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Detection of Current-Induced Resonance of Geometrically Confined Domain Walls

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Magnetic domain walls are found to exhibit quasiparticle behavior when subjected to geometrical variations. Because of the spin torque effect such a quasiparticle in a potential well is excited by an ac current leading to a dip in the depinning field at resonance for current densities as low as 2×10^{10} A/m^2. Independently the resonance frequencies of transverse walls and vortex walls are determined from the dc voltage that develops due to a rectifying effect of the resonant domain wall oscillation. The dependence on the injected current density reveals a strongly nonharmonic oscillation.

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As recently demonstrated, spin-transfer torque effects can be used to depin and displace a magnetic domain wall in a simple nanoscale single layer structure by injecting high current pulses [1–6]. In contrast to field-induced domain wall motion, current-induced domain wall motion (CIDM) still lacks a thorough understanding. Most of the theoretical models describing the current interaction with wide domain walls are based on the adiabatic approximation [7], but nonadiabatic corrections have recently been introduced [8,9].

Dynamic measurements have so far been limited to investigating the combined action of field and current [4], and recently first dynamic measurements of pure current-induced domain wall motion have been reported [5]. Rather than using continuous currents, ac excitations were found to be more efficient, moving domain walls at far lower current densities than in the case of pulses [6]. Excitations using ac fields have been extensively researched recently [10–12].

Particular interest has been raised by one of the smallest confined magnetic structures, the singularity in the center of a vortex spin configuration, which points out of the plane and moves in the direction perpendicular to the force acting on it [13,14]. Such a gyrotropic motion then leads to a spiraling of the core after it has been excited, e.g., by a field pulse, and a circular motion if a resonant ac field excitation is used [12].

We have combined the fields of spin-transfer torque and eigenmode excitations by studying current-induced domain wall resonances using two independent methods: the depinning field is determined and, using a homodyne detection scheme, the dc response due to the anisotropic magnetoresistance is measured concurrently. Modeling reveals the type of resonant eigenmodes that are excited.

A scanning electron microscopy (SEM) image of a 25 nm thick and 200 nm wide $Ni_{80}Fe_{20}$ ring structure with 2 μm diameter and 10–30 nm wide notches with electrical contacts, which was fabricated as described in Ref. [15], is shown in Fig. 1(a).

Using magnetoresistance measurements the wall positions and wall types can be determined [16,17]. The measurements were carried out at 4 K using a current of 5 μA. The ring geometry has the particular advantage that a domain wall can easily be generated and positioned by applying a homogeneous magnetic field [18]. Domain walls in such structures are head-to-head 180° walls with a vortex or a transverse spin structure [19,20]. For this particular geometry, the domain wall type was determined to be a vortex wall when positioned outside the constriction and a transverse wall when positioned inside. Micromagnetic simulations performed with the OOMMF code [21] and the LLG micromagnetic simulator [22] (parameters: $M_S = 800 \times 10^3$ A/m, $A = 13 \times 10^{-12}$ J/m, 5 nm cell size) agree with the experimentally observed spin structures for a transverse wall inside the constriction [Fig. 1(b)], a vortex wall pinned adjacent to the constriction [Fig. 1(c)], and a free vortex wall [Fig. 1(d)].

Depending on the wall type, the current was injected between contacts 3 and 4 [transverse or pinned vortex wall, see Figs. 1(b) and 1(c)], or between 4 and 5 [free vortex wall, see Fig. 1(d)].

To measure the dc component generated by the rectifying action of the domain wall we use lock-in detection. The microwave generator was modulated with a 3 kHz square wave, to which the lock-in amplifier was synchronized. The microwaves are injected into contact 4 of the sample using a bias tee. The dc voltage signal is measured between the dc port of the bias tee and contacts 3 or 5.

As shown earlier [16,17,23], constrictions generate a single potential well for transverse walls [as also seen in Fig. 1(b)]. Vortex walls, on the other hand, are repelled from the constriction but pinned adjacent to it [Fig. 1(c)] [23,24].

To characterize the potential well, we measure the width and depth: for a vortex wall we find a depinning field of 12 mT that corresponds to 0.4×10^3 J/m^3, as shown in Ref. [23], and for a transverse wall we measure a depinning field of about 55 mT, corresponding to 2.4×10^3 J/m^3.

