Magnetization damping in polycrystalline Co ultra-thin films: Evidence for non-local effects

J-M. L. Beaujour, J. H. Lee, A. D. Kent
Department of Physics, New York University, 4 Washington Place, New York, NY 10003, USA
(Dated: February 9, 2006)

The magnetic properties and magnetization dynamics of polycrystalline ultra-thin Co layers were investigated using a broadband ferromagnetic resonance (FMR) technique at room temperature. A variable thickness (1 nm ≤ t ≤ 10 nm) Co layer is sandwiched between 10 nm thick Cu layers (10 nm Cu|t Co|10 nm Cu), while materials in contact with the Cu outer interfaces are varied to determine their influence on the magnetization damping. The resonance field and the linewidth were studied for in-plane magnetic fields in field swept experiments at a fixed frequency, from 4 to 25 GHz. The Co layers have a lower magnetization density than the bulk, and an interface contribution to the magnetic anisotropy normal to the film plane. The Gilbert damping, as determined from the frequency dependence of the linewidth, increases with decreasing Co layer thickness for films with outer Pt layers. This enhancement is not observed in structures without Pt layers. The result can be understood in terms of a non-local contribution to the damping due to spin pumping from Co through the Cu layer and spin relaxation in Pt layers. Pt layers just 1.5 nm thick are found to be sufficient to enhance the damping and thus act as efficient “spin-sinks.” In structures with Pt outer layers, this non-local contribution to the damping becomes predominant when the Co layer is thinner than 4 nm.

PACS numbers:

I. INTRODUCTION

The magnetization dynamics of ultra-thin magnetic layers (<10 nm) is of great scientific and technological interest, as such layers are widely used in spin-injection and transport studies as well as in magnetic devices. There has been particular interest in non-local effects whereby layers separated from a magnetic layer influence its magnetization dynamics through non-magnetic (NM) metallic contact layers, i.e., via conduction electrons. Such effects were modeled and studied in the early 1970’s by Silsbee et al. [1]. More recently, a scattering theory approach has been employed to describe the enhancement of the damping [2,3]. There have also been experiments [4, 5, 6] which indicate quantitative agreement with this theory based on interface parameters that can be determined from ab-initio theory [6] as well as transport experiments [5].

The current interest in this mechanism is at least three-fold. First, it is a fundamental mechanism of damping that can provide important information on interface and bulk spin diffusion. Second, the effect is known to play an important role in current-induced magnetization excitations in spin-transfer devices [2]. In such devices, a few nanometer thick magnetic layer is embedded between NM layers which separate it from a thick ferromagnetic layer that sets the spin-polarization of the current [11]. The threshold current density for magnetic excitations is proportional to the damping [11]. In order to understand the physics of spin transfer, it is therefore important to investigate the effect of adjacent NM layers on the magnetic relaxation of ultra-thin films. Finally, from a technological point of view, this process provides a way to engineer the damping, which is important for high speed magneto-electronic devices.

Mizukami et al. studied the Gilbert damping of sputtered NM|t Py|NM films as a function of the FM layer thickness (2 ≤ t ≤ 10 nm) and for different adjacent non-magnetic metals NM=Cu, Pd and Pt using a X-band FMR technique [4]. The damping was found to be consistent with the spin pumping picture: increasing with decreasing Py thickness for the films with NM=Pt and Pd only. Further, the magnetization damping of Cu|Py|L Cu|Pt structures as a function of Cu layer thickness L and with fixed Py thickness, showed evidence for a non-local effect. However, the non-local damping has been studied mainly in NM|t FM|NM structures as a function of the FM layer thickness and varying the material directly in contact with the FM layer [4,6]. There have also been no experimental studies of polycrystalline Co layers, which are widely used in spin-transfer devices.

