of magnetization of self-assembled spheres, in which exchange coupling is present in the necks joining adjacent sections. The primary emphasis is on a chain of two spheres with the vortices leaving and reentering. Experiments are in progress on systems with vortices in geometries related to chains of spheres.[3,4]

Consider a chain of four or five spheres, each of which has a diameter of 50 nm. To stop these from forming a closed ringlike configuration,[1] it is assumed that the spheres are aligned along a central axis and joined by cylindrical sections of finite radius. At sufficiently high fields, the magnetization pattern in each sphere is almost completely uniform and aligned along the field. Inhomogeneous dipolar fields that arise from the finite grid approximation superimpose a small splay of magnetization. When the field is lowered continuously and slowly, the splay of magnetization develops a curl in a smooth transition. The sense of the curl can be clockwise or counterclockwise for each sphere, depending on the symmetry breaking operation in the nucleation process. For n spheres in the chain, symmetry breaking operations can lead, in principle, to 2^n distinct magnetic configurations.

As the configuration at high fields for the chain of spheres and the LLG equations both have inversion symmetry, the dynamically occurring configuration for step reductions in the field is one that preserves that inversion symmetry. This configuration usually is not the lowest energy state. Symmetry breaking is necessary to nucleate the lower energy states.

For a chain of an even number of spheres with the field along the chain axis, here denoted as the x axis, the magnetization patterns on one side of the center would have one handedness and those on other side would have the opposite

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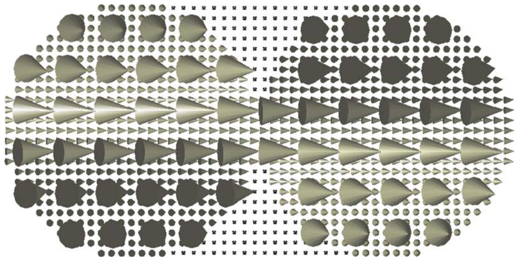

FIG. 1. Geometry used in micromagnetic simulations of a chain of spheres of diameter of 50 nm on a cubic grid of 2-nm cells. The gray elements in the background represent the magnetization direction as conical shells in the central cross section of the chain. That this is a vortex state with opposite handedness in the two spheres has been made clearer by superimposing large cones that represent the average direction of magnetization in 16 neighboring cells. The diameter of the neck joining the two spheres is seven cells or 14 nm. The cells shown as small dark squares are activated in sequence to give diameters of 9, 11, 13, 15, 17, 19, 21, 23, and 25 cells, with the latter becoming a cylinder with hemispherical caps.

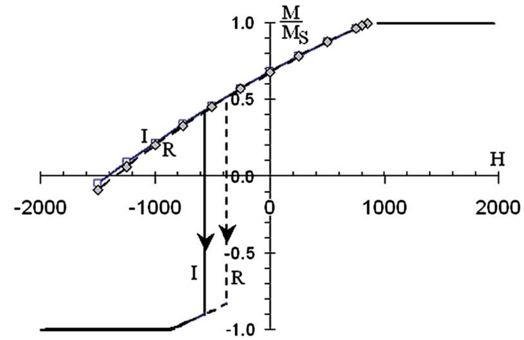

FIG. 2. Hysteresis loops for two spheres of radius of 25 nm with centers separated by 50 nm and joined by a cylinder of radius of 7 nm, as shown in Fig. 1. The magnetization, applied field, and vortex cores are along the line joining the centers of the spheres (the *x* axis). The two vortices have opposite handedness in the inversion symmetry configurations, labeled I, and the same handedness in the simple curling configuration with reflection symmetry, labeled R. The symbols are for the fields for which the convergence criterion was a maximum change per iteration of one part in 10^{10}. This criterion was reached in 3 ns. The lines with arrows show the transitions when the calculations were allowed to proceed for 300 ns.

handedness. With an odd number of spheres the central sphere would break the inversion symmetry if it was to choose a handedness. All of the spheres are forced to have the same handedness when a current is passed along the x axis.

When a field H_y, perpendicular to the x axis, is lowered from saturation, each sphere must choose a handedness for a vortex along the y axis. With inversion symmetry for an even number of spheres, the sense of rotation alternates between spheres for the vortex cores along the y axis. This is a lower energy state compared to adjacent spheres having the same sense because it is then necessary to form Bloch walls at the connection. Thus it is to be expected that states with the same handedness in adjacent spheres are favored for vortex configurations along the x axis but not for vortex configurations along the y axis.

