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Control of magnetization states in microstructured permalloy rings

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Magnetization processes of microstructured NiFe rings are studied by the fringe-field-induced local Hall effect and numerical model calculations. The changes in reversible and irreversible magnetization of single rings are detected with very high resolution. We observe that the type of magnetic transition depends on the ratio between the inner and outer ring diameter. For narrow rings, sharp transitions from so-called "onion" to the "vortex" state are observed. In rings with smaller inner diameter, the transitions are more complex. The creation of local vortices and their spatial movement by applying an external magnetic field are detected. © *2004 American Institute of Physics.* [DOI: 10.1063/1.1646223]

In recent years the interest in microstructured magnetic rings has increased rapidly because they offer potential application in magnetoresistive random access memories (MRAMs)[1] Therefore stable well defined magnetic states with reproducible transitions are necessary. Generally narrow microstructured rings show two stable magnetic states[2,3] which are the so-called "onion" state for saturation fields and the vortex state. In the vortex state the magnetization is orientated circularly and almost no stray field is generated, which offers the potential for high integration storage densities.[4] Most noninvasive investigations have used the magneto-optical Kerr effect (MOKE) and measured averaged magnetization values of ring arrays[2,3,5,6] or used anisotropic magnetoresistance measurements.[7,8] The application of local Hall effect (LHE) measurements[9–11] allows one to investigate the magnetization transitions of single rings and increases the resolution dramatically. In this letter, sharp transitions from the onion to the vortex state are observed in narrow rings and we measure more complex behavior in rings with small hole diameters.

In our devices an InGaAs based heterostructure with a two-dimensional electron gas (2DEG) 31.5 nm under the surface similar to the one in Ref. 12 is used as a local Hall probe. The charge carrier density was determined to be $n = 1.7\times10^{12}$ cm^{-2} and the mobility $\mu = 26\,000$ cm^2/V s at $T = 0.3$ K. A Hall cross is prepared by electron-beam lithography and by chemical dry etching. The permalloy ($Ni_{80}Fe_{20}$) rings described here have an outer diameter of $r_{out} = 2$ μm and an inner diameter that is varied between $r_{in} = 0.0$ (disk) and $r_{in} = 1.6$ μm in steps of 0.4 μm, so we investigate a total of five rings. Rings of 60 nm thickness were fabricated by electron-beam evaporation at base pressure of 5×10^{-7} mbar and a lift-off technique. To attain the maximum signal-to-noise ratio the rings are dislocated on the Hall crosses. A typical sample is shown in the inset of Fig. 1. All measurements were performed at a temperature of 0.3 K and the magnetic field was applied in the plane of the 2DEG. Thus the external field does not induce magnetoresistance and the changes in the Hall signal measured can be attributed to changes in the magnetization of the rings only.

The Hall resistance measurements are shown in Fig. 1 for different inner diameters. The hysteresis curves change systematically from a reversible transition for the disk to an irreversible hysteresis curve with two sharp transitions for narrow rings with inner diameters of 1.2 and 1.6 μm. The fact that the absolute change in resistance from saturation at positive and negative magnetic fields decreases with an increase in hole diameter can be attributed to a systematic change in the stray field distribution. The measured hysteresis curves are normalized and are offset in the following graphs for a better comparison with the computational results.

Detailed insight into the magnetic transitions is obtained by micromagnetic simulations using OOMMF.[13] The three most significant magnetic transition types are discussed here. In Fig. 2, the hysteresis and magnetization pattern for a disk are shown. By applying saturation fields almost all magnetic moments are oriented in the field direction (i) in Fig. 2. Reducing the external field yields the creation of a wave-like

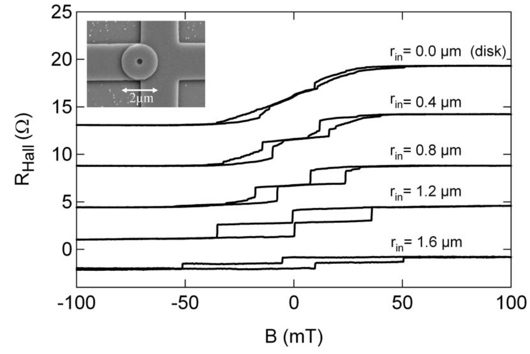

FIG. 1. Local Hall measurements of permalloy rings with an outer diameter of $r_{out} = 2$ μm and different inner diameters at film thickness of 60 nm. Offset is added for clarity. The inset shows a typical Hall bar sample.

