Ferromagnetic resonance and interlayer exchange coupling in magnetic multilayers with compositional gradients

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Ferromagnetic resonance (FMR) in magnetic multilayers of type F1/f/F2, where two strongly ferromagnetic layers F1 and F2 are separated by a weakly magnetic spacer f with a compositional gradient along its thickness, is investigated. The method allows to detect the weak signal from the spacer in additional to the more pronounced and readily measured signal from the outer strongly-magnetic layers, and thereby study the properties of the spacer as well as the interlayer exchange interaction it mediates. Variable temperature FMR measurements, especially near the relevant Curie points, reveal a rich set of properties of the exchange interactions in the system. The obtained results are useful for designing and optimizing nanostructures with thermally-controlled magnetic properties.

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I. INTRODUCTION

Magnetic multilayer structures of the spin-valve type F1/NM/F2, where two ferromagnetic (FM) layers F1 and F2 are separated by a nonmagnetic (NM) spacer, exhibit rich physics including spin-dependent scattering,2,4 interlayer exchange coupling,2,4 spin-torque effects,2,5 etc., to control the magnetic state in the nanostructure. The configuration used in magnetic resonance measurements and the layout of the multilayer system should be expected to also detect the key magnetic characteristics of specifically f* spacers, as well as the interlayer exchange properties they mediate.

The experiments described in Ref. 13 and 14 confirmed the concept of parallel-antiparallel switching in F1/f/F2 nanostructures, in particular incorporating Ni$_x$Cu$_{100-x}$ spacers enclosed by exchange-pinned Co$_{90}$Fe$_{10}$ and free Ni$_{80}$Fe$_{20}$ (Py) layers. A serious disadvantage of such structures is a relatively wide temperature range of the transitional state between the P and AP configurations. This mainly occurs due to the high nonuniformity of the effective interatomic exchange coupling and the magnetization distribution throughout the spacer thickness, especially in the proximity to the strongly ferromagnetic interfaces. The use of a gradient-type spacer f* = PM/weak FM/PM can greatly improve the effective-exchange uniformity and lead to a significantly narrower magnetic transition range, as was demonstrated in Ref. 11. Unfortunately, traditional measurement tools, such as magnetometry, are unable to probe and characterize the state of the f* spacer, which impedes the development of competitive CSs with reliably predictable properties. Ferromagnetic resonance (FMR), which was particularly useful for characterization of CS structures with uniform spacers, should be expected to also detect the key magnetic characteristics of specifically f* spacers, as well as the interlayer exchange properties they mediate.

In this work we study FMR in CS-multilayers containing gradient spacers. We directly detect the magnetic response from the spacer and conduct variable temperature studies of the interlayer exchange in the system near the spacer’s Curie point.

II. SAMPLES AND MEASUREMENTS

The configuration used in magnetic resonance measurements and the layout of the multilayer system...
F1/f/F2/AFM, where AFM is the pinning antiferromagnetic layer, are illustrated in Fig. 1. Thin-film magnetic multilayers Py(6 nm)/f(14 nm)/Py(2 nm)/Co90Fe10(2 nm)/Ir20Mn50(12 nm) (hereafter – F1/f/F2/AFM system) were deposited at room temperature on thermally oxidized silicon substrates using magnetron sputtering in an AJA Orion 8-target system (details of the fabrication are described in Ref. 11 and 13). The exchange pinning between the Py(2 nm)/CoFe(2 nm) bilayer and Ir20Mn50(12 nm) was set in during the deposition of the multilayers using an in-plane magnetic field $H_{dep}$ $\approx$ 1 kOe. Three samples in the series studied here, labelled S-gr, S-fm and S-pm, have different spacer compositions. The S-gr sample has a gradient-type PM/weak FM/PM spacer: $f^* =$ Ni50Cu50(4 nm)/Ni72Cu28(6 nm)/Ni50Cu50(4 nm). The S-fm and S-pm samples have uniform spacers $f =$ Ni72Cu28(14 nm) and $f =$ Ni56Cu44(14 nm), respectively. Diluted alloys Ni72Cu28 and Ni56Cu44 in the bulk form are, respectively, ferromagnetic and paramagnetic in the temperature interval of measurements used in this work, $T = 120$–$380$ K.

The FMR measurements were performed using an X-band Bruker ELEXSYS E500 spectrometer equipped with an automatic goniometer. The operating frequency was $f = 9.46$ GHz. In-plane FMR spectra were obtained with the external magnetic field applied $H$ parallel (P) and antiparallel (AP) to the AFM pinning direction (Fig. 1) at $T = 120$–$380$ K.

III. RESULTS AND DISCUSSION

A. Experimental FMR spectra

Fig. 2 shows typical FMR spectra measured at different temperatures for the P and AP orientations of field $H$. The signal of the highest intensity in all panels originates from the free layer, Py(6 nm). For the S-gr sample, at higher temperatures, the position of this signal is weakly dependent on the orientation of the magnetic field, while at lower temperatures the dependence becomes noticeable (Fig. 2a). In addition to the Py resonance line, the spectra for S-gr contain the line (labeled sf), with the resonance field close to 2 kOe, which is not observed in the spectra for the S-pm or S-fm samples. The intensity of the sf signal is highly dependent on temperature: it decreases with the increase in $T$ and vanishes as $T$ exceeds 320 K. The P and AP resonance fields of the sf signal are different at lower temperatures, but the lines approach each other and eventually merge as temperature increases. At the same time, their average position is shifted to higher fields compared to the signal from Py, which means that the effective magnetization of this component is lower than that of Py. Since bulk Ni72Cu28 alloy has lower magnetization than Py, the sf signal can be ascribed to the Ni72Cu28(6 nm) layer in the gradient spacer PM/weak FM/PM. The Curie temperature of bulk Ni72Cu28 is relatively low ($\approx 330$ K), which explains the strong temperature variation of the sf resonance field in the studied temperature region.

