Switching through intermediate states seen in a single nickel nanorod by cantilever magnetometry

SangGap Lee, Eric W. Moore, Steven A. Hickman, Jonilyn G. Longenecker, and John A. Marohn^{a)}

Department of Chemistry and Chemical Biology, Cornell University, Ithaca, New York 14853, USA

(Received 15 October 2010; accepted 4 March 2012; published online 20 April 2012)

In-plane to out-of-plane magnetization switching in a single nickel nanorod affixed to an attonewton-sensitivity cantilever was studied at cryogenic temperatures. We observe multiple sharp, simultaneous transitions in cantilever frequency, dissipation, and frequency jitter associated with magnetic switching through distinct intermediate states. These findings suggest a new route for detecting magnetic fields at the nanoscale. © 2012 American Institute of Physics. [<http://dx.doi.org/10.1063/1.3699363>]

I. INTRODUCTION

Quantifying both the average moment and magnetic fluctuations of individual nanometer-scale ferromagnets is critically important for developing stable high-density recording media,^{1–4} sensitive magnetoresistive heads and spin-based electronic devices,⁵ and pushing magnetic resonance imaging to atomic resolution via mechanical detection.^{6–8} Magnetization fluctuations in individual sub-micron ferromagnets have been detected through voltage and current noise measurements,⁹ SQUID magnetometry,¹⁰ magnetic force microscopy,¹¹ and, at record sensitivity, by frequency-shift torque magnetometry.^{12–15} The highest-sensitivity cantilever magnetometry studies to date have employed high-compliance cantilevers^{16,17} to examine in-plane switching of individual magnetic nanorods.^{13,15} Here we present a cantilever magnetometry study of *in-plane* to *out-of-plane* magnetization switching and fluctuations in a nickel nanorod at low temperature. We observe multiple sharp, simultaneous transitions in cantilever frequency, quality factor, and frequency jitter associated with individual switching events in the nanorod not seen in previous cantilever magnetometry experiments.

II. METHODS

A schematic of the experiment is shown in Fig. 1(a). Nickel nanorods were fabricated near the end of an attonewton-sensitivity cantilever, as described below. The external swept magnetic field, H , points through the thickness of the cantilever and, as the field is increased, the nanorod's magnetic moment switches from in-plane to out-of-plane. As a control, we also examined in-plane switching, Fig. 1(b), by remounting the cantilever so that the magnetic field was aligned instead with the long axis of the cantilever and nanorod.

Cantilevers ($L = 200\ \mu\text{m}$ long, $4\ \mu\text{m}$ wide, and $0.34\ \mu\text{m}$ thick) were fabricated from a single crystal silicon-on-insulator wafer.^{17,18} Cantilever parameters are given in Table I. For cantilevers C1–C3 a single nickel nanorod was fabricated at the end of each cantilever using e-beam patterning and

lift-off; 5 nm of Cr was evaporated as an adhesion layer, followed by 50 or 90 nm of Ni, both deposited at 0.25 nm/s. The resulting nickel nanorods were 1500 nm long, 160 to 200 nm wide, and 50 or 90 nm thick. A scanning electron microscope image of the leading edge of a representative cantilever is shown in Fig. 1(c). For cantilever C4 the nickel nanorod was fabricated separately on a freestanding silicon microchip using similar e-beam patterning and lift-off. The tip of the microchip supporting the nanorod was subsequently removed from the substrate via focused-ion beam milling and attached to a bare cantilever using focused-ion beam deposition of platinum.¹⁹ A separate nanorod with dimensions $1500\ \text{nm} \times 150\ \text{nm} \times 100\ \text{nm}$ was prepared for analysis by scanning transmission electron microscopy (STEM) and electron energy-loss spectroscopy (EELS) by underetching the silicon at the cantilever's leading edge.¹⁸ This nanorod was found to have an oxide-rich/nickel-poor coating 15 to 20 nm thick (EELS; data not shown, see Ref. 18) and was polycrystalline with grain sizes in the 20 to 40 nm range (STEM image; Fig. 1(d)).

Cantilever magnetometry experiments were performed at 4.2 K in high vacuum, as described in Ref. 15. Cantilever deflection was observed with a temperature-tuned 1310 nm optical fiber interferometer.²⁰ The cantilever deflection signal was sent to an analog gain-controlled positive feedback circuit²¹ whose output excited a piezoelectric crystal located near the cantilever base. The phase and gain of the feedback loop was adjusted to drive the cantilever into self oscillation at a zero-to-peak amplitude of $z_c = 134\ \text{nm}$ (except where noted). A software frequency demodulator (supporting information of Ref. 22) was used to determine the instantaneous cantilever frequency from a record of the cantilever deflection versus time, from which the average cantilever frequency was obtained and the frequency-fluctuation power spectrum was computed. Spring constant shifts were calculated from observed frequency shifts using $\Delta k = 2k\Delta f/f_c$, with k and f_c the cantilever spring constant and resonance frequency, respectively. The gain of the positive feedback loop was controlled using a software PI loop and the instantaneous gain used to infer the cantilever quality factor, Q , from which the dissipation was calculated using $\Gamma = k/2\pi f_c Q$.

