Current-Induced Spin-Wave Excitations in a Single Ferromagnetic Layer

Y. Ji,[1] C. L. Chien,[1] and M. D. Stiles[2]
[1]Department of Physics and Astronomy, The Johns Hopkins University, Baltimore, Maryland 21218
[2]National Institute of Standards and Technology, Gaithersburg, Maryland 20899-8412

(Received 24 July 2002; published 11 March 2003)

Evidence for a current-induced spin-transfer torque effect has been investigated in a series of point contacts to *single* ferromagnetic layers. At specific current densities, abrupt resistance changes, similar to those attributed to current-induced spin-wave excitations in multilayers, have been observed for one current polarity. The critical current for these resistance changes depends linearly on the external field applied perpendicular to the layer. The observed effect is interpreted as a current-driven heterogeneous instability in an otherwise uniform ferromagnetic layer.

DOI: 10.1103/PhysRevLett.90.106601 PACS numbers: 72.25.–b, 73.40.Jn, 75.30.Ds

Recently, spin-transfer torques have attracted a great deal of attention due to potential device applications [1] as well as novel fundamental physics. In a magnetic multilayer, the magnetic configuration of the layers is known to affect its electrical behavior, an effect called giant magnetoresistance (GMR) [2]. Spin-transfer torque is an example of the reverse effect, where an electrical current can alter the magnetic configuration of a multilayer. It has been theoretically predicted [3–5] and experimentally confirmed [6–10] that, at sufficiently high current densities, the spin-polarized currents that flow in multilayers are able to exert torques on the magnetizations. These torques can switch the magnetization directions for small applied magnetic fields or stimulate spin precession (spin waves) in the same system for high fields.

With a few exceptions, spin-transfer torques have been studied in heterostructures such as FM/NM multilayers or FM/NM/FM trilayers, where FM denotes ferromagnet and NM denotes nonmagnetic metal, with a current flowing perpendicular to the layers. Two considerations suggest heterostructures for investigating spin-transfer torques. First, the predictions of spin-transfer induced magnetization reversal and precession are based on noncollinear magnetizations. It is relatively easy to get noncollinear magnetizations in two layers separated by a nonmagnetic layer. Second, heterostructures also exhibit GMR, which becomes a detection mechanism for the magnetization reversal or spin precession. The parallel and the antiparallel configurations of the FM layers define the low and high resistance states, respectively, in the system. Deviations in configuration, such as that of magnetization reversal, result in changes in the resistance.

In typical experimental investigations of spin-transfer torques, one layer has a fixed magnetization (realized by shape anisotropy and/or the application of an external field) and another layer has a relatively free magnetization direction. The free layer is separated from the static layer by a nonmagnetic metal. As the spin-polarized current passes between the magnetic layers, the current carriers transfer part of their spin angular momentum to the magnetizations, thereby exerting torques. The consequence of the torques depends on the polarity of the current. If the electrons flow from the static layer to the free layer, the torques favor the free-layer magnetization parallel to that of the static layer. For electrons flowing in the opposite direction, the torques favor the free-layer magnetization antiparallel to that of the static layer. As the current is swept between polarities, the magnetization of the free layer can be altered between parallel and antiparallel alignment with respect to the static layer. In the presence of a strong external field (>1 T), however, full magnetization reversal into the antiparallel state becomes infeasible. Instead, spin waves can be stimulated, featuring a precession of spin moments around the parallel configuration. This precession occurs only for one polarity of the current.

Experimental evidence for the effects of spin-transfer torques comes from changes in the differential resistance of the system. For switching between parallel and antiparallel alignment, there is the discrete change in the differential resistance that would be expected from the giant magnetoresistance. For large applied fields, an increase in the resistance (V/I) or a peak in differential resistance at a certain critical current has been interpreted as an evidence for excitation of spin waves.

Tsoi *et al.* [6,7] first reported differential resistance peaks, which they interpreted as spin-wave excitations, in Co/Cu multilayers by current injection through a mechanical point contact. They showed that the multilayers couple to microwaves for currents larger than that required for the resistance anomaly and did not couple for smaller currents. Such behavior would be expected for a transition into a precessing state. Myers *et al.* [8] observed current-induced switching as well as resistance anomalies attributed to spin precession in point contacts made by nanolithography on Co/Cu/Co trilayers [11]. Both magnetization switching and possible signatures of spin precession have been reported by Katine *et al.* [9] and Grollier *et al.* [10] in patterned Co/Cu/Co trilayered nanopillars. Other current-induced effects have also been observed in Ni nanowires [12] and manganite junctions [13].

