PHYSICAL REVIEW B **75**, 140404(R) (2007)

Low-field current-hysteretic oscillations in spin-transfer nanocontacts

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(Received 3 January 2007; revised manuscript received 16 February 2007; published 19 April 2007)

We measured spin-transfer-driven, large-amplitude, current-hysteretic, low-frequency (<500 MHz), narrowband oscillations in nanocontacts made to spin valve structures. The oscillations occur in zero field, persist up to 5 mT for in-plane applied fields, and to beyond 400 mT for out-of-plane fields. Unlike for previous measurements, here the oscillation frequency is well below that for uniform-mode ferromagnetic resonance, is a weak function of the applied field and current, and is highly anharmonic. The oscillations are hysteretic with dc current, appearing at high currents but persisting to lower currents upon decrease of the current. We suggest that these observations are consistent with the dynamics of a nonuniform magnetic state, one nucleated by both the spin-transfer torque and dc current-generated Oersted fields, with dynamics driven by spin transfer. The electrical oscillations are large amplitude and narrowband, with the largest amplitudes on the order of 1 mV and the narrowest linewidths below 1 MHz.

DOI: 10.1103/PhysRevB.75.140404 PACS number(s): 75.47.De, 85.75.−d

Since the prediction that spin-polarized currents can exert significant torques in magnetic nanostructures, a wide variety of magnetization dynamics driven by spin-transfer torques have been observed in a wide range of device geometries and experimental conditions.[1,2] The general characteristics of these observed dynamics—the amplitude, the fundamental excitation frequency f_0, the change of f_0 with current I and applied field $\mu_0 H_{\text{app}}$—are roughly understandable using theories that approximate the free-layer dynamics as quasiuniform large-angle magnetization motion in the region of the device where current flows.[3,4] In the case of nanopillars, this region is the entirety of the free layer (possibly ignoring some region at the edge), and in nanocontacts it consists of the region directly under the contact; in the latter case the mode remains centered (i.e., stationary) on the symmetry axis. Even this rough correspondence between theory and experiment is somewhat surprising, since one might expect excitations with nonuniform magnetization (on the scale of the contact) due to the large, spatially varying Oersted fields generated by the dc current itself. The effect of these fields, which approach 6.5 mT/mA (65 Oe/mA) at the edge of a 60-nm-diameter contact, is an active area of computational magnetic research.[5]

In this Rapid Communication we present measurements of large-amplitude, narrowband signals from nanocontacts that are *not* easily explainable using such radially symmetric quasiuniform-mode approximations. The measurements were performed on nanocontacts nominally identical to those measured previously. The principal difference in the measurements reported here is that the in-plane field magnitude is always less than 5 mT, whereas previously this magnitude was greater than 60 mT. We suggest that the observed dynamics may result from the generation and perturbation of a nonuniform magnetic state, such as a magnetic vortex, in the vicinity of the contact.

We observe oscillations with frequencies less than 500 MHz that are present only from zero to 5 mT for in-plane fields, and persist to above 0.4 T for fields applied directly out of plane. For either field orientation, the oscillation frequency is typically significantly below the uniform-mode ferromagnetic resonance (FMR), and changes very little with applied field strength. In addition, the *presence* of the oscillations is hysteretic with dc current, with oscillations appearing at a high current with increasing current but persisting to lower currents upon decrease of the current. These results are markedly different from results presented previously,[6,7] which showed significant df_0/dI and df_0/dH_{app}, higher frequencies, and no current hysteresis. The field dependence, in particular, observed here is consistent with measurements of vortex dynamics in patterned microstructures.[8,9] Furthermore, the current-generated Oersted fields are among the largest applied fields in the system, suggesting that the hysteresis observed may be due to the nucleation of a nonuniform mode by the combination of Oersted fields and spin transfer, the dynamics of which are also stabilized by the circumferential Oersted field.