In this paper, we report systematic studies of the thickness dependence of the linewidth and Gilbert damping of ultra-thin Co layers in ||y1 Pt|Cu|t Co|Cu|y2 Pt|| structures. The thickness of the Cu layers in contact with Co is kept fixed at 10 nm, which is chosen to be less than the spin-diffusion length in Cu. The Pt layers have no direct interface with the FM layer. The structure is modified by removing one or both of the Pt layers (y1 or y2 = 0). The observation of changes in the Gilbert damping confirm the non-local nature of this damping mechanism and the data allow for quantitative analysis of the interface spin-mixing conductances in the scattering theory approach.

The paper is organized as follows. In section II, the film fabrication and the FMR setup are described. Section III explains the method of analysis of the resonance field and linewidth. In section IV, the resonance field and the effective demagnetization field are studied as a
function of Co layer thickness. The FMR linewidth and the Gilbert damping data are presented. This is followed by a discussion of the dependence of the Gilbert damping on the Co layer thickness for films with and without Pt and a quantitative analysis of the data.

II. EXPERIMENTAL TECHNIQUE

Four series of films were fabricated with the layer structure |\(y_1\) Pt|10 nm Cu |\(t\) Co|10 nm Cu|\(y_2\) Pt| on GaAs substrates. First, symmetric structures with a variable thickness of Co between Pt and Cu layers were grown with \(y_1 = y_2 = 1.5\) nm and \(1 \leq t \leq 10\) nm. The second set of samples were asymmetric, without the top Pt layer (\(y_1 = 1.5\) nm and \(y_2 = 0\)), and with Co of 1.5, 2 and 2.5 nm thickness. In addition, films without Pt layers (\(y_1 = y_2 = 0\)), with Co of 2 and 3 nm thickness were fabricated. In the fourth and final set of films, the thickness of the Pt layers was varied from 0 to 5 nm in a symmetric way with \(y_1 = y_2 = 0, 1.5, 3\) and 5 nm with a fixed Co layer thickness of \(t = 2\) nm. Note that the studies in which Pt layer thicknesses were varied focused on thin Co layers because the non-local effect on the damping were found to be significant only in Co layers thinner than 4 nm.

Films were prepared by a combination of e-beam (Co, Pt) and thermal (Cu) evaporation in an UHV system at a base pressure of \(5 \times 10^{-8}\) Torr on polished semi-insulating \(4 \times 6\) mm² GaAs wafers. Note that the chamber is equipped of an in-situ wedge growth mechanism that enables the fabrication of a number of samples with different Co or Pt thickness in the same deposition run, without breaking vacuum. The evaporation rate for Co and Cu were 0.5 and 0.8 Å/sec respectively.

X-ray measurements conducted on |\(|\text{Pt|Cu}|t\) Co|Cu|Pt|| with \(t = 1, 3\) and 6 nm showed that the films are polycrystalline and the Co and Cu have a fcc structure. The morphology of the films were studied using non-contact Atomic Force Microscopy (AFM). From Fig. 1, it can be seen that the film consists of small grains with size of the order of the film thickness. From such images, the rms roughness was found to be \(1.1 \pm 0.4\) nm and the lateral correlation length is \(28 \pm 7\) nm.

FMR measurements were conducted in an in-plane field geometry at room temperature employing a coplanar waveguide (CPW) as an ac magnetic field generator and inductive sensor. The CPW was fabricated on a 350 µm thick semi-insulating and polished GaAs wafer from a 200 nm thick Au film patterned using bi-layer photolithographic process. It is characterized by a transmission line of 50 µm width, a gap to the ground plate of 32 µm and a length of 4 mm, which is designed to have 50 Ω impedance above 4 GHz. The CPW was placed into a brass cavity, with its ends connected directly to the ports of a Network Analyzer. Care was taken to avoid magnetic components in the cavity and in all contacts to the CPW. FMR spectra were measured by placing the magnetic sample metal face down on the CPW and sweeping the external magnetic field at fixed microwave frequency while measuring the S-parameters of the transmission line. Our setup enables measurement of the FMR response of Co layers as thin as 1 nm. Fig. 2a shows the geometry of the measurements. The applied field produced by an electromagnet is directed along the axis of the transmission line and perpendicular to the ac magnetic field generated by the CPW. The applied field was in the film plane, and was monitored with a Hall probe sensor that was calibrated using electron paramagnetic resonance (EPR) on 2,2-diphenyl-1-picrylhydrazyl (dpph), a spin 1/2 system. The measured absorption of dpph is shown in Fig. 2b. The resonance fields were always in agreement with the readings from the Gauss-meter within 10-15 Gauss.