The initial theoretical works by Slonczewski [4], Berger [3], and more recent literature [14–18] describe an interfacial origin of the torque. Other work by Heide [19,20] and Zhang *et al.* [21] attribute the torque in whole or in part to an "effective field" that acts throughout the bulk of the ferromagnetic layers. In predictions of precession [9,22,23] based on an interfacial effect, the resistance anomaly is an increase in the resistance of the multilayer due to misalignment of the magnetizations as in the giant magnetoresistance effect. In Heide's model [19,20], which is in part related to the model of Berger [3], the resistance anomaly is due to an extra scattering channel that opens up when there is large spin accumulation in the ferromagnet. If the spin accumulation is large enough, it becomes possible to excite a magnon by flipping the spin of a conduction electron. Heide's model predicts that the resistance anomalies should also occur in single ferromagnetic layers.

In this Letter, we study spin-transfer effects in single ferromagnetic layers. In high fields, we find behavior that is very close to what is observed in multilayers. The observed similarity suggests that a similar explanation should be responsible for the effect in both types of systems. We show that the theory of Heide *et al.* [19,20] is not consistent with our measurements. We postulate that the system may be behaving as a multilayer; most of the ferromagnet layer has a fixed magnetization and the magnetization of the part directly under and close to the contact precesses around it.

We have used a mechanical point contact technique [24] to inject a current with a current density in excess of 10^9 A/cm^2 from a silver tip into a 3000 Å sputtered Co layer, with an external field up to 9 T applied perpendicular to the Co layer. All the measurements have been carried out at 4.2 K. For current in the negative polarity, electrons are flowing from the tip into the Co film. Figure 1 shows a typical contact that exhibits the unusual behavior of V/I and dV/dI. The contact resistance is about 28 Ω at zero bias and the external field is 5 T. In the positive polarity, both quantities are slowly varying as a function of current I. The small increase of V/I or dV/dI at higher bias has been attributed to phonon and magnon scattering [24]. At negative polarity, however, a sharp peak in dV/dI and a prominent step in V/I (enlarged in the inset) can be seen at a bias current of $I = -3.27$ mA. The upward jump of V/I is about 1 Ω, about 3% of the total resistance. The differential resistance changes by more than 100% at the same bias. Beyond the main peak, dV/dI also displays a small upward step at even higher bias. We have studied more than 50 point contacts that show similar features. The peak in dV/dI or step in V/I is always present in the negative bias, and never in the positive bias. The field orientation, upward or downward, does not alter the asymmetry of the spectra.

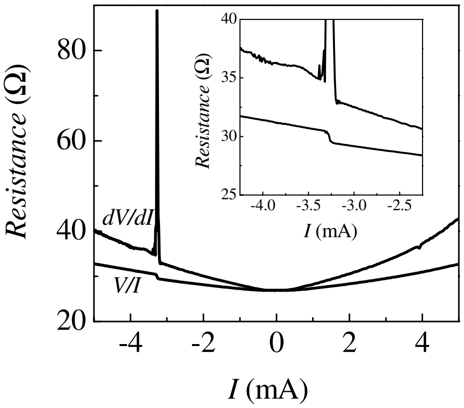

FIG. 1. The V/I-I and dV/dI-I plots for a point contact between an Ag tip and a Co film subject to an external field of 5 T perpendicular to the Co layer at 4.2 K, showing the peak (or step) at bias current $I = -3.27$ mA, enlarged in the inset.

Figure 2(a) shows the results of an Ag/Co contact at different external fields from 2 to 9 T. All the curves display a peak structure but at different negative bias current. All the curves fall onto the same background, demonstrating that the contact is not altered throughout the measurements. We define the current value corresponding to the peak in dV/dI as the critical current I_c, which, as shown in Fig. 2(b), depends linearly on H.