^{a)}Electronic mail: jam99@cornell.edu.

FIG. 1. Relative orientation of cantilever, nickel nanorod tip, and applied magnetic field $\mu_0 \mathbf{H}$ for (a) hard-axis and (b) easy-axis cantilever magnetometry experiments. The cantilever oscillates in the z direction. When modeling the tip at high field as a uniformly magnetized particle, we will treat the tip magnetization, $\mathbf{M}$, as oriented in the y - z plane and inclined at an angle θ_m with respect to the nanorod's hard axis, z . (c) Scanning electron micrograph of cantilever C1's leading edge; scale bar = 200 nm. (d) Bright-field scanning transmission electron micrograph of a nanorod fabricated to overhang the cantilever's leading edge; scale bar = 50 nm.

III. RESULTS

The results of a representative easy-axis magnetometry control experiment ($\mathbf{H} \parallel y$) are shown in Fig. 2 for cantilever C1. The observed coercive field of $B_c = 2$ to 20 mT is consistent with in-plane switching via either a curling mechanism^{23,24} or domain wall nucleation and depinning.²⁵ Above the coercive field the observed Δk was fit to^{12,13}

$$\Delta k = \frac{B_{\text{sat}} V}{\mu_0 L_{\text{eff}}^2} \frac{B B_a}{B + B_a} \quad (1)$$

using the known tip volume V , applied magnetic field $B = \mu_0 H$, effective length for the first flexural mode $L_{\text{eff}} = L/1.377$, and an anisotropy field of $B_a = B_{\text{sat}} \Delta N_{zy}$ with $M_{\text{sat}} = B_{\text{sat}}/\mu_0$ the saturation magnetization and $\Delta N_{zy} = N_z - N_y$ the difference in z and y axis demagnetization factors. The best-fit values are shown in Table I. The measured values of B_{sat} and ΔN compare reasonably well with the $B_{\text{sat}} = 0.60$ T and $\Delta N = 0.50$ expected for a high aspect ratio nickel rod.

In addition to measuring the cantilever spring constant shift, the magnetic field dependent dissipation and frequency jitter were also measured and are shown in Fig. 2 for cantilever C1. Although the cantilever dissipation, Fig. 2(b), does change with the magnetic field, the magnitude of the shift is similar to that experienced by a bare silicon cantilever (data not shown) as has been previously observed for slightly larger nickel tips.¹⁵ The frequency jitter, Fig. 2(c), in a bandwidth $b = 15$ Hz shows no dependence on magnetic field. The magnitude of the observed frequency jitter can be entirely accounted for by considering two sources of frequency fluctuations. The first source of frequency fluctuations is the thermomechanical position fluctuations of the cantilever which give rise to a white frequency fluctuation spectral density,^{21,22} $P_{\delta f}^{\text{therm}}(f) = 4.8 \times 10^{-7} \text{ Hz}^2/\text{Hz}$. Secondly, the noise floor of the displacement sensor appears as frequency fluctuations proportional to the square of the offset frequency, $P_{\delta f}^{\text{det}}(f) = 5.3 \times 10^{-8} f^2 \text{ Hz}^2/\text{Hz}$.²¹ The calculated jitter,

$$J = \int_0^b (P_{\delta f}^{\text{therm}}(f) + P_{\delta f}^{\text{det}}(f)) df = 6.7 \times 10^{-5} \text{ Hz}^2,$$

TABLE I. Summary of cantilever and magnet properties. The hard axis fit for cantilever C1 and C2 extends to only 2 T. The magnet properties for cantilever C4 are a simultaneous fit to both the easy axis and hard axis data. The nominal magnetic moment, $\mu_{\text{sat}}^{\text{nominal}} = B_{\text{sat}} V/\mu_0$ was calculated assuming $B_{\text{sat}} = 0.6$ T and a nanorod volume of $V = l_m w_m t_m$.

