

Spectroscopy of Phonons and Spin Torques in Magnetic Point Contacts

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Phonon spectroscopy is used to investigate the mechanism of current-induced spin torques in non-magnetic/ferromagnetic (N/F) point contacts. Magnetization excitations observed in the magnetoconductance of the point contacts are pronounced for diffusive and thermal contacts, where the electrons experience significant scattering in the contact region. We find no magnetic excitations in highly ballistic contacts. Our results show that impurity scattering at the N/F interface is the origin of the new single-interface spin torque effect.

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Electrical point contacts are known to be an efficient tool for studying electronic scattering in conductors, taking place on the nanometer length scale [1]. High electrical current concentrations that can be obtained in nanoconstrictions allow us to discriminate various electronic relaxation mechanisms in the system. Three regimes of electron current flow through a point contact are distinguished, depending on the size of the contact in relation to the characteristic scattering lengths. A ballistic regime occurs for very small contacts, with the size smaller than any scattering length in the material. In this case, the resistance of the system does not depend on any material specific dissipation and is determined purely by the geometry [the so-called Sharvin resistance [2]]. A diffusive regime corresponds to a significant elastic scattering of electrons on impurities in the point contact area, with the inelastic electron scattering length still exceeding the size of the contact. Finally, a thermal regime occurs for relatively large contacts where both elastic and inelastic scattering of electrons take place within the contact, leading to a significant local heating.

Electron transport in magnetic point contacts has become a focus of intense theoretical and experimental study after the seminal predictions that the magnetization of an inhomogeneous ferromagnet can be strongly affected by a current of high density [3,4]. The electron spin plays the role of a mediator, transferring magnetization between noncollinear ferromagnetic regions, which can lead to current-driven magnetization precession as well as switching. These magnetic excitations in turn affect the transport through the giant magnetoresistance effect [5]. Current-induced magnetization precession and switching have been observed in a number of experiments on magnetic multilayers [6–11]. It has recently been proposed that such current-induced magnetization excitations should occur even for single ferromagnetic layers [12,13]. The new mechanism, in contrast to that of [3,4], relies on spin

transfer in the direction normal to the current flow. The spin transfer is mediated by electrons, which are spin-dependently reflected from the N/F interface, as illustrated in Fig. 1(a). The spin-dependent reflection can be viewed as a transfer of a magnetic moment δm_1 from the ferromagnet to the backscattered electron, which becomes spin polarized. Impurities in N scatter this electron back at the interface. The second incidence at the N/F interface results in a spin transfer between point 1 and point 2 of the interface [see Fig. 1(a)], such that $\delta m_1 \neq \delta m_2$. It is predicted that such transverse spin transfer mediated by backscattered electrons at the two interfaces of thin ferromagnetic layers having asymmetric normal metal electrodes can

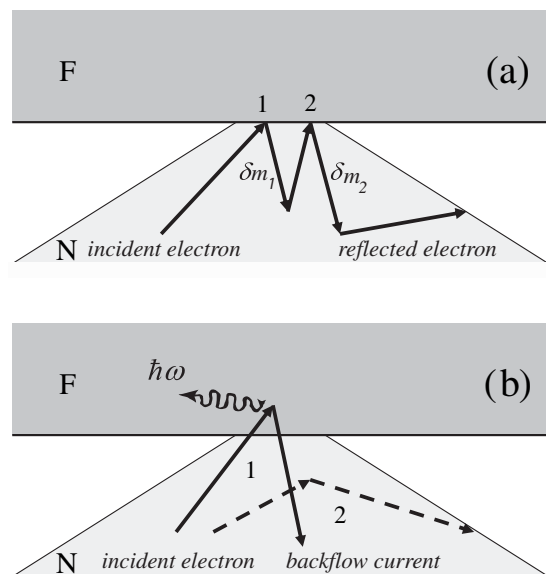


FIG. 1. Schematic of: (a) the single-interface spin transfer mechanism (here between points 1 and 2 of F); (b) inelastic phonon scattering in ballistic (trajectory 1) and diffusive (trajectory 2) point contacts.

result in a net spin torque, sufficient for exciting spin waves in the direction normal to the current flow [12]. It is also predicted that, even in the absence of such two-interface asymmetry, magnetic excitations can occur if the spin distribution in F at the N/F interface is nonuniform [13]. Such single-layer, or single-interface, spin torques have been used to interpret singularities in the differential resistance of N/F point contacts and nanopillars reported recently [14,15].