The devices presented here are 60–80 nm diameter nanocontacts made to pseudo-spin-valves comprising Ta (3 nm) /Cu (15 nm) /$Co_{90}Fe_{10}$ (20 nm) / Cu (4 nm) /$Ni_{80}Fe_{20}$ (5 nm), essentially similar to devices measured previously in high fields and discussed in detail elsewhere.[6,7] The low-frequency oscillations were observed for a range of contact resistances, with little correlation between the resistance and oscillation characteristics, other than that high-resistance (>15 Ω) contacts tended to show oscillations less frequently than low-resistance contacts. We also observed similar low-frequency excitations in other material systems, but these will not be discussed here. Note that the fixed layer is unpinned, and may also be modified by the Oersted fields and involved in the dynamics.[10] The devices were measured at room temperature, with magnetization dynamics detected electrically via the giant magnetoresistance (GMR) effect[11] and measured by either a spectrum analyzer or a real-time oscilloscope.

Typical results for in-plane applied fields are shown in Fig. 1. In the measurement, a large saturating field is first applied, and the field is then reduced to the measurement value. The dc current through the contact is ramped from 4 to 12 mA and back down to 4 mA so that hysteresis in the output vs dc current can be identified. Figures 1(a) and 1(b)

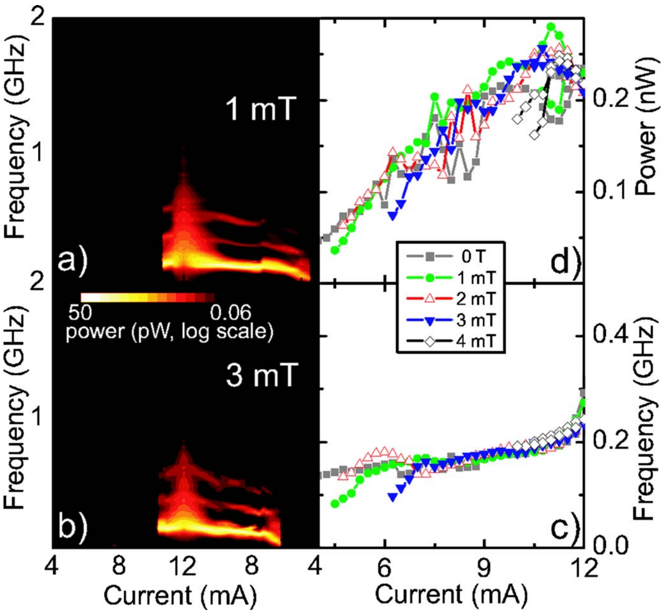

FIG. 1. (Color online) Output from nanocontact for in-plane fields: Contour plots of spectral output for (a) 1 mT (10 Oe) and (b) 3 mT. Note symmetric current scale: current is ramped up to 12 mA, then down. Color denotes power on a logarithmic scale. Results of Lorentzian fits to spectra for several fields: (c) fundamental frequency vs I; (d) Power of fundamental vs I. Both up and down scans of I are plotted.

show contour plots of the spectral output vs current for 1 and 3 mT, respectively. In Fig. 1(a), the device produces no ac output until just below 11 mA—the "turn-on" current—whereupon it emits a signal at approximately 188 MHz along with strong second and third harmonics. This narrowband signal (18 MHz full width at half maximum for the first harmonic) persists with slightly increasing frequency until just below 12 mA, where the output evolves into a signal with lower power density. This evolution is typical for the measurements presented here, with narrowband signals evolving into a broader-band output at larger currents, possibly due to nonlinearities driven by the increasing spin-transfer torque.

Upon decrease of the current from 12 mA, the large-amplitude narrowband signal reemerges, but persists as the current drops below 11 mA, the turn-on current. The linewidth narrows as the current decreases, reaching a minimum (for this particular device and geometry) of approximately 4 MHz at 8 mA, and the frequency decreases at roughly 10 MHz/mA. The output ceases just above 4 mA—the "turn-off" current—demonstrating substantial hysteresis in the presence (but not frequency) of oscillations with current. This hysteretic behavior has been observed in many devices, with the particulars—onset current, fundamental frequency, relative harmonic power, and hysteresis—varying from device to device.[12]