We perform micromagnetic simulations by approximating the spheres using a finite grid of 2 nm cubes, which is sufficiently fine to treat the subtleties of vortex nucleation as previously described for vortices leaving and entering square nanoboxes of similar dimensions and also of Permalloy.[5] In each 50-nm-diameter sphere there are 25 slices with "diameters" of 7, 11, 13, 15, 17, 19, 21, 23, or 25 cells. The slices in each sphere are identical along the x, y, and z axes. Chains were created by connecting the slices at the ends of the spheres rather than by sharing a slice between adjacent spheres. The interface neck is then a cylinder with a diameter of seven cells or 14 nm, see Fig. 1. Simulations are carried out for cylindrical necks that have diameters up to 25 cells formed by activating the darker cells shown in Fig. 1.

For micromagnetic simulations on a 2 nm grid, the dynamical calculations must use time steps smaller than a picosecond to avoid chaotic instabilities of purely mathematical origin. For the present calculations with a damping parameter □=1, corresponding to critical damping, our time step, 0.125 ps, remains mathematically stable. Normally equilibrium is established on the time scale of nanoseconds. But, in regions of transitions between configurations, the time scale can be much longer. Local equilibrium is still established in a nanosecond, but the configuration as a whole drifts for as long as a microsecond while slowly developing the critical configuration. Typically near a transition, the change per time step increases exponentially with a time constant of 13 ns for 200 ns after which there is a dramatic spike in the rate of change per iteration.

When calculations for a vortex in a single 50-nm sphere are carried out, the cubic grid creates the effect of a cubic anisotropy acting on the vortex as a unit. If the sphere is uniformly magnetized there is no anisotropy, that is, the energies are identical for magnetization along the $\langle 100\rangle$ and $\langle 111\rangle$ axes. Once a vortex is present, the energy for the vortex with its core along a $\langle 111\rangle$ is lower than when it is along a $\langle 100\rangle$. It takes 35.5 Oe along the $[100]$ to rotate the vortex from the $[111]$ to the $[100]$. It returns spontaneously on the removal of the field. An analytical model of the magnetization of the sphere, assuming a rigid rotation by the fields of a vortex with a constant magnetic moment of $0.476MsV$, where V is the volume of the sphere, matches well the LLG calculations. The model includes a small effect from the susceptibility of the magnetization pattern as a whole to the small fields along the axis of the vortex. Results for several directions of the field can be explained quantitatively by this model if the rigid vortex senses a cubic shape anisotropy arising from the grid. Presumably such an anisotropy acts locally on portions of the vortex even when the vortex itself distorts as it does for the chains of spheres in much larger fields. This effect, which should be absent by symmetry in a perfect sphere, could still be present in a real atomic lattice shaped to approximate a sphere.

The field dependence of the magnetization for two spheres that are joined by a 14-nm neck is shown in Fig. 2, both for a vortex pattern with inversion symmetry, labeled I, and for a vortex pattern, labeled R, that curls the same way in both spheres. For the field along the axis, it is easier to reverse two spheres with the same handedness. At the apparent saturation fields in Fig. 2, there is a small deviation from complete saturation, typically with $M_x/M_s=0.995$, leaving 10% of the magnetization to participate in the splay caused by the coarse graining at the surface. As $\mu_0 M_s$ for Permalloy is 1 T, the graphs, which are actually fractional moments,

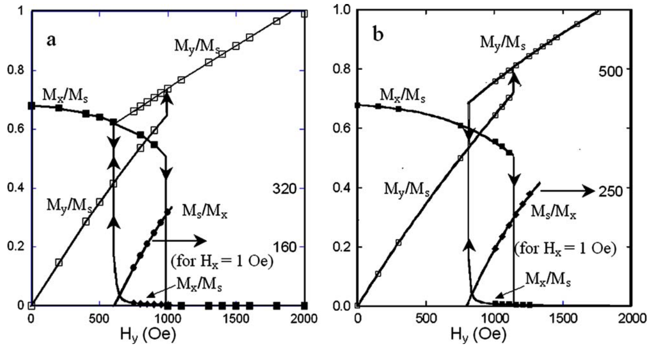

FIG. 3. Hysteresis loops for two spheres, as shown in Fig. 1, with the field along the y axis, perpendicular to the chain axis, starting with inversion symmetry in (a) and starting with the simple curling configuration with reflection symmetry in (b). The onset of the switching back from magnetization along y to magnetization along x is extremely slow. A small field, H_x=1 Oe, along x measures the transverse susceptibility, the inverse of which extrapolates to zero near the critical field.