The key feature in the above single-interface effect is the electron backscattering on impurities near the N/F interface. Another phenomenon originating from the backscattering of electrons in point contacts is inelastic relaxation, which constitutes the basis of point contact spectroscopy (PCS) [1]. PCS resolves relatively rare inelastic scattering events for electrons having excess energy controlled directly by the voltage applied to the contact [16]. Such scattering events induce a backflow electron current, represented by trajectory 1 in Fig. 1(b). The second derivative of $I(V)$ —the so-called point contact spectrum—reflects the energy dependent coupling of the conduction electrons with the elementary excitations in the material. Interactions of electrons with phonons, magnons [17], and other excitations in metals, semiconductors, superconductors, and magnets have been successfully studied using PCS [1]. In contrast to the single-interface spin torque effect, impurity scattering of electrons affects point contact (PC) spectra destructively, diminishing the backflow of phonon-scattered electrons [see trajectory 2 in Fig. 1(b)]. The result is less pronounced PC spectra (phonon peaks) as the mean free path is reduced and becomes smaller than the size of the contact. Thus, PC spectrum is a direct probe of the intensity of impurity scattering in a point contact.

A direct experimental verification of the new mechanism of spin torque, induced by backscattered electrons, would probe independently the strength of impurity scattering at the N/F interface and correlate it with the strength of the magnetic excitations. In this Letter we present such a study using PCS, correlating the regime of current flow with the magneto-conductance. Our results clearly show that the current-induced magnetization excitations are pronounced in the diffusive and thermal regimes and are practically absent in the ballistic regime. This observation is a direct evidence of the impurity origin of the single-interface spin torque effect, and serves as a clear demonstration of the theoretical predictions [12,13].

The current-voltage characteristic (IVC), $I(V)$, and its first, $dV/dI(V)$, and second, $d^2V/dI^2(V)$, derivatives were measured for heterocontacts between needle-shaped non-magnetic Cu and Ag and ferromagnetic Co in both bulk and film form. The film samples were 100 nm Co layers on 100 nm of Cu, acting as the bottom electrode, both e beam evaporated onto oxidized Si substrates. Most contacts were made using a sharpened 0.15 mm diameter Ag wire, with the micro-positioning and contact pressure controlled from

outside the cryostat. All measurements were done at 4.2 K, with the contacts created and measured directly in liquid helium. We have recorded hundreds of PC spectra, which are illustrated and analyzed below.

Figure 2 shows PC spectra, $R^{-1}dR/dV \propto d^2V/dI^2$, of Co/Cu(Ag) heterocontacts, which, according to theory [18], represent a sum of partial contribution of both metals. The spectra have the usual form of symmetric about $V = 0$ extrema, observed at voltages corresponding to the maxima of the electron phonon interaction (EPI) function in Co and Cu or Ag [1]. The intensity of the phonon peaks varies depending on the exact position of the N/F boundary with respect to the narrowest point of the nanoconstriction [typically ~ 10 nm [19]] as well as on the strength of EPI of the interfaced metals. The spectra showed predominantly Co peaks located at approximately 19 and 33 meV, in agreement with earlier point contact investigations [20]. This indicates that the N/F interface was within the point contact since the strength of EPI in Co is several times higher than that in the noble metals [20], the effect favoring the Co spectral contribution in a symmetric contact. Infrequent spectra, dominated by Cu or Ag phonon peaks, are illustrated by curves 1 and 2 in Fig. 2 and indicate a deeper penetration of the noble metal in to the Co electrode. Curve 3 illustrates the intermediate case, where the phonon features of both metals are resolved. The S- and N-shaped features near zero bias are typical for scattering on magnetic impurities [likely Co atoms in N—the so-called Kondo anomaly [1]]. Thus, the spectra provide detailed information on the composition and purity of the contacts.

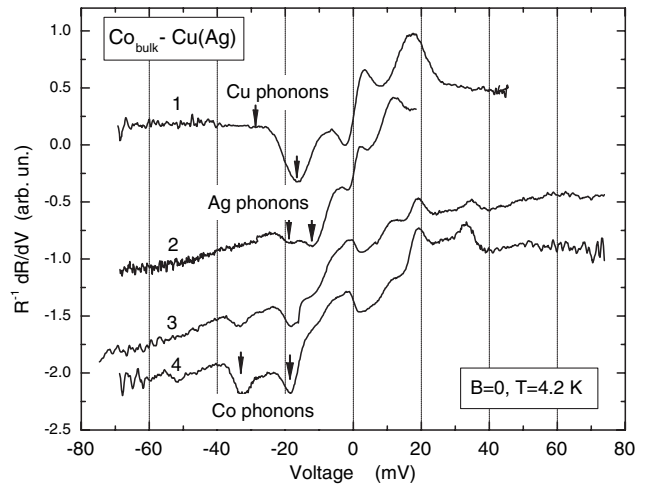


FIG. 2. PC spectra of heterocontacts between bulk Co and Cu (curve 1, $R = 31.5 \Omega$) or Ag (curve 2 and 3, $R = 5.7 \Omega$ and $R = 8.1 \Omega$) in zero magnetic field. Curve 4 is the spectrum of a contact with $R = 5.2 \Omega$ between a 100 nm Co film and a Cu needle. The modulation voltage is $V_1 \approx 1$ mV rms. The curves are offset vertically with respect to curve 1 for clarity. The arrows indicate the positions of the main phonon peaks of the corresponding metals [see [1]]. The spectra are independent of field.

