Ferromagnetic resonance study of polycrystalline cobalt ultrathin films

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We present room-temperature ferromagnetic resonance (FMR) studies of polycrystalline [Pt/10 nm Cu/t Co/10 nm Cu/Pt] films as a function of Co layer thickness (1 ≤ t ≤ 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 functions of the ferromagnetic layer thickness. The evaporated films exhibit a lower magnetization density (Mrs = 1131 emu/cm³) compared to the sputtered films (Mrs = 1333 emu/cm³), with practically equal perpendicular surface anisotropy (Ku = -0.5 erg/cm²). 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 dependence of the linewidth can be understood in terms of the spin-pumping effect, from which the interface spin-mixing conductance is deduced. © 2006 American Institute of Physics. [DOI: 10.1063/1.2151832]

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 ferromagnetic (FM) layers separated by a normal metal (NM) and two contact layers made of the same NM on top and bottom of the structure.1 One of the FM layers, about 10 nm thick, provides a spin-polarized current that is used to excite and switch the magnetization of a few nanometer thick FM layer. 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. Ferromagnetic resonance (FMR) is a sensitive technique to study magnetic ultrathin films. It provides information on magnetization density, magnetic anisotropy, and damping. The precession of the magnetization M about an effective field Heff is described by the Landau-Lifshitz equation. For a polycrystalline film that is magnetically saturated in the film plane, the resonance condition is

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

where γ=gμB/h is proportional to g, the Landé g factor. The effective field \(4\pi M_{\text{eff}}\) is defined as

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

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 \(\Delta H\) is commonly fitted to

\[
\Delta H = \Delta H_0 + \frac{2G}{\gamma^2 M_s} 2\pi f.
\]

The constant \(\Delta H_0\) is a phenomenological term related to inhomogeneous broadening of the FMR line. The slope of \(\Delta H\) vs f is directly proportional to the Gilbert damping constant, G. The two terms, \(\Delta H_0\) and the slope, are referred to as the extrinsic and intrinsic contributions 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 setup. 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 5×10⁻⁶ Torr on polished semi-insulating GaAs (001) substrate of 350 μm 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 was made using magnetron sputtering. Those films have a thicker Pt layer than the evaporated films (1.5 nm). In both series of samples, the ferromagnetic layer thickness varied from 1 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 microwave device was fabricated on a semi-insulating GaAs wafer, employing a bilayer 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 ground signal and dividing by the relative change in power at resonance. The absorption lines are Lorentzians, with a slight dependence: decreasing about 6 kOe when the Co layer thickness is decreased from 10 to 1 nm [Fig. 1(a)]. The best fit to the experimental data with Eq. (3) gives the surface anisotropy constant for e-beam films, \( K_s = (-0.46 ± 0.04) \text{ erg/cm}^2 \), and for sputtered films, \( K_s = (-0.54 ± 0.12) \text{ erg/cm}^2 \). The negative sign reflects a perpendicular magnetic surface anisotropy. Within the error bar, the surface anisotropy is practically independent of the film deposition technique. In contrast, the sputtered films exhibit a larger magnetization density, \( M_s = 1333 \text{ emu/cm}^3 \), compared to the films prepared by evaporation, \( M_s = 1131 \text{ emu/cm}^3 \). Those values are smaller than the bulk magnetization density of fcc cobalt, 1400 emu/cm³. The results are in good agreement with previous work conducted on t Co/2.5 nm Cu (111) epitaxial superlattices (0.5 ≤ t ≤ 4 nm) grown on a GaAs (110) wafer. Indeed, it was found that those films exhibit a surface anisotropy constant \( K_s = -0.47 \text{ erg/cm}^2 \) and have a density of magnetization of 1241 emu/cm³ on average.

The full width at half power \( \Delta H \) was also studied as a function of the frequency. The linewidth increases linearly with frequency from 10 to 25 GHz for both evaporated and sputtered films. Figure 3(a) shows the thickness dependence does not exhibit a clear thickness dependence. Within the error bars, the average values of \( g \) for the evaporated and sputtered films are practically equal, 2.49±0.14 and 2.36±0.06, respectively. Nevertheless, this is about 15% larger than the value reported in the literature for fcc Co films (\( g = 2.14 \)).

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 data were normalized 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 \( 4\pi M_{\text{eff}} \) and the \( g \) factor were deduced from the best fit of the experimental data, \( f^2/H_{\text{res}} \) vs \( H_{\text{res}} \), to Eq. (1). For the two series, the \( g \) factor

![Figure 1](image1.png)

**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.

![Figure 2](image2.png)

**FIG. 2.** Effective field vs inverse thickness for sputtered and evaporated films. The solid and dash lines are fits of the experimental data based on Eq. (2). The insets (a) and (b) show \( 4\pi M_{\text{eff}} \) and the \( g \) factor vs thickness, respectively.

