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Spin dynamics in point contacts to single ferromagnetic films

O. P. Balkashin,[1] V. V. Fisun,[1,2] I. K. Yanson,[1] L. Yu. Triputen,[1] A. Konovalenko,[2] and V. Korenivski[2]
[1]*B. Verkin Institute for Low Temperature Physics and Engineering, National Academy of Sciences of Ukraine, 61103 Kharkiv, Ukraine*
[2]*Nanostructure Physics, Royal Institute of Technology, SE-10691 Stockholm, Sweden*
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Excitation of magnons or spin waves driven by nominally unpolarized transport currents in point contacts of normal and ferromagnetic metals is probed by irradiating the contacts with microwaves. Two characteristic dynamic effects are observed: a suppression of spin-wave nonlinearities in the point contact conductance by off-resonance microwave irradiation and a resonant stimulation of spin-wave peaks in the differential resistance of the nanocontacts by the microwave field. These observations provide direct evidence that the magnetoresistance peaks observed are due to gigahertz spin dynamics at the ferromagnetic interface driven by the spin transfer torque effect of the transport current.

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The pioneering predictions of spin transfer torque (STT) effects[1,2] have been confirmed in numerous experiments on ferromagnetic/nonmagnetic nanostructures. Most of the experiments have been performed on spin valves where the current, spin polarized by a hard ferromagnetic layer of normalized magnetization $\mathbf{m}_2=\mathbf{M}_2/M_s$, produces a spin torque on a magnetically soft layer resulting in a precession or switching of the soft layer's magnetization ($\mathbf{m}_1$). Due to the effect of giant magnetoresistance[3] these switching and precession are translated into either abrupt hysteretic changes in the resistance of the trilayer[4,5] or an ac voltage at the frequency of the magnetization precession.[6–8] The oscillation frequency is a function of the magnitude of the driving current—the effect considered to be highly promising for current controlled oscillators for use in microelectronics.[9] This spin-dynamic effect is often analyzed in the macrospin approximation[2,10] using the Landau-Lifshitz-Gilbert-Slonczewski equation,[2] in which the torque caused by a spin polarized current of magnitude I, counteracting the intrinsic damping torque, is

$$(d\mathbf{m}_1/dt) \propto I\eta(\Theta)\mathbf{m}_1 \times [\mathbf{m}_1 \times \mathbf{m}_2]. \tag{1}$$

Here $\Theta=\cos^{-1}(\mathbf{m}_1\cdot\mathbf{m}_2)$ reflects the degree of the magnetization misalignment for the two layers and $\eta(\Theta)$ reflects the effective spin polarization in the system.[10] Thus, the current, spin polarized by $\mathbf{m}_2$, produces a torque on $\mathbf{m}_1$, which can compensate for the intrinsic dissipation in $\mathbf{m}_1$ and lead to stationary gigahertz-range oscillations. Depending on the magnitude of the current, the associated STT can increase or decrease the amplitude of the oscillation.[6–8,10]

Several recent experiments observed STT effects in mechanical 10 nm range needle/surface contacts[11] as well as 50 nm range lithographic contacts[5,12] to single continuous ferromagnetic films. Our previous experiments on such magnetic point contacts (PC)[13] have demonstrated the same static magnetoconductance properties as those found in spin valves and confirmed the mechanism of the effect to be due to energetically distinct atomically thin surface spin layers. The spin misalignment (Θ) in this *single magnetic layer* case is due to spatial spin perturbations at the interface within the contact core. In this Brief Report we report an observation of two spin-dynamic effects in the conductance of magnetic point contacts, which directly demonstrate the spin precessional nature of the phenomenon.