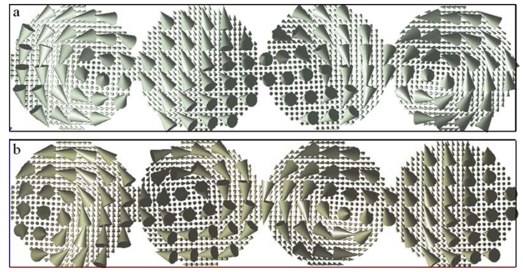

FIG. 4. Two views of a chain of four 50-nm spheres during a reversal process starting from a simple curling pattern about the axis of the chain. The large cones represent the average of 16 neighboring cells in a single-cell-deep cross section through the central axis for the x-y plane in (a) and the x-z plane in (b). All of the cells in each plane are shown in the background.

labeled as M/M_s, could be labeled as μ_0M in teslas.

The application of a field along the axis of the chain causes the vortex cores to move away from the central axis, leave the spheres, and then reenter with reversed direction of core polarization and reversal of the handedness when viewed from a given direction. The vortices bend and tilt during the migrations to and from the surfaces.

For vortices with opposite handedness, during reversal, the axes of the vortices in both spheres leave by migrating to the same side of the chain and then reenter on the opposite side with the opposite polarization and opposite handedness, maintaining inversion symmetry.

When the two vortices have the same curl, the vortex cores in the two spheres move in opposite directions, leave on opposite sides, and then reenter on the sides opposite to those they left. Again the vortices reappear with opposite polarization and opposite handedness, recovering the simple curling state.

As the neck diameter is increased, both the inversion symmetry configuration and curling configuration become harder to reverse. But as the geometry approaches that of the cylinder with hemispherical ends, the state of inversion symmetry becomes unstable with respect to the curling state in zero field.

For a field along the y axis, vortices in the spheres with the opposite handedness switch more easily from having the vortex axis along the x axis to along the y axis than do the vortices that curl in the same direction, see Fig. 3. This reflects both the greater stability of the curling configuration along the x axis and the lower stability when the vortices have the same handedness along the y axis.

The application of a field H_y perpendicular the x axis along the chain causes the x-axis vortices to migrate away from the x axis and leave the spheres just as the y-axis vortices enter. Starting with inversion symmetry, the M_x components and M_y components respond to H$_y$, the field in y, as shown in Fig. 3(a). The x-axis vortices move in the opposite sense with one departing near the z direction and the other departing near the $-z$ direction. When the x-axis vortices reform on lowering H_y, they enter on the same side that they left. The y-axis vortices in each sphere enter and leave on the side opposite to that where the x-axis vortices enter and leave. The y-axis vortices have opposite handedness, allowing the magnetization in the neck to lie in the x-z plane. Starting with the simple curling configuration with reflection symmetry, the M_x components and M_y components respond to H_y, as shown in Fig. 3(b). The x-axis vortices move in the same sense, departing in the z direction. When the x-axis vortices reform on lowering H_y, they enter on the same side that they left. The y-axis vortices in each sphere enter and leave on the side opposite to where the x-axis vortices enter and leave. In this case the y-axis vortices have the same handedness, forcing the magnetization in the neck to point in the y direction, as part of a Bloch wall formed between the two spheres. The application and removal of H_y in both cases returns the configuration to the starting symmetry, if H_y is not taken to full saturation.

The critical fields on reducing H_y are found by observing the M_x component in the presence of a small bias field H_x =1 Oe. The extrapolation to zero of the magnetic stiffness H_x/M_x as a function of H_y indicates the critical field at which the stiffness vanishes and the x-axis vortices replace the y-axis vortices, see Fig. 3.

With five spheres there are at least five vortices involved, but there can be more as some vortices enter while others are leaving. The longer chains have additional jumps in the magnetization both for hysteresis loops in off-axis field directions and for rotational hysteresis. These were illustrated in the conference poster, but space limitation prevents showing more than one instant in the reversal process for the curling state in a chain of four spheres in Fig. 4. At this point in the complex reversal process, vortices have formed in the x-y plane for the two outer spheres and in the x-z plane for the two inner spheres. The smooth flow of magnetization from sphere to sphere is maintained throughout the reversal process in an applied field of −700 Oe compared to the critical field of −682.3 Oe indicated by the path method.[6]

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