Generation of current-driven magnons in Co/Cu multilayers with antiferromagnetic alignment of adjacent Co layers

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We study experimentally the current-driven magnon generation (CDMG) by a flux of spin polarized conduction electrons in magnetic multilayers. The usual prerequisite for CDMG in magnetic nanostructures is a sufficiently high spin polarization of the flux. Here we report observation of CDMG in Co/Cu multilayers by an electron flux with negligible spin polarization. The latter is mediated by antiferromagnetic alignment of adjacent Co layer magnetizations in our multilayers in zero applied magnetic field. We propose that in this case CDMG is produced by the Cherenkov radiation of magnons. By applying magnetic field perpendicular to the layers of our multilayer we could vary the direction of magnetization in the excited ferromagnet with respect to the magnon wave vector in the plane of the layers. The latter offers novel possibilities for calibration of microcontact spectrometer of magnetic excitations *in situ*. The Cherenkov radiation of magnons can be used for studying Fermi surface topology.

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Excitation of a ferromagnet from its ground state, where all spins are parallel due to exchange interaction, results in a generation of spin waves (or magnons). The reason for that are topological properties of the Landau-Lifshitz equation, which favor certain spatial spin configurations with minimum energy (configuration minimums). The latter defines the equilibrium state of an excited ferromagnet usually established via relativistic and spin-lattice interactions. In 1963 Akhiezer, Bar'yakhtar, and Peletminskii[1] suggested a novel mechanism for spin wave generation and amplification–spin wave irradiation by a flux of charged particles (the Cherenkov irradiation). The quintessence of Cherenkov irradiation is a strong interaction of a charged particle with an electromagnetic field of a wave when the particle moves in phase with the wave. In the latter case the particle enhances the wave amplitude. More complex, but in many respects similar phenomenon occurs if we consider a flux of charged particles, e.g., conduction electrons. For instance, the Cherenkov irradiation of phonons by conduction electrons is well known.[2]

In 1996 Slonczewski[3] and Berger[4] have suggested an alternative mechanism for magnon generation—transfer of spin angular momentum by an electric current. Following these pioneering predictions,[3–5] it was shown that injection of a large electrical current density into a magnetic multilayer results in current-driven magnon generation (CDMG).[6–13] This phenomenon has attracted considerable attention recently because it combines interesting fundamental science with the promise of application to high-speed, high-density magnetic recording and storage. The essential feature of CDMG is a sufficiently high spin polarization of the current needed to produce excitations.[3–5] In this paper we report on experimental observation of CDMG when spin polarization of the exciting current is negligible. We propose that in this case the basic mechanism for CDMG is the Cherenkov radiation of magnons.[1]

Our samples were sputtered $(\mathrm{Co/Cu})_N$ multilayers with bilayer number N ranging from 20–50 and layer thicknesses $t_{\mathrm{Co}}=1.5$ nm and $t_{\mathrm{Cu}}=2.0$-2.2 nm (for details see Refs. 6 and 14). In such samples indirect exchange interaction favors antiferromagnetic alignment of adjacent Co layers.[15] We excite spin waves, or "magnons," in Co layers[6,10] by means of a high current density ($\sim 10^9\ \mathrm{A/cm^2}$) injected into the multilayer film through a point contact between a sharpened Ag tip and the film (see Fig. 1). This experimental scheme is similar to the one used in Ref. 12, where the excited Co layer is laterally constrained by the pillar geometry of a nanofabricated device. In our case the excited ferromagnet is a small portion of a magnetic layer under the point contact, where the current density is high. At helium temperature (4.2 K) we have measured the current-voltage (I-V) characteristics, and their derivatives, of point contacts at different magnetic fields **B** applied perpendicular to the multilayer.

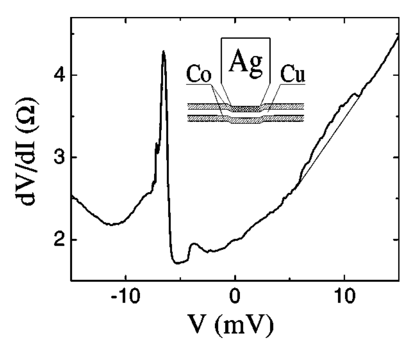

FIG. 1. The point contact $dV/dI(V)$ spectrum for $B=0$. CDMG occurs for *both polarities* of the applied voltage V (equivalent to I), but is strongly suppressed at positive Vs. The inset shows a resonator (shaded) initiated in the process of Ag tip installation onto the multilayer.

