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Magnetization reversal and spin waves in exchange coupled NiFe/Cu/Co nanodisks

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We present an experimental study of the static and high frequency dynamic properties of NiFe(10 nm)/Cu(t_{Cu})/Co(10 nm) nanometric disks for different values of the Cu spacer thickness (t_{Cu}=0.7, 1.2, and 2.0 nm). We found that the exchange interlayer coupling dominates over the dipolar interaction favoring parallel alignment between the two layers of magnetization with formation of vortex states at remanence. Brillouin light scattering technique from thermally excited spin waves was used to estimate the value of the interlayer exchange coupling in the unpatterned NiFe/Cu/Co films as well as to investigate the magnetic normal modes in the corresponding multilayered nanodisks. In the latter case, evidence is given for a discretization of the measured spectrum with reduction in the mode frequency associated to the demagnetizing effect induced by lateral confinement. Micromagnetic simulations indicate that these discrete modes correspond to an in-phase precession of the magnetization in the two ferromagnetic layers while, at variance with the continuous film, no evidence of optical modes is obtained. © *2009 American Institute of Physics*. [DOI: 10.1063/1.3070643]

The functionality of novel magnetic devices based on patterned multilayered stacks depends on controlling the properties of ever smaller magnetic structures, which are continuously investigated using a variety of experimental techniques. Research is currently focused on laterally confined layered structures of increasing complexity, containing magnetic and nonmagnetic layers configured so as to provide the best performance for magnetoresistive and spin-polarized tunneling read heads or nonvolatile memories in the magnetic random access memory technology.[1,2] The magnetic behavior of such elements can be particularly complex and is due to the interplay between intrinsic properties and coupling effects, e.g., exchange coupling through a nonmagnetic interlayer, exchange-spring coupling between magnetic layers in contact, and dipolar coupling between layers brought about by the lateral confinement. On the other hand, this complexity can introduce further possibilities for manipulating the magnetic behavior of the system with a great potential for future applications. Along these lines, in this paper we investigated the magnetization reversal process and the magnetization dynamics of nanoscale size multilayered disks consisting of Permalloy ($Ni_{80}Fe_{20}$) (10 nm) and cobalt (10 nm) ferromagnetic layers separated by a thin nonmagnetic copper spacer with thickness in the range 0.7–2.0 nm. This study extends the results of a previous investigation carried out on a similar NiFe/Cu/Co pseudospin valve nanostructure having a copper interlayer spacer thickness of 10 nm.[3]

The NiFe(10 nm)/Cu(t_{Cu})/Co(10 nm) disks studied in the present study were fabricated by deep ultraviolet lithography at 248 nm exposing wavelength on Si(001) substrate.[4] The disks have a diameter of 230 nm, an edge-to-edge spacing of 160 nm, and Cu thicknesses of t_{Cu}=0.7, 1.2, and 2.0 nm. Continuous (unpatterned) NiFe(10 nm)/Cu(t_{Cu})/Co(10 nm) films with the abovementioned values of the Cu spacer thickness were also fabricated and used as reference samples to estimate the intensity of the interlayer exchange constant.

The magnetic reversal of each layer of our NiFe/Cu/Co pseudo-spin valve nanostructures has been investigated by the element sensitive technique of x-ray resonant magnetic scattering (XRMS). The dynamical properties were studied by Brillouin light scattering (BLS) from thermally excited spin wave modes. Spectral measurements were carried out in backscattering geometry using a Sandercock model tandem Fabry-Perot interferometer in a (3+3)-pass configuration. Understanding of the magnetization configurations in the two magnetic layers as well as calculation of the frequency and spatial profiles of the spin wave modes is facilitated by three-dimensional micromagnetic modeling which was carried out by using the OOMMF code from NIST.[5] The disks were discretized into cells of $5\times5\times2\ nm^3$, and the magnetic parameters used for NiFe and cobalt are the following: M_s(NiFe) $=800\times10^3$ A/m and M_s(Co)$=1200\times10^3$ A/m for the saturation magnetization, A(NiFe)$=10\times10^{-13}$ J/m and A(Co)$=21\times10^{-13}$ J/m for the exchange stiffness constant.