	Quantity	C1 ^a	C2	C3	C4 ^b	unit
Cantilever properties at $T = 4.2$ K	f_c	8778	9000	8635	4838	Hz
	k	780 ± 130	852 ^c	852 ^c	703 ± 52	$\times 10_{-6} \text{ N m}_{-1}$
	Q	86 500	135 000	135 000	94 000	(unitless)
	Γ	163	112	116	246	$\times 10_{-15} \text{ N s m}_{-1}$
Magnet dimensions	l_m	1500	1500	1500	1500	nm
	w_m	200	160	200	220	nm
	t_m	50	50	50	90	nm
Magnet properties from easy-axis fits	μ_{sat}	8.04 ± 1.29	4.14 ± 0.62		11.72 ± 1.27	$\times 10_{-15} \text{ A m}_2$
	$\mu_0 M_{\text{sat}}$	0.68 ± 0.11	0.43 ± 0.07		0.49 ± 0.08	T
	ΔN	0.54 ± 0.09	0.89 ± 0.13		0.40 ± 0.10	(unitless)
Magnet properties from hard-axis fits	μ_{sat}	8.03 ± 1.34	5.48 ± 0.56	9.77 ± 1.47		$\times 10_{-15} \text{ A m}_2$
	$\mu_0 M_{\text{sat}}$	0.67 ± 0.11	0.57 ± 0.06	0.82 ± 0.12		T
	ΔN	0.36 ± 0.06	0.41 ± 0.04	0.29 ± 0.04		(unitless)
	$\mu_{\text{sat}}^{\text{nominal}}$	7.16	5.73	7.16	14.18	$\times 10_{-15} \text{ A m}_2$

^aCantilever C3 of Ref. 18.

^bCantilever C6 of Ref. 19.

^cCalculated from cantilever dimensions and material properties.

FIG. 2. Cantilever magnetometry data taken with the field applied along the easy-axis direction ($\mathbf{H}||y$) of cantilever C1 (y , Fig. 1(b)), sweeping from -4 T to $+4$ T. (a) Plot of the fractional cantilever spring constant shift (solid line) and a fit to Eq. (1) used to extract the magnet properties (dashed line), with inset showing magnetization switching with a coercive field of ~ 5 mT. (b) The cantilever dissipation Γ is slightly field dependent; however, for a magnet of this size, the field induced dissipation is no larger than that experienced by a cantilever without a magnetic tip. (c) The cantilever root-mean-square frequency fluctuations measured in a 15 Hz bandwidth.

agrees quite well with 8×10^{-5} Hz² jitter apparent in Fig. 2(c).

The results of a representative hard-axis magnetometry experiment ($\mathbf{H}||z$) from cantilever C3 are shown in Fig. 3. The hard-axis experiment showed numerous, simultaneous transitions in the cantilever spring constant, dissipation, and frequency jitter which were entirely absent in the easy-axis data of Fig. 2. For the hard-axis experiment at high field we can derive an expression for the spring constant shift similar to Eq. (1). As in deriving Eq. (1), the Stoner-Wohlfarth model²⁶ is the starting point. This model applies when $\theta_m \ll 1$, a condition that will not be met in our system until the external field becomes strong enough to align the magnetization along the field, which occurs when $B \approx B_a$. Above $B = B_a$, we derive that the spring constant shift should follow

$$\Delta k = -\frac{B_{\text{sat}} V}{\mu_0 L_{\text{eff}}^2} \frac{B B_a}{(B - B_a)}. \quad (2)$$

The results of fitting the high-field data to this model are shown in Table I and are in reasonable agreement with the results of the easy-axis experiments. However, the extracted values for ΔN_{zy} were uniformly smaller than those found in the easy-axis experiment and the values obtained by Aharoni for a rectangular prism.²⁷

The Δk measured in the hard-axis experiment ($\mathbf{H}||z$) showed multiple abrupt changes near 0.3 T. The biggest Δk dip was more than ten times larger in magnitude than any shift

FIG. 3. Cantilever magnetometry data taken with the field applied along the hard-axis direction ($\mathbf{H}||z$) of cantilever C3 (z , Fig. 1(a)), sweeping from -0.6 to $+0.6$ T. Left: Fractional cantilever spring constant shift (top) and cantilever dissipation Γ (middle), both showing large discontinuous transitions. Cantilever root-mean-square frequency fluctuations measured in a 15 Hz bandwidth (bottom); note the logarithmic scale and the 10 000-fold variation. Right: magnified view of two transitions; note the greatly expanded horizontal axes. The magnetic field was swept at a rate of 0.1 to 0.2 mT s⁻¹ and the cantilever frequency, dissipation, and jitter were measured every 0.5 s.

seen in an easy-axis magnetometry experiment. Moreover, the dips were in many cases only a few mT wide. Some of the Δk peaks showed sharp edges (Fig. 3, right) and exhibited little or no associated dissipation and jitter; we assign these peaks to domain wall depinning (Barkhausen noise). Most Δk dips *did* show a simultaneous peak in dissipation.