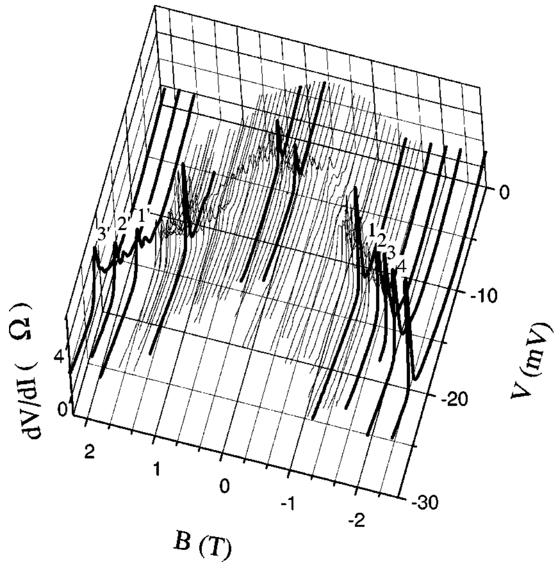

FIG. 2. The panoramic view of CDMG spectra (dV/dI vs V) for a series of applied fields B. Thick lines indicate spectra for ferromagnetic alignment of Co layers and those for resonances (see the text for details).

In high fields, larger than the saturation field B_S of the multilayer ($\approx$1.7 T), all Co layer magnetic moments are aligned parallel to **B**. CDMG is observed when sufficiently high current density is applied to the multilayer.[6,10,11] In low fields, where parallel alignment of adjacent Co layers is disturbed, there is usually no CDMG.[6] However, the situation may differ dramatically[11] if the excited ferromaget is a resonator (see the insert to Fig. 1), particularly due to the swaser effect.[3,10,11] Namely this case is the focus of the present work.

Figure 1 shows a CDMG spectrum (dV/dI vs V) at zero applied field. CDMG occurs at *both polarities* of the applied voltage $V=IR$, where R is the contact resistance, but is strongly suppressed at positive Vs. Moreover, a small nonzero $B \sim \pm 0.05$ T suppresses CDMG at positive Vs completely. To give a general sense of the observed phenomenon Fig. 2 shows a panoramic view of CDMG spectra for a B-sweep from 2.2 T to -2.6 T. Solid lines in Fig. 2 show the variation of the derivative contact resistance dV/dI as a function of V for a series of Bs. Some detailed characteristics of these spectra are presented in Figs. 3 and 4.

The $dV/dI(I)$ traces in Fig. 2 reveal a number of peaks (also at $|B| < B_S$) evolving with magnetic field in a regular fashion. Peaks of small amplitude may originate, in our view, from electron scattering at interfaces in our multilayered samples. This topic is out of the scope of the present paper and will be discussed elsewhere.[16] In the following we focus on the peaks of large amplitude. Figure 3 shows the values of $V^*(B)$ where we observe these peaks (found from the data in Fig. 2). Above B_s (parallel alignment of adjacent Co layers) the peak amplitude and location in V vary linearly with B in agreement with our previous results[6] (see peaks indicated by 1, 2, 3, 4, and $1'$, $2'$, $3'$ in Fig. 2). In contrast, below B_S the amplitude of peaks is nonmonotonic versus B. For instance, there are two maxima (resonances) at 0.15 and 1.18 T (thick traces in Fig. 2) for $B > 0$. At $B < 0$ the data reveal similar behavior except for some differences which are tentatively attributed to the magnetic hysteresis in our multilayer system.

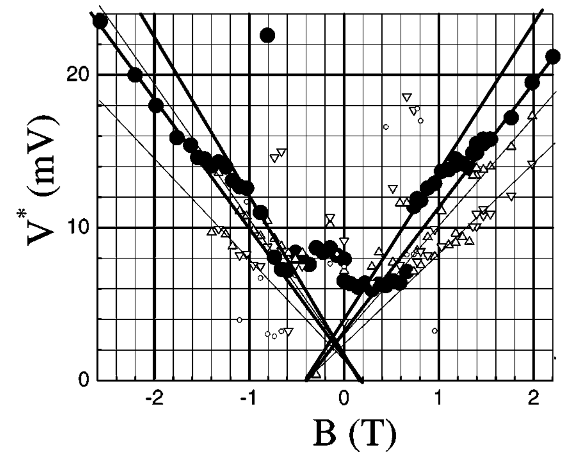

FIG. 3. CDMG phase diagram. Closed symbols show the values of $V(B)$ where we observe peaks of large amplitude in the $dV/dI(V)$ spectra of Fig. 2. Open symbols show $V(B)$ for smaller peaks. The sizes of symbols are indicative of the peak amplitude. Note that the singularities in contact resistance occur both above and below the saturation field of the multilayer ($\approx$1.7 T).