It is interesting to note that Fig. 2(b) establishes also a phase diagram for that contact, excluding the low field region where resistance peaks were not detected. The region above the line represents the excited states with

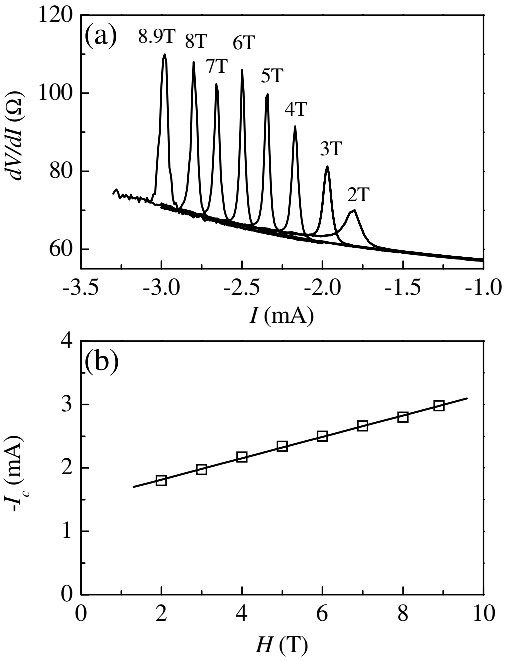

FIG. 2. (a) The dV/dI-I plots at different fields for an Ag/Co point contact at 4.2 K. The current value at the peak position, defined as I_c, depends linearly on the external field as shown in (b).

spin precession, whereas the region below the line is the ground state where all the spin moments are aligned by the external field. Each measurement performed in Fig. 2(a) corresponds to a scan along a vertical line at a fixed H in Fig. 2(b). As the boundary defined by the straight line is crossed, resistance changes (a step in V/I and a peak in dV/dI) are encountered. This phase diagram is specific to a given contact.

The phase diagram in Fig. 2(b) indicates that one can also perform a field scan along a horizontal line and monitor resistance and dV/dI as the phase boundary is crossed. The result of such a scan using a different contact is shown in Fig. 3. At a field of 5 T, as the current is scanned from -5 to -3 mA, as shown in Fig. 3(a), a peak appears in dV/dI at -3.8 mA, signifying the excitation of spin waves beyond this critical value. We then hold the current at -3.0 mA, ramp down the field, and measure V/I and dV/dI [Fig. 3(b)]. At 2.67 T, a peak in dV/dI and a step in V/I appear. As shown in Fig. 2, as the field is decreased, the critical current value will also decrease. At a lower field, 2.67 T in this case, the critical current value becomes -3.0 mA, hence the dV/dI peak.

The geometry that we use for spin injection through a point contact is schematical in Fig. 4. In the negative polarity, where the spin waves are excited, electrons are flowing from the tip into the Co film. The contact radius a can be estimated from the contact resistance R, the resistivity ρ, and the electron mean-free path l using $R = 4\rho l/(3\pi a^2) + \rho/(2a)$, the Wexler formula [24,25]. In Fig. 2(a), the estimated critical current density is above 5×10^9 A/cm^2, which is considerably higher than the value of 10^8 A/cm^2 in trilayered pillars [9], and the value of about 1×10^9 A/cm^2 for multilayers [6,7].

According to Heide's model [19,20], spin waves can be excited when the longitudinal spin accumulation in a ferromagnetic layer is sufficiently large, even without the second ferromagnetic layer. The longitudinal spin accumulation decays at the length scale of the spin diffusion length, which is 60 nm for Co [26–28]. In the case of a NM/FM/NM structure, for a fixed current density, the maximum value of spin accumulation occurs at the interface and is independent of the FM thickness if the FM layer is much thicker than the spin diffusion length. Otherwise it decreases with decreasing FM thickness [18]. Therefore the critical current density should be larger for Co films thinner than the spin diffusion length. dV/dI peaks at negative bias have been observed for a 38 nm Co film and even a 2 nm Co layer deposited on top of a thick Cu layer. The critical current densities at 5 T are 3×10^9 A/cm^2 for the 38 nm film, and 6×10^8 A/cm^2 for the 2 nm film. As a comparison, the average critical current density at 5 T for 26 point contacts made on 300 nm samples is $(5 \pm 2) \times 10^9$ A/cm^2. While the result of the 38 nm film is still within the variability of 300 nm films, the critical current density for the 2 nm film is much lower. In Heide's model, the thin film would have less spin accumulation for the same current, and, hence, the critical current should increase, not decrease. For this model to explain the variation of critical current with film thickness, the spin-flip scattering rates in Heide's model [Eq. (15) of Ref. [19]] would have to vary in a way that has not been anticipated in any theoretical model.