In Figs. 3(a) and 3(b) the field was swept from -0.6 T to $+0.6$ T; the Δk dips (and the Γ peaks) were narrower and more pronounced at positive field. If the field was subsequently swept from $+0.6$ T to -0.6 T, then the Δk dips and Γ peaks were narrower at *negative* field. Sweeping again from -0.6 T to $+0.6$ T restored the original asymmetry. If the hysteresis loop was run repeatedly, the Δk curve showed some run-to-run variability in dip depth and width, as shown in Fig. 4. The location of each individual dip was relatively robust from run to run, as long as the sweep rate was unchanged, but did exhibit variability at a level below what is easily discerned from the plot. Taken together, these findings are consistent with each Δk dip and Γ peak arising from a single domain that is weakly coupled to its neighbors,

FIG. 4. Cantilever magnetometry data from cantilever C3, with the magnetic field applied along the hard-axis ($\mathbf{H}||z$). The magnetic field was swept from 0.15 T to 0.35 T, with the remainder of the hysteresis loop swept between sequential, (a) to (c), runs. The depth of the Δk dips showed run-to-run variability. For example, the depth of the sharp dip near $\mu_0 H = 0.17$ T (left arrow) grew from (a) $\Delta k = -357$ ppm to (b) -519 ppm and (c) -666 ppm. Other features, such as the bump near $\mu_0 H = 0.322$ T (right arrow) in (a) and (b), disappeared entirely in (c).

whose magnetizations are history dependent and not completely reproducible (due to, for example, depinning).

Attempts to stop the field sweep on one of the Δk dips were unsuccessful, in part due to the movement of the Δk dips. Additionally, our current experimental apparatus cannot sweep slower than 0.02 mT/s which does not allow our software frequency demodulator to detect the dip fast enough to stop the sweep before the dip has been passed.

To rule out in-plane switching or domain motion caused by a small in-plane component of the applied field as the source of the Δk dips, the experiment of Fig. 3 was reproduced with the applied field angle intentionally misaligned from the hard axis by 2° and 4° . See Fig. 5. This range of angles is much larger than our estimated uncertainty in angle of $\pm 0.5^\circ$. If the field is misaligned from the hard axis by an amount θ , the component along the easy axis will be $B_\perp = B \sin \theta$, which for small θ is approximately $B\theta$. If the Δk dips were due to in-plane switching we would expect the magnetization to switch at a field that makes $B_\perp = B_c$. This condition is met when the external field is

$$B = \frac{B_c}{\sin \theta} \approx \frac{B_c}{\theta}. \quad (3)$$

However, Fig. 5 clearly shows that although the observed Δk dips were smaller with the field misaligned, they were still present and centered near $B = 0.3$ T, inconsistent with in-plane switching caused by the small in-plane component of the

FIG. 5. Cantilever magnetometry data from cantilever C4 taken with the field applied along the magnetic hard axis, $\mathbf{H}||z$, sweeping from -0.6 T to $+0.6$ T for three different nominal angles between the hard axis and the applied field, (a) 0° , (b) 2° , and (c) 4° .

external field. We also note that moving from 0° to 2° of misalignment eliminated most of the smaller Barkhausen events.

In Fig. 3, we highlight two kinds of Δk features distinguishable by the presence or lack of increased dissipation. Figure 6 demonstrates that these two types of features are also distinguishable by their dependence on cantilever amplitude. In the left plot of Fig. 6, one feature of each type is visible: a small step in the Δk at higher field that did not show a corresponding increase in cantilever dissipation and a large Δk dip that did have an accompanying increasing in dissipation. As shown in Fig. 6, the depth of the dissipation accompanied Δk dips were strongly dependent on the cantilever amplitude,

FIG. 6. Left: Fractional cantilever spring constant shift vs field for cantilever amplitudes ranging from 250 nm (upper trace) to 50 nm (lower trace) for cantilever C2. The data has been offset vertically for clarity. Because the cantilever dissipation is changing too rapidly for the feedback loop to respond in this experiment, a fixed drive amplitude was applied and the magnetic field was swept. Right, lower: Peak cantilever spring constant shift vs cantilever amplitude. The peak shift $\Delta \Delta k$ was computed by comparing the resonance frequency at the dip to the zero-field value (Method 1, circles) and to a linear baseline computed from the observed frequency just above and below the dip (Method 2, squares). The lines are fits to Eq. (9). Right, upper: Fit residuals.

while the step-like Barkhausen features showed no amplitude dependence.

