

Tracking Random Walk of Individual Domain Walls in Cylindrical Nanomagnets with Resistance Noise

Amrita Singh,^{*} Soumik Mukhopadhyay,[†] and Arindam Ghosh

Department of Physics, Indian Institute of Science, Bangalore 560 012, India

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The stochasticity of domain-wall (DW) motion in magnetic nanowires has been probed by measuring slow fluctuations, or noise, in electrical resistance at small magnetic fields. By controlled injection of DWs into isolated cylindrical nanowires of nickel, we have been able to track the motion of the DWs between the electrical leads by discrete steps in the resistance. Closer inspection of the time dependence of noise reveals a diffusive random walk of the DWs with a universal kinetic exponent. Our experiments outline a method with which electrical resistance is able to detect the kinetic state of the DWs inside the nanowires, which can be useful in DW-based memory designs.

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Domain-wall (DW) dynamics in ferromagnetic nanowires has received intense interest in recent years due to their potential application in a novel class of memory devices, as well as from the viewpoint of exciting fundamental physics [1–3]. The process of DW propagation, driven either by magnetic field (H) or by electric current, is intimately connected to the magnetization reversal mechanism, and hence influenced by the geometry and magnetic anisotropy properties, as well as intrinsic disorder within the nanowires that act as pinning centers. A consequence of this is the nondeterministic, or stochastic, kinetics of the DWs, which is a subject of great fundamental and technological importance [1,4–9]. Randomness associated with the magnetization reversal process is the major source of stochasticity, and a common mechanism involves random walk of DWs through Barkhausen avalanches, where the DWs are treated as particles undergoing Brownian motion according to the Langevin equation [10]. Such a mechanism has been established in magnetic thin films, where Barkhausen statistics result in universal scaling exponents in the avalanche size or duration distribution functions [4,7]. The viscous DW flow has also been observed in Mn-doped semiconductor epilayers [11], but a clear signature of H -driven random walk of DWs in magnetic nanowires has not been observed experimentally. This issue is of particular interest in the case of cylindrical magnetic nanowires, where the DWs behave as “massless” particles with zero kinetic energy [12], and hence whether the general mechanisms of stochastic kinetics can at all be relevant in this case is unknown. In this Letter, we provide the first unambiguous evidence of diffusive random walk of DWs in cylindrical high-aspect ratio magnetic nanowires by tracking their motion at small H (just above the depinning field). We show that not only the stochasticity in DW kinetics within magnetic nanowires can be described by Brownian diffusion with universal exponents, but the nature of the stochasticity can be employed to probe the kinetic state of the DWs themselves.

Quantifying stochasticity with conventional probes such as the Kerr effect, x-ray, electron, or force microscopy, involves analyzing magnetization burst size, variations in DW displacement, or the depinning fields, etc., where the sensitivity to the evolution in the DW motion in time domain can be limited. Time-of-flight probing, for example, in the context of first time arrival [4], or planar Hall effect [11,13,14], has been useful in locating DWs or measuring their average velocity between spatially separated probes. Here we have adopted a different route and measured the low-frequency fluctuations in longitudinal electrical resistance (R) of magnetic nanowires at small H above the depinning threshold. In disordered metallic systems these fluctuations, often known as $1/f$ noise, are extremely sensitive to slow relaxation of defects (dislocations, cluster of point defects, etc.). Random movement of the scatterers, even at a scale of approximately Fermi wavelength ($\lambda_F \lesssim 1$ nm), changes the interference pattern of coherently backscattered electrons, resulting in the time-dependent fluctuations in the resistivity [15]. In magnetic systems, the DWs themselves can act as scatterers of spin-polarized conduction electrons and modify the R of the nanowires. This can occur either through direct reflection when DW width $\Delta \sim \lambda_F$ [16] or by spin-dependent scattering of electrons by the disorder inside the DWs [17,18]. Recently, the fluctuations in R in different forms of nanomagnetic structures have been associated with the motion of DWs [19,20], although the details of the time dependence of R due to motion of individual DWs remain unexplored.

