Quantitative studies of spin-momentum-transfer-induced excitations in Co/Cu multilayer films using point-contact spectroscopy

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We have measured current-induced magnetic excitations in a variety of exchange-coupled Co/Cu multilayers using point-contact spectroscopy. A step in the dc resistance and corresponding peak in dV/dI are observed at a critical current I_c whose value depends linearly on applied magnetic field B_{app}, in agreement with Slonczewski's theory. These features are observed for both in- and out-of-plane fields. Excitations in ferromagnetically coupled films occur even without an applied field. The spin transfer efficiency is determined from the slope and intercept of I_c vs B_{app} and varied from contact to contact. For out of plane magnetized samples, the deduced spin transfer efficiency values are in good agreement with the predictions of Slonczewski. [DOI: 10.1063/1.1556168]

Slonczewski and Berger[1–3] predicted that a spin-polarized current propagating into a ferromagnetic layer would exert a torque on the magnetization of the layer, due to the exchange field between the conduction electrons and the local magnetic moments. In multilayered systems with the current perpendicular to the plane (CPP) of the layers, a current polarized by one layer will transfer its spin angular momentum to another layer, an effect called spin-momentum transfer (SMT). For this torque to be sufficient to disturb the magnetization from equilibrium, large current densities ($>10^7$ A/cm^2) are required. If two stable equilibria exist for the magnetization, the SMT torque can switch the magnetization from one equilibrium position to another. If only one stable equilibrium state exists, as when a large magnetic field is applied, the magnetization becomes unstable and steady-state oscillations are predicted.[1,2] Applications of such an effect include dc-current-driven microwave oscillators for telecommunications applications.[4] Subsequent to this prediction, current-induced SMT effects were seen in a variety of CPP geometries,[5–10] including a mechanical point contact.[11] However, these studies have not addressed how interlayer exchange coupling and magnetic field direction affect the qualitative or quantitative aspects of SMT in unbounded films. This study investigates the effect of these parameters in Co/Cu multilayers. Most importantly, we find that the signature of SMT-induced dynamics can occur at zero applied field $B_{\mathrm{app}}=\mu_0 H$ if interlayer exchange coupling strongly favors parallel alignment of the magnetic layers.

We use a mechanical point contact to study SMT features using Co/Cu multilayers grown with different Cu layer thicknesses. The mechanical point contact system used in our studies is similar to those described elsewhere.[12] An Ag wire was used to make the point contact and data were acquired with a four-point measurement of the contact resistance. All measurements were made in the range of 5.5–6 K so that stable high-resistance contacts could be easily made. Contact resistances in the range 10–50 Ω were routinely obtained. Both the dc resistance and differential dV/dI curves were simultaneously measured for all contacts.

The films studied were Co/Cu multilayers of the form Fe (5 nm)/[Cu (t nm)/Co (1.2 nm)]$_{\times 10}$/Cu (1 nm) sputter deposited onto oxidized Si wafers.[13] The Cu thicknesses ranged from $t=0.9$ to 2.1 nm, spanning the first and second antiferromagnetic (AFM) coupling maxima as well as the ferromagnetic (FM) coupling peak at a Cu thickness of 1.3 nm.[14] The final Cu capping layer helped prevent oxidation of the multilayer. The films showed sheet resistance $\Delta R/R$ values of 80%, 4%, and 40% at 5.5 K for Cu spacer thicknesses of $t=0.9$, 1.3, and 2.1 nm, respectively, where $\Delta R/R = [R(B_{\mathrm{app}}=0)-R(B_{\mathrm{app}}=B_{\mathrm{sat}})]/R(B_{\mathrm{app}}=B_{\mathrm{sat}})$.

A representative set of differential resistance curves taken on a sample grown at the first AFM coupling maximum as a function B_{app} applied perpendicular to the sample plane is shown in Fig. 1. The peaks seen in the dV/dI signal occur for only one direction of current flow, consistent with SMT as the cause of resistance change.[15] The excitation occurs for electrons flowing from the tip into the film.[1] The peaks in dV/dI correspond to roughly 0.2 Ω steps in the dc resistance. We find that for $B_{\mathrm{app}}>B_{\mathrm{sat}}=\mu_0(M_s-H_{\mathrm{ex}})$, where H_{ex} is the interlayer exchange field, the size of the resistance step does not depend on B_{app}. As shown in the inset of Fig. 1, I_c increases linearly with B_{app}.

