Excitation of a Magnetic Multilayer by an Electric Current

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We describe variations in the resistance of Co/Cu multilayers, induced by means of a high current density $\approx 10^8$ A/cm^2 injected into the multilayer through a point contact. We propose that the observed resistance changes are due to excitations of zero-wave-number spin waves in the magnetic layers. As predicted, such current-driven excitation of a magnetic multilayer occurs for only one direction of current flow and has a current threshold which increases linearly with the applied magnetic field. [S0031-9007(98)06055-4]

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Berger [1] and Slonczewski [2] have argued that a sufficiently large electric current flowing perpendicular to a magnetic multilayer composed of alternating ferromagnetic (F) and nonmagnetic (N) metals can transfer vector spin between the magnetic layers, exciting precession of the layer magnetizations, stimulated emission of spin waves, and high frequency switching with potential technological applications to high-speed, high-density storage and memory. The required current density is estimated to be only $j = 10^6 - 10^7$ A/cm^2, easily achievable with point contacts. If the multilayer is in its high field saturated state with the layer magnetizations aligned along the externally applied magnetic field $\mathbf{H}$, then excitations should occur only for current flowing in the direction such that the layer magnetizations can rotate out of this orientation. The current density needed to generate such excitations is predicted to increase linearly with H.

In this Letter we describe the first observations of such current-driven excitations in a magnetic multilayer. Current densities as high as 10^9 A/cm^2 were injected into the multilayer through a point contact with area $\approx 10^2$ nm^2. The contact area was estimated from the measured contact resistance, assuming a combination of Sharvin (ballistic) and Maxwell (diffusive) scattering as described in [3,4]. The excitations are observed both as decreases in sample resistance with increasing H and as increases in resistance with increasing applied dc voltage V (equivalent to increasing injected current density).

Our samples were sputtered $(\mathrm{Co/Cu})_N$ multilayers with bilayer numbers N ranging from 20–50 and layer thicknesses $t_{\mathrm{Co}} = 1.5$ nm and $t_{\mathrm{Cu}} = 2.0-2.2$ nm, some capped with a 1.6 nm thick Au protective layer. Such samples lie near the second antiferromagnetic coupling peak in Co/Cu [5], and give a 4.2 K usual current-in-plane magnetoresistances ≈30% [4,5]. The multilayers were sputtered onto sapphire or Si substrates in a system and using techniques already described [6]. No significant differences in behavior were found for different samples. Point contacts between a sharpened Ag tip and a magnetic multilayer were made with a standard system described elsewhere [3,4].

At helium temperature (4.2 K), and in magnetic fields up to 8 T applied perpendicular to the layers, we have made two sets of measurements. First, to look for current-driven excitations, we measured: (i) The current-voltage $(I\text{-}V)$ characteristics, and their derivatives, of point contacts at different applied magnetic fields H, and (ii) the magnetoresistance (MR) of contacts at different dc currents. At negative polarity, current flows from the tip into the multilayer. Second, to look for independent evidence of magnetic excitations in our multilayers, we measured absorption and dispersion in spin-wave resonance [7] in the microwave frequency range 40–60 GHz.

The usual point contact d^2V/dI^2 spectra (not shown), measured as a function of dc bias voltage V, did not show the phonon structure expected for ballistic contacts [3]. We thus conclude that our contacts were primarily diffusive, and they did not satisfy the condition $l_\varepsilon \gg a$, where a is the contact size and l_ε is the inelastic electron diffusion length. To check for possible effects on our spectra of local heating, we cooled the sample down to 1.3 K to obtain a superfluid bath. The resulting much larger heat removal produced no significant changes, leading us to conclude that the influence of Joule heating is negligible.

In low fields, the dV/dI spectra usually varied smoothly with increasing V. However, the spectra changed dramatically in a field larger than the saturation field H_S of the multilayer (≈1.5 T). Figure 1 shows the variation of dV/dI as a function of V for a series of magnetic fields. For a given field $H > H_S$, there is a peak structure in dV/dI for a certain bias voltage $V^*(H)$ for one direction of the current flow, but not for the opposite one. This peak structure corresponds to an upward step in the static contact resistance $R_c = V/I$. The inset of Fig. 1 shows that $V^*(H)$ increases linearly

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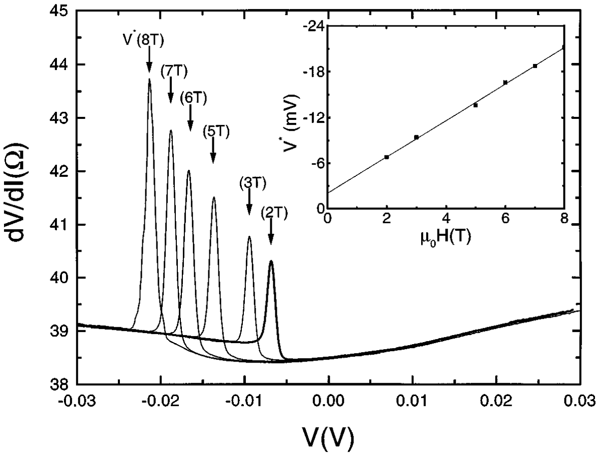