We have used nickel nanowires that were electrochemically grown inside anodic alumina templates—a well-characterized system in the context of magnetic storage [21–23]. We have used nanowires of average diameter ≈ 200 nm, where strong shape anisotropy (aspect ratio ~ 200) aligns the easy axis of magnetization along the long axis of the nanowires. Details of the growth process and structural characterization can be found elsewhere

[20]. Following the growth, freestanding nanowires were obtained by dissolving the alumina template in 2M NaOH solution. Nanowires were then drop casted on flat silicon oxide substrates, after which electron-beam lithography was used to form Ti/Au contact pads for electrical measurements. Scanning electron micrograph of the device used for the present experiments appears in Fig. 1(a), where the length (L) of the nanowire between the voltage probes (indicated by $V+$ and $V-$) was $\approx 4.5 \mu\text{m}$. Edge roughness, and also the branching or clusters attached at the end of the nanowire, reduces the DW nucleation barrier substantially [21]. To measure small changes in R , a dynamically balanced ac Wheatstone bridge arrangement was used (excitation frequency of 226 Hz) (see Refs. [20,24] for more details on noise measurements). All measurements were performed with a very low excitation current density ($\leq 10^7 \text{ A/m}^2$) to avoid heating, electromigration, or the spin-torque effect. The background fluctuations consisted mainly of Nyquist noise, and the resolution to change in R was $\sim 10 \text{ ppm}$. Figure 1(b) shows the magnetoresistance curves at three different angles (θ) between H and the electric current density (nanowire long axis). The nanowire exhibits anisotropic magnetoresistance (AMR) where the switching field H_{sw} , identified by the dip in the AMR, increases continuously from $\approx 250 \text{ Oe}$ at $\theta = 0$ to the maximum of $\approx 850 \text{ Oe}$ at $\theta = 90^\circ$. This indicates the magnetization reversal to occur via curling mode as expected in nickel nanowires with diameter $\geq 45 \text{ nm}$ [22].

To find the signature of the DWs, expected to be of vortex type in our case [2], we have recorded R as a function of time at fixed values of H applied parallel to

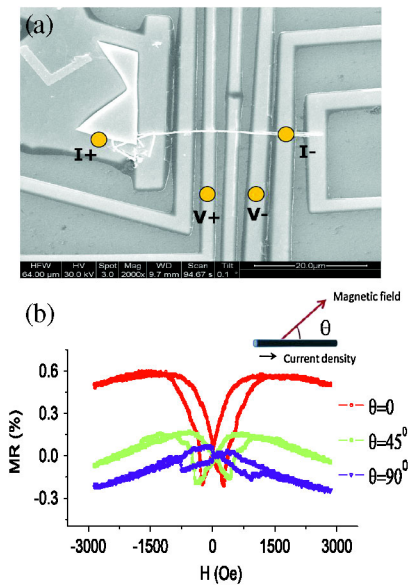


FIG. 1 (color online). (a) Scanning electron micrograph of the device used in the present experiments. The voltage and current probes are indicated as $V+$, $V-$ and $I+$, $I-$, respectively. (b) Anisotropic magnetoresistance (AMR) for three different angles between the current and external magnetic field (H).

the nanowire axis. H was increased monotonically in small steps, starting from $H = 0$, and at every step time dependence of R was measured over $\approx 60 \text{ min}$. In Fig. 2, time series recorded at four different H are shown. At very low H ($\ll 1 \text{ Oe}$) the fluctuations in R are featureless with a power spectral density (PSD) of noise, $S_R/R^2 \propto f^{-\alpha}$, where $\alpha \approx 1$ [also see Fig. 3(a)]. At $H \geq 1 \text{ Oe}$, discrete multilevel states in R appear as a function of time as shown in the two lower panels of Fig. 2 for $H = 1.5$ and 3 Oe . Further increase in H somewhat obscures the visibility of the multilevel states, which disappear completely for $H \geq H_{\text{sw}}$ (time series not shown). The same sequence was repeated over many magnetization cycles, indicating the phenomena to be due to application of H , and not due to relaxation of internal disorder driven by temperature or electric current.