![Figure 3](image3.png)

**FIG. 3.** (a) Thickness dependence of the full width at half power \( \Delta H \) at 14 GHz. (b) The Gilbert damping vs the Co layer thickness \( t \), deduced from the slope \( d\Delta H/dt \). The top inset shows the intercept \( \Delta H_0 \) vs thickness. The lower inset shows the slope \( d\Delta H/dt \) vs thickness.
of $\Delta H$ for the data recorded at 14 GHz. The linewidth is significantly enhanced for films with Co thickness below 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(a)]. $\Delta H_0$ 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, and it increases by a factor of 3 for the thinnest film. The Gilbert damping constant was estimated from Eq. (3) and its thickness dependence is shown in Fig. 3(b). We used the average $g$ factor and the saturation magnetization 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. Tserkovnyak et al., recently proposed a model for spin pumping in NM$_2$/NM$_1$/FM/NM$_1$/NM$_2$ structures, where NM$_1$ is a non-magnetic metal with a long spin diffusion length, and NM$_2$ is a perfect spin sink. In this case, the additional damping scales inversely with the thickness of the FM layer:

$$G(t) = G_0 + \left(8\mu_B e\right)^2 \frac{\tilde{G}_{\text{eff}}^{\uparrow\downarrow} S^{-1}}{t},$$

where $G_0$ is the bulk damping and $\tilde{G}_{\text{eff}}^{\uparrow\downarrow} S^{-1}$ is the effective spin mixing conductance at the Co/Cu and Cu/Pt interfaces. The best fit was obtained for $G_0=(2.09 \pm 0.44) \times 10^8$ s$^{-1}$ and $\tilde{G}_{\text{eff}}^{\uparrow\downarrow} S^{-1}=(0.34 \pm 0.05) \times 10^{15}$ $\Omega^{-1}$ m$^{-2}$ for the evaporated films, and $G_0=(1.52 \pm 0.71) \times 10^8$ s$^{-1}$ and $\tilde{G}_{\text{eff}}^{\uparrow\downarrow} S^{-1}=(0.63 \pm 0.07) \times 10^{15}$ $\Omega^{-1}$ m$^{-2}$ for the sputtered films. After correction for the Sharvin resistance, the effective spin mixing conductance is: $G_{\text{eff}}^{\uparrow\downarrow} S^{-1}=(0.26 \pm 0.04) \times 10^{15}$ $\Omega^{-1}$ m$^{-2}$ for evaporated and $G_{\text{eff}}^{\uparrow\downarrow} S^{-1}=(0.41 \pm 0.05) \times 10^{15}$ $\Omega^{-1}$ m$^{-2}$ for sputtered films. The method of deposition has practically no effect on $G_0$. The effective mixing conductance for evaporated films is a factor of two less than that of sputtered films. Note that Eq. (4) is valid for a system where the NM$_2$ is a perfect spin sink, i.e., the angular momentum generated by the processing magnetization is dissipated in NM$_2$. We conducted FMR measurements on evaporated films with different Pt layer thicknesses. The Gilbert damping saturates when the Pt layer thickness is greater than 1.5 nm. Therefore, a Pt layer as thin as 1.5 nm is a perfect spin sink and the smaller value of $G_{\text{eff}}^{\uparrow\downarrow} S^{-1}$ found for the evaporated films cannot be explained by the thinner Pt layers. Another mechanism that gives rise to the broadening of the linewidth with decreasing thickness is the two-magnon-scattering mechanism. Arias and Mills calculated that this contribution is proportional to $H_s^2$, where $H_s$ is the interface magnetic anisotropy, and so scales as $1/t^2$ with $n=2$. A log-log plot of the thickness dependence of the linewidth at 14 GHz, for instance, for sputtered and evaporated films gives $n = 0.8 \pm 0.1$. Furthermore, we conducted FMR measurements on films without Pt layers and with Co thickness layer of 2 and 3 nm. The Gilbert damping is about the value found for the thickest films with Pt layers (to be published). Therefore, the two-magnon-scattering mechanism does not appear relevant to understand the thickness dependence of $\Delta H$.

IV. CONCLUSION

Polycrystalline Pt/Cu/Co/Cu/Pt ultrathin films exhibit smaller magnetization density compared to the bulk material. Furthermore, sputtered films exhibit a larger magnetization of 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 behavior. 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.

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