Assuming that the features in the $I-V$ curve result from the excitation of precessional motion of a region within the top ferromagnetic layer of the film, Slonczewski derived the relation[1]

$$I_c(B_{\mathrm{App}})=\frac{et_1M_s}{\hbar\epsilon}\left[\frac{23D}{2\hbar\gamma}+2A\alpha_{\mathrm{LLG}}\left(\frac{B_{\mathrm{App}}}{\mu_0}+H_{\mathrm{ex}}-M_s\right)\right] \tag{1}$$

for the critical current. Here, t_1 is the thickness of the top layer, A is the area of the point contact, D is the exchange parameter, γ is the gyromagnetic ratio, α_{LLG} is the Landau–Lifshitz–Gilbert damping parameter, M_s is the saturation magnetization, and μ_0 is the permeability of free space. For an AFM-coupled multilayer, H_{ex} is negative. The spin transfer efficiency is denoted by ϵ. The linear dependence of I_c on B_{app} shown in Fig. 1 is in agreement with Eq. (1).

In order to more fully investigate the predictions of the theory presented in Ref. 1, a series of contacts was made to samples grown at the first AFM coupling maximum, with the layer magnetizations saturated out of the film plane. Repre-

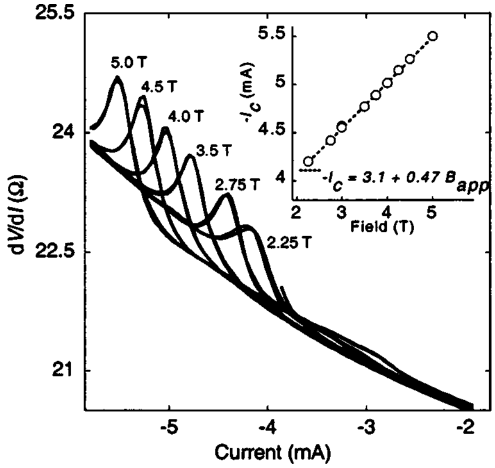

FIG. 1. Differential resistance curves for a Co (1.2 nm)/Cu (0.9 nm) multilayer film grown at the first AFM coupling maximum as a function B_{app}=2.25–5.0 T out of the film plane. Inset shows linear dependence of I_c on B_{app} along with a fit.

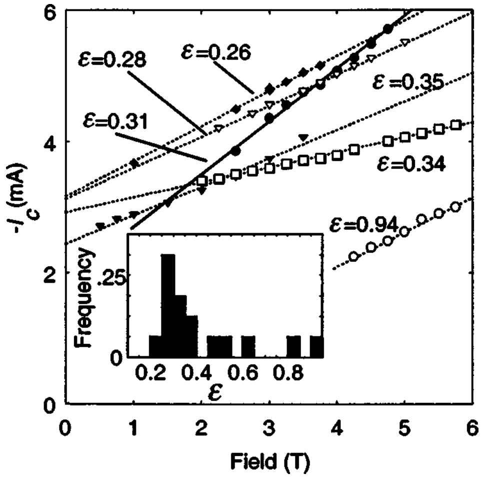

FIG. 2. Plot of representative I_c vs B_{app} data for several contacts to Co (1.2 nm)/Cu (0.9 nm) multilayers grown at the first AFM coupling maximum. The contacts have diameters calculated from Eq. (1) and contact resistances of (○) 84 nm, 29 Ω; (□) 34 nm, 32 Ω; (▼) 44 nm, 11 Ω; (●) 60 nm, 14 Ω; (▽) 44 nm, 20 Ω; and (♦) 44 nm, 15 Ω. Inset shows statistics for ϵ using all data sets.