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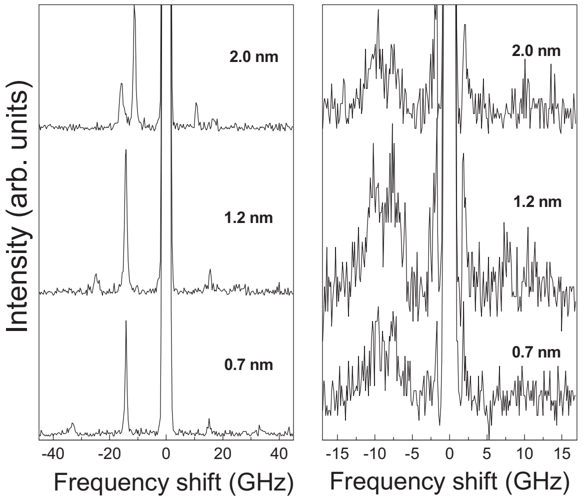

FIG. 1. Sequence of measured BLS spectra for the unpatterned (left panel) and NiFe/Cu/Co disks (right panel) for the different Cu spacer thicknesses in an applied external field of 0.8 kOe.

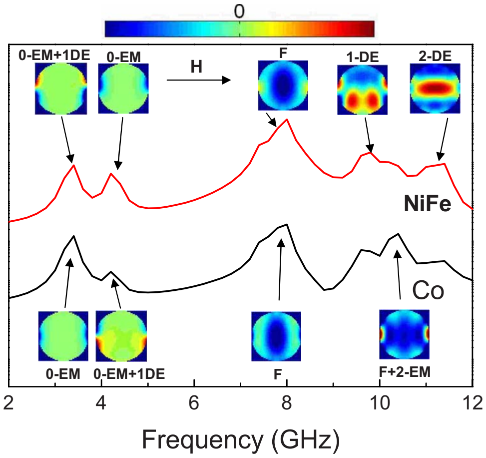

FIG. 3. (Color online) Calculated power spectra for the NiFe and Co disks for the $t_{Cu}=2.0$ nm sample in an external magnetic field of 0.8 kOe. The spatial profiles corresponding to some relevant eigenmodes are shown as insets. The external field direction relative to the spatial profiles is shown.

We preliminarily investigated by BLS the spin wave properties of the NiFe/Cu/Co reference samples (continuous layers) for different values of t_{Cu}. We found that in the whole Cu thickness range investigated, the Brillouin spectra consist of two spin wave modes associated to the in-phase (acoustic) and out-of-phase (optic) precessions of the spin in the NiFe and Co layers (Fig. 1, left panel). The presence of these two distinct modes enables us to rule out any partial contact between the NiFe and Co layers (pinholes) due to nonhomogeneity of the thin Cu spacer.

The measured frequencies for an applied external field of 0.8 kOe (saturating field) are plotted in Fig. 2 as a function of the Cu spacer thickness. We notice that the frequency of the lowest mode has little dependence on the Cu thickness, while that of the high frequency mode largely increases on reducing the Cu-layer thickness. We have reproduced the magnetic field dependence of these modes and also their dispersion (frequency versus transferred wave vector) by using the bilinear interlayer coupling as a unique adjustable parameter in the fitting procedure. As can be seen in the inset of Fig. 2, the coupling term J_1 is always positive (ferromagnetic coupling) in the whole range of Cu spacer thicknesses investigated and increases from 0.15×10^{-3} J/m^2 (for $t_{Cu}=2.0$ nm) to 22×10^{-3} J/m^2 (for $t_{Cu}=0.7$ nm). The BLS measurements performed on the NiFe/Cu/Co disks, with $t_{Cu}=0.7$, 1.2, and 2.0 nm, reveal the presence of two dispersionless peaks whose frequency values (7.6 and 9.5 GHz) are smaller than that of the acoustical mode in the unpatterned samples (Fig. 1, right panel).