We study point contacts formed nanomechanically between sharpened needles of Cu or Ag and Co films with thicknesses of 5, 10, and 100 nm. The Co films were deposited in ultrahigh vacuum on oxidized Si substrates buffered with a 100 nm thick layer of Cu. A subset of the samples was capped with a 2–3 nm thick layer of Cu or Au to prevent natural oxidation of Co. The schematic of the experiment is shown in the inset of Fig. 1. Point contacts were formed directly in a liquid He bath using a two-axis micropositioning mechanism allowing us to scan the surface in selecting the contact location and gradually vary the mechanical strain on the needle. The resistance of the point contacts varied from 5 to 30 Ω, which when using the standard formula[14] corresponds to a diameter range of 20 to a few nanometers. Differential resistance $dV/dI(V)$ was measured using a lock-in technique, with the modulating current amplitude of 10–50 μA and frequency of 443 Hz. The negative dc bias polarity corresponds to the electron current flowing from the needle into the film. An external magnetic field of up to 5 T was applied either in or perpendicular to the plane of the films. The microwave radiation was supplied by directly connecting a coaxial cable to the point contact electrodes and decoupling the dc and HF circuits using a bias tee (as shown in the inset of Fig. 1). We have also used a radiating loop at the end of the coax, which yielded essentially identical results. This is to be expected for the point contact spectroscopy (PCS) technique used, where the needle (top contact) acts as an efficient antenna at gigahertz frequencies, convert-

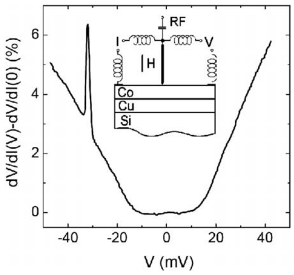

FIG. 1. Relative differential resistance for point contacts of a Cu needle and a 100 nm thick Co film, $R_0=7.2\ \Omega$, $H_\perp=4$ T. The inset shows the schematic of the experiment.

ing microwaves into an ac and vice versa. The maximum rf power in the contact region was estimated to be a few tens of microwatts. The results we report did not depend on the material of the nonmagnetic needle. In what follows, we present the data collected using needles of Cu.

The measured differential resistance exhibited peaks, characteristic of the STT effect in normal/ferromagnetic structures. The peaks observed at negative bias, such as those shown in Fig. 1, are not caused by the effect of the Oersted field of the bias current, which should be symmetric with respect to the bias polarity. The position of the peak on the bias axis changed linearly in proportion to the applied field magnitude, indicating its magnetic origin (see also Refs. 4, 12, and 13). Such a sharp increase in the resistance is highly reproducible for a given contact and, in the multilayer case, has been conclusively identified as due to a thresholdlike activation of the magnetization precession (spin wave) or a change in the magnetization precession angle (a transition into a different precession mode[8]).

We observe two distinct effects in the response of such N/F point contacts to a microwave radiation of varying frequency and power: a rectification of off-resonance microwaves by the magnetic nonlinearities in the conductance (magnetization precession is caused by the dc) and a resonant stimulation of the differential resistance peaks by the microwave field (magnetization precession is caused primarily by the ac field). The measured point contacts differed in their microscopic and micromagnetic properties, such as the local stress and anisotropy and the exchange field profile in the contact core, as well as the external field strength and direction. Among hundreds of point contacts measured in this study, ~50% showed current-induced spin-wave peaks in the differential resistance and ~10% pronounced *microwave-field stimulated* spin-wave peaks. These observations unambiguously identify the origin of the phenomenon as a spin precession at the *single* ferromagnetic interface within the point contact core.

Figure 2(a) shows the effect of the rf power of frequency $f=\Omega/2\pi=2$ GHz on the amplitude and shape of a magnetoconductance peak for a Cu-Co(100 nm) point contact measured in an in-plane magnetic field of 1.82 T. The magnetic origin of this conductance peak is confirmed by the field dependence of its position shown in the inset, quite similar to the behavior of the STT peaks in conventional spin valves. The initial sharp peak in dV/dI (curve 1) is suppressed and broadened as the rf power is increased to 24 μW.

The rf power level near the PC was estimated by measuring the transmission coefficient of the coaxial line. A further increase in the irradiation power leads to a splitting of the peak. We observed such behavior versus rf power in many contacts and find it to be highly characteristic of the spin-wave peaks in dV/dI.