sentative sets of I_c vs B_{app} data obtained are shown in Fig. 2, along with linear fits. At an applied field $B_{\mathrm{app}}=\mu_0(M_s-H_{\mathrm{ex}})$, Eq. (1) reduces to

$$I_c^*[B=\mu_0(M_s-H_{\mathrm{ex}})]=\frac{23et_1DM_s}{2\hbar^2\gamma\epsilon}, \tag{2}$$

which depends solely on known material constants and the efficiency of the current-induced torque ϵ. Hence, we can determine the value of ϵ for a given contact from the value of $I_c^*(B_{\mathrm{app}}=2.4\ \mathrm{T})$, using the measured values $H_{\mathrm{ex}}=-600$ kA/m and $M_s=1.32$ MA/m, and a value of $D=5\ \mathrm{meV\,nm^2}$ from the literature.[16] The interlayer exchange was extracted from in-plane magnetoresistance and alternating gradient magnetometry measurements and M_s was obtained by ferromagnetic resonance (FMR) spectroscopy.

According to Ref. 1, ϵ depends on the type of contact under investigation, i.e., ballistic or diffusive. For purely ballistic contacts ϵ depends solely on the polarization of the material. For Co, ϵ=0.28, using a polarization value P=38%.[17] For purely diffusive contacts, ϵ is determined by the spin-dependent resistivities of the material. Under a few assumptions, Slonczewski derived a lower bound of $\epsilon \gtrsim 0.25$. In practice our contacts are likely neither purely ballistic nor purely diffusive. Consequently, we expect ϵ to vary between 0.28 and 0.25.

The measured values of I_c^* typically give ϵ=0.2 to ϵ=0.5 (see Fig. 2), in reasonable agreement with the predictions of Slonczewski. We also occasionally obtain larger values of $\epsilon \gg 0.5$ (corresponding to 100% polarization). As discussed in Ref. 1, the measured value of I_c^* is expected to be lower than the predicted value given in Eq. (2) when tip-induced damage of the contact area reduces spin-wave radiation away from the contact, e.g., $I_c^* \to 0$ mA in the case of complete suppression of radiation damping. Application of Eq. (2) to data obtained with such a contact will result in artificially large values of ϵ. However, the second term in Eq. (1) does not include spin-wave radiation damping effects, and so dI_c/dB_{app} should be largely unaffected.[1] Indeed, data sets that yield large values of ϵ also correspond to unusually low values of I_c^* while having slopes similar in size to those data sets returning reasonable values of ϵ (see Fig. 2). This behavior occurs in about 15% of contacts.

The damping parameter for two of these films was determined as α_{LLG}=0.020 and 0.016 from FMR measurements performed at 300 K with an excitation frequency of 24 GHz. From the slopes of the I_c vs B_{app} curves, the values of ϵ as determined earlier, and the measured value of α_{LLG}, we can determine the effective excitation area of our contacts. From this analysis, we obtain contact diameters between 10 and 60 nm, in agreement with typical contact areas found in previous mechanical point contact experiments.[12] Calculating the contact diameter from the contact resistance using a Sharvin–Maxwell model[18] gives diameters two to three times smaller, on average. We have not determined the cause of this discrepancy. It may be that formation of surface oxides on the sample and tip result in an additional series resistance, leading to errors in our calculated electrical contact area.[19] It is also possible that the value for α_{LLG}, measured from FMR, to determine A does not correspond to the effective value of α_{LLG} in the case of SMT dynamics where large amplitude excitations are possible. However, time-resolved studies of large angle dynamics suggest that α_{LLG} is not a strong function of the excitation amplitude.[20]

Measurements on these multilayer samples were also made with in-plane fields, shown in Fig. 3. In this geometry, we found I_c to vary linearly with applied field as well. For in-plane magnetization, the Kittel spin-wave equation generally predicts a nonlinear dependence of frequency on applied field for a given magnon wave number.[21] However, for small-wavelength excitations in thin films the spin-wave dispersion relation is approximately linear in field:

$$\omega \simeq \gamma\mu_0\left(\frac{Dk^2}{\hbar\gamma\mu_0}+\frac{M_s}{2}+\frac{B_{\mathrm{App}}}{\mu_0}+H_{\mathrm{ex}}\right), \tag{3}$$

when the magnon excitation energy is dominated by the intralayer exchange forces, which in our case occurs for con-

