Ferromagnetic resonance study of polycrystalline Cobalt ultrathin films

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(Dated: March 23, 2022)

We present room temperature ferromagnetic resonance (FMR) studies of polycrystalline $|\text{Pt}/10$ nm Cu/$t$ Co/10 nm Cu/Pt$|$ films as a function of Co layer thickness ($1 \leq t \leq 10$ nm) grown by evaporation and magnetron sputtering. FMR was studied with a high frequency broadband coplanar waveguide (up to 25 GHz) using a flip-chip method. The resonance field and the linewidth were measured as a function of the ferromagnetic layer thickness. The evaporated films exhibit a lower magnetization density ($M_s = 1131$ emu/cm$^3$) compared to the sputtered films ($M_s = 1333$ emu/cm$^3$), with practically equal perpendicular surface anisotropy ($K_\bot \simeq -0.5$ erg/cm$^2$). For both series of films, a strong increase of the linewidth was observed for Co layer thickness below 3 nm. For films with a ferromagnetic layer thinner than 4 nm, the damping of the sputtered films is larger than that of the evaporated films. The thickness dependence of the linewidth can be understood in term of the spin pumping effect, from which the interface spin mixing conductance $g^{12} S^{-1}$ is deduced.

I. INTRODUCTION

Polycrystalline ferromagnetic films a few nanometers thick are commonly used in spin-transfer devices and, in general, in spintronic applications. For instance, the spin torque effect is typically studied in devices that consist of two magnetic layers separated by a normal metal (NM) and two contact layers made of the same NM on top and bottom of the structure [4]. One of the magnetic layers, about 10 nm thick, provides a spin polarized current that is used to excite and switch the magnetization of a very thin adjacent layer (few nm). The threshold current density for magnetic excitations is proportional to the Gilbert damping constant $G$, and the effective magnetization [2]. In order to understand the physics of spin transfer, it is therefore important to characterize the magnetic properties and magnetic relaxation of ultrathin films. FMR is a sensitive technique to study magnetic ultrathin films. It provides information on the magnetization density, the magnetic anisotropy and the damping. The precession of the magnetization $\vec{M}$ about an effective field $\vec{H}_{\text{eff}}$ is described by the Landau-Lifshitz equation. For a polycrystalline film that is magnetically saturated in the film plane, the resonance condition is [3]:

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

where $\gamma = g\mu_B/\hbar$ is proportional to $g$, the Landé $g$-factor. The effective field $4\pi M_{\text{eff}}$ is defined as [3]:

$$4\pi M_{\text{eff}} = 4\pi M_s + \frac{2 K_s}{M_s t}.$$  (2)

The last term of Eq. (2) is the surface anisotropy field. It characterizes a thickness dependent anisotropy associated with interface anisotropy and/or strain-magnetoelastic interactions. Another parameter of importance in FMR is the linewidth. The full width at half power $\triangle H$ is commonly fitted to [4]:

$$\triangle H = \triangle H_0 + \frac{2 G}{\gamma^2 M_s} 2\pi f.$$  (3)

The constant $\triangle H_0$ is a phenomenological term related to inhomogeneous broadening of the FMR line. The slope of $\triangle H$ vs. $f$ is directly proportional to the Gilbert damping constant. The two terms, $\triangle H_0$ and the slope, are referred to as the extrinsic and intrinsic contribution to the linewidth respectively.

In this paper, we compare the FMR response of ferromagnetic ultrathin films grown by evaporation and by sputtering. We first discuss the sample fabrication and the experimental set up. Then the thickness dependence of $4\pi M_{\text{eff}}$ and $G$ will be presented and analyzed.

II. EXPERIMENTAL TECHNIQUE

The samples are made of a single polycrystalline Co layer embedded between two Pt/Cu bilayers. Two series of samples were fabricated by evaporation and sputtering. The samples were prepared in a UHV system with a base pressure of $5 \times 10^{-8}$ Torr on polished semi-insulating GaAs (001) substrate of 350 $\mu$m thickness. For the evaporated films, an e-beam was used to evaporate the Pt layers and the Co layers. The Cu layers were deposited using thermal evaporation. The second set of films were made using magnetron sputtering. Those films have a thicker Pt layer (5 nm) than the evaporated films (1.5 nm). In both series of samples, the ferromagnetic layer thickness varied from 1 nm to 10 nm, while the Cu layer thickness was kept fixed at 10 nm. The FMR measurements were carried out at room temperature using a coplanar
waveguide (CPW), designed to have a 50 Ω impedance within a broad frequency range (up to 25 GHz). The device was fabricated on a similar GaAs wafer than the films employing a bi-layer photoresist. The metallic layer is made of 1.5 nm Pt for adhesion, and 200 nm Au. The waveguide, 4 mm long, has a transmission line of 50 μm width and a gap to the ground lines of 32 μm. The two ends of the line were directly connected to the ports of an Agilent Network Analyzer. The CPW was employed as an ac magnetic field generator with the assumption that the dominant mode was the TEM mode, and as an inductive sensor. Samples were placed directly on top of the CPW (flip-chip), as shown in the inset of Fig. 1. A dc magnetic field (up to 4.5 kOe), generated by an electromagnet was directed along the axis of the transmission line and perpendicular to the ac magnetic field. The dc applied field was measured with a Hall probe sensor, that was calibrated using EPR on dpph, a spin 1/2 system. All the measurements were done with the dc field and the ac field aligned in the plane of the film. The absorption line from 4 GHz to 25 GHz was measured by monitoring the relative change in the transmitted power as a function of the applied magnetic field. As will be shown below, the technique is sensitive enough to enable FMR studies in Co magnetic layers as thin as 1 nm.