Before analyzing the time dependence of the fluctuations, we address the origin of the discrete jumps in R at $H \geq 1 \text{ Oe}$. In all cases the jumps involve *increase* in R from its base value R_0 ($\approx 4.0 \Omega$ at room temperature) by ΔR or $2\Delta R$, where $\Delta R \approx 3 \text{ m}\Omega$. Since H is kept fixed, AMR or Lorentz contributions to R do not change, and hence a natural explanation involves the DWs, which nucleate at the defect sites and travel intermittently across the voltage probes. Increasing R by ΔR and $2\Delta R$ then corresponds to fitting a domain partially (one DW) or fully (two DWs) between the voltage probes, respectively. Indeed, the positive correction ΔR can be quantitatively understood from the Levy-Zhang model of spin mixing due to disorder scattering inside the DWs [17], which estimates the fractional change in R from the inclusion of a single DW between the voltage probes as $(\Delta/L)[1 + \xi^2(\rho^\uparrow - \rho^\downarrow)^2/5\rho^\uparrow\rho^\downarrow] \approx 0.7\%$. Here ρ^\uparrow and ρ^\downarrow correspond to resistivities of the up and down spin

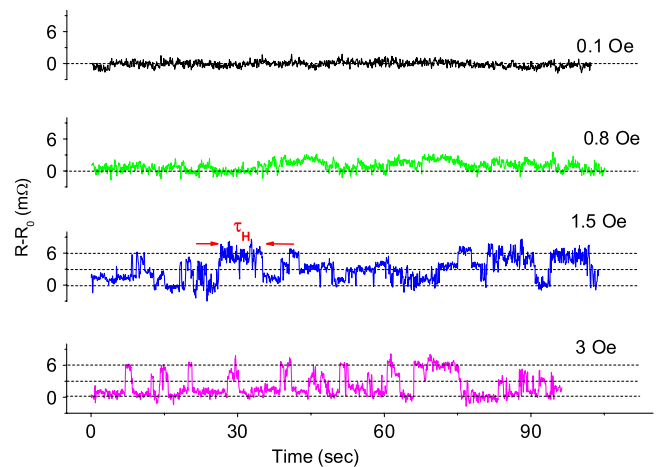


FIG. 2 (color online). Time variation of resistance at four different magnetic fields applied parallel to the long axis of the nanowire. The high resistance states for $H = 1.5$ and 3 Oe are indicated by the arrows and their duration by τ_H . The dashed horizontal lines identify the discrete resistance states observed in the time traces.

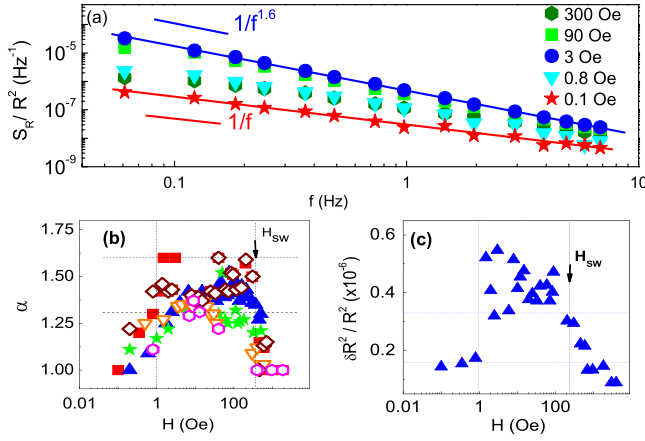


FIG. 3 (color online). (a) Noise power spectral density (PSD) at different values of H . Nonmonotonic variation of (b) the spectral exponent and (c) the normalized variance in noise. In (b) different symbols signify different magnetization cycles. The switching field H_{sw} obtained from the AMR measurements is also indicated in (b) and (c).

channels respectively, with $\rho^1/\rho^l \approx 3$ in nickel, $\xi = \pi \hbar^2 k_F / 4m_e J \Delta \approx 1$ with Fermi wave vector $k_F = 1.5 \times 10^{10} \text{ m}^{-1}$, nickel exchange energy $J = 4.46 \times 10^{-21} \text{ J}$, and DW width $\Delta = 24 \text{ nm}$ [23]. Experimentally, we find $\Delta R/R_{4.2 \text{ K}} \approx (0.4\text{--}0.5)\%$, which agrees with the expected DW contribution within a factor of 2 (we used the low temperature residual resistance $R_{4.2 \text{ K}} \approx 0.8 \Omega$ of the nanowire to eliminate the phonon contribution). Occasionally, the time series at larger H shows direct jumps of $2\Delta R$, which could be due to nucleation of domains within the region between the voltage probes. In the time domain, the jumps did not show any regular pattern or sequence, which prompted us to focus on the frequency domain through power spectral analysis.

