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Precessional dynamics and damping in Co/Cu/Py spin valves

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We have studied the precessional dynamics of Co/Cu/Py (where Py = $Ni_{81}Fe_{19}$) trilayers by time-resolved x-ray resonant magnetic scattering at the synchrotron radiation facility BESSY II. We have found that the magnetic precessional decay time of Fe magnetic moments in Py layers decreases when changing the mutual orientation of the magnetization direction of Py and Co layers from parallel to antiparallel. The observed changes of the decay time can be associated with the spin pumping induced damping effect. © *2011 American Institute of Physics*. [doi:10.1063/1.3633115]

A simple realization of giant magnetoresistance devices is by F_s/N/F_h spin valve trilayers, where F_s is a "soft" ferromagnetic film with a magnetization direction that can be changed easily in an external field, whereas F_h is a "hard" magnetic layer whose magnetization reversal requires a distinctively higher field. Here, N designates a nonmagnetic spacer layer. The key parameter describing the reorientation of F_s is the magnetization reversal time (or the magnetic relaxation time) because this parameter determines the speed of magnetic recording. In order to tune the magnetization dynamics, one needs to understand the mechanisms which control the relaxation processes in these systems. The magnetic relaxation time is usually described by its inverse value, the so-called damping parameter. It has been shown (e.g., reviews (Refs. 1 and 2)) that an interface damping in F/N multilayers may be caused by pumping of spin current from a ferromagnetic layer into an adjacent layer. The spin current is generated by precessing magnetic moments in the F layer at the F/N interface, which creates an accumulated dynamical magnetic moment density in N. As a result, it may lead to a spin-pumping-induced damping which, in turn, can transfer the magnetization from one to another F layer in the F_s/N/F_h trilayers.

We have studied the spin pumping effect in Co/Cu/Py (where Py = $Ni_{81}Fe_{19}$) spin valve systems with different thicknesses of the Cu-spacer layer. Using time-resolved x-ray resonant magnetic scattering (TR-XRMS) at the synchrotron radiation facility BESSY II of the Helmholtz Zentrum in Berlin (ALICE station[3]), the element specific free precessional decay of the magnetization vector can be analyzed in response to a field pulse excitation H_p (in the scattering plane). Fast rise-time magnetic field pulses (pump) are synchronized with a variable delay with respect to the x-ray single photon bunches (probe) from the storage ring (for details see Refs. 4–6). Time delay scans are measured using an external bias magnetic field $H_B = 11$ Oe-35 Oe applied along the easy axis of the F layers (perpendicular on the scattering plane). Free precessional frequency of Fe magnetic moments in permalloy layers at the maximum bias field $H_B \sim 35$ Oe does not exceed 1.5 GHz. Therefore, the delay step was chosen equal to 100 ps, that is 2 times higher than the experimental resolution limit.

The studied trilayers were deposited at room temperature on 10×10 mm sapphire (Al_2O_3) A-plane substrates by magnetron sputter deposition at a base pressure of 3×10^{-8} mbar. Magnetic anisotropy was induced using a static magnetic field of 1000 Oe applied along the substrate C-axis [0001], creating an effective uniaxial magnetic anisotropy of the Py layers in the film plane. A 5 nm thick Pt seed layer was deposited prior to sputtering a 65 nm thick Cu conductive layer, which generates a pulsed Oersted field H_p when applying a current pulse. The thick Cu layer is followed by Co/Cu/Py trilayers with 25 and 40 nm thick Cu spacer layers. For both samples, the thicknesses of the Co and Py layers were 10 and 25 nm, respectively. All samples were capped by 5 nm Al_2O_3 to prevent oxidation. Then in a lithography step, a 350 μm wide stripe was prepared, where a short current pulse is converted into the field pulse excitation perpendicular to the stripe (and current) direction. Stripe shaped samples were fabricated *via* electron-beam lithography and subsequently etched by ion-milling. For lithography, we used a FEI QUANTA 200 FEG scanning electron microscope which allows to write stripes into the negative resist in any direction with high accuracy. For the present samples, stripes were fabricated along the [0001] substrate axis which was parallel to the direction of applied magnetic field during film deposition, such that the magnetic easy axis of Py layers is parallel to the stripe axis. The head and tail ends of the stripes were etched down to the Cu bottom layer for providing electrical contacts.

Magnetic hysteresis loops of the Co/Cu(40 nm)/Py sample measured by superconducting quantum interference device (SQUID) magnetometry are presented in Fig. 1(a). The spin valve character of the hysteresis is clearly visible with extended plateaus where the magnetization vectors in the adjacent F layers are antiparallel (AP), in contrast to parallel (P) alignments in saturation.