To investigate this amplitude dependence, one would ideally sweep repeatedly through the peak, stepping the cantilever's amplitude between each sweep and holding it constant through a given sweep using a feedback loop. The ideal experiment was problematic because controlling the amplitude of a high- Q oscillator via feedback requires a relatively small feedback bandwidth.²⁸ Because of the limited field-sweep rates available in our experiment, the cantilever dissipation, and thus the cantilever amplitude, was changing more rapidly than our feedback loop could accommodate. To avoid this feedback problem we instead swept through the frequency dip without a feed-back loop controlling the cantilever amplitude and used a fixed drive voltage. To generate the data shown in the right plot of Fig. 6, we systematically varied the drive voltage, measured the cantilever amplitude and frequency simultaneously, and plotted the resulting peak frequency shift as a function of the cantilever amplitude.

Surprisingly, the Δk dip was largest for small cantilever amplitudes and decreased with increasing cantilever amplitude. This is further evidence that these features are not a result of switching due to the small in-plane component of the magnetic field since the in-plane component is directly proportional to the cantilever amplitude. We attribute the sharp Δk dips instead to in-plane to out-of-plane switching events. The multiple sharp, simultaneous transitions in cantilever frequency, dissipation, and frequency jitter seen in Fig. 3 indicate that in-plane to out-of-plane switching of our nanorods' magnetization proceeds via distinct intermediate states.

IV. ANALYSIS AND DISCUSSION

As the cantilever displaces by an amount z , the apparent angle of the applied field experienced by the magnetic particle will change by $\delta\theta \approx z/L_{\text{eff}}$. To model the amplitude dependence of the cantilever frequency shift near the switching field B_{sw} , let us take the view that the magnetization of a domain reorients continuously to minimize energy as the cantilever vibrates, and let us make the ansatz that the energy of the domain is given by, for small angular displacements,

$$U_m = -\mu_d B_{\text{sw}} c_\theta |\delta\theta|^m, \quad (4)$$

where μ_d is the magnetic moment of the domain, c_θ is a constant of order one, and the power m will be taken to be greater than zero. In writing Eq. (4), we are neglecting hysteresis, for simplicity. The torque associated with this energy is $\tau_x = -\partial U_m / \partial \delta\theta$. This torque is kinematically equivalent to a restoring force

$$F_z = \frac{\tau_x}{L_{\text{eff}}} = \pm \frac{\mu_d B_{\text{sw}} c_\theta}{L_{\text{eff}}} \left(\frac{z}{L_{\text{eff}}} \right)^{m-1}, \quad (5)$$

where the $\pm$ signifies that the sign of the force should be positive for $z > 0$ and negative for $z < 0$. We use Hamilton-Jacobi perturbation theory to calculate the perturbation to the cantilever spring constant Δk resulting from the displacement-dependent force²⁹ of Eq. (5):

$$\Delta k = -\frac{2}{z_{0p}^2} \langle F_z(t) z(t) \rangle_{\text{period}}, \quad (6)$$

where z_{0p} is the zero-to-peak cantilever amplitude and the $\langle \dots \rangle$ indicates a temporal average over one cantilever period of duration T . Substituting $z(t) = z_{0p} \sin(2\pi t/T)$, and using the fact that the perturbation is an antisymmetric function of the displacement,

$$\Delta k = -\frac{2c_\theta \mu_d B_{\text{sw}}}{z_{0p}^2} \left(\frac{z_{0p}}{L_{\text{eff}}} \right)^m \left[\frac{2}{T} \int_0^{T/2} \left\{ \sin\left(\frac{2\pi t}{T}\right) \right\}^m dt \right]. \quad (7)$$

The integral [...] in Eq. (7) is independent of T and can be carried out analytically in terms of the gamma function Γ . The result yields

$$\frac{\Delta k}{k} = -\frac{c_\theta \mu_d B_{\text{sw}}}{k L_{\text{eff}}^m z_{0p}^{2-m}} \frac{4\sqrt{\pi} \sec(\frac{m\pi}{2})}{\Gamma(\frac{1-m}{2}) \Gamma(\frac{m}{2})}. \quad (8)$$

The right-most fraction in Eq. (8) is a slowly varying function of m . For $m=2$, this equation reduces to $\Delta k/k = 2c_\theta \mu_d B_{\text{sw}} / k L_{\text{eff}}^2$ —independent of cantilever amplitude, as expected for a potential energy which depends quadratically on the cantilever displacement. For $m < 2$, Eq. (8) predicts an amplitude-dependent change in spring constant, in qualitative agreement with experiment.

To analyze the spring-constant dips in Fig. 6 (left), the depth of the dip was inferred using two methods. In Method 1, the frequency at the bottom of the dip was compared to the cantilever frequency at zero field, and the computed frequency shift converted to an equivalent spring constant shift. In Method 2, the frequency shift at the bottom of the dip was compared to a frequency baseline obtained by fitting the data to either side of the dip to a line (Fig. 6, left, dotted line). The shifts computed by Methods 1 and 2 are plotting in Fig. 6 (right) as circles and squares, respectively.