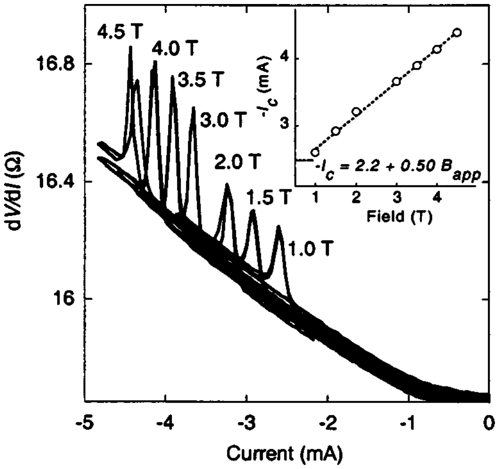

FIG. 3. Differential resistance curves for a Co (1.2 nm)/Cu (0.9 nm) multilayer film grown at the first AFM coupling maximum as a function $B_{\mathrm{app}}=1.0$–4.5 T in the film plane. Inset shows linear dependence of I_c on B_{app} along with a fit.

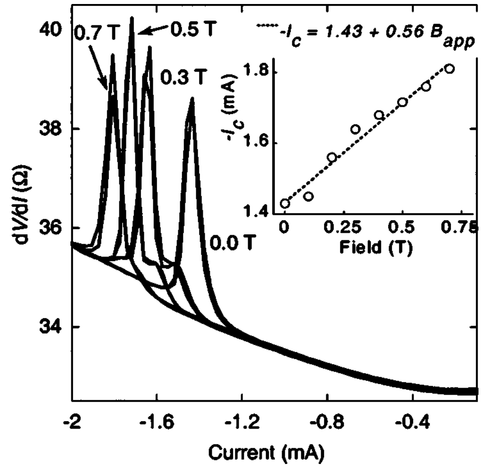

FIG. 4. Differential resistance curves for a FM-coupled Co (1.2 nm)/Cu (1.3 nm) multilayer film as a function $B_{\mathrm{app}}=0.0$–0.7 T in the film plane. Inset shows linear dependence of I_c on B_{app} along with a fit.

tact diameters of less than 25 nm. A simple extension of the Slonczewski model[1] using a linear dispersion relation as in Eq. (3) results in

$$I_c(B_{\mathrm{App}})=\frac{et_1M_s}{\hbar\epsilon}\left[\frac{23D}{2\hbar\gamma}+2A\alpha_{\mathrm{LLG}}\left(\frac{B_{\mathrm{App}}}{\mu_0}+H_{\mathrm{ex}}+\frac{M_s}{2}\right)\right],\tag{4}$$

which predicts a linear dependence of I_c with B_{app}. An analysis similar to that discussed earlier can be performed for in-plane magnetizations using Eq. (4). About 25% of the data give values of ϵ in the range of 0.2–0.4, a majority of the data give values for the efficiency of $\epsilon \geqslant 0.5$. Hence, while the linear dependence of I_c on B_{app} suggests that intralayer exchange dominates the energetics of the excitations, our modified Slonczewski theory fails to accurately predict the magnitude for I_c. We note that the slopes of the I_c vs B_{app} curves for the in- and out-of-plane data sets are very similar, ranging from 0.05 to 2 mA/T. Consequently, if similar contact areas for the different magnetization directions are assumed, then similar values of ϵ are obtained for the two geometries.

According to the predictions of Ref. 2, the excitations measured here occur when the magnetic layers are put into a stable near-parallel alignment while a current of sufficient magnitude is passed through the film in such a way as to destabilize this configuration. To date, all published data of this type have been obtained by using an externally applied field (typically of ~1 T) to align the magnetic layers.[6,7,10,11] Here we show that the exchange field in a ferromagnetically exchange-coupled multilayer film can also provide the requisite field for the observation of SMT-induced dynamics. Shown in Fig. 4 is a set of dV/dI curves taken on a FM-coupled Co/Cu multilayer, for in-plane fields. We note that the dV/dI response remains reversible (anhysteretic) at zero applied field, where current-induced switching is expected in the absence of strong ferromagnetic interlayer-exchange coupling. Furthermore, the response amplitude is unattenuated as $B_{\mathrm{app}}\rightarrow 0$ T. Again we find that I_c is a linear function of applied field. If the resistance changes measured here do indeed correspond to dynamic excitations, this scheme makes it possible to create a magnetic oscillator not only with a dc current but also without the need for an externally applied magnetic field.

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