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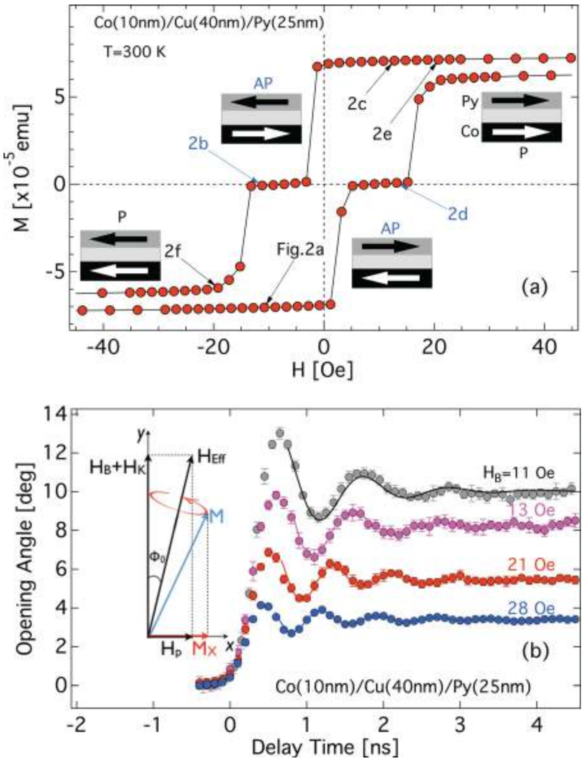

FIG. 1. (Color online) (a) Hysteresis loop of the Co/Cu(40 nm)/Py sample, measured by SQUID magnetometry. Arrows indicate the position on the hysteresis loop, where delay scans were measured (see Fig. 2). (b) Time-domain magnetization dynamics of Py layer in Co/Cu(40 nm)/Py in the P state for different values of the bias fields. Solid lines represent the fits of data using the damped sinusoidal function described in the text.

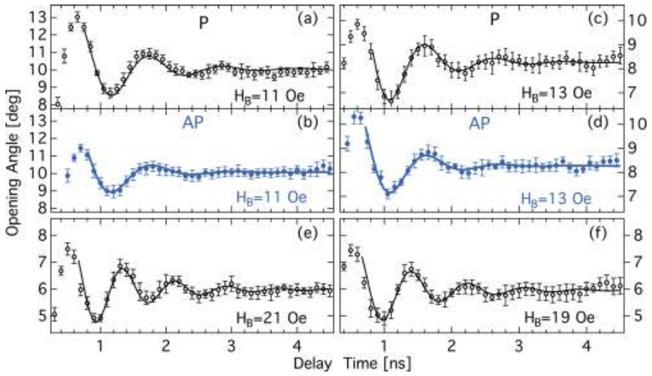

FIG. 2. (Color online) Comparison of the magnetization dynamics of Py layer in the Co/Cu(40 nm)/Py sample measured for the parallel (black open circles) (a), (c) and antiparallel (blue closed circles) (b), (d) mutual orientations of Co and Py magnetization and for two different values of the bias field (see corresponding arrows in Fig. 1(a)). (e) and (f) represent delay scans for the P state with different signs of the magnetization direction (positive (e) and negative (f), see corresponding arrows in Fig. 1(a)). Solid lines represent the fits.

In Fig. 1(b), we present the results on the magnetization precession of the Fe magnetic moments within the Py layer of the Co/Cu(40 nm)/Py sample for different H_B in the P state. The photon energy was set to the Fe L_3—resonance edge (708 eV). It has been shown that measuring at the Fe resonance edge is sufficient to describe the magnetization dynamics of Py completely, as Fe and Ni moments are aligned parallel on the timescales of our experiment.[4–6] The damped oscillations are the response to a step-like excitation H_p converted into time dependent opening angles $\psi(t)$ of Fe magnetic moments in Py (see inset in Fig. 1(b)) plotted as a function of delay time. The opening angles are calibrated *via* hysteresis loops by sweeping the transverse bias field (for details see Refs. 4–6).

The damped precessional oscillations are clearly seen in Fig. 1(b). The amplitude of the opening angle decreases from 10° to 3° with increasing H_B from 11 to 28 Oe. The solid lines in Fig. 1(b) are fit to the data points using the solution of the Landau-Lifshitz (LL) equation for our experimental conditions.[7] After the quasi step excitation, this solution is given by

$$\psi(t) = \psi_0 + \beta_0 \exp(-t\lambda/2)\sin(\omega_p t + \phi), \tag{1}$$

where ψ_0 is a steady-state equilibrium magnetization angle, λ is the step damping constant, and $f_p = \omega_p/2\pi$ is a precessional frequency. The fitting parameters β_0 and ϕ were introduced to take into account the presence of a finite rise time of H_p.[7] From the fit, we obtain that with increasing H_B the frequency f_p increases from 0.9 GHz to 1.35 GHz and the LL damping parameter $\lambda/4\pi$ slightly changes from 172 ± 20 MHz to 205 ± 20 MHz. Qualitatively, the precessional dynamics of the Py layer in the P state of the spin valve is in very good agreement with the dynamics observed for single Py films.[6]