Increasing the in-plane field alters the range of currents over which such output is observed, but does not appreciably change the output frequency itself. For an applied field of 3 mT [Fig. 1(b)] the turn-on current decreases below that observed for 1 mT, while the turn-off current increases to above 6 mA. The turn-on and turn-off currents tend to approach each other with increasing field, and the narrowband oscillations cease above a certain field (about 5 mT for the device in Fig. 1), leaving only the lower-power-density broadband output seen at higher currents. The output frequencies remain relatively constant from zero field through 4 mT, as shown in Fig. 1(c), with significant variations seen primarily near the turn-off current. The integrated power of the fundamental frequency [Fig. 1(d)] is insensitive to the applied field, further indicating that the mode is not strongly affected by H_{app}. Interestingly, reversing the in-plane field direction gives similar oscillation frequencies, but yields different results for the current hysteresis, relative harmonic power, and field dependence. This may indicate that local variations in the effective field are of similar magnitude to these applied fields.

The results presented here are markedly different from those reported previously for in-plane fields greater than 50 mT,[6] which showed a higher-frequency mode that redshifted with current ($df_0/dI \approx -200$ MHz/mA), and an appreciable $df_0/d\mu_0 H$ (≈ 25 GHz/T). By contrast, the results presented here have $df_0/dI \approx +10$ MHz/mA and $df_0/d\mu_0 H \approx 0$. Also, the output power at f_0 of the higher-field oscillations was typically more than an order of magnitude smaller than that presented here. Most significantly, the higher-field oscillations did not show the hysteresis with dc current seen here. While the results in Ref. 6 were roughly understandable as large-angle versions of quasiuniform mode precession, we see no such correspondence for the results presented here. For example, for in-plane fields the uniform-mode ferromagnetic resonance frequency for a NiFe film with 0.5 mT in-plane uniaxial anisotropy increases from 600 MHz to 2.1 GHz from zero to 5 mT, whereas here the frequency is effectively constant. Large-angle in-plane uniform precession also predicts that $df_0/dI < 0$, at least near the critical current.[4,6]

When the applied field is directed along the surface normal, these oscillations persist to much larger fields than for in-plane fields. As shown in Fig. 2(a), 20 mT applied out of plane (to the same device presented in Fig. 1) does not suppress the narrowband output. The frequency of this mode is again a weak function of current, increasing at about 8 MHz/mA. Out-of-plane fields also reduce the current-induced hysteresis, but without changing the turn-off current significantly; instead, the turn-on current is generally reduced, resulting in a spectral output roughly symmetric in current [see Fig. 2(b)] at higher fields.

A major effect of increasing out-of-plane fields is to decrease the onset current for a broader-band, more rapidly blueshifting output, seen at 10 mA in Fig. 2(a) and 9 mA in Fig. 2(b). Thus, the current range over which narrowband precession is observed shrinks with increasing field. Above a certain field (in this case about 500 mT) only the broad blueshifting mode remains, along with another broadband signal at higher frequency, seen just appearing at $I = 12$ mA in Fig. 2(b) at 1.3 GHz, whose onset current also decreases with field strength. Line plots of the spectral outputs at low and high currents are shown in Fig. 2(c) for $\mu_0 H_{app} = 300$ mT, showing narrowband multiharmonic output at low currents and the two broader modes that develop at higher currents. Larger fields eventually suppress these low-frequency out-