The FMR response was recorded at different frequencies in the range 4-25 GHz. The spectra is measured as the relative change in the transmitted power versus applied field. At 13 GHz for example, the absorption from 5 nm thick Co film at resonance leads to a 0.66% decrease in the transmission. Thus, the susceptibility of the magnetic films only causes a small change in the impedance of the CPW and the absorption line can be analyzed as a small perturbation to the CPW transmission.

III. METHOD OF ANALYSIS OF THE RESONANCE FIELD AND LINEWIDTH

The dynamics of the magnetization can be described in the classical limit by the Landau-Lifshitz equation of
motion:

\[ \frac{1}{\gamma} \frac{\partial \vec{M}}{\partial t} = \vec{H}_{\text{eff}} + \frac{G}{\gamma^2 M_s^2} \vec{M} \times \frac{\partial \vec{M}}{\partial t}, \]

where \( \vec{H}_{\text{eff}} \) is the effective field, \( \vec{M} \) is the magnetization vector and \( G \) is the Gilbert damping constant. The gyromagnetic ratio, \( \gamma = g \mu_B / h \), is proportional to \( g \), the Landé gyroscopic factor. For a film magnetized in the film plane in an ac field, the resonance condition is \[ 13 \]:

\[ \left( \frac{2\pi f}{\gamma} \right)^2 = H_{\text{res}} (H_{\text{res}} + 4\pi M_{\text{eff}}), \]

where for a continuous film, the effective demagnetization field is given by:

\[ 4\pi M_{\text{eff}} = 4\pi M_s + \frac{2K_s}{M_s t}. \]

\( M_s \) is the saturation magnetization. The uniaxial anisotropy field \( H_s = 2K_s/M_s t \) is characterized by a 1/t thickness dependence, where the anisotropy originates from interface and/or strain-magnetoeelastic interactions. If \( K_s \), the uniaxial anisotropy constant, is negative, \( H_s \) is directed out-of the film plane, corresponding to a perpendicular component to the magnetic anisotropy.

The Gilbert damping is determined by the frequency dependence of the FMR linewidth \( \Delta H \) [14]:

\[ \Delta H(f) = \Delta H_0 + \frac{4\pi G}{\gamma^2 M_s} f, \]

where the slope of \( \Delta H(f) \) is the intrinsic contribution to the linewidth, and is proportional to the Gilbert damping constant \( G \). \( \Delta H_0 \), the zero-frequency intercept, is usually considered to be an extrinsic contribution to the linewidth. \( \Delta H_0 \) is sensitive to the film quality: the highest quality films typically exhibit a smallest residual or zero field linewidth [14, 15].

FIG. 2: a) The FMR setup and field geometry. b) Absorption of dpph at different frequencies. The resonance field \( H_{\text{res}} \) depends linearly on frequency: \( H_{\text{res}} = (2\pi f / g \mu_B) f \), and is used to verify the calibration of a Hall sensor used in this study.

FIG. 3: Typical absorption line at 13 GHz for \( ||\text{Pt}||\text{Cu}||\text{t nm Co}||\text{Cu}||\text{Pt}|| \) film with \( t = 10, 3 \) and 1.5 nm. With decreasing Co thickness the absorption line shifts to higher field and broadens.

