Interface-related damping in polycrystalline Ni$_{81}$Fe$_{19}$/Cu/Co$_{93}$Zr$_7$ trilayers

S. Zohar and W. E. Bailey

Department of Applied Physics and Applied Mathematics and Materials Science and Engineering, Columbia University, 500 W 120th Street, New York, New York 10027, USA

(Presented 13 November 2008; received 23 September 2008; accepted 17 November 2008; published online 24 February 2009)

We have searched for a signature of nonlocal magnetization dynamics or magnetization dynamics driven by pure spin currents, in magnetically soft polycrystalline Ni$_{81}$Fe$_{19}$/Cu/Co$_{93}$Zr$_7$ trilayers using ferromagnetic resonance. An interface-related enhancement of damping is expected for each ferromagnetic layer when incorporated in a trilayer; the enhancement should be absent where layer resonances overlap. While size effects in Gilbert damping have been identified, we note that expectations specific to spin pumping are not confirmed. © 2009 American Institute of Physics. [DOI: 10.1063/1.3072030]

“Spin pumping,” the generation of pure spin currents through magnetization precession, is a new idea in magnetization dynamics. In the proposed mechanism, magnetization precession at the broken symmetry of a ferromagnetic/noble metal (FM/NM) interface creates a source for pure spin current ejected into the NM layer. The associated loss of angular momentum in the FM layer manifests itself through an enhanced relaxation rate (damping) acting at the interface.

Spin pumping has been identified in three different forms of interface-related damping in ferromagnetic heterostructures. In all cases, the enhanced damping is predicted to be Gilbert type ($\Delta H \propto \omega$) and inversely dependent on FM layer thickness ($\Delta H \propto 1/t_{FM}$). First, in structures with a single FM layer, enhanced damping has been attributed to the propagation of spin currents into “spin sink” layers, typically Pt or Pd, which can be in direct contact with the FM layer or removed through a NM layer. Second, in structures with multiple ferromagnetic layers, such as “spin-valve” type FM$_1$/NM/FM$_2$ trilayers, spin current generated at one layer is thought to be absorbed at the opposite layer. For a single layer undergoing ferromagnetic resonance (FMR) precession, this enhances its damping while exerting a small influence on the motion of the opposite layer. Finally, where the two layers have nearly equal FMR frequencies, a third hallmark is that the motion tends to “lock” in phase and the enhanced damping vanishes.

Magnetization dynamics resulting from spin pumping can be described through additional terms in the Landau-Lifshitz Gilbert equation (LLG) (Ref. 7). For FM$_1$/NM/FM$_2$ heterostructures, the LLG equation is modified as

$$\mathbf{m}_1 = -\gamma [\mathbf{m}_1 \times h_{eff} + \alpha_1 \mathbf{m}_1 \times m_1 \alpha'_1 (\mathbf{m}_1 \times \mathbf{m}_2) \times \mathbf{m}_2],$$

where the first two terms describe precession and relaxation in the absence of spin pumping, and $\alpha'_1$ is the spin-pumping damping parameter described by

$$G' = \alpha' \gamma M_S = \frac{g_1^2 \mu_B^2}{2\hbar} \left( \frac{g_1}{S} \right) \frac{1}{d}.$$

in cgs units; $G'$ is an additional Gilbert relaxation rate, $\gamma$ is the gyromagnetic ratio, $M_S$ is the saturation magnetization, $g_1$ is the Lande-$g$ factor, $\mu_B$ is the Bohr magneton, $\mathbf{m}$ is the magnetization divided by the saturation magnetization, and $\hbar$ is Planck's constant. The prefactor evaluates to 28.35 MHz nm$^3$ for the typical case of $g_1=2.09$. The parameter $g_1/S$ is the effective mixing conductance per interfacial area; $d$ is the FM layer thickness. When the FM$_1$ layer is precessing and the FM$_2$ layer is stationary ($m_2=0$), the FM$_1$ layer is subjected to an additional damping of $\alpha'_1$. When both FM layers are precessing, the motion is coupled and is treated by solving Eq. (1) for both layers simultaneously; if the motions of $\mathbf{m}_1$ and $\mathbf{m}_2$ are equal, the $\alpha'_1$ goes to zero.

In prior studies, damping from spin sink overlayers has been identified primarily in studies of polycrystalline films, particularly, in Ni$_{81}$Fe$_{19}$. Damping in spin-valve systems, on the other hand, has been identified exclusively in epitaxial Fe/Au/Fe on GaAs. It has not yet been shown that polycrystalline spin valves (trilayer structures) exhibit any additional interface-related damping when compared with similar FM layer structures of comparable size.