To model this behavior we use the theory in Ref. 15 for rf irradiated nonmagnetic point contacts, where the nonlinear conductance is due to electron-phonon scattering. The results from this work are applicable to any point contacts where the conductance is due to one electron process. In particular, a good agreement with the experiment has been obtained for superconducting tunnel contacts, semiconductor/metal, and superconductor/normal metal, as well as all metal point contacts.[16,17]

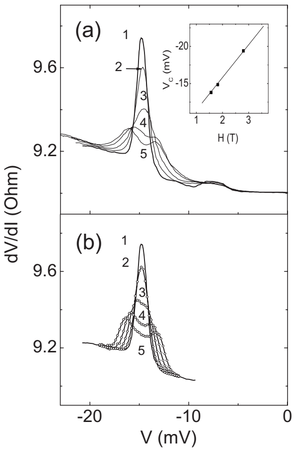

FIG. 2. (a) dV/dI as a function of bias for a point contact of a Cu needle and a 100 nm thick Co film under irradiation with frequency of 2 GHz and powers $P=0$, 12, 24, 36, and 48 μW (curves 1, 2, 3, 4, and 5, respectively). (b) Calculated dependence according to Eq. (2) for $V_1=0.5$, 1, 1.5, and 2 μV (curves 2, 3, 4, and 5, respectively). Curves 1 in (a) and (b) are identical. Inset: critical voltage (STT peak position) as a function of the external field.

In the case where a constant bias V_0 is superposed with a weak ac signal V_1 of frequency Ω induced in the contact by an applied rf power, $V(t)=V_0+V_1\cos\Omega t$, the time-averaged current-voltage characteristic (IVC) is given by[15,16]

$$\bar{I}(\bar{V}) = (\Omega/\pi)\int_0^{\pi/\Omega} I_0(V_0 + V_1 \cos \Omega t)dt, \tag{2}$$

where $I_0(V_0)$ is the unperturbed IVC in the absence of rf. It is assumed that the frequency is low compared to the inverse of the characteristic electron relaxation time producing the nonlinearity and that the system is not in resonance. These conditions require that the energy of the rf photons is much lower than the width of the nonlinearity in the IVC and that $I_0(V_0)$ is not affected by the microwaves directly but only through $V_0 \rightarrow V_0+V(t)$ as given by Eq. (2). In our experiment $\hbar\Omega \sim 10^{-2}$ meV, indeed much smaller than the peak halfwidth in Fig. 2 (~1 meV). Equation (2) is the well-known result for a classical detector[16] describing ac rectification by an *off-resonance* conductance nonlinearity. The unperturbed $I_0(V_0)$ is obtained by integrating the experimental $dV/dI(V)$ measured without irradiation [curve 1 in Fig. 2(a)]. Equation (2) is then used to obtain the IVC expected under irradiation, with a subsequent numerical differentiation to obtain the predicted differential resistance. Thus calculated dV/dI for several amplitudes of the ac voltage across the contact, $V_1^2 \sim P$, are shown in Fig. 2(b). Curves 1 in Figs. 2(a) and 2(b) are identical. A good agreement between the measured data and the predicted behavior is obtained [curves 2–5 in Figs. 2(a) and 2(b)], which allows us to conclude that the effect observed is a rectification of the off-resonance microwave current by the magnetic nonlinearity in the conductance of the nanocontact.

A number of contacts showed a distinctly different behavior. A sharp peak in the differential resistance appeared only under rf irradiation in an otherwise monotonously increasing dependence, as illustrated in Fig. 3. This peak is analogous in shape to the one discussed above (Figs. 1 and 2) and was

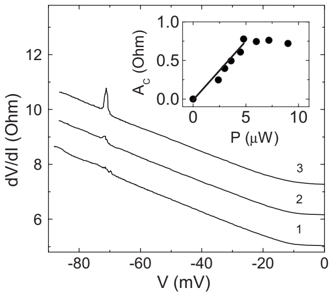

FIG. 3. Spin-wave peak in dV/dI stimulated by increasing the power of irradiation at 2 GHz for rf powers $P=0$, 2.4, and 3.6 μW (curves 1, 2, and 3, respectively). The curves are shifted vertically by 1 Ω for clarity. The contact is Cu-Co(100 nm), $R_0=5.04$ Ω, and $H_\perp=2.47$ T. The inset shows the amplitude of the induced peak as a function of rf power.

observed only for negative bias polarity. The effect was completely reversible, with dV/dI returning to its original monotonous form after the rf irradiation was removed. For some contacts the original dependence showed a small irregularity in the same region of bias where later a pronounced peak would develop under irradiation (curve 1). Other contacts with rf-induced peaks showed no signs of any singularity in the differential resistance in the rf-unperturbed state. The amplitude of the induced peak increased approximately linearly with the rf power in the low power range, then saturated at higher power, as shown in the inset of Fig. 3. Such behavior is expected for a transition from a low- to a high-angle magnetization precession with increasing excitation power. It results in a saturation of the effective precession angle, analogous to the spin response in the ferromagnetic resonance (FMR). Thus, a large angle precession of the spins localized to the point contact core at the surface of the ferromagnetic film, with the spins outside the core being essentially static, produces an additional magnetic contribution to the resistance through the PC core-film domain-wall magnetoresistance.