IV. RESONANCE FIELD

The lineshape of the FMR curves is typically Lorentzian. Fig. 3 shows the normalized FMR peak at 13 GHz for a selection of \( ||\text{Pt}||\text{Cu}||\text{t nm Co}||\text{Cu}||\text{Pt}|| \) films. The absorption lines were normalized by subtracting the background signal and dividing by the relative change in power at resonance. Fig. 4 shows the thickness dependence of the resonance field \( H_{\text{res}} \) at 14 GHz for films with and without 1.5 nm Pt. The resonance field is practically constant (\( H_{\text{res}} = 1.2 \) kOe) when the Co layer thickness is larger than 5 nm. For thinner layers, \( H_{\text{res}} \) increases with decreasing \( t \), reaching a value of 1.6 kOe for the film with 1 nm Co layer. The films with the same thickness of Co exhibit about the same resonance field, independent of the presence of the Pt layers. The run-to-run variations in magnetic properties from small changes in film deposition conditions, for instance, are significantly less than the changes in \( H_{\text{res}} \) observed in the very thin film limit.

The resonance field was measured at different frequencies (Fig. 5). The effective demagnetization, \( 4\pi M_{\text{eff}} \), and the \( g \)-factor were found by fitting \( f^2 / H_{\text{res}} vs. H_{\text{res}} \) to Eq. 2. The slope of \( f^2 / H_{\text{res}} \) gives the \( g \)-factor and the zero frequency intercept provides the effective demagnetization field (see the inset of Fig. 5). Films with equal Co layer thickness have nearly the same \( g \) and \( 4\pi M_{\text{eff}} \). This suggests that the Pt underlayer and capping layer do not affect the magnetic properties of the films. The effective field exhibits a clear thickness dependence, decreasing
netic anisotropy associated with Co

FIG. 5: The frequency dependence of the resonance field for f=14 GHz.

from about 15 kOe to about 8 kOe when the Co thickness varies from 10 nm to 1 nm (Fig. 6b). The thickness dependence of the effective field can be understood as an uniaxial anisotropy field that depends on thickness as 1/t. The magnetization density is assumed to be independent of the film thickness, as Co and Cu are immiscible. The best fit to Eq. 3 gives a saturation magnetization density of Ms = 1131 emu/cm^3 and an uniaxial anisotropy constant Ks = -0.46 erg/cm^2. The value of Ms is smaller than the magnetization density of bulk fcc Co (Ms=1400 emu/cm^3). The negative sign of Ks reflects a perpendicular component of magnetic anisotropy. As noted earlier, the origin of this perpendicular anisotropy may be a magnetic anisotropy associated with Co/Cu interfaces or magnetoelastic interactions associated with strain in the Co layers, which increases with decreasing Co thickness. The results are in good agreement with magnetometry studies of 150 nm thick epitaxial Co/Cu multilayers grown on GaAs substrates, with Co layer thickness ranging from 0.5 to 4 nm [16]. The authors found an average magnetization density Ms=1241 emu/cm^3 and an anisotropy constant Ks = -0.47 erg/cm^2. Note that the g-factor is practically unchanged when the thickness of the Co layer is varied. The average value is g =2.49±0.14 (Fig. 5a). This is larger than the value reported in the literature for fcc phase Co (g=2.15) [17].

V. LINewidth AND GILBERT DAMPING

The linewidth was studied as a function of frequency and Co layer thickness. The linewidth at 10 and 14 GHz is plotted versus the thickness in Fig. 7 for the films with and without Pt. For thick films (t ≥ 5 nm) with two Pt outer layers, ∆H is practically independent of thickness. However, the linewidth of thinner films (t < 5 nm) increases strongly with decreasing Co layer thickness. The three series of films show different increases of the linewidth for thin layers. For instance, the film with 2 nm Co layer thickness and no Pt has a linewidth of 120 Oe at 10 GHz. This is smaller than that of the film with a Pt underlayer (∆H=180 Oe), and that with two Pt layers (∆H=260 Oe). The frequency dependence of ∆H enables a determination of the Gilbert damping and the inhomogeneous contribution to the linewidth. Fig. 8 shows the frequency dependence of ∆H for a symmetric film with Pt layers (y1 = y2 = 1.5 nm) and a 3 nm thick layer of Co. The linewidth depends linearly on frequency, with a zero frequency offset. Below 10 GHz, the data points are more scattered. In this frequency range, the resonance field is of the order of or smaller than the film saturation field, and the absorption line becomes asymmetric, due likely to the formation of magnetic domains. A linear fit to the data is shown in Fig. 8. The thickness dependence of the slope d∆H/df and intercept ∆H0 are shown in Fig. 9. The two parameters exhibit similar thickness dependence: decreasing with increasing Co layer thickness. Therefore, both changes in the Gilbert
In the present study, particularly from the effect of “remote” Pt layers on the linewidth, it is clear that non-local interactions are important. We discuss this in detail below and follow this with a brief discussion of two-magnon interactions are important. We discuss this in detail below and follow this with a brief discussion of two-magnon interactions.