The PSD of the fluctuations in R over the entire (approximately hour long) time series was found to vary as $S_R/R^2 = A_R/f^\alpha$ [Fig. 3(a)], where both noise amplitude (A_R) and α depend strongly (and nonmonotonically) on H [Figs. 3(b) and 3(c)]. Three regimes can be clearly identified, and understood in term of the DWs. (1) At $H < 1 \text{ Oe}$, which we can now identify as the depinning field, the noise magnitude [expressed as relative variance $\delta R^2/R^2 = \int (S_R/R^2) df$ in Fig. 3(c)] is low and α is $\approx 1\text{--}1.2$ [Fig. 3(b)]. This H -independent background noise arises from slow relaxation of disorder (such as dislocations, vacancy clusters, etc.), which has a PSD $\sim 1/f^\alpha$, where $\alpha \approx 1$, due to the broad distribution of associated time scales. (2) For intermediate H ($1 \text{ Oe} < H \leq H_{sw}$), we identify a sharp increase in both $\delta R^2/R^2$ and α ($\sim 1.4\text{--}1.7$). We can understand this with two parallel mechanisms. First, random fluctuations in the number of DWs between the voltage probes lead to PSD $\sim 1/f^\alpha$ with $\alpha \sim 2$, and second, the fluctuations in R generated by any given DW during its flight between the probes. The latter causes R to fluctuate in a given state and embodies the stochasticity of DW propagation which will be treated

separately. (3) Finally, for $H > H_{sw}$ the number of domains diminish, and both $\delta R^2/R^2$ and α return to their zero-field background values.

Can the stochasticity in DW propagation be extracted from the kinetics of resistance noise? To answer this we return to Fig. 2 and focus on the fluctuations only in the $R = R_0 + 2\Delta R$ state, which would correspond to one propagating domain (i.e., two DWs) between the voltage probes. For a preliminary time-of-flight analysis, we note that the time (τ_H) that the system stays in this state corresponds to the time the domain takes to travel from one voltage probe to the other. In Fig. 4 two histograms of τ_H obtained at $H = 1.5$ and 3 Oe are shown. Clearly, the modal magnitude of τ_H decreases with increasing H , due to increase in the DW velocity (inset). Two important points are to be noted here. (1) The width of the velocity distribution decreases with increasing H , which can be attributed to the H -induced reduction in the effective propagation barrier that suppresses (lower) part of the barrier energy distribution. (2) Secondly, the typical velocity is about 5 orders of magnitude lower than thin film-based magnetic nanostrips, which can be understood from the suppression of DW mobility ($\sim \Delta^{4.4}$) at greatly reduced DW width in nanowires of cylindrical cross section [16].

The PSD of noise in the high resistance state (spanning over τ_H) shows a strikingly universal behavior. At all τ_H segments [see typical time traces in Fig. 5(a)], the PSDs vary as $S_R/R^2 \sim 1/f^\alpha$, where $\alpha = 1.5 \pm 0.05$ at both $H = 1.5$ and 3 Oe [Figs. 5(b) and 5(c), respectively]. This is distinctly different in the low resistance states, where α was found to be $\approx 1.0\text{--}1.2$ (not shown). In disordered metals, which is not undergoing plastic deformation or any structural phase transitions [25], the observation of $\alpha = 1.5$ in resistance noise signifies diffusion or random walk of the charge scatterers, such as dislocations, vacancy, or interstitial clusters, etc. [26,27]. The exponent is universal in the sense that it is a direct outcome of the fluctuation-

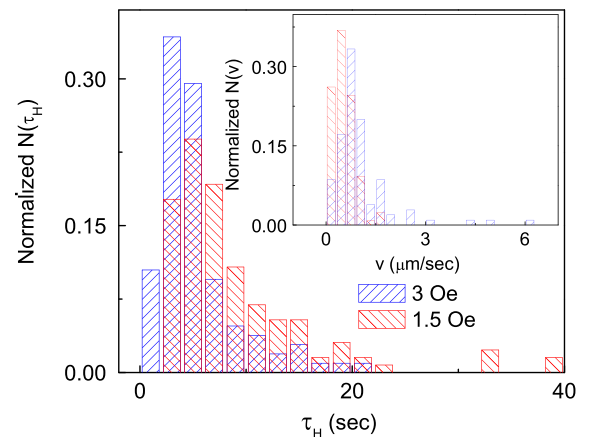


FIG. 4 (color online). The distribution of τ_H for two magnetic fields ($H = 1.5$ and 3 Oe). Inset: Distribution of the velocity of the domain walls $v = L/\tau_H$, where L is the distance between the voltage probes, at the same values of H .