For the photon energy corresponding to the Co L_3 edge (778 eV), we also obtain a pulse step response but without noticeable oscillations from coherent precession of the Co magnetic moments. We suppose that this incoherence may be caused by crystalline anisotropy fields, which vary randomly in direction within a polycrystalline Co layer leading to the formation of domains ripples.[8]

Next we discuss TR-XRMS scans for P and AP orientations of the magnetization vectors in the Co and Py layers by approaching the same bias field value on the ascending and descending branches of the hysteresis loop. The respective field values are indicated by arrows in Fig. 1(a). In Figs. 2(a) and 2(b), we plot the magnetization precession of Fe in the Py layer for P (black open circles) and AP (blue closed circles) orientations in the Co/Cu(40 nm)/Py sample and for a bias field $H_B = 11$ Oe. In Figs. 2(c) and 2(d), the corresponding precession is shown for a bias field of $H_B = 13$ Oe. In both cases, a decrease of the precessional relaxation time in the Py-layers upon transition from the P to AP state is clearly seen. From the fits, we derive a noticeable increase in the LL damping parameter $\lambda/4\pi$ from 190 ± 20 MHz for the P orientation to about 270 ± 30 MHz for the AP orientation. The damping parameters are essentially identical for both samples with different Cu spacer layer thicknesses.

In Figs. 2(e) and 2(f), delay scans for the P state with different signs of the magnetization direction are presented (positive (e) and negative (f)). For both cases, the values of the damping parameter are the same and equal to 190 ± 20 MHz. Since the magnetization in the Co layer reverses the direction from AP to P orientation in respect to the magnetization direction in the Py layer (see Fig. 2(f) and hysteresis loop in Fig. 1(a)), the damping parameter decreases back to the value as it was before at positive fields (Figs. 2(e) and 1(a)). This fact proves that the observed precessional damping of the Fe magnetic moments in Py is indeed intimately connected with the mutual orientation of the magnetic moments in the Co and Py layers and independent of their absolute orientation.

The main result of the present study is the decrease of the magnetic precessional decay time for Fe moments in Py layers when changing the mutual orientation of the magnetization vector of the Py and Co layers from P to AP. For Cu-spacer thicknesses of 25 and 40 nm, the interlayer exchange coupling of the magnetic layers in the trilayers can be neglected.[9] At the same time these thicknesses are below the spin diffusion length of the conduction electrons in Cu (300 nm at room temperature[10]). Therefore, the increase of damping of the Fe magnetic moments in Py for the AP orientation of Co and Py magnetic layers can be associated with the spin-pumping effect. Preliminary results of ferromagnetic resonance measurements in our samples confirm that Co and Py layers are dynamically coupled. The positions of the resonance lines attributed to the Co and Py layers move towards each other when decreasing the temperature (down to 20 K). Bearing in mind that with decreasing temperature, the diffusion coefficient of the conduction electrons of the Cu spacer layer increases, we conclude that coupling of the Co and Py layers occurs due to the spin-pumping. Note that with decreasing temperature down to 20 K, the change of the saturation magnetization value of the Co and Py magnetic layers is negligibly small so that the dipolar coupling *via* stray fields most likely is not responsible for an increased coupling between ferromagnetic layers at low temperature.

In our spin valves, the Co layer acts as a sink[11] for transverse spin current pumped by the Py layer through the Cu spacer. Thus the Co layer opens an additional relaxation channel for the magnetization precession of the Py-layer. The orientational dependence of the damping in the spin valves due to spin pumping was investigated theoretically by Kim and Chappert.[12] They show that for the AP case, the damping parameter can be higher than that for the P case.

For completeness, we also discuss here the effect that the magnetization reversal of the Co layer has on the precessional dynamics. As magnetic moments in the Co layer reverse their direction along the descending branch from P configuration in positive field to P configuration in negative field, the free precessional oscillation of the Py magnetic moments remains essentially the same (see Figs. 2(e) and 2(f) and hysteresis loop in Fig. 1(a)). This fact implies that possible stray field inhomogeneities that may emanate from the Co layer do not affect strongly the spin dynamics in the Py layer. As stray fields have no affect on the precessional dynamics in the P state, it is proper to conclude that they also have no effect on the dynamics in the AP state.

In conclusion, we measured the free and damped precessional dynamics via element specific TR-XRMS in Co/Cu/Py trilayers with spin valve magnetic hysteresis characteristics and with different thicknesses of the Cu-spacer layers (25 and 40 nm). For both samples, we observe a noticeable increase of the Landau-Lifshitz damping parameter with changing magnetization direction of Py and Co layers from the parallel to the antiparallel state. Our experiments provide evidence that the dominating mechanism responsible for this change is the spin-pumping effect, where the Co layer may act as a spin sink for transverse spin current pumped by the precessing Py layer through the Cu spacer.

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