Following Eq. (8), we fit the data of Fig. 6 (right) to the power-law function

$$\frac{\Delta \Delta k}{k} = -\kappa_{\text{ref}} \left(\frac{z_{\text{ref}}}{z_{0p}} \right)^{2-m}, \quad (9)$$

with $z_{\text{ref}} = 41.9$ nm a reference amplitude and κ_{ref} a prefactor representing the relative spring constant shift at the reference amplitude. The domain magnetic moment in Eq. (4) is computed from best-fit parameters using

$$\mu_d = \frac{\kappa_{\text{ref}} k L_{\text{eff}}^m z_{\text{ref}}^{2-m} \Gamma(\frac{1-m}{2}) \Gamma(\frac{m}{2})}{c_\theta B_{\text{sw}} 4\sqrt{\pi} \sec(\frac{m\pi}{2})}, \quad (10)$$

taking $c_\theta = 1$ for simplicity. The standard error in the domain magnetic moment, which depends on the error in both the prefactor and the power, is computed numerically as $\sigma_{\mu_d} = ((\partial \mu_d / \partial \kappa_{\text{ref}})^2 \sigma_{\kappa_{\text{ref}}}^2 + (\partial \mu_d / \partial m)^2 \sigma_m^2)^{1/2}$. The number of domains in the tip, N_d , is computed by dividing the total tip magnetic moment reported for cantilever C2 in Table I by μ_d .

TABLE II. Analysis of Fig. 6 data. The reported error bars represent a 95% confidence interval.

Value	Unit	Method 1	Method 2
κ_{ref}	—	$620 \pm 36 \times 10^{-6}$	$401 \pm 50 \times 10^{-6}$
m	—	1.740 ± 0.053	1.52 ± 0.13
μ_d	10^{-15} A m^2	4.4 ± 1.9	0.53 ± 0.53
N_d	—	1.3 ± 0.5	11 ± 11

Fitting results are presented in Table II. The Method 1 data, when analyzed in terms of the model of Eq. (8), give a domain magnetic moment which is too large. The domain parameters extracted from the Method 2 data, in contrast, predict a number of domains (0 to 22) in good agreement with the total number of frequency dips seen in Figs. 3 and 4. In spite of the large uncertainty in the domain magnetic moment inferred from the Method 2 data, we can nevertheless conclude that the domains giving rise to the frequency dips seen in 3 and 4 are well described by Eq. (4) with $m = 1.52 \pm 0.13$. Comparing the results of Methods 1 and 2, we conclude that it is essential to account for the background shift arising from already-flipped domains when analyzing the Δk dips.

We now turn our attention to the dissipation data in the middle panel of Fig. 3. Field-dependent dissipation in a cantilever magnetometry experiment arises from transverse magnetization fluctuations.^{13,15} For a field oriented as in Fig. 1(a), fluctuations in magnetization angle give rise to a fluctuating x -axis torque $\delta\tau_x(t) = \delta\mu_y(t) B$. This torque is kinematically equivalent to a fluctuating z -axis force of magnitude $\delta F_z(t) = \delta\tau_x(t)/L_{\text{eff}}$. This force will lead to a dissipation $\Gamma_m = P_{\delta F_z}(f_c)/4k_bT$ with $P_{\delta F_z}(f)$ the one-sided power spectrum of force fluctuations and f_c the cantilever frequency.^{13,15} At B_{sw} , the power spectral density of magnetic moment fluctuations giving rise to a dissipation peak is thus

$$P_{\delta\mu_y}(f_c) = \frac{4k_bTL_{\text{eff}}^2}{B_{\text{sw}}^2} \Gamma_m. \quad (11)$$

For a dissipation peak with $\Gamma_m = 0.25 \times 10^{-12} \text{ N s m}^{-1}$, $B_{\text{sw}} = 0.221 \text{ T}$, and $T = 4.2 \text{ K}$, we compute $P_{\delta\mu_y}(f_c) = 2.6 \times 10^{-42} \text{ A}^2 \text{ m}^4 \text{ Hz}^{-1}$.