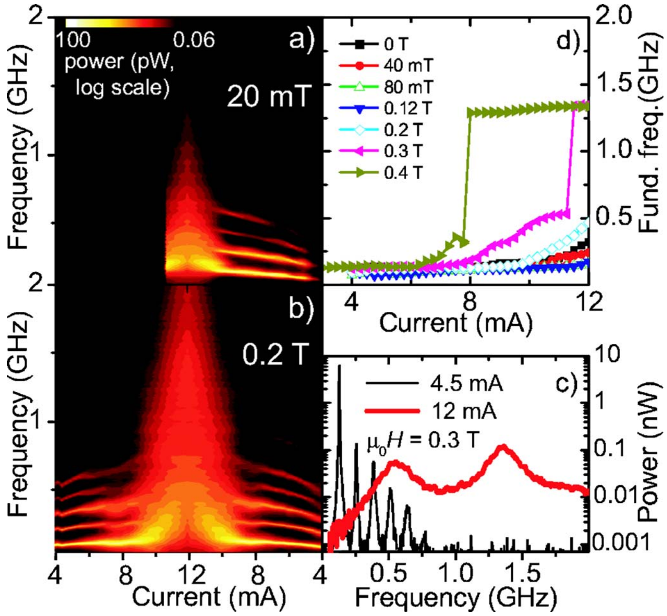

FIG. 2. (Color online) Output for out-of-plane fields: Contour plot of spectral output for (a) 20 and (b) 200 mT. Color again denotes power, logarithmic scale. (c) Spectral output at two currents; $\mu_0 H_{\rm app}$=300 mT. (d) Fits to fundamental frequency (highest power) vs I for several fields.

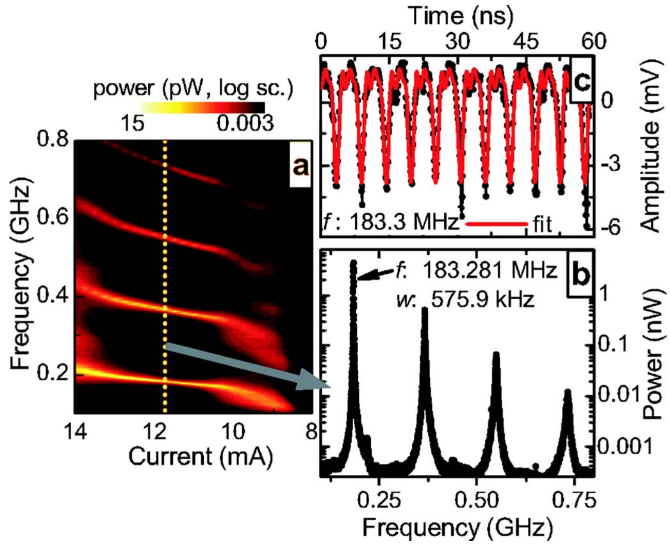

FIG. 3. (Color online) Comparison of spectral and temporal outputs. Amplitudes include 30 dB gain. (a) Spectral output vs I; $\mu_0 H_{\rm app}$=2.5 mT. (b) Log-power spectrum at I=11.75 mA, showing harmonics. Fitted $V_{\rm fund}$=1.94 mV. (c) Time trace of output at I =11.75 mA, with fit of fundamental and three harmonics. Fitted $V_{\rm fund}$=1.99 mV.

puts, so that they do not connect at higher fields with the narrowband high-frequency oscillations reported previously.[6] As shown in Fig. 2(d), the frequency of the narrowband output is again only a weak function of out-of-plane field strength, initially decreasing with field at −150 MHz/T below 140 mT, and then increasing at a similar rate above this field. These results are again different from those observed previously,[6] which showed that, for large (>600 mT) out-of-plane fields, the observed precessional mode was not hysteretic in current, and its frequency was a strong function of both current and field, increasing with field at 30 GHz/T. Those results also roughly followed those expected for large-angle uniform-mode precession (but with some significant unexplained differences).[7,13]

The power of the fundamental frequency and its harmonics is typically substantial for this low-frequency mode, as shown in Fig. 3 for a different device. Figure 3(a) shows the spectral output from 14 to 8 mA, while Fig. 3(b) shows the spectrum at 11.75 mA. The peak-to-peak amplitude of the fundamental (unamplified, and uncorrected for device impedance mismatches) approaches 0.3 mV for this device; other devices show amplitudes over 1 mV. The amplitude for full (180°) precession should be 2–4 mV, inferred from the dc GMR of other nanocontacts. At the same time, the powers of the harmonics sum to approximately 60% of the power in the fundamental. Interestingly, in this case the linewidth of the fundamental is 576 kHz, the lowest observed thus far in a nanocontact made to a NiFe-CoFe spin valve, in any field geometry. This may be an intrinsic property of this mode (e.g., somehow having greater thermal stability) and may also be related to the small df_0/dI and $df_0/d\mu_0 H$, which reduce noise modulation broadening.