VI. DISCUSSION AND INTERPRETATION

There are a number of mechanisms which lead to the broadening of FMR linewidth in very thin magnetic films. In the present study, particularly from the effect of “remote” Pt layers on the linewidth, it is clear that non-local interactions are important. We discuss this in detail below and follow this with a brief discussion of two-magnon scattering, which has been extensively discussed in the context of damping in ultra-thin films.

FIG. 7: Thickness dependence of the linewidth at 10 and 14 GHz for the films of series without and with Pt. The insets show the corresponding data on a log-log scale.

FIG. 8: Typical frequency dependence of the linewidth for the film ||PtCuCoCuPt|| with Co layer thickness of 3 nm. \( \Delta H_0 \) and \( d\Delta H/df \) are extracted from the linear best fit (solid line).

Damping and inhomogeneous broadening contribute to the enhanced linewidth for thin layers. \( \Delta H_0 \) approaches zero for thick Co reflecting the good quality of these layers. The slope is also practically constant when \( t \geq 5 \) nm, and it is about 3 times larger for the thinnest films with 2 Pt layers.

The Gilbert damping \( G \) was estimated from \( d\Delta H/df \) (Fig. 9) with Eq. 4. The thickness dependence of the damping is shown in Fig. 10 for the films with and without Pt layers. The damping of ||CuCoCu|| films is thickness independent. In fact, \( G \) for films without Pt is about equal to the damping of structures with thick Co layers \( (t > 5 \text{ nm}) \). Note, however, that the inhomogeneous contribution to the linewidth increases with decreasing Co thickness in such samples (Fig. 9)—even though the damping is thickness independent. The films with one or two Pt layers show an increase in the damping when the Co layer is thinner than 4 nm. 1.5 nm thick Pt layers are thus sufficient to lead to the enhancement of the damping.

In order to investigate whether the damping is a function of the Pt outer layers, films with 2 nm thick Co layers and variable Pt layer thickness were studied. The film structure was ||y PtCu2||. The results are shown in the inset of Fig. 10. The films without Pt have two times smaller damping than the films with Pt. However, remarkably, the damping does not increase further as the Pt layer thickness is increased beyond 1.5 nm. It saturates at a value of about \( 6 \times 10^8 \text{ s}^{-1} \). This result clearly shows that the main origin of the enhancement of the damping in thin Co layers are the Cu|Pt interfaces. Note that the films of this series, including the ones with \( y = 0 \) and \( y = 1.5 \) nm were fabricated a few months after the other series of films. It can be seen that the Gilbert damping of the samples with \( y = 0 \) and \( y = 1.5 \) nm, plotted in the inset, are consistent with the films deposited earlier (shown in the main part of Fig. 10).
The dependence of $G$ on the thickness of the FM and on the presence of the Pt can be understood in terms of spin pumping induced enhancement of the magnetic damping. In this model, the precessing magnetization of the thin Co layer generates a spin current that flows through the Cu layers. In absence of Pt ($||$Cu|Co|Cu| system), there is no additional damping with decreasing Co layer thickness because the Cu layers of 10 nm, which are much thinner than the spin diffusion length in Cu, are poor spin sinks. When the Cu layer is adjacent to Pt, a strong spin scatterer, the spin current is absorbed in Pt. There is no back flow of spin current. As a consequence, the Gilbert damping of the FM is enhanced. For a symmetric film with two Pt layers, the effect is more pronounced because the pumping current is absorbed at the two interfaces with Pt. Furthermore, above 1.5 nm Pt, the Gilbert damping does not depend on the thickness of Pt. In assuming that the film is continuous, a Pt layer as thin as 1.5 nm is thus sufficient to act as a perfect spin sink, i.e., the entire spin current is absorbed. This is in agreement with the results in [22], where it was reported that the spin loss parameter at the Pt|Cu interface is $0.9 \pm 0.1$, which implies about 70% spin randomization at the interface. For very thin Co layers ($t \leq 4$ nm), the non-local damping becomes predominant.