Let us consider the effect of such tip magnetization fluctuations on sample spins below the tip in a magnetic resonance force microscope experiment.^{13,15,30} Modeling the fluctuating domain as a dipole, the resulting power spectral density of magnetic field fluctuations at a distance r from the domain is

$$P_{\delta B_y}(f_c) = \left(\frac{\mu_0}{\pi r^3}\right)^2 P_{\delta\mu_y}(f_c). \quad (12)$$

At $r = 220 \text{ nm}$, where the field from the dipole is estimated to be 0.20 T , we calculate $P_{\delta B_y}(f_c) = 3.6 \times 10^{-12} \text{ T}^2 \text{ Hz}^{-1}$. Since $f_c \sim \text{few kHz}$ is similar to the Rabi frequency in a magnetic resonance experiment, the magnetic fluctuations underlying the dissipation peaks in Fig. 3 are at the right frequency to affect $T_{1\rho}$, the spin-lattice relaxation time in the

FIG. 7. Potential energy of magnetization as a function of magnetization angle θ_m . The field, which is applied along the z axis of Fig. 1(a), increases from left to right.

rotating frame.¹⁵ The associated spin relaxation rate, $\gamma_j^2 P_{\delta B_y}$ with γ_j the gyromagnetic ratio, evaluates to 15 ms for protons and 0.4 ns for electrons. This calculation indicates that efficient relaxation of sample spins in a magnetic resonance experiment could be induced by adjusting the external field to coincide with one of the dissipation peaks in Fig. 3. The dissipation peaks are only a few gauss wide, suggesting that rapid modulation of sample relaxation times could be achieved.

Qualitatively, the existence of the multiple dissipation peaks seen in Fig. 3 requires multiple domains, each having a magnetic potential energy function with states of many different magnetization angles thermally populated near $\sim 0.3 \text{ T}$. One such potential is shown in Fig. 7.

V. CONCLUSIONS

In summary, we have observed dramatic changes in cantilever spring constant, dissipation, and frequency jitter in a cantilever magnetometry study of in-plane to out-of-plane magnetization switching in a single nickel nanorod. Many of these features are robust toward angular deviations of up to a few degrees, and show a strong dependence on cantilever amplitude. These findings are quite general, having been observed for every nanorod tipped cantilever we have investigated to date, spanning approximately two years and including extensive changes in the cantilever and nanorod fabrication process during that time.

We derived a model for the changes in the cantilever spring constant above the anisotropy field by treating the nanorod as a uniformly-magnetized Stoner-Wohlfarth particle, and find reasonable agreement between the model and the experimental results. An estimate for the active volume from the amplitude dependence of a single Δk dip is consistent with the presence of multiple dips, and is comparable to the grain size of our nanorods as estimated using STEM.

The existence of multiple weakly coupled volumes within the nanorod that switch quasi-independently could be explained by the presence of crystalline domains (Fig. 1(d)), spatial variations in the nickel thickness, or the templating of magnetization by an antiferromagnetic nickel oxide coating. One possible mechanism of quasi-independent switching is in-plane to out-of-plane coherent rotation of magnetization. There is precedent for observing magnetization switching in nickel nanorods via thermally-activated coherent rotation in magnetic force microscopy,²³ anisotropic magnetoresistance,³¹ and SQUID²⁴ magnetometry, but in these prior works only a single switching event was typically apparent. The

grain size was much smaller in the nickel films used in these prior studies, however, which may explain why they did not observe switching via distinct intermediate states as seen here. While the coherent-rotation model does qualitatively explain the presence of multiple switching events as well as quantitatively predict the correct observed switching field, it does not quantitatively account for the observed dependence of Δk on cantilever amplitude. It seems likely, therefore, that another mechanism of in-plane to out-of-plane switching is at play in our nanorods.

Whatever the underlying mechanism, the results of Fig. 3 suggest a new method for creating giant tunable magnetic field fluctuations and for mechanically detecting magnetic fields at high sensitivity and nanoscale spatial resolution.⁶⁻⁸

ACKNOWLEDGMENTS

We thank David Muller and Pinshane Huang for assistance with electron microscopy. This work was supported by the U.S. Army Research Office (MURI W911NF-05-1-0403), the National Institutes of Health (5R01GM-070012) and was performed in part at the Cornell NanoScale Science & Technology Facility (NSF, ECS-0335765) and the Cornell Center for Materials Research (NSF, MRSEC DMR-0520404).

¹H. N. Bertram, *Theory of Magnetic Recording* (Cambridge University Press, 1994).

²D. Weller and A. Moser, *IEEE Trans. Mag.* **35**, 4423 (1999).

³C. A. Ross, *Annu. Rev. Mater. Res.* **31**, 203 (2001).

⁴A. Moser, K. Takano, D. T. Margulies, M. Albrecht, Y. Sonobe, Y. Ikeda, S. Sun, and E. E. Fullerton, *J. Phys. D* **35**, 157 (2002).

⁵S. A. Wolf, D. D. Awschalom, R. A. Buhrman, J. M. Daughton, S. Von Molnar, M. L. Roukes, A. Y. Chtchelkanova, and D. M. Treger, *Science* **294**, 1488 (2001).