In this study, we investigate polycrystalline spin valves for the same hallmarks of spin pumping observed in epitaxial spin valves. Four series [(a)–(d)] of samples were deposited for the study. The first two series [(a) and (b)] compare interface-related damping of Ni$_{81}$Fe$_{19}$ layers in single films and spin valves: for (a), Ni$_{81}$Fe$_{19}(5\,\text{nm})$/Cu(3\,\text{nm}) and for (b), Ni$_{81}$Fe$_{19}(d)$/Cu(5\,\text{nm})/Co$_{93}$Zr$_7$(5\,\text{nm})/Cu(3\,\text{nm}). The second two series [(c) and (d)] compare interface-related damping of Co$_{93}$Zr$_7$ layers in single films and spin valves: for (c), Cu(5\,\text{nm})/Co$_{93}$Zr$_7$(d)/Cu(3\,\text{nm}) and for (d), Ni$_{81}$Fe$_{19}(5\,\text{nm})$/Cu(5\,\text{nm})/Co$_{93}$Zr$_7$(d)/Cu(3\,\text{nm}).

All layers were deposited by UHV magnetron sputtering, at a base pressure of $3 \times 10^{-9}$ Torr onto thermally oxidized Si substrates. Pressures immediately prior to deposition were typically $3 \times 10^{-8}$ Torr; Argon gas pressures were $3.9 \times 10^{-2}$ Torr during sputtering. Deposition rates were calculated using a quartz crystal balance, which could be positioned removably at the substrate location. Deposition rates were measured as $-6$ Å/s for Ni$_{81}$Fe$_{19}$, $-3$ Å/s for Co$_{93}$Zr$_7$, and $-4$ Å/s for Cu, with sputtering powers in the range of 250–300 W for Ni$_{81}$Fe$_{19}$ and Co$_{93}$Zr$_7$ and 100 W for Cu.
The Argon pressure has been elevated by $\sim 30$--$50\%$ above typical sputtering pressure in these depositions to enhance uniaxial anisotropy of the films. Orthogonal induced anisotropies are formed in the Ni$_{81}$Fe$_{19}$ and Co$_{93}$Zr$_7$ films of $\sim 20$ Oe and $\sim 50$ Oe, respectively, roughly along the direction of the deposition flux in the confocal sputtering geometry. This orthogonal induced anisotropy was used to engineer a crossing of the field dependent FMR frequencies $\omega(H)$ between 3.0 and 4.5 GHz, in order to search for the "third" hallmark of spin pumping.

Magnetic properties of the films were investigated by broadband FMR. We measure in-plane (parallel condition) field-swept FMR over a frequency range of 1--18 GHz using a coplanar wave guide to excite rf fields. We fit the the single layer FMR line shapes with a dispersion-corrected Lorentzian to extract resonant fields $H_{\text{res}}$ and full width half power linewidths $\Delta H_{1/2}$. In the vicinity of the FMR frequency crossing, the FMR line shapes are fit to the sum of two dispersion corrected Lorentzians. When this method does not converge, we fit the data with a single Lorentzian. Gilbert damping constants for each thickness are extracted using variable-frequency FMR linewidth, as $\Delta H_{1/2} = \Delta H_0 + 2 \alpha \omega / \gamma$. Effective $4 \pi M_s$ values $g_\perp$ and anisotropy fields $H_K$ were fitting using the Kittel equation $\omega^2 = \gamma^2 (H + H_K + 4 \pi M_s) (H + H_K)$ valid along the easy and hard axes.

The variable frequency FMR linewidth data for the four series of samples are presented in Fig. 1. The linewidths found are linear in the frequency in all cases with a small inhomogenous component $\Delta H_0 < 20$ Oe. There is an evident thickness dependence of the slopes in series (b), (c), and (d). The extracted thickness dependence of $\alpha$ is much stronger in series (b) compared with series (a), where we have added the effect of the Cu/Co$_9$Zr$_7$ interface on the Ni$_{81}$Fe$_{19}$ damping. However, in comparing series (c) and (d), we note that the primary effect of adding the Cu/Ni$_{81}$Fe$_{19}$ interface on the Co$_9$Zr$_7$ layer damping is to reduce the size effect in damping. While the behavior of Ni$_{81}$Fe$_{19}$ damping is qualitatively consistent with additional damping from the opposite Cu/Co$_9$Zr$_7$ interface, the behavior of the Co$_9$Zr$_7$ damping cannot be interpreted in this way.