In a symmetric structure $||$NM$_2$|NM$_1$|FM|NM$_1$|NM$_2||$, where NM$_2$ is a perfect spin sink and NM$_1$ thickness is much smaller than the spin diffusion length of the material, the Gilbert damping is [2]:

$$ G(t) = G_0 + \left( \frac{g\mu_B}{e} \right)^2 \frac{G_{\text{eff}}^{11} S^{-1}}{t}. \quad (5) $$

$G_0$ is the residual Gilbert damping (bulk damping), $S$ is the surface area of the sample and $G_{\text{eff}}^{11}$ is the effective spin mixing conductance. $G_{\text{eff}}^{11}$ accounts for the spin mixing conductance at the Co|Cu and Cu|Pt interfaces:

$$ \frac{1}{G_{\text{eff}}^{11} S_{11}} = \frac{1}{G_{\text{Co|Cu}}^{11} S_{11}} + \frac{1}{G_{\text{Cu|Pt}}^{11} S_{11}}, \quad (6) $$

where $G_{\text{Cu}} = 1/(2L\rho)$ is the conductance per spin of the Cu layer of thickness $L$ and resistivity $\rho$. Using the literature value of the resistivity for pure Cu, $\rho = 1.7 \times 10^{-8}$ Ωm, the conductance per spin of 10 nm Cu layer is $G_{\text{Cu}} = 2.94 \times 10^{15} \Omega^{-1} m^{-2}$. In the films $||$Pt|Cu|Co|Cu|Pt|| studied here, the Cu thickness (10 nm) is much smaller than the Cu spin diffusion length $\lambda_{\text{sd}} (\approx 350$ nm at room temperature [21]). In addition, we found that a 1.5 nm Pt layer is sufficient to saturate the additional Gilbert damping, and therefore is a perfect spin sink. The best fit of the thickness dependence of the magnetic damping gives $G_{\text{eff}}^{11} S_{11} = (0.34 \pm 0.05) \times 10^{15} \Omega^{-1} m^{-2}$ and $G_0 = 2.09 \pm 0.44$ s$^{-1}$, using the average value of the $g$ factor reported in section IV. Note that the conductance per spin of a 10 nm Cu layer is about 10 times larger than the estimated effective spin mixing resistance, meaning that the main contributions to the resistance in the layered structures originates from that associated with the spin mixing at the Cu|Co and at the Cu|Pt interfaces. After correction of the Sharvin conductance [3], the effective spin mixing conductance is $G_{\text{eff}}^{11} S_{11} = 0.26 \pm 0.04 \times 10^{15} \Omega^{-1} m^{-2}$. Using the theoretical values of the mixing conductance for Cu|Co (0.55 × 10$^{15}$ Ω$^{-1}$m$^{-2}$) and Cu|Pt (1.36 × 10$^{15}$ Ω$^{-1}$m$^{-2}$) given in [23] and the conductance per spin of Cu as calculated above, the effective spin mixing conductance of the films is predicted to be 0.34 × 10$^{15}$ Ω$^{-1}$m$^{-2}$. The experimental value of the effective spin mixing is about 30% smaller than the calculated value. A similar FMR study was conducted on sputtered films with the same structure. It was found an effective spin mixing conductance $G_{\text{eff}}^{11} S_{11} = 0.41 \pm 0.05 \times 10^{15} \Omega^{-1} m^{-2}$. The result implies that the interface spin mixing conductance depends on the film deposition method.