A single-shot measurement of the output voltage vs time from this device is shown in Fig. 3(c), with the oscillator in the same state as for the spectrum analyzer measurement shown in Fig. 3(b). The spectrum in Fig. 3(b) corresponds to a highly nonsinusoidal wave form. A multiharmonic sinusoidal fit to the wave form is shown, and gives frequencies and amplitudes in good agreement with those found from Lorentzian fits to the spectrum. The rms noise at the oscilloscope is 0.35 mV, accounting for some of the variations seen in the time trace.

The results presented above for this mode—its frequency, hysteresis with current, and weak dependence on field and current—indicate that this low-frequency mode is substantially different from previously measured (quasiuniform-mode) spin-transfer resonances, and from FMR. This suggests that, instead of quasiuniform-mode dynamics, a nonstationary mode with nonuniform magnetization (on the scale of the contact) may be being driven in these measurements. While the magnetization distribution of this system on the length scale of the contact is unknown at this point, one process that reasonably accounts for these results is the nucleation of a nonuniform vortex-type state by the dc current, through a combination of the spin-transfer torque and the circumferential Oersted fields generated by the current itself.

In a patterned magnetic structure such as a micrometer-sized disk, in which a vortex is a stable state, the vortex will circulate about the structure's center in response to a perturbation.[8–10,14] The restoring force is provided by demagnetizing fields due to the finite device size, with the frequency scaling as the disk thickness and inversely with disk diameter. The vortex oscillation frequency is a weak function of applied field, and is annihilated in sufficiently large field, the magnitudes of which differ with field orientation. The main points of correspondence between the data presented here and vortex dynamics are the weak dependence of frequency on field, the differing quenching field for in- and out-of-plane fields, and the hysteresis with dc current.

In the nanocontact geometry, the lack of a boundary requires that the circumferential Oersted field (or interlayer interactions) provide the restoring force. The field magnitude varies to a good approximation as r inside the contact (where r is the radial distance from the center of the contact), and $1/r$ outside.[15] The 75 mT generated at the edge of a 60 nm contact by a 12 mA current is the largest applied field in the system for many of the results presented above. Micromagnetic simulations[16] indicate that such fields alone (i.e., without spin-transfer effects) are sufficient to nucleate and stabilize a vortexlike state at the contact in one or both layers, although in mesas smaller than those measured here. These simulations further show that this circumferential field stabilizes an existing vortex at the contact so that, once nucleated, the vortex persists to currents below the nucleation current, consistent with the observed hysteresis with current.[17] Also, because the angle of the magnetization varies across a nonuniform state, the oscillation of such a state around the contact center would result in effective large-angle magnetization motion at the contact relative to the reference layer, and hence in large output powers via GMR.

Although these results are suggestive, a more quantitative comparison is complicated by both the conjectured nonuniform magnetization and the spin-transfer effect. If both the fixed and free layers are affected by the Oersted fields, there may be significant dipolar coupling across the 5 nm spacer because of the stray fields from the nonuniform magnetization. Beyond this, the spin-transfer torque for such currents drives large-angle magnetization dynamics in other geometries,[6,18] and so will likely also play a large role here. Other work has measured the anisotropic magnetoresistance and spin-transfer excitation of vortices in nanostructures with a single magnetic layer and current in the plane of the film.[19] In the present case, with current perpendicular to the plane, nonuniform magnetization in the contact region of both the free and fixed layers makes determining the role of spin-transfer torque in driving these dynamics a challenge, and an area of ongoing study.[20] Nonetheless, the results presented above describe a mode substantially different from those observed previously, and are consistent with the nucleation and dynamics of a nonuniform magnetic mode.

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[17] A simple calculation of the frequency of small oscillations based on a single-rigid-vortex model (Ref. 9) overestimates the frequency ($\approx$1 GHz at 1 mA) and predicts a linear dependence of frequency on current, different from our observations, but indicates that the Oersted field exerts a substantial restoring force on a vortex.

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