The same spectral features were observed for point contacts to Co films, as illustrated by curve 4 in Fig. 2.

Figure 3 shows a PC spectrum for a point contact between a bulk Co sample and a Cu needle. The electron current flow is nonballistic as witnessed by the smeared out kink at positive bias of about 16 mV, which is characteristic for Cu phonons [1] in a nonspectroscopic regime (close to the thermal regime). Two maxima in dV/dI , clearly resolved as N-shaped features in the second derivative, are observed on the negative bias branch, corresponding to electrons flowing into the ferromagnet. These maxima are similar to those reported recently [14] and correspond to steps in the static resistance of the contact of typically several percent. Their width in bias voltage is smaller than the spectral resolution for the modulation used, indicating their threshold rather than spectral character. They are shifted to high bias by magnetic field, as shown in the inset to Fig. 3, with a slope of 0.3–1 mA/T typical for other spin torque studies [11,14]. Field sweeps at fixed near-threshold bias produce characteristic bell-shaped magnetoresistance (not shown). All these features point to magnetic excitations as the origin for the observed effect. Similar to [13,14] we assume a nonuniform spin distribution in F near the point contact, induced or enhanced by the high density current through the contact, which in turn gives rise to magnetoresistance. The characteristic length scales in Co (the exchange length, spin diffusion length, domain wall thickness) are all shorter than 100 nm, so spin profiles in the point contact region (~ 10 nm in size) for bulk Co and 100 nm Co films are expected to be essentially the same.

It is interesting to compare point contacts having nearly equal resistance, and therefore same current density in the nanoconstriction, but different electron flow regimes. Such a comparison is shown in Fig. 4 for three contacts to both bulk and film Co. The N-shaped magnetic peaks are pro-

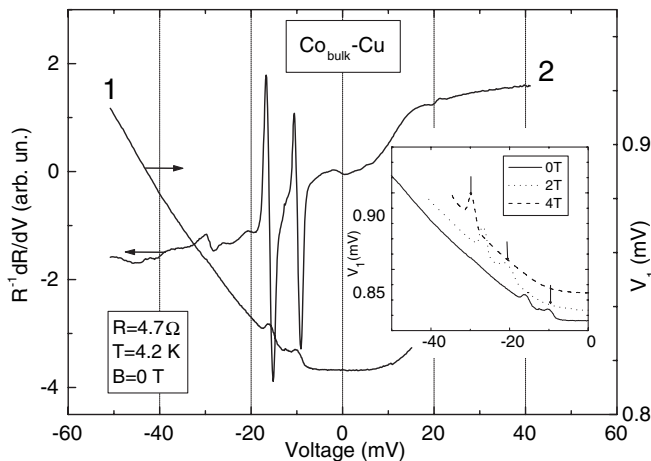


FIG. 3. First (1) and second (2) derivatives of the IVC for a heterocontact of bulk Co-Cu, $R = 4.7 \Omega$. Inset shows the dependence of the first maximum (shown by arrows) in modulation voltage $V_1 \propto dV/dI$ on external magnetic field.

nounced for the diffusive contacts (having weak phonon features and high background levels, solid lines) and practically absent for the ballistic contacts (having well-resolved phonon peaks and relatively low background levels, dashed lines). These data clearly show that, for a given current density, the probability of observing current-induced magnetic excitations is determined by the strength of the impurity scattering in the contact near the N/F interface. This observation is qualitatively the same for bulk Co and Co films, which indicates that the observed behavior is a single-interface effect.