FIG. 1. The point contact $dV/dI(V)$ spectra for a series of magnetic fields (2, 3, 5, 6, 7, and 8 T) revealing an upward step and a corresponding peak in dV/dI at a certain negative bias voltage $V^*(H)$. The inset shows that $V^*(H)$ increases linearly with the applied magnetic field H.

with H. However, both the slope and intercept of the line in the inset vary from contact to contact. In contrast to the asymmetric behavior as a function of V shown in Fig. 1, the equivalent peak structure is symmetric in H, as we show next.

To investigate further these current-driven excitations we have measured the magnetoresistance (MR) of the contacts biased with a high dc current. Figure 2 shows two independent sweeps of $R_c = V/I$ and dV/dI versus H for fixed dc bias current $I = -0.3$ mA. Estimating the contact area as $\approx 40\ \text{nm}^2$ [3,4], yields $j \approx 0.75 \times 10^9\ \text{A/cm}^2$. Both sets of curves show the usual giant magnetoresistance (GMR) at low fields as studied systematically in a previous publication using low ac currents $\approx 1\ \mu$A [4]. However, the additional structure at ± 5.3 T, consisting of a downward step in R_c and a corresponding peak structure in dV/dI, was observed only with high dc bias currents.

From these data we conclude the following: (a) A small contact between a Ag tip and a magnetic multilayer shows singularities in contact resistance when excited by a high bias current density if the current flows from the tip into the multilayer. (b) The singularity is an upward step in resistance vs V (Fig. 1), but a downward step vs H (Fig. 2). (c) The location of the step in V (equivalent to I) varies linearly with H.

Lastly, we looked for independent evidence of magnetic excitations in our multilayers with microwave resonance studies made with a high field/high frequency electron spin resonance (ESR) spectrometer described in [8]. A multilayer was placed at the bottom [actually ≈ 0.5 mm (substrate thickness) above the bottom] of a cylindrical cavity operated in the TE011 mode, with a static field $\mathbf{H}$ perpendicular to the layer plane and a small rf field $\mathbf{h}$ in the layer plane. Figure 3 shows a typical absorption spectrum at a microwave frequency $\omega/2\pi = 53$ GHz for a sweep of H from high positive field to high negative field and back. The spectrum reveals two basic features. First, there is a GMR-like signal in absorption of microwaves at low fields. While the source of this signal is complex, it occurs over the same field range as the GMR effect and thus probably contains a significant contribution from the GMR. Second, there are resonance peaks, symmetric in $\pm H$, that we attribute to excitations of standing spin waves in thin F layers [7]. In Fig. 3, this interpretation would have the strong peak at about ± 3.3 T corresponding to the excitation of a zero-wave-number spin-wave mode in the

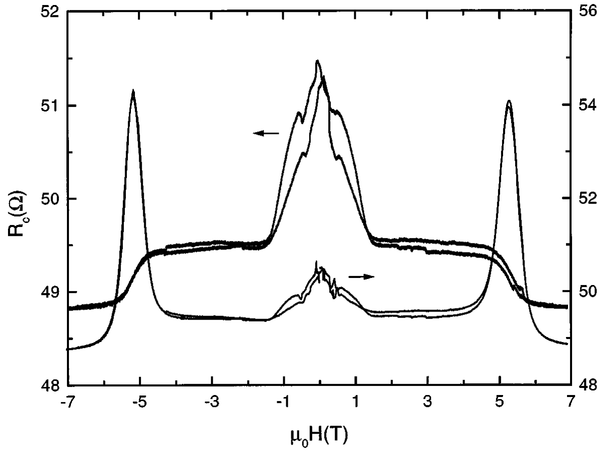

FIG. 2. The magnetoresistance of a contact biased with a high dc current $I = -0.3$ mA. Two independent sweeps of $R_c = V/I$ versus H (upper curve and left hand scale) and of dV/dI versus H (lower curve and right hand scale) show the usual GMR at low fields, a downward step in R_c at ± 5.3 T, and a corresponding peak structure in dV/dI.