The highly intensive resonance line from the free layer F1 in the S-fm sample (Fig. 2b) has different resonance fields for the P and AP measurement configurations ($H_{r1}^P$ and $H_{r1}^{AP}$) in the whole temperature range. The nonzero difference ($H_{r1}^{AP} - H_{r1}^P$) indicates that the exchange pinning field from AFM, which acts on the F2 layer, transmits to the F1 layer due to a relatively strong interlayer coupling in the S-fm stack. At higher temperatures, an additional low-field signal is observed, but only for the AP orientation of the magnetic field. This signal should be assigned to the pinned F2 layer, as detailed in Ref. 14. The fact that this signal is almost indistinguishable in the AP spectra for the S-pm and S-gr samples needs additional investigation.

The same position of the P and AP resonance lines for the S-pm sample (Fig. 2c) means that the F1 and F2 layers are fully decoupled, which is the case at all measurement temperatures.

B. Analysis of experimental data and discussion

In our earlier FMR studies, a phenomenological theory was developed for modelling the dynamics of CS-systems containing compositionally uniform spacers. Based on this theory, a comprehensive quantitative analysis of the experimental FMR results for CSs with spacers of different alloy dilution and thickness was performed, and the key magnetic parameters were determined. In this work, we will show that the same theoretical approach forms a reliable basis for understanding the temperature-dependent behavior of the resonance parameters for multilayers with gradient spacers (such as S-gr).

Fig. 3(a) presents the temperature dependences of the resonance-field difference indicative of the exchange through the spacer, $\Delta H_{r1} = H_{r1}^{AP} - H_{r1}^P$, where $H_{r1}^P$, $H_{r1}^{AP}$ are the resonance fields for the F1 layer (in our case Py) with the external field applied parallel and antiparallel to the AF pinning direction, respectively. According to eq. (14) in Ref. 14, $\Delta H_{r1} \sim \kappa^2 \cdot H_0$, where $\kappa$ is the constant of interlayer coupling, which depends on the magnetizations and thicknesses of the F1 and F2 layers and also includes the effective magnetization ($m$) and magnetic exchange length ($\Lambda$) of the weakly ferromagnetic spacer; $H_0$ is the effective biasing field acting on magnetization M2 of the F2 layer and is the measure of AFM pinning. Thus, for a constant $H_0$, $\Delta H_{r1}$ reflects the strength of the interlayer coupling between strongly FM layers through the weakly FM spacer.

In our case, $\Delta H_{r1}$ is relatively high for S-fm (F1 and F2 are fully coupled) and zero for S-pm (F1 and F2 fully decoupled) in the whole temperature range, which is in agreement with the expected behavior. The decrease of both $\Delta H_{r1}$ and $\Delta H_{r2}^P$ for the S-gr sample with increasing
FIG. 1. Configuration used in magnetic resonance measurements (left panel) and layout of multilayers studied (right panel).

FIG. 2. Typical FMR spectra measured with the external magnetic field applied parallel (P) and antiparallel (AP) to the direction of the exchange pinning for (a) S-gs, (b) S-fm, and (c) S-pm samples. Panel (a) shows only the sf resonance signal for temperatures between 120 and 320 K.

temperature implies that the interlayer coupling, being significant at low temperatures, weakens as the temperature increases.

The nontrivial effect that should be pointed out is the increase of $\Delta H_{r1}$ observed in the S-fm sample as temperature is increased (Fig. 2(a)). When the interlayer exchange coupling between F1 and F2 is weak, the temperature behavior of $\Delta H_{r1}$ is mainly governed by $\kappa^2 \sim m^4$. As temperature increases, $m$ decreases, which should lead to a decrease in $\Delta H_{r1}$. However, when the interlayer coupling is sufficiently strong, the assumption of a constant $H_b$ becomes invalid. In this case, the F1/F2 stack behaves like a single magnetic layer, and the effective biasing field from AFM acts on the whole F1/F2/F2 structure, rather than only on F2. When the interlayer coupling between F1 and F2 becomes weaker, the action of the biasing field becomes localized to F2. As a result, the biasing effect becomes stronger and $\Delta H_{r1}$ increases. It is this situation that is believed to manifest in the S-fm sample as temperature is increased.

The resonance signal from the weakly FM spacer was undetectable in our earlier studies on CS-structures having spacers of uniform composition. A possible reason for this is a strong influence of the adjacent FM layers on the magnetic state of the spacer. The gradient-type spacer studied herein suppresses the ferromagnetic proximity effect at the interface with the strongly ferromagnetic layers, and its core is therefore much more uniform magnetically, with presumably a much better defined FMR. This should make it easier to detect the signal...
the interlayer exchange. The strong interlayer coupling inherent to S-gr can not be defined by only one dominant mechanism: strong changes with temperature are at play.

Finally, the sp signal from the pinned F2 layer is distinguishable only in the AP spectra for S-fm at higher temperatures (Fig. 2(b) and Fig. 3(b)). Due to the strong AFM pinning, F2 must have negative resonance field for the P orientation, which is not observable. It is interesting that this signal has a significantly reduced intensity in the spectra for the S-gr and S-pm samples.

**IV. SUMMARY**

FMR spectroscopy and its theoretical analysis provide an excellent tool for describing the magnetism in multilayers of F1/f/F2 type, and determining the key magnetic parameters of the nanostructure as a whole and the Curie-spacer in particular. F1/f/F2 multilayers with gradient-type spacers exhibit clear peaks due to the FMR in the spacer, which are used to characterize this critical layer in terms of its magnetization and the exchange coupling it mediates between the outer ferromagnetic layers.

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