To understand the profiles of such modes we performed micromagnetic simulations which solve the discretized Landau-Lifshitz-Gilbert equation in the time domain and calculate locally the Fourier transform.[3] The micromagnetic simulations were carried out for the multilayered stack with Cu thickness of 2.0 nm, only, because the smaller thickness values of the other Cu spacers require the use of a much smaller cell height that increases too much the calculation time. Looking at the simulated power spectra for the $t_{Cu}=2.0$ nm sample, shown in Fig. 3, we can see several peaks corresponding to different eigenmodes of the two magnetic disks. Spatial profiles corresponding to the most relevant eigenmodes are shown as insets in Fig. 3. Starting from lower frequencies one can see, for the NiFe layer, a mode localized near the edges and with no nodal planes (0-end mode), the fundamental mode (F), and a couple of Damon-Eshbach (DE) modes with one and two nodal planes parallel to the direction of the applied field, 1-DE and 2-DE, respectively. A sort of hybrid mode, which is neither a pure fundamental mode nor an end mode, labeled as F+2-EM, is found in the Co disk, in addition to the 0-EM and the F modes. The 1-DE and 2-DE modes of Co are at 14 and 17 GHz outside the frequency range explored here. At first look the two calculated power spectra are quite different and so are the frequencies of the corresponding eigenmodes in NiFe and Co disks. We note that for both the NiFe and Co layers, in correspondence with the 0-EM mode, there is an antisymmetric EM with vanishing value of the averaged dynamical magnetization in the other layer.

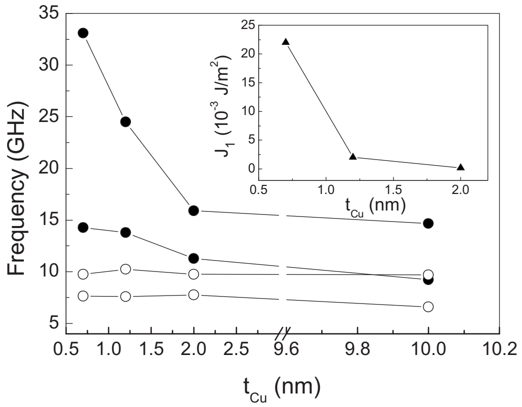

FIG. 2. Spin wave frequency measured by BLS in the unpatterned (full points) and patterned (open points) NiFe/Cu/Co samples for different values of the Cu spacer thickness. The applied field value is of 0.8 kOe. The data for $t_{Cu}=10$ nm taken from Ref. 3 are shown for comparison. The fitted values of the interlayer coupling constant values are reported in the inset (for $t_{Cu}=10$ nm the interlayer coupling constant is zero).

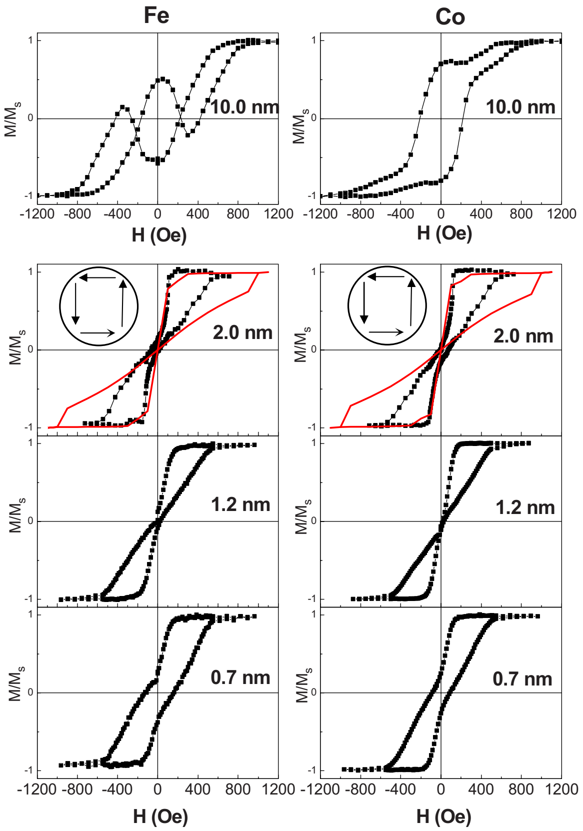

FIG. 4. (Color online) Normalized longitudinal hysteresis curves measured by XRMS for different thickness of the Cu spacer. XRMS data for Cu thickness of 10 nm, taken from Ref. 3, are shown in the first line. For the sample with Cu=2.0 nm the simulated magnetization curves are plotted (continuous curve).