For one typical point contact exhibiting a spin-wave peak, we have performed a detailed spectroscopic study in the frequency range of 1–12 GHz. The amplitude, A_c, of a magnetoresistance peak induced by microwave irradiation is shown in Fig. 4 as a function of the irradiation frequency for two values of the rf power, 4 dB m (1–12 GHz) and 10 dB m (7–12 GHz), measured at the output of the generator. The higher power allowed us to enhance the measured signal, which was then linearly scaled down to 4 dB m for a direct comparison. The data are mainly scattered in the vicinity of two frequencies, 3.9 and 7.8 GHz, where the peak amplitude is greatly enhanced. The dependence is thus highly nonmonotonic—no peaks are observed for irradiation at <1 GHz or >10 GHz. The spread in the A_c data is significant as can be seen from the data at 3 and 6 GHz, for which several measurements (I-V sweeps) were performed for a given frequency. Taking into account this amplitude spread, only two main peaks in frequency can be distinguished with sufficient certainty. These observed broad peaks at 3.9 and 7.8 GHz are likely due to the first and second harmonics of a resonant spin excitation in the nanocontact core, where the STT is maximum due to the high current density. These spin excitations must consist of a whole spectrum of spin-wave modes since the spin distribution in the contact is expected to be nonuniform, resulting in broad resonance peaks. The experimental A_c values are consistent with two Lorenzian maxima and qualitatively reflect the frequency dependence of the magnetization precession intensity. The fact that the rf-stimulated peaks are excited by specific frequencies is evidence for the resonant character of the irradiation effect observed.

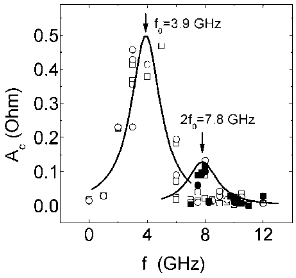

FIG. 4. Amplitude of a spin-wave peak for a Cu-Co(10 nm) contact with $R_0=6.7$ Ω as a function of the rf for $P_{\mathrm{rf}}=4$ and 10 dB m, open and solid symbols, respectively. Circles and squares correspond to the positive and negative bias sweep directions. $H_\parallel=1$ T. Lines are Lorenzian peaks approximating the data, with characteristic frequencies f_0 and $2f_0$.

The observed resonance frequencies of 1–10 GHz discussed above are too low if the resonating object was a uniformly magnetized film in a field of 1 T. However, the phenomenon studied in this work differs in a principal way from the uniform film FMR and therefore from the majority (if not all) work on spin torques in multilayers (see Ref. 18 for a recent review, including spin-valve-type point contacts). The spin perturbation (nanodomain, surface layer, or spin vortex) at the core of the point contact, responsible for the magnetotransport observed, is ~10 nm in diameter in our case and is significantly different in magnetic properties from the bulk of the ferromagnetic film. This difference can be due to a number of factors, such as potentially high mechanical stress in the point contact core, appreciable magnetostriction (in Co), and as a result potentially large magnetic anisotropy which can vary significantly in strength and direction from contact to contact. It is therefore not surprising that the HF properties are different from those of the uniform FMR of the underlying ferromagnetic film.