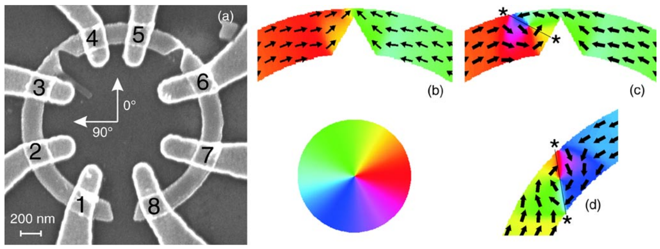

FIG. 1 (color online). (a) SEM image of the device with numbered contacts. Micromagnetic simulation of a transverse wall inside the constriction (b) and of a vortex wall adjacent to the constriction (c). (d) Micromagnetic simulation of the free vortex wall. The two stars indicate the topological edge defects and the resonant mode corresponds to the vortex core moving along the line connecting the two stars. The color (or shaded) circle indicates the direction of the magnetization.

The total width of the potential well has been determined to be about 800 nm using the method explained in Ref. [16].

To further characterize the potential well, the domain wall resonance frequencies need to be ascertained since they are governed by the well curvature. To probe the resonance, we measure the depinning field of the domain wall from the constrictions as a function of the frequency of the injected current. Current-induced resonance due to spin torque is a particularly apt technique, since it moves the wall in the current direction which follows the curvature of the ring [6].

On resonance we expect a dip in the depinning field, as the field necessary to lift the oscillating quasiparticle domain wall above the potential barrier is reduced.

We first measure the depinning of a transverse wall [Fig. 1(b)] by positioning the wall with a field along the notch direction (35°, between contacts 3 and 4) as detailed in Ref. [16] and then applying a perpendicular field along 305°. In Fig. 2(a) (blue or dark gray squares) we see that the depinning field off resonance is 53.7 mT and exhibits a dip to 51.5 mT at a resonance frequency of about 1.3 GHz for a peak current density of 2×10^{10} A/m^2. The position of the dip corresponding to the resonance frequency has been found to be independent of the applied power, as long as the power is larger than the threshold [as discussed later and in Fig. 3(b)]. Below this threshold no significant dip is seen.

To determine the nature of this eigenmode, micromagnetic simulations were carried out and a resonant eigenmode at a frequency of 1.2 GHz was obtained. The eigenmode consists of the whole wall moving in the constriction, so that here the analogy with a quasiparticle holds very well.

Next we consider a pinned vortex wall [Fig. 1(c)]. From topological considerations the simplest soft eigenmode of the vortex wall is the motion of the vortex core along the diagonal connecting the two topological edge defects [indicated in Fig. 1(c)]. Qualitatively this eigenmode was predicted to occur for vortex walls by Tchernyshyov *et al.* [25,26]. This corresponds to a first approximation of the vortex core motion in a disc, which has been widely studied. Guslienko *et al.* determined the frequency of the vortex core oscillatory eigenmode analytically for a disc [14], and taking the wire width as the disc diameter a frequency of 900 MHz is predicted.

Experimentally a dip in the depinning field is observed at around 800 MHz [Fig. 2(b), blue or dark gray squares], so that the simple theoretical model yields a surprisingly good agreement, even though it is calculated for zero field. Micromagnetic simulations corroborate this picture, they reveal a combination of the linear motion predicted by Tchernyshyov and the circular motion expected in a disc resulting in an ellipsoidal motion with the long axis along the diagonal connecting the two edge defects, from which it is clear why no perfect agreement to the disc model can be expected [27]. It is important to note that the eigenmode that leads to a reduction of the depinning field is not a translational mode of the entire domain wall (as claimed