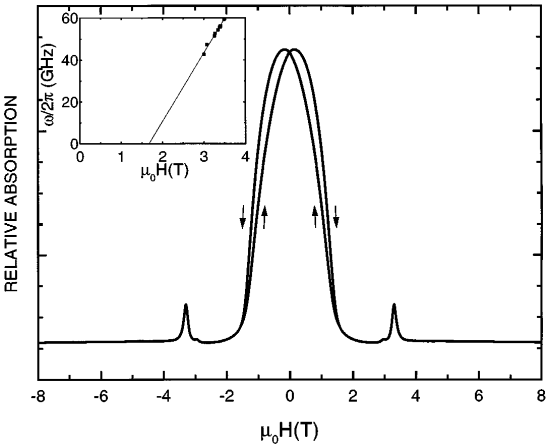

FIG. 3. Microwave absorption in the multilayer at $\omega/2\pi = 53$ GHz for a sweep of H from high positive field to high negative field and back. The rf absorption reveals a GMR-like signal at low fields and the resonance of zero-wave-number spin waves at $\approx \pm 3.3$ T. The inset shows the frequency shift of the spin-wave resonance.

multilayer. This peak was seen in all of our ESR scans. Additional peaks, such as the much smaller one closer to the origin in Fig. 3, were also resolved on some samples. The resonance condition for zero-wave-number spin waves for **H** applied perpendicular to a thin film is simply the ferromagnetic resonance condition $\omega/\gamma = H - 4\pi M_S$ [7], where $\gamma = g\mu_B/\hbar$ is the gyromagnetic ratio, and M_S is the saturation magnetization. The inset to Fig. 3 shows that the frequency of the zero-wave-number peak shifts linearly with H in agreement with this relation. The slope and intercept of the line give values of $4\pi M_S$ (1.66 T) and g factor (2.1) in good agreement with those expected for Co [9].

These microwave measurements show the presence of excitations with a well-defined energy (frequency) that is a linear function of H (inset of Fig. 3), a dependence similar to that of the current-driven excitations seen in the same samples. While our analysis of the microwave results is completely consistent with our point contact studies, it is not definitive, as similar behavior to that in the inset to Fig. 3 should occur simply for standard ferromagnetic resonances.

As a heuristic supplement to the analyses in [1,2], we explain what we observe using a simple model based upon conservation of energy and angular momentum. Since the excitation occurs for $H > H_S$, where all the layer magnetic moments are aligned parallel to **H**, we replace the multilayer by a homogeneous F film. As noted above, our point contacts involve diffusive electron transport; therefore the electrochemical potential μ may be defined at any point across the contact. In terms of the usual two-current model for an F metal [10,11], where spin-up and spin-down electrons carry current independently in parallel, two electrochemical potentials—of spin-up ($\mu_\uparrow$) and spin-down ($\mu_\downarrow$) electrons—may be defined, which need not be equal. When a current flows from N into F, its distribution over spin-up and spin-down current has to change [10]. There results a difference $\Delta\mu = \mu_\uparrow - \mu_\downarrow$—spin gap—on the scale of the spin diffusion length Λ from the F/N interface [12]. From the solution of the diffusion equation given by van Son, van Kempen, and Wyder [12], we deduce $\Delta\mu$ just at the F/N interface

$$\Delta\mu = ej\,\frac{2(2\alpha_F - 1)(\sigma_N^{-1}\Lambda_N)(\sigma_F^{-1}\Lambda_F)}{(\sigma_F^{-1}\Lambda_F) + 4\alpha_F(1-\alpha_F)(\sigma_N^{-1}\Lambda_N)}, \tag{1}$$

where j is the current density, σ_N and σ_F are N and F conductivities, Λ_N and Λ_F are spin diffusion lengths in N and F, α_F is the bulk spin asymmetry coefficient in F, and e is the electron charge. Choosing realistic parameters for Co/Cu [13]—$\alpha_F = 0.75$, $\sigma_N^{-1} = 5$ nΩm, $\sigma_F^{-1} = 50$ nΩm, $\Lambda_F \approx 50$ nm, $\Lambda_N \approx 500$ nm—we find $\Delta\mu(\mathrm{eV}) \approx 1.4 \times 10^{-12} j(\mathrm{A/cm^2})$. Only above a critical current density where $\Delta\mu(j) \geq \hbar\omega(H)$, is the emission of spin waves possible. The additional dissipative channel opened, gives an increase in resistance, such as that shown in Fig. 1. In contrast, raising H to a value high enough so that $\Delta\mu(j)$ becomes $<\hbar\omega(H)$ should lead to suppression of the excitations, and a decrease in resistance such as that shown in Fig. 2.

To produce the $\Delta\mu = \hbar\omega(H) = 0.2 \times 10^{-3}$ eV (for $\omega/2\pi = 50$ GHz) needed to excite the zero-wave-number spin-wave mode of Fig. 3 would thus require a minimum current density $j_m \approx 1.4 \times 10^8$ A/cm^2 at the contact location. But the excited F layer in our samples is separated from the contact by one or more layers, unavoidably damaged in the process of making the contact [4]. Current spreading between the contact and the F layer will decrease the effective j at the F layer, causing the required j_m to increase by as much as an order of magnitude. Such current spreading leads therefore to scatter in the critical current values and also in the resistance step values for different contacts (compare Figs. 1 and 2) as different fractions of the total current produce the excitations.