Figure 4 shows how the peak amplitude, point contact dV/dI resistance at $V=0$, and the square resistance of our multilayer film vary with B. Note that the square resistance of the film partially contributes to the total contact resistance.[14] Both contact and film resistances reveal the usual GMR signal at low fields. This signal can be used as a measure of the ferromagnetic order of Co layers in our multilayer. For instance an increase in resistance at low fields indicates that parallel alignment of adjacent Co layer magnetizations is disturbed below $\approx \pm 1.5$ T. A local magnetic order in the contact region may differ somewhat from that in the multilayer, however similar shapes of the contact and

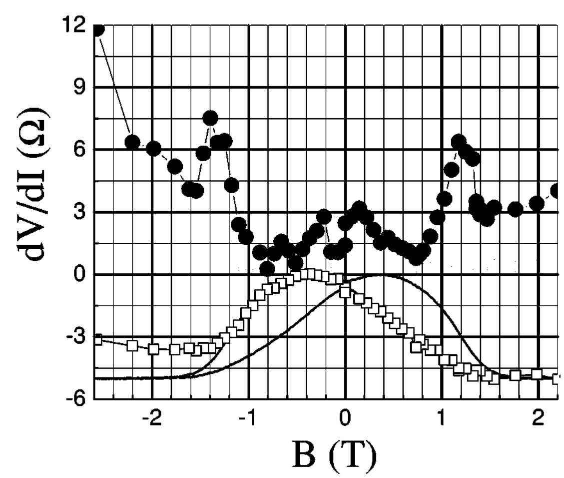

FIG. 4. Peak amplitude (●), $dV/dI(V=0)$ (□) and GMR (solid trace) vs B. $dV/dI(V=0)$ and GMR are normalized to show only qualitative behaviors. The arrows indicate directions of the field sweep.

film GMRs do not support such a hypothesis.

According to the original models[3–5] the essential prerequisite for CDMG is a sufficiently high spin polarization of the exciting current. The latter is usually achieved via passing the current though a ferromagnet F with a high intrinsic spin asymmetry α, which defines the current polarization. Our Co/Cu multilayer can be viewed as an effective ferromagnet where α depends on its internal magnetic configuration and is highest for the parallel alignment of adjacent Co layer magnetizations and negligibly small for the antiparrallel alignment. This assumption is justified for Co and Cu layer thicknesses much smaller than the corresponding spin diffusion lengths.[17,18]

In high fields ($B > B_S$) the effective α in our multilayer is high and the usual spin-transfer mechanism[3–5] controls CDMG. Here the critical voltage V^* where the CDMG peak appears shifts linearly with B (solid line in Fig. 3) in agreement with previous experiments.[6–13] In lower fields, however, smaller α should necessarily induce deviations from this linear dependence. Indeed Fig. 3 shows that V^* increases at ~ 1.2 T with decreasing B, but thereafter a linear decrease of V^* prevails (dashed line in Fig. 3). We argue that such a behavior is due to a change of the CDMG mechanism. Therewith we propose that the Cherenkov radiation of magnons is responsible for CDMG when spin polarization of the exciting current is low.

At very low fields ($B \ll B_S$) magnetizations $\mathbf{M}$ of adjacent Co layers lie essentially in the plane of the layers and aligned antiparallel to each other. In this limit the wave vector $\mathbf{k}_m$ of magnons excited by the current is almost parallel to $\mathbf{M}$ and their frequency is a factor $\sim 2^{1/2}$ smaller than that for $\mathbf{k}_m \perp \mathbf{M}$ at high fields ($B > B_S$).[10] Our experimental data are consistent with these predictions–transition from $\mathbf{k}_m \parallel \mathbf{M}$ to $\mathbf{k}_m \perp \mathbf{M}$ at ~ 0.8 T results in an increase of V^* by a factor $\sim 2^{1/2}$. This feature of CDMG can be used for calibrating our microcontact spectrometer of magnetic excitations *in situ*.