Remarkably the only exception seems to be the fundamental mode, the most intense peak in both the power spectra, which is exactly at the same frequency, about 8.0 GHz, and shows the same profile both in NiFe and Co disks. We think that this is a direct evidence of the presence of a non-negligible interlayer exchange coupling in this system. As a matter of fact the same calculation done in the past on the system with a 10 nm thick spacer showed that the fundamental modes of NiFe and Co disks had different frequencies.[3] It is noteworthy that this fundamental eigenmode oscillates in-phase in the two disks (acoustical mode) with a frequency smaller than that measured in the unpatterned sample. This can be explained in terms of the demagnetizing field generated by the finite size of the disks.

In Fig. 4 we show the measured XRMS longitudinal hysteresis loops for both the NiFe and Co layers for different values of the Cu spacer thickness. The XRMS loops are almost identical for the NiFe and Co layers, indicating that both layers undergo the same magnetization reversal process due to the presence of an interlayer ferromagnetic coupling.

Our micromagnetic simulations for the disks with Cu $=2.0$ nm, shown in Fig. 4 as continuous curve, qualitatively well reproduce the shape of the measured loop but fail in reproducing the vortex annihilation field, which is overestimated by simulations mainly because the OOMMF calculations are performed at $T=0$ K. The value we used for the interlayer coupling constant is $J_1=0.21\times10^{-3}$ J/m^2 slightly larger than that obtained from BLS. Going into details of the magnetization reversal process micromagnetic simulations indicate that, starting from saturation and decreasing the external field value, the magnetization in the two disks evolves toward an "S" configuration followed by a sudden transition into a vortex state at zero field with the same chirality as in the two ferromagnetic layers, as reported in the insets of Fig. 4 showing the static micromagnetic configurations at remanence. When the field increases toward negative values the system keeps its vortex state until the core is finally expelled and the magnetization is aligned to the external field. It is important to note that, during the whole hysteresis loop, the magnetizations of the two disks remain parallel to each other because of the positive (ferromagnetic) interlayer exchange coupling term. We want to stress that the presence of this coupling term is crucial in order to correctly reproduce the measured hysteresis loops. In fact, if we set this coupling term to zero, the simulated loops completely change and they become very similar to those of the $t_{\mathrm{Cu}}=10$ nm sample,[3] which are also reported in Fig. 4, for the sake of comparison.[3] If the value of J_1, derived from the BLS investigation, is used in the micromagnetic simulations, the hysteresis loop does not reproduce the measured one because the vortex formation in the two layer occurs at negative applied field.

We notice that the shape of the XRMS loops changes appreciably upon decreasing the Cu spacer thickness, showing an increase in the loop remanence while the saturation field remains almost constant. Remarkably, the saturation field is smaller than that measured for the Cu spacer of 10 nm because in the latter case, a larger magnetic field is necessary to force the layer magnetization to be parallel against the dipolar interaction, which favors the antiparallel alignment.

In this work we have studied the magnetic properties of NiFe(10 nm)/Cu(t_{Cu})/Co(10 nm) trilayered disks for different values of the nonmagnetic Cu spacer in the range 0.7–2.0 nm. XRMS measurements accounted for the presence of a strong interlayer exchange coupling, and the analysis of BLS measurements allowed us to quantitatively determine the intensity of this coupling as it varies with the thickness of the nonmagnetic Cu spacer. Adding such an interlayer exchange coupling term into our micromagnetic simulations, we were able to satisfactorily reproduce both the shape of the measured hysteresis loops and the frequencies of the magnetic excitations of the system.

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