For an alternate model, we adapt the model of Slonczewski [22] to the single film geometry. Immediately after the current injection into the Co film, the current spreads out and the current density decreases rapidly due to the expanding geometry. We postulate that, beyond a certain depth, which is marked by a horizontal dashed line in Fig. 4, the current density is too low to affect the magnetization. All the spin moments below are aligned in the external field direction. In

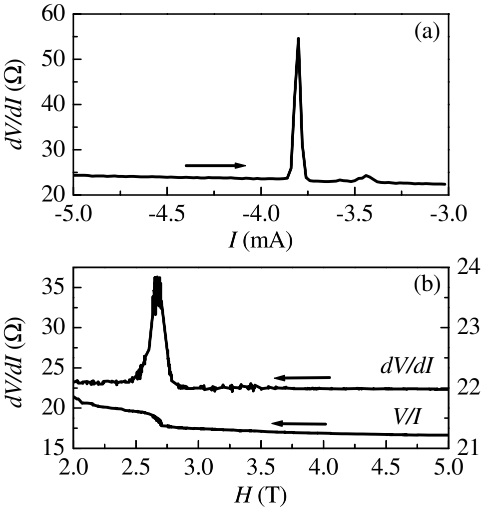

FIG. 3. Resistance and dV/dI of an Ag/Co point contact at 4.2 K. (a) Vary the current from -5 to -3 mA in a fixed field of 5 T. (b) Vary the magnetic field at a fixed current of -3 mA.

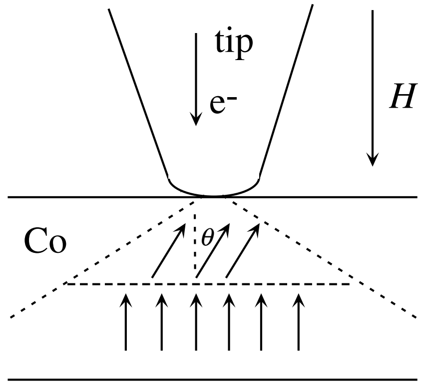

FIG. 4. A microscopic picture of a point contact between an Ag tip and a Co film with an external magnetic field applied perpendicular to the Co layer. On entering the Co film, electrons first pass through a localized "free region" right underneath the tip and before entering the "static region" as the current spreads out. The horizontal dashed line marks the boundary between the free and static regions.

analogy with the multilayer geometry, we postulate that the region below serves as a static region in the system. The region above the boundary and under the contact, where the current density is sufficiently high, acts as the free region. In this manner, the single Co layer is separated into a free "layer" immediately below the point contact and a fixed layer for the remainder of the Co layer. The thickness of the "free" layer is determined by the current distribution underneath the point contact. It may vary for different Co thicknesses and specific contact configurations.

Electrons from the tip first flow through the free region and then enter the static region. As discussed earlier, in this polarity the spin-transfer torque tends to deflect the free-region magnetization away from the parallel alignment, causing spin precession. The resistance step or dV/dI peak, which is considered the signature of spin precession, can be understood as such. As the precession is excited, the magnetization in the free region will have a tilt angle with respect to the magnetization in the static region. Then, since the magnetizations are no longer parallel, the resistance rises as in the giant magnetoresistance effect [29].

In Slonczewski's model [22] for precession in a nanocontact, the region of the top layer under the nanocontact is exchange coupled laterally to the rest of the layer. That region precesses and radiates spin waves laterally into the rest of the layer away from the contact. The critical current is determined by a balance of this loss mechanism plus the loss due to intrinsic damping against the energy pumped into the layer by the spin-transfer torque. The lateral exchange coupling is responsible for the nonzero intercept at $H = 0$. In our model for a thick single ferromagnetic layer, the precessing region is both laterally and vertically exchange coupled to the rest of the layer. It radiates spin waves in many directions. The increased radiation increases the critical current in the thick single films we have measured as compared to previous results on multilayers. The thin layer we have studied radiates only laterally, leading to a smaller critical current. In addition, since the 2 nm layer is thinner than the exchange length (approximately 8.5 nm for Co), we expect that the variation in the magnetization across the film is reduced compared to the thick film. This could explain the smaller dV/dI peak that we observe in the thin film. The percentage change of the differential resistance for the 2 nm film at 5 T is 1%, whereas the average change for 300 nm films at 5 T is $(60 \pm 30)\%$.