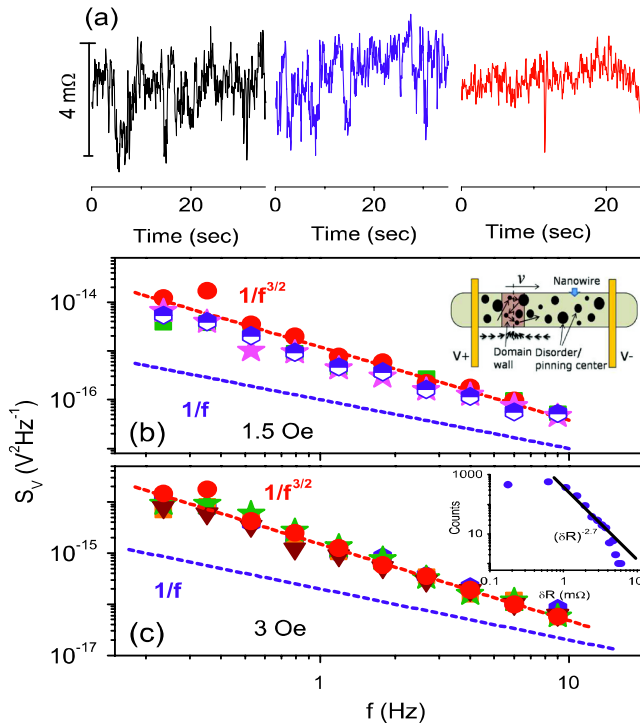


FIG. 5 (color online). (a) Resistance-time behavior within three high resistance states (see Fig. 2 also). PSD of resistance fluctuations in this state is shown for (b) $H = 1.5$ Oe and (c) $H = 3$ Oe. Inset of (b): Schematic of electron scattering events within a domain wall which becomes time dependent as the wall moves between the voltage probes. Inset of (c): Distribution of resistance jumps (in the high resistance state) for $H = 3$ Oe.

dissipation theorem for a system in thermal equilibrium, and largely independent of its material or geometrical properties, layout of disorder, etc. [26]. In our magnetic nanowires, however, disorder is mostly quenched and contributes very little (see Fig. 3), indicating that the noise in R originates from the movements of the DWs themselves.

We suggest a mechanism with the help of the schematic shown in the inset of Fig. 5(b) and the Levy-Zhang model of electron scattering within the DWs by disorder that mixes the spin-up and spin-down channels [17]. As the DW moves, the scatterers move to the opposite direction with respect to the DW. Hence the wave function of the electrons within the DW, which depends on the mistracking of the electron spin to local magnetization, “see” a time-varying layout of the scatterers. This will cause a time-dependent mixing of the spin channels, i.e., $\rho^\uparrow/\rho^\downarrow$ will fluctuate with time, leading to fluctuations in the measured R . The diffusive kinetics of the scatterers indicated by the PSDs in Fig. 5(c) then implies that the DW itself moves by diffusive random walk from one pinning center to the other, providing the first evidence of such a behavior in magnetic nanosystems. A distribution function of resistance jumps in these states is difficult to compare with the theoretical models that associate universal expo-

nents to distribution of DW displacements [8,10], but we do observe a power law behavior in such constructions with an exponent of ≈ 2.7 , which is presumably nonuniversal [inset of Fig. 5(c)]. Nevertheless, observation of $\alpha \approx 1.5$ in noise can act as a detector of moving DW inside the nanowire, while static or localized hopping of DWs would lead to α that is closer to unity.

In conclusion, we have shown that low-frequency fluctuations in electrical resistance of magnetic nanowires can be a sensitive probe to domain kinetics under an applied magnetic field. Both noise magnitude and spectral exponent can detect the number fluctuation and propagation stochasticity of the domain walls. We find the first evidence of random walk in the propagation of individual domain walls, which display a universal kinetic exponent in nanowires at small magnetic fields.

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*amrita@physics.iisc.ernet.in

†soumik@physics.iisc.ernet.in

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