A more quantitative description of the interface-related damping is presented in Fig. 2. Here we plot $(\alpha - \alpha_0) f / f_0$ as a function of thickness $d$ after $^2$ where $\alpha_0$ is the bulk damping, $f$ is the thickness dependent atomic magnetization in $\mu_B$/atom, and $f_0$ is the corresponding value for bulk films. $(f$ and $4 \pi M_s$ are related to good accuracy by $1 \mu_B$/atom $\sim 10$ kG.) This form takes into account the increased effectiveness of the torque from pumped spin current on a layer with reduced magnetic moment, as described in Eq. (2). Bulk saturation magnetization values $M_s$ were found to be 10.5 and 16.7 kOe for Ni$_{81}$Fe$_{19}$ and Co$_{93}$Zr$_7$, respectively, which are in good agreement with previously reported bulk values. $^9$ $^11$ Bulk damping values $\alpha_0$ were taken as 0.0067 and 0.007 for Ni$_{81}$Fe$_{19}$ and Co$_{93}$Zr$_7$, respectively, which are in good agreement with bulk values in other investigations. $^9$ $^11$ We find the interface-related damping for the Ni$_{81}$Fe$_{19}$ to be $\alpha' = 0.014$ nm/d in the single layer and $\alpha' = 0.036$ nm/d in the spin valve for an additional contribution due to the second FM layer of 0.022 nm/d. The damping enhancement for the Co$_9$Zr$_7$ single layer and Co$_9$Zr$_7$ spin valve are found to be $\alpha' = 0.036$ nm/d and $\alpha' = 0.008$ nm/d, respectively. In this case, any additional damping arising from the second FM layer could be zero, negative, or masked by some other dominant effect.

Our experimental data are plotted together with Pt/Ni$_{81}$Fe$_{19}(d)/$Pt data recorded by Mizukami et al. $^2$ which are divided by two to reflect the effect of a single interface, and which have been interpreted previously with a $g^{1/2}/S$ = 25.8 nm$^{-2}$. $^1$ The effect of spin pumping in the Pt spin sink is inferred to be roughly twice as large as any which might be present in the Ni$_{81}$Fe$_{19}$ layers considered here. Note, however, that an interface-related damping of comparable magnitude (0.036 nm/d) is seen in the single Co$_9$Zr$_7$ layer; here no obvious spin sinks are present.

Selected spin valves from series (b) were rotated by 90° aligning Ni$_{81}$Fe$_{19}$ along its easy axis ($H_K \sim 20$ Oe) and Co$_9$Zr$_7$ along its hard axis ($H_K \sim 50$ Oe) with respect to the applied field. Because of the larger moment of the
Co$_{93}$Zr$_7$ estimated from $\omega(H)$ at $4\pi M_S = 16.7$ kG ($g_L = 2.15$) compared with $4\pi M_S = 10.5$ kG ($g_L = 2.09$) for the Ni$_{81}$Fe$_{19}$, the slope of $\omega(H)$ is expected to be higher for the Co$_{93}$Zr$_7$ than for the Ni$_{81}$Fe$_{19}$ resonance, and the resonance lines will cross between 3.0 and 4.5 GHz, as shown Fig. 4. Ferromagnetic resonance was characterized at small frequency intervals ($\sim$48 MHz) over the range of 2.5–5.5 GHz. Representative line shapes are shown in Fig. 3. For 3.016 GHz, one can see the Co$_{93}$Zr$_7$ line shape at low field and that for Ni$_{81}$Fe$_{19}$ at high field; for 5.432 GHz, the resonance positions are reversed, with Ni$_{81}$Fe$_{19}$ at high field and Co$_{93}$Zr$_7$ at low field. In the range of 4–4.2 GHz, the modes appear as a single FMR absorption.

In Fig. 4, we show the field for resonance and linewidths ($\Delta H_{1/2}$) for the two fitted lines. For each trilayer, the resonance associated with Cu/Co$_{93}$Zr$_7$ increases more rapidly than that for Ni$_{81}$Fe$_{19}$ and crosses the zero frequency axis at higher $g_L$ values. While Gilbert type “interface-related” (inverse thickness dependent) damping is clearly seen, the dominant contribution is not clearly related to the addition of a second FM layer, particularly, in the Co$_{93}$Zr$_7$ damping, and does not diminish when the FMR of both layers is excited simultaneously. Thus two important hallmarks of spin pumping are not identified here.

Finally we remark that it is not clear at the time of writing how general the present result may be to polycrystalline trilayers. We cannot rule out at present that some nonideality of the structure prevents the propagation of spin currents in our films alone or perhaps in the use of the Co$_{93}$Zr$_7$ alloy. We note that robust giant magnetoresistive signals have been observed for Cu/Co$_{93}$Zr$_7$ spin valves in other reports.

We acknowledge the National Science Foundation under Grant No. ECCS-06-22038 and the Army Research Office under Grant No. DAAD19-01-0326 for support.