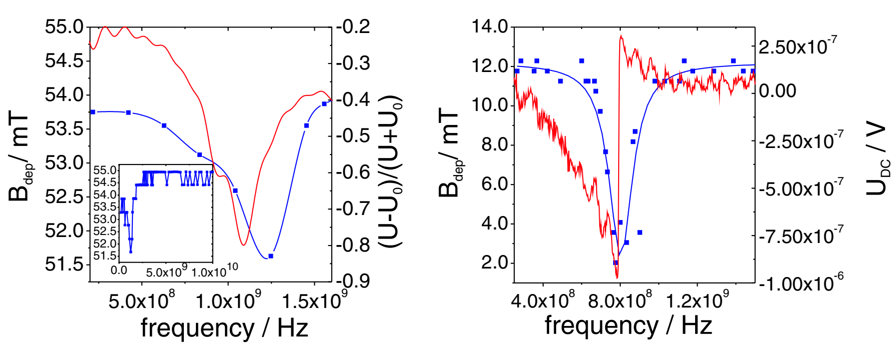

FIG. 2 (color online). (a) Depinning field (blue or dark gray squares, blue or dark gray line) of the transverse wall located inside the constriction as a function of frequency for a constant current density of 2×10^{10} A/m^2. A dip at 1.3 GHz is observed. The inset shows the full frequency spectrum scanned. The red or gray line is the dc response, with a feature at the same frequency. (b) Depinning field (blue or dark gray squares) for a vortex wall pinned adjacent to the constriction with a dip at around 800 MHz. The blue or dark gray line is a Lorentzian fit to the depinning data. For the vortex wall the dc response (red or gray line) exhibits in addition to the dip a dispersionlike signal due to the change in phase at the resonance frequency. The power level used is -5 dBm corresponding to a current density of about 6×10^{10} A/m^2 in both cases.

for an unpinned wall in Ref. [6]) but the oscillation of the vortex core described above.

To determine the resonance frequencies independently and at variable fields, a homodyne detection scheme based on a dc signal is found to be ideally suited.

The spin torque exerted by the injected high-frequency current $I = I_{\mathrm{ac}} \sin(\omega t)$ will cause the domain wall to oscillate. This oscillation will cause a periodic resistance change ΔR [16] at ω and higher harmonics. If we now multiply the ac current $I = I_{ac} \sin(\omega t)$ with ΔR, the resulting voltage $U = RI$ will contain the sum and difference frequencies. The first terms of the product will contain the frequencies zero, i.e., a dc voltage, and 2ω. The dc component will then be $U_{\mathrm{dc}} = I_{\mathrm{ac}} \frac{\Delta R(\omega)}{2} \cos(\chi)$, with χ the phase shift between the exciting ac current and the resistance change. By this synchronous demodulation the high-frequency current is partly rectified. This process is called homodyne detection and is well known in the field of signal processing, but has not been previously observed and used in a magnetic system with a domain wall.

For a weakly damped oscillator at resonance the phase lag will be $\chi = \pi/2$; therefore, at resonance the measured voltage will be zero, with extrema of different sign on both sides. As χ is increased, one of the extrema will disappear, leading to a single peak or dip. If the direction of the vortex core is changed, the force acting on the vortex core will change its sign, leading to an additional phase shift of π. This phase shift will swap the signs of the two extrema on both sides of the resonance, allowing us to identify the direction of the vortex core. We did not observe an inversion of the line shape; therefore, the polarity of the vortex core was not flipped by the injection of a resonant current, as has been observed by Ref. [28].

We plotted the dc response for the vortex wall pinned at the constriction in Fig. 2(b) (red or gray line). For the vortex wall in Fig. 2(b) we see a dispersionlike signal which indicates that the system is only weakly damped and $\chi \approx \pi/2$ at resonance. We carried out calculations using the LLG micromagnetic simulator and could reproduce the signal measured including the line shape. Therefore the same eigenmode, the vortex core oscillation described above, is responsible both for the reduction of the depinning field and for the rectification of the microwave current.

For the transverse wall the expected signal is much weaker since the oscillation has a smaller amplitude, as visible from the smaller change in the depinning field compared to the vortex wall. Therefore the signal shown in Fig. 2(a) (red or gray line) had to be low-pass filtered and normalized with respect to the voltage measured without a domain wall. From the occurrence of an asymmetric single dip in Fig. 2(a) we can conclude that at resonance the phase shift is not exactly $\chi = \pi/2$, which may be caused by an asymmetric excitation or a stronger damping which shifts the resonance frequency below the frequency where $\chi = \pi/2$.

The dc detection method now allows us to also study the field dependence of the vortex core oscillation. For this measurement we use a free vortex wall since the vortex core motion eigenmode is expected to be present also in a free vortex wall, where the influence of the notch is eliminated [Fig. 1(d)]. Here the finite wall propagation field is due to pinning at defects such as the edge roughness.

The wall resonance occurs at a lower frequency of 480 MHz. This lower frequency compared to the pinned vortex core can be understood in terms of the larger effective width of the wire, which is 200 nm wide, whereas in the pinned case the average width is reduced due to the constriction on one side of the wall.

In Fig. 3(a) the maximum of the dc signal (free vortex) is plotted for different external fields. A weak increase of the frequency with increasing field is visible, which is in line with theoretical predictions [29]. For applied fields above 7 mT the domain wall is drawn out of the area between the contacts and no dc signal is measured. Using the nonlinearity induced by the oscillating domain wall not only allows to rectify a high-frequency signal but might prove useful for mixing or demodulating microwaves in magnetic nanostructures, which has also been reported for multilayer pillars [30].