⁶S. Kuehn, S. A. Hickman, and J. A. Marohn, *J. Chem. Phys.* **128**, 052208 (2008).

⁷C. L. Degen, M. Poggio, H. J. Mamin, C. T. Rettner, and D. Rugar, *Proc. Natl. Acad. Sci. U.S.A.* **106**, 1313 (2009).

⁸E. W. Moore, S.-G. Lee, S. A. Hickman, S. J. Wright, L. E. Harrell, P. P. Borbat, J. H. Freed, and J. A. Marohn, *Proc. Natl. Acad. Sci. U.S.A.* **106**, 22251 (2009).

⁹N. Smith and P. Arnett, *Appl. Phys. Lett.* **78**, 1448 (2001).

¹⁰W. Wernsdorfer, E. B. Orozco, K. Hasselbach, A. Benoit, B. Barbara, N. Demoncey, A. Loiseau, H. Pascard, and D. Maillly, *Phys. Rev. Lett.* **78**, 1791 (1997).

¹¹P. Grütter, Y. Liu, P. LeBlanc, and U. Dürig, *Appl. Phys. Lett.* **71**, 279 (1997).

¹²J. A. Marohn, R. Fainchtein, and D. D. Smith, *Appl. Phys. Lett.* **73**, 3778 (1998).

¹³B. C. Stipe, H. J. Mamin, T. D. Stowe, T. W. Kenny, and D. Rugar, *Phys. Rev. Lett.* **86**, 2874 (2001).

¹⁴C. W. Miller, U. M. Mirsaidov, T. C. Messina, Y. J. Lee, and J. T. Markert, *J. Appl. Phys.* **93**, 6572 (2003).

¹⁵T. N. Ng, N. E. Jenkins, and J. A. Marohn, *IEEE Trans. Mag.* **42**, 378 (2006).

¹⁶T. D. Stowe, K. Yasumura, T. W. Kenny, D. Botkin, K. Wago, and D. Rugar, *Appl. Phys. Lett.* **71**, 288 (1997).

¹⁷N. E. Jenkins, L. P. DeFlores, J. Allen, T. N. Ng, S. R. Garner, S. Kuehn, J. M. Dawlaty, and J. A. Marohn, *J. Vac. Sci. Technol. B* **22**, 909 (2004).

¹⁸S. A. Hickman, E. W. Moore, S.-G. Lee, J. G. Longenecker, S. J. Wright, L. E. Harrell, and J. A. Marohn, *ACS Nano* **4**, 7141 (2010).

¹⁹J. G. Longenecker, E. W. Moore, and J. A. Marohn, *J. Vac. Sci. Technol. B* **29**, 032001 (2011).

²⁰K. J. Bruland, J. L. Garbini, W. W. Dougherty, S. H. Chao, S. E. Jensen, and J. A. Sidles, *Rev. Sci. Instrum.* **70**, 3542 (1999).

²¹T. R. Albrecht, P. Grütter, D. Horne, and D. Rugar, *J. Appl. Phys.* **69**, 668 (1991).

²²S. M. Yazdani, J. A. Marohn, and R. F. Loring, *J. Chem. Phys.* **128**, 224706 (2008).

²³R. O'Barr, M. Lederman, S. Schultz, W. Xu, A. Scherer, and R. J. Tonucci, *J. Appl. Phys.* **79**, 5303 (1996).

²⁴W. Wernsdorfer, B. Doudin, D. Maillly, K. Hasselbach, A. Benoit, J. Meier, J.-Ph. Ansermet, and B. Barbara, *Phys. Rev. Lett.* **77**, 1873 (1996).

²⁵W. Wernsdorfer, K. Hasselbach, A. Benoit, B. Barbara, B. Doudin, J. Meier, J.-Ph. Ansermet, and D. Maillly, *Phys. Rev. B* **55**, 11552 (1997).

²⁶E. C. Stoner and E. P. Wohlfarth, *Philos. Trans. R. Soc. London, Ser. A* **240**, 599 (1948).

²⁷A. Aharoni, *J. Appl. Phys.* **83**, 3432 (1998).

²⁸U. Dürig, H. R. Steinauer, and N. Blanc, *J. Appl. Phys.* **82**, 3641 (1997).

²⁹F. J. Giessibl, *Phys. Rev. B* **56**, 16010 (1997).

³⁰J. D. Hannay, R. W. Chantrell, and D. Rugar, *J. Appl. Phys.* **87**, 6827 (2000).

³¹J. E. Wegrowe, D. Kelly, A. Franck, S. E. Gilbert, and J.-Ph. Ansermet, *Phys. Rev. Lett.* **82**, 3681 (1999).