Thus, in addition to the *off-resonance rf rectification* effect, we report an observation of a *resonant absorption* of rf radiation by spin precessional modes in the presence of spin transfer torques for single ferromagnetic interfaces. The interpretation of the effect is as follows. When the frequency of the rf field f equals the frequency of the magnetization precession f_0—a function of the magnitude of the bias current through the contact and the applied magnetic field—a resonant increase in the amplitude of the precession occurs, corresponding to a transition from predominantly stochastic oscillations to a stationary precession. Taking into account the highly nonlinear nature of the system, the resonance condition is $mf \approx nf_0(V_0,H)$, where m and n are integers. The energy of the spin subsystem in the contact core increases when this resonance condition is met, which leads to a new precessional state with a different trajectory, amplitude, and

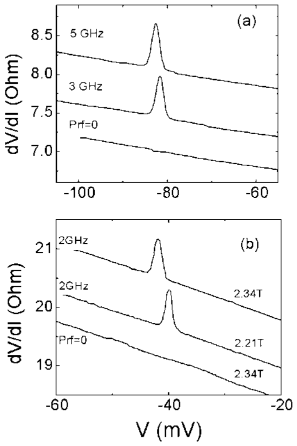

FIG. 5. Differential resistance versus bias voltage for point contacts with (a) $R=6.7\ \Omega$ for $f=3$ and 5 GHz and (b) $R=18\ \Omega$ for $f=2$ GHz, $P_{\mathrm{rf}}=0$ and 4 dB m.

axis of precession of the spins involved. This causes a sharp change in the domain-wall magnetoresistance of the contact seen as a peak in dV/dI at the critical bias V_C (or I_C) corresponding to the resonance condition. Therefore, the critical bias parameters of a magnetic point contact in resonance with an rf field are a function of the frequency of the field.

In this interpretation a higher externally applied magnetic field would create a higher effective magnetic field in the point contact, which would then correspond to a higher characteristic precession frequency. Thus, magnetic field and rf should be expected to shift the position of resonant spin-torque peaks in a similar fashion. This is indeed observed. Figures 5(a) and 5(b) show the differential resistance for two resonant STT peaks (absent without rf irradiation), where in one case the peak is shifted to high bias by increasing the rf and in the other by increasing the external magnetic field. These field and frequency transitions are fully reversible, and the peaks vanish when the rf is switched off.

Spin-wave excitations in point contacts to Co/Cu multilayers stimulated by 50 GHz range microwaves were reported in Ref. [19]. No off-resonance ac rectification effects were observed. The shape of the rf-induced features reported in Ref. [19] is also significantly different from the simple resonance like the maxima we report. It will be informative to mention that our tests on point contacts to *multilayer* films of Co/Cu revealed essentially identical spin-torque effects to those found in single layer contacts, showing no dependence on the thickness of the ferromagnetic films down to a few nanometers. This strongly suggests that the effects under consideration are dominated by spin-wave excitations in the nanocontact core in the immediate vicinity of the normal/ferromagnetic interface. This is especially true for point contacts of high resistance, $R \gg 1\ \Omega$, much greater than the "bulk" resistance of the metallic multilayer, where the layered structure should contribute insignificantly to the measured total resistance. Our spectroscopic study of spin-torque-driven hysteresis in point contacts to nanometer-thin ferromagnetic films[13] is additional evidence for the interface rather than bulk nature of the effects discussed herein.

We would like to point out that the technique of point contact spectroscopy is unique as it allows us to study transport in sublithographic, often atomic or near-atomic structures. However, as detailed above, the point contacts created can vary significantly in their properties. In this case it is the magnetic anisotropy and the exchange field profiles that are most relevant. Such a spread in properties can be a disadvantage in terms of exact *a priori* control of the nanocontact. In our case of many different nanocontacts analyzed *a posteriori*, the result is an advantage—we are able to distinguish two broad types of behavior: resonant and nonresonant. In one case the "spin dot" created in the contact core can resonantly absorb radiation of a specific frequency and start a large angle precession which results in substantial magnetoresistance (appearance of a STT peak). In the other case, an existing STT peak is suppressed in a predictable way by an off-resonant irradiation (of sufficient power, nonspecific in frequency).

In conclusion, we have probed the high frequency dynamics of the current-induced spin excitations in point contacts to single ferromagnetic films by irradiating the contacts with microwaves. The observed STT-induced spin-wave excitations are shown to be of resonant spin precessional nature. We further show that such spin excitations rectify off-resonance rf current as theoretically expected. Thus, we demonstrate that the effect under consideration is the same in its spin-dynamic character as the STT driven spin dynamics in spin valves.

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