In conclusion, we report evidence for spin-wave excitations in a single ferromagnetic layer by high-density current injection through a point contact. Without a multilayer structure involving nonmagnetic metal, we have observed evidence for spin precession, albeit at a higher current density. We believe that much of the physics that describes the behavior of multilayers applies to the single ferromagnetic layers that we have measured. The large gradients in the current density allow the magnetic layer to "break up" into regions that behave like a static layer and a free layer. Then, the same balance of energy gain and loss mechanisms determines the critical currents.

This work was supported by NSF Grants No. DMR00-80031 and No. DMR01-01814.

[1] J. Slonczewski, United States Patent No. 5 695 864, December 9, 1997.
[2] M. N. Baibich *et al.*, Phys. Rev. Lett. **61**, 2472 (1988).
[3] L. Berger, Phys. Rev. B **54**, 9353 (1996).
[4] J. Slonczewski, J. Magn. Magn. Mater. **159**, L1 (1996).
[5] Ya. B. Bazaliy, B.. Jones, and S.-C. Zhang, Phys. Rev. B **57**, R3213 (1998).
[6] M. Tsoi *et al.*, Phys. Rev. Lett. **80**, 4281 (1998).
[7] M. Tsoi *et al.*, Nature (London) **406**, 46 (2000).
[8] E. B. Myers *et al.*, Science **285**, 867 (1999).
[9] J. A. Katine *et al.*, Phys. Rev. Lett. **84**, 3149 (2000).
[10] J. Grollier *et al.*, Appl. Phys. Lett. **78**, 3663 (2001).
[11] They also observed a resistance anomaly in zero applied field for a single Co layer.
[12] J.-E. Wegrowe *et al.*, Europhys. Lett. **45**, 626 (1999).
[13] J. Z. Sun, J. Magn. Magn. Mater. **202**, 157 (1999).
[14] X. Waintal *et al.*, Phys. Rev. B **62**, 12 317 (2000).
[15] D. H. Hernando *et al.*, Phys. Rev. B **62**, 5700 (2000).
[16] A. Brataas, Yu.V. Nazarov, and G. E.W. Bauer, Phys. Rev. Lett. **84**, 2481 (2000).
[17] K. Xia *et al.*, Phys. Rev. B **65**, 220401(R) (2002).
[18] M. D. Stiles and A. Zangwill, J. Appl. Phys. **91**, 6812 (2002); M. D. Stiles and A. Zangwill, Phys. Rev. B **66**, 014407 (2002).
[19] C. Heide, Phys. Rev. Lett. **87**, 197201 (2001).
[20] C. Heide, P. E. Zilberman, and R. J. Elliott, Phys. Rev. B **63**, 064424 (2001).
[21] S. Zhang, P. M. Levy, and A. Fert, Phys. Rev. Lett. **88**, 236601 (2002).
[22] J. Slonczewski, J. Magn. Magn. Mater. **195**, L261 (1999).
[23] Ya. B. Bazaliy, B. A. Jones, and S.-C. Zhang, J. Appl. Phys. **89**, 6793 (2001)
[24] A. G. M. Jasen, A. P. van Gelder, and P. Wyder, J. Phys. C **13**, 6073 (1980).
[25] G. Wexler, Proc. Phys. Soc. London **89**, 927 (1966).
[26] L. Piraux *et al.*, Eur. Phys. J. B **4**, 413 (1998).
[27] A. Fert and L. Piraux, J. Magn. Magn. Mater. **200**, 338 (1999).
[28] J. Bass and W. P. Pratt, Jr., J. Magn. Magn. Mater. **200**, 274 (1999).
[29] Calculating the change in resistance due to the rotating magnetization in this model is complicated by the lateral inhomogeneity. For uniform current flow, van Hoof *et al.* [Phys. Rev. B **59**, 138 (1999)] have calculated the domain wall resistance for Fe and Ni as a function of the layer-to-layer turn angle. For domain walls with turn angles as slow as 5° per layer, they find $\Delta G/G$ values comparable to typical $\Delta R/R$ values we measure.