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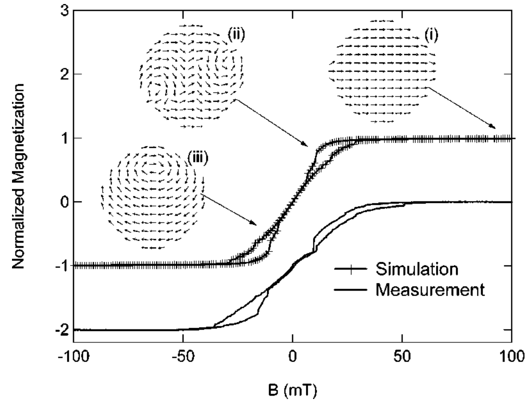

FIG. 2. Measured and simulated hysteresis curves for a disk with 2 μm outer diameter. At saturation (i) almost all magnetic moments point in the field direction. A reversible change into a wave-like state (ii) with two vortices arising at the edges of the disk is observed followed by an irreversible transition into a single local vortex state (iii). The vortex is shifted spatially by the external magnetic field until it reaches the disk's edge and is annihilated.

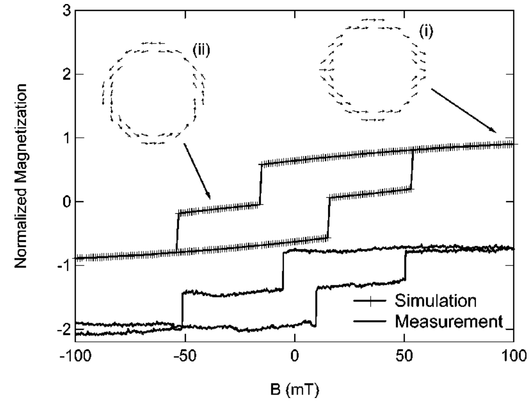

FIG. 4. For narrow rings (r_{out}=2 μm and r_{in}=1.6 μm) only two sharp transitions are measurable. For saturation fields the onion state (i) is observed which enters the global vortex state (ii) without any intermediate configurations. Another sharp transition back into the onion state arises at about −50 mT.

state (ii) with two local vortices at the edges of the disk. The transition into this state happens reversibly and therefore a smooth change in the corresponding hysteresis curve is observed. Further reduction of the magnetic field results in a magnetization change with the generation of a single local vortex (iii). Such a vortex may be the configuration with the lowest energy for a defined external field because antiparallel orientation of the magnetic moments is minimized toward the vortex center. The vortex is shifted through the disk reversibly by the external magnetic field until it is annihilated at the disk's edge and the saturation configuration is restored at negative magnetic fields.

For rings with small holes r_{in}=0.4 μm the onion state (i) is observed at saturation magnetization as shown in Fig. 3. Via a wave-like state (ii) similar to the transition in the disk the ring irreversibly enters the global vortex state (iii). This state is stable for the interval between +6 and −14 mT and thus a plateau in the hysteresis is created. By a second irreversible transition the configuration changes from the global vortex state into a local vortex (iv) which is shifted until annihilation. The complex transition via wave-like and local vortex states described becomes much simpler by increasing the hole diameter of the ring. Figure 4 shows the hysteresis curve for a ring with r_{in}=1.6 μm inner diameter and only two sharp transitions observable. The corresponding magnetic configurations, i.e., the onion state (i) at saturation and the global vortex state (ii) are the only stable magnetic configurations. The creation of intermediate states is suppressed because the width of the ring is too small for the creation of local vortices. From the measurements in Fig. 1 a value between r_{in}=0.8 μm and r_{in}=1.2 μm necessary for the inner diameter can be estimated to obtain sharp transitions at r_{out}=2 μm and 60 nm film thickness. For smaller inner diameters the creation of local vortices is favored energetically.