The current asymmetry of Fig. 1 is explained as follows: In the high magnetic fields where we see the excitations of present interest, the sample magnetization is saturated. Excitation of a spin wave requires a decrease in the magnetization. To satisfy conservation of angular momentum, the electrons crossing the F/N interface must increase their magnetization—i.e., flip their spins from down to up. Since conservation of energy requires $\mu_\downarrow > \mu_\uparrow$, the resulting sign of $\Delta\mu = \mu_\uparrow - \mu_\downarrow < 0$ requires the correct sign of $j < 0$ [see Eq. (1)].

We must also explain why such excitations have not been seen in point contact measurements on bulk F metals, where the energy threshold for excitation is the same as in a thin film. A local perturbation in the contact area should be much more efficient at exciting a normal mode (the spin-wave) in a very thin film than in a bulk sample.

Figure 4 shows that we sometimes saw more complex resistance excitations. This sweep was taken with $R_c = 22\ \Omega$ at $H = 0$ and $I = -1.6$ mA, corresponding to $j \approx 1 \times 10^9$ A/cm^2. Between the tail of the GMR structure at low fields, and the downward step in R_c at 6.4 T similar to what we described above, there are a series of both upward and downward steps in resistance, mostly with associated rapid fluctuations similar to telegraph noise in two-level systems [14]. While we tentatively attribute these additional features to the excitation of nonuniform magnetization structures in the F layers, their details are not yet sorted out.

To conclude, we have presented the first evidence of current-induced excitation of a F/N multilayer. We have shown that a diffusive point contact can be used as a spectrometer for magnetic excitations. We propose that the simplest excitations that we see, a simple step increase (with increasing V at high enough field) or decrease (with increasing H at high enough V) in resistance, are due to excitation or suppression, respectively, of zero-wave-number spin waves. This result is consistent with

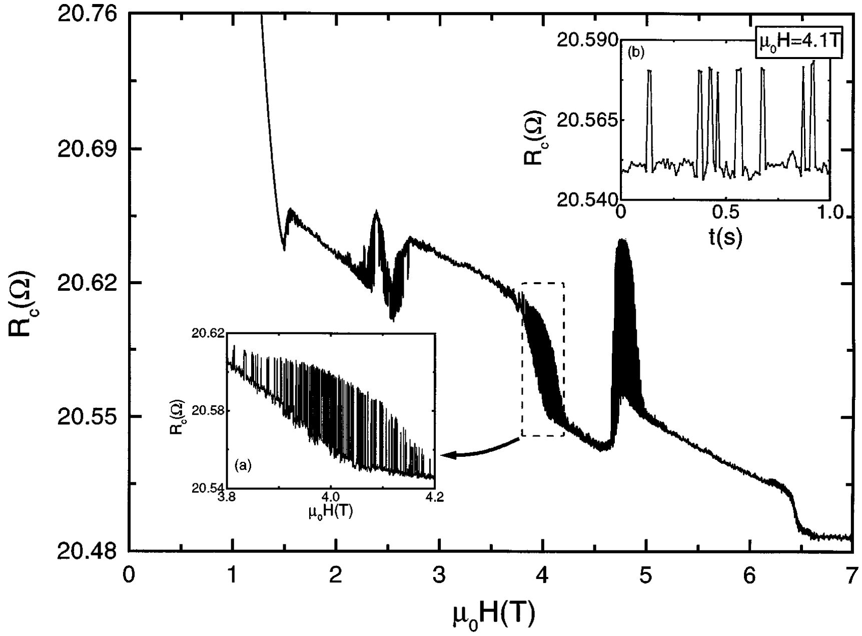

FIG. 4. An example of complex variations of $R_c = V/I$ versus H. This sweep was taken with $R_c = 22\ \Omega$ at $H = 0$ and $I = -1.6$ mA. Between the tail of the GMR structure at low fields, and the downward step in R_c at 6.4 T, there are a series of both upward and downward steps in resistance, mostly with associated rapid fluctuations similar to telegraph noise in two-level systems. The inset (a) zooms into the structure at ≈4 T. The inset (b) shows the time dependence of R_c at a constant magnetic field (4.1 T).

the analyses in Refs. [1,2] and with the supplementary heuristic model that we have presented. We have also shown evidence for more complex excitation structures that are not described by our simple model and that are less clearly related to Refs. [1,2]. To clarify whether these latter involve finite-wave-number spin waves, interactions between layers, etc., will require further studies.

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