The coherent amplification (excitation) of magnons by a beam of charged particles has been predicted in Ref. 1. It is based on the phenomenon of the Cherenkov radiation,[1] which refers to strong interaction between a charged particle and an electromagnetic wave when the particle moves in phase with the wave. In the latter case the wave amplitude grows. We apply these results to the Cherenkov radiation of magnons by conduction electrons. The resonance condition for the magnon generation is given by

$$\boldsymbol{v}_D \boldsymbol{k}_m = \omega_m(\boldsymbol{k}_m) \tag{1}$$

where $v_D \sim I$ is the drift velocity of electrons and $\omega_m(\boldsymbol{k}_m)$ is the magnon frequency, or assuming quadratic dispersion

$$v_D \cos \beta = [\varepsilon_m/(2m_m)]^{1/2}, \tag{2}$$

where $\varepsilon_m = m_m(\gamma v_F I^* \cos \beta)^2/2$ is the kinetic energy of magnon, β the angle between v_D and $\boldsymbol{k}_m, m_m$ the magnon effective mass, and γ=const. In our experiments v_D is of the order of the spin-wave velocity ($\lambda_m \approx 10$ nm),[11] which implies $\cos \beta \sim 1$. In point contacts the current is initially injected normal to the layers, i.e., $\cos \beta \sim 0$. However a strong spreading of the injected current can account for the above discrepancy. Note that point injection of the current, strong electron reflection from interfaces,[19] and the Fermi surface topology in Cu[20] with "necks" along [111] direction, i.e., perpendicular to the layers in our samples, all enhance the current spreading.

We note that unlike beam of free particles, the flux of conduction electron is produced by nonequilibrium electrons or electron excitations near the Fermi surface. An in-depth theoretical study is needed to analyze our data in detail. We limit our discussion to the following qualitative arguments. For a fixed $\boldsymbol{k}_m$ the condition (1) can be fulfilled for different groups of electrons, i.e., at different currents. Due to a complex topology of the Fermi surface the flux of conduction electrons can contain multiple internal fluxes of high intensity. Such fluxes define, for instance, longitudinal electron focusing[21] and electron focusing in zero magnetic field[22] and can produce an enhanced Cherenkov radiation of magnons. The latter would result in a fine structure of microcontact spectra that ultimately can be used for studying the Fermi surface topology. Such a technique might be useful where conventional ones[23] fail as in the case of small scale samples where the electron de Brogli wavelength is comparable to the sample size and strong Fermi surface reconstruction occurs.[23] The details of the spectrum shown in Fig. 1 can, in principle, be explained by taking into account the Fermi surface reconstruction in our layered samples.

The Cherenkov mechanism for CDMG [Eqs. (1) and (2)] disregards all magnetic aspects of the phenomenon, e.g., a non-zero spin polarization of the exciting current. The latter is of crucial importance in the original models[3–5] where CDMG is strongly enhanced at one current polarity and completely suppressed at another one. Such a high sensitivity of CDMG to the current polarity in combination with nonzero residual spin polarization of the current in our experiments could explain the observed suppression of CDMG at positive V biases and resonances in peak amplitude at low fields (see Figs. 1 and 2). Note that (i) the density of spin-transfer per electron has a singularity when magnetizations of adjacent Co layers are antiparallel[3] and (ii) fluctuations of the layer magnetizations are increased near the transition from parallel to antiparallel layer ordering. Both these reasons should enhance CDMG by spin-polarized current and can account for the resonances at 0.15 T and 1.18 T, respectively.

A low spin polarization of the exciting current in low magnetic fields is a key point of our proposal. Ideally, the low spin polarization is mediated by the antiferromagnetic order of Co layer magnetizations, which is due to antiferromagnetic coupling (AFC) between the layers. In reality, the AFC is non-uniform over the multilayer; however, it should be relatively high on average to produce high GMR ratios. Namely GMR characterizes the average disturbance of the ferromagnetic order of Co layer magnetizations. This disturbance suppresses the spin polarization of exciting current. In our case the spin polarization of the exciting current is defined by a magnetic order in a large volume near the contact with a typical size of the order of the spin relaxation length ($\gg$ contact size). The crucial point is that an average magnetic order in this volume is similar to that of the whole film, otherwise GMR measured by point contact and that of the whole film would differ markedly. In contrast, the measured values are practically the same (see Fig. 4). There are a lot of other details (see above) supporting low spin polarization of exciting current in low field.

In summary, we have observed CDMG in Co/Cu multilayers at low external magnetic fields where spin polarization of the exciting current is negligible due to a strong disturbance of the ferromagnetic alignment of adjacent Co layer magnetizations. We propose that this generation is produced by the Cherenkov radiation of magnons. Techniques for calibration of microcontact spectrometer of magnetic excitations *in situ* and for studying Fermi surface topology are proposed.

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