Previously, low frequency large-scale domain wall motion was reported (though the exact displacement was not determined) [6]; therefore, we monitored also the dc resistance response between contacts 3,4 and 4,5 to the injected ac currents. We find no change in the resistance at resonance, which means that the wall is confined between the contacts and no large-scale motion is occurring. We have used current densities of 5×10^{10} A/m^2, on the same order of magnitude as those observed for resonant wall motion by Saitoh *et al.* [6].

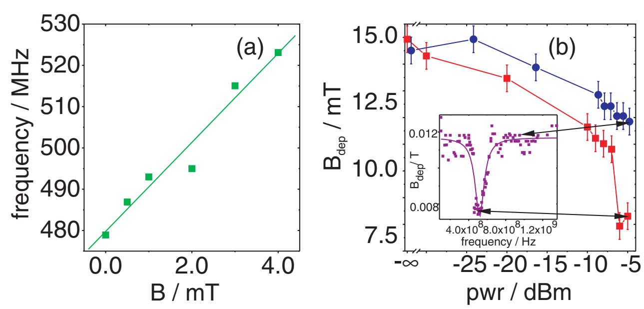

FIG. 3 (color online). (a) The frequency dependence of the free vortex wall on the strength of an applied field exhibits a linear increase as theoretically predicted. The green or light gray line results from a linear fit. (b) Dependence of the depinning field of the free vortex wall on the injected current density (power) for current injection on-resonance (480 MHz, red or gray) and off-resonance (850 MHz, blue or dark gray). The reduction for the off-resonant case can be attributed to heating. A threshold power of -7 dBm is visible, which points to a strongly nonlinear oscillator. The inset shows the depinning spectrum corresponding to a power level of -5 dBm.

Using the formula given in Ref. [6] we determined the quasiparticle domain wall masses to be 5.6×10^{-25} kg for the transverse and 6.2×10^{-24} kg, respectively, 6.3×10^{-25} kg for the free and pinned vortex. These values are smaller than those given in Ref. [6] in line with the higher resonance frequencies observed due to the different geometry.

To measure the critical current density, we plot in Fig. 3(b) the dependence of the depinning fields as a function of the injected power for on- and off-resonance frequencies. For low injected currents there is virtually no change in the depinning field between the different frequencies. Above a threshold power of -7 dBm, the depinning field starts to be strongly reduced for the resonant case, whereas the nonresonant current only weakly influences the depinning field due to heating. This pronounced nonlinear behavior points to a strongly nonharmonic potential as previously observed for field-induced resonance [31]. Such domain wall oscillators have recently been proposed theoretically [32], and the observed nonlinearity bodes well for a future possible device that would rely on phase locking a large number of wall oscillators.

To rule out frequency dependent heating we measured the sample temperature using the technique detailed in Ref. [33] which we found independent of the frequency. We can exclude heating as a cause for the strong decrease of the depinning field [Fig. 3(b), red or gray curve] at -7 dBm, since for the off-resonance excitation (blue or dark gray curve) the power coupled into the sample and therefore the heating is exactly the same without any corresponding decrease of the depinning field.

What remains to be explained is the larger effect of the current on the vortex wall than on the transverse wall in terms of relative change of the depinning field with current density. As pointed out earlier [34], for ac currents, momentum transfer can start to dominate over spin transfer and becomes particularly important when large magnetization gradients occur [35], such as in the case of vortices where the magnetization changes by 180° within a few nanometers. This stronger nonadiabaticity of the spin torque effect would then induce the larger oscillations of the vortex core compared to the transverse wall case, leading to a stronger decrease in the depinning field. While the oscillations could be reproduced with simulations including the spin transfer torque terms corroborating our explanation, there might also be contributions of the Oe field due to the inhomogeneous current path.

In conclusion, we have investigated current-induced resonances due to the spin torque effect for vortex and transverse wall spin structures. We find sharp dips in the depinning fields at the resonant frequencies corresponding to the transverse wall moving in the attractive potential well and the vortex core of the vortex wall moving within the wall spin structure. The domain wall resonance also yields a rectifying effect, that leads to a dc voltage at resonant ac excitation and from the resonance frequencies we determined the quasiparticle masses. We find that the oscillations are strongly localized and we can exclude a large-scale displacement of the domain wall. In agreement with theoretical predictions the vortex core frequency increases proportional to the applied external field. The dependence of the depinning field on the injected ac current density exhibits a threshold power, which points to a pronounced nonlinear oscillator.

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