The above conclusion on the role of impurity scattering in the single-interface spin torque effect is supported by our measurements on a large number of point contacts. The statistics of observing magnetic excitations is shown in Fig. 5 as a function of the spectral quality of the contacts. The latter is characterized by a phenomenological γ parameter, the inverse of which is the strength of the phonon peaks relative to the background (see the inset to Fig. 5). The probability of observing the current-induced magnetic excitations for ballistic ($\gamma < 1$) versus nonballistic

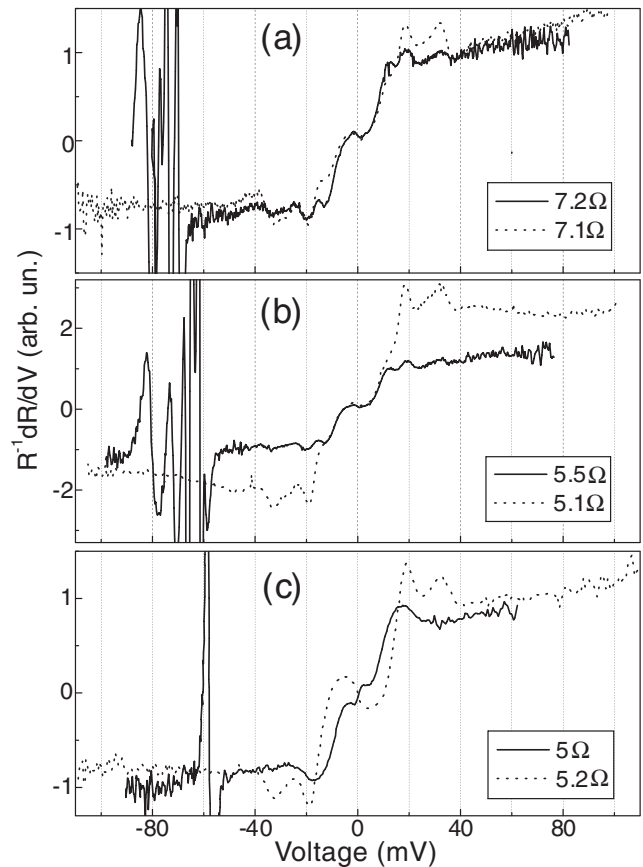


FIG. 4. A comparison of the PC spectra for pairs of contacts of nearly equal resistance but different current flow regimes: (a) and (b) spectra between bulk Co and Ag taken in zero field; (c) spectra between 100 nm Co film and Ag (solid line, $B = 3$ T) or Cu (dotted line, $B = 4$ T). The threshold current density for the magnetic peaks is $5 - 6 \times 10^9$ A/cm².

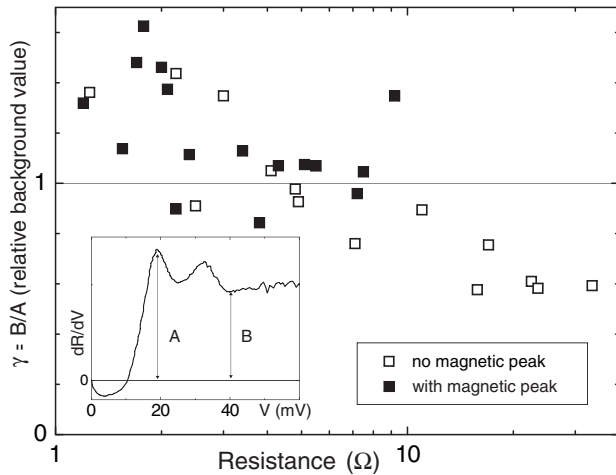


FIG. 5. Background value γ for point contact spectra with magnetic peak(s) (solid squares) and without magnetic peak(s) (open squares). Inset: γ is the ratio of the background intensity at around 40 mV to the intensity of the main phonon maximum at around 20 mV (Co).

(diffusive or thermal, $\gamma > 1$) contacts clearly demonstrates that the ballistic regime disfavors spin transfer torque effects (open squares). Note that a diffusive character of current flow through a contact may not be a sufficient condition for occurrence of magnetic instabilities. The relatively rare diffusive contacts without magnetic peaks ($4/17 \approx 24\%$ for $\gamma > 1$) may result from some unfavorable spin distribution in the ferromagnet [a nonuniform, domainlike spin distribution is required for observing magneto-conductance [14]]. On the other hand, among hundreds of point contacts measured, we have never observed a single highly ballistic contact that would exhibit magnetic excitations (0 of 6 contacts with $\gamma < 0.8$). Thus, our results provide a direct evidence for the recently proposed single-interface mechanism of current-induced spin torques [12,13], which relies on impurity mediated “secondary” polarization of a nominally *unpolarized* current incident on a N/F interface and should be absent in the ballistic regime.

In summary, we have used phonon spectroscopy to study the mechanism of the single-interface spin torque effect in nonmagnetic/ferromagnetic point contacts. In contrast to spin torques in magnetic multilayers, this new mechanism relies on strong impurity scattering near the N/F interface. We find no magnetic excitations in highly ballistic contacts and pronounced spin torque effects in contacts where the electron flow is diffusive or thermal. Our results provide a direct evidence for the mechanism of the single-interface spin torque effect and should be useful for design of spin torque devices based on single magnetic layers or particles.

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