We now briefly discuss FMR line broadening due to two magnon scattering. The scattering of magnons by defects and imperfections at the surface and interface of a thin ferromagnetic film produces modes that are degenerate with the FMR mode ($k=0$) [22], leading to an additional contribution to the linewidth. The mechanism is operative when the magnetization vector lies in the film plane, and it is not operative in the perpendicular geometry. Recently, Arias and Mills developed a theory of the two-magnon scattering contribution to the FMR linewidth in ultrathin films [23]. The authors calculated that one of the signatures of the linewidth broadening from two-magnon scattering is $\Delta H \propto H_s^2$, where the coefficient of proportionality contains information related to the roughness of the film. As the uniaxial anisotropy $H_s$ scales as $1/t$ (Eq. 3), it is predicted that the linewidth increases as $1/t^2$ for the very
thin films. The theory was found consistent with FMR measurements on sputtered NiFe films, and epitaxial CrFeGaAs ultrathin films. The insets of Fig. 7a and 7b show the linewidth versus the Co layer thickness in log-log plot at two frequencies, 10 and 14 GHz respectively. From the linear best fit, we found that $\Delta H$ increases as $1/t^{0.8}$. This implies that the model of two-magnon scattering contribution developed by Arias and Mills cannot explain the thickness dependence of $\Delta H$. Another result that confirms that the two-magnon scattering is irrelevant for explaining the observed linewidth broadening can be found in comparing the films with two Pt layers and those with a single underlayer Pt. The films grown with a Pt underlayer ($y_1 = 1.5$ nm) and with or without top Pt ($y_2 = 1.5$, 0 nm) are expected to have similar microstructure, since the underlayer structure is identical ([11.5 nm Pt][10 nm Cu]). As a consequence, in the picture of two-magnon scattering induces linewidth broadening, the linewidth of those films should be about the same. However, the thickness dependence of $\Delta H$ shows that the films with two Pt layers have a larger linewidth than those with a single Pt layer.

VII. CONCLUSION

We have conducted a FMR study of polycrystalline ultrathin Co films embedded between 10 nm Cu. The outer interfaces of Cu were placed in contact with different environments, by adding Pt layers. We have found that very thin Co layers sense additional magnetization relaxation process that depend on the non-local environment. The Co layers exhibit a lower magnetization density compared to the bulk material, and an uniaxial anisotropy field perpendicular to the film plane. The large difference between the g-factor value of the ultra-thin Co layer compared to the bulk fcc Co remains an open question.

The FMR linewidth, studied as a function of the Co layer thickness and of the non-local environment, increases with decreasing Co layer thickness. We gave evidence that the two-magnon scattering mechanism cannot explain the linewidth thickness dependence. The inhomogeneous contribution to $\Delta H$ increases with decreasing Co layer thickness, independently of the presence of the Pt layer. However the dependence of the Gilbert damping, the intrinsic contribution to the linewidth, was found to be function of the Co layer thickness and also depends on the non-local environment. In particular, the Gilbert damping increases with decreasing Co layer thickness only in the presence of a Pt/Cu interface. The thickness dependence of G is consistent with the theory of spin pumping. By changing the outer interface environment of [Cu][Co][Cu] by adding or removing Pt in contact with Cu, we gave unambiguous experimental evidence that the damping enhancement is a non-local mechanism. The non-local damping becomes predominant compared with other relaxation mechanism when the Co layer is a few nanometer thick ($t \leq 4$ nm).

In summary, the adjacent layers material as well as the non-local environment are critical for understanding the magnetization relaxation in ultra-thin FMs. This important result must be taking into account in the study of spin transfer devices.

We thank C-C. Kao for the X-ray scattering studies of the thin films. We also appreciate very stimulating discussions with C. E. Patton and J. Z. Sun. This research is supported by NSF-DMR-0405620 and by ONR N0014-02-1-0995.

[18] S. Chikazumi and C. D. Graham, Physics of Ferromag-