III. RESULTS

Typical absorption lines at 13 GHz of a selection of Pt/Cu/Co/Cu/Pt evaporated and sputtered films are shown in Fig. 1. The normalized data were obtained by subtracting the background signal and dividing by the relative change in power at resonance. The absorption lines are Lorentzians, with a slight asymmetry observed at certain frequencies. For each film, the effective magnetic field $4\pi M_{eff}$ and the g-factor was deduced from the best fit of the experimental data, $f^2/H_{res}$ vs. $H_{res}$, to Eq. 2. The insets (a) and (b) shows $4\pi M_{eff}$ and the g-factor versus thickness, respectively.

The linewidth is significantly enhanced for films with Co layer thicker than 5 nm. Following Eq. 3, the parameters $\Delta H_0$ and the slope $d\Delta H/df$ were extracted. The two contributions to the linewidth exhibit similar thickness dependence, characterized by a strong increase for Co layers thinner than 5 nm (inset of Fig. 3). $\Delta H_0$ is close to 0 Oe for films with Co layer thicker than 5 nm, and it reaches 200 Oe when the ferromagnetic layer is 1 nm thick. The slope is about constant for $t \geq 4$ nm.

**FIG. 1:** The normalized absorption curve at 13 GHz for a selection of Pt/Cu/Co/Cu/Pt films, where the magnetic layer is (a) 5 nm, (b) 3 nm and (c) 1.5 nm thick. The inset of (a) shows the experimental geometry.
nm, and it increases by a factor 3 for the thinnest film. The Gilbert damping constant was estimated from Eq. 8 and its thickness dependence is shown in Fig. 3. We used the average g-factor and the magnetization of saturation obtained from the study of the thickness dependence of the effective field. The sputtered and evaporated films have equivalent damping constant for thick Co layers. However, with decreasing FM layer thickness, G increases more rapidly for sputtered films than for evaporated films. The enhancement of the damping for the ultrathin ferromagnetic films can be interpreted in terms of the spin pumping effect. Brataas and co-workers recently proposed a mechanism for additional Gilbert damping in the spin pumping effect. 

FIG. 3: (a) Thickness dependence of the full width at half power, ΔH, at 14 GHz. (b) The Gilbert damping versus the Co layer thickness t, deduced from the slope dΔH/df. The top inset shows the intercept ΔH₀ versus thickness. The lower inset shows the slope dΔH/df versus thickness.

Polycrystalline Pt/Cu/Co/Cu/Pt ultrathin films exhibit smaller magnetization density compared to the bulk material. Furthermore, sputtered films exhibit a larger magnetization saturation compared to the evaporated films. In contrast, the interface anisotropy is not affected by the deposition technique. The linewidth increases strongly with thickness decreasing below 4 nm. The estimated Gilbert damping shows similar behaviour. The spin mixing conductance at Co/Cu interface was calculated and found to be smaller for evaporated films with a Pt layer of 1.5 nm than for sputtered films that have a Pt layer of 5 nm.

This research is supported by NSF-DMR-0405620 and by ONR N0014-02-1-0995.

IV. CONCLUSION

[1] see, for example, J. A. Katine et al., Phys. Rev. Lett. 84, 3149 (2000); B. Oezylilmaz et al., Phys. Rev. Lett. 91, 067203 (2003).
[2] J. Z. Sun, Phys. Rev. B 62, 570 (2000).
[3] Y. K. Kim and T. J. Silva, Appl. Phys. Lett. 68, 2885 (1996).
[4] see, for example, D. L. Mills and S. M. Rezende in Spin Dynamics in Confined Magnetic Structures II (Eds. B. Hillebrands and K. Ounadjela), pp. 27-58, (Springer, Heidelberg 2002).
[5] U. Wiedwald et al., J. Vac. Sci. Technol. A 19 (4), (2001).
[6] C. H. Lee et al., Phys. Rev. B 42, 1066 (1990); G. Bochi et al., Phys. Rev. B 50, 2043 (1994).
[7] Y. Tserkovnyak et al., Rev. Mod. Phys. (2006) and cond-mat/0409224 (2004).
[8] S. Mizukami et al., Phys. Rev. B 66, 104413 (2002).
[9] R. Arias and D. L. Mills, Phys. Rev. B 60, 7395 (1999).