In Fig. 5 the irreversible transition fields extracted from the measurements as well as from the simulations are depicted for all rings. Only the upward sweeps of the curves are evaluated but all necessary information is obtained due to symmetry. The hysteresis curve of the disk shows no irreversible changes and is not evaluated. The transitions are referred to as "onion to vortex" and "vortex to onion" transitions, since we know that intermediate states like local vortices can arise. The inner diameter allows one to vary the

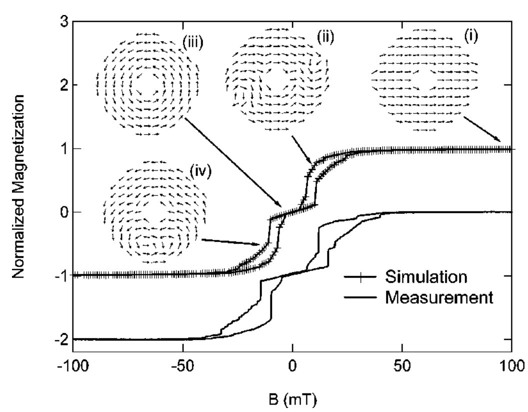

FIG. 3. Measured and simulated hysteresis curves for a ring with r_{out}=2 μm and r_{in}=0.4 μm. Starting from the onion state (i) the ring reversibly enters a wave-like state (ii). The global vortex state (iii) is irreversibly reached and forms a stable configuration that produces a plateau in the hysteresis. Via an irreversible transition into a single local vortex state (iv) the saturation configuration is reached again.

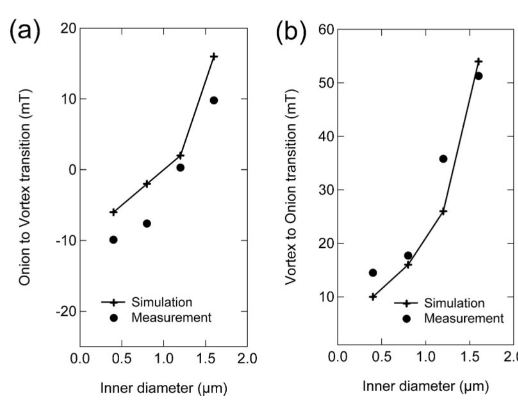

FIG. 5. Transition field dependence on the inner diameter. Only the upward sweeps are evaluated. The simulated values show good agreement with measurements for parameters $A=3\times10^{-12}$ J/m and M_s=500 000 A/m.

switching fields by changing the shape anisotropy for both kinds of transition and therefore is a powerful tool in the design of rings. In our model calculations we use saturation magnetization of M_s=500 000 A/m and exchange constant of $A = 3\times10^{-12}$ J/m. Although these values are smaller than the values of M_s=676 000–851 000 A/m and for $A = 5.5–9.3\times10^{-12}$ J/m obtained from spin wave resonance,[14] the model calculations agree with the experimental results. The saturation magnetization and exchange constant of NiFe probably depend on the sample preparation process, the substrate, the film thickness, and the composition. All simulations are performed for zero temperature which is a good approach for our measurements at 0.3 K. For higher temperatures, i.e., room temperature the OOMMF code still delivers qualitatively correct results[15] but the switching values of the rings might show temperature dependence.

In conclusion, we have applied local Hall magnetometry to micron-sized NiFe rings. The magnetic transitions were investigated with high resolution. For narrow rings, a sharp transition between the onion and the vortex state is detected. Our LHE measurements at low temperatures and numerical simulations show that in rings with small holes local vortices are created and that the interplay between reversible and irreversible transitions rules the hysteresis curve. This observation reveals that rings are interesting magnetic systems. The switching fields can be controlled by the inner diameter, in good agreement with our computational results.

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