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Microscopic view on a single domain wall moving through ups and downs of an atomic washboard potential

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Abstract

Propagation of ferromagnetic domain walls on sub-atomic scale was measured in a thin uniaxial garnet film by using ballistic Hall magnetometry. Domain walls are found to move by equidistant steps, which correspond to the crystal lattice constant in this material. Our results are in good agreement with the theory of intrinsic pinning of a domain wall in the Peierls potential. We have also measured AC susceptibility of a domain wall moving inside a Peierls valley. The observed nonlinear behavior of the AC susceptibility can be understood within the framework of kinks and breathers nucleating and spreading along the domain wall.

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1. Introduction

The concept of a ferromagnetic domain wall moving in response to external magnetic field is widely used to explain major features of the ferromagnetic hysteresis loop. A variety of techniques were used to study dynamics of domain walls, interaction of a domain wall with individual defects and statistical properties of domain wall's dynamics. Recently, due to the development of new methods for detection of movements of domain walls, it became possible to study the domain wall propagation on sub-micron scale [1–4]. Usually, standard micromagnetic calculations describe the experimental results very well. However, it was shown theoretically, that in the case of narrow (in comparison with interatomic distances) domain walls, the discrete nature of crystal structure should be taken into account [5–7]. This effectively leads to a new term in energy of the magnetic crystal—the Peierls potential. The Peierls energy has a periodicity of the crystal lattice and it makes the domain wall preferentially staying between atomic planes. The effect is called an intrinsic pinning.

The Peierls potential was experimentally observed for the case of dislocations [8–10] and superconducting vortices [11–13] a number of years ago. There was also reported some indirect evidence for intrinsic pinning for ferromagnetic domain walls [14]. However, no direct experiment has confirmed this so far. To

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detect the propagation of a domain wall on a sub-atomic scale, one basically needs very high sensitivity to magnetic field, which has not been achieved by any technique yet. Another problem is that the strength of the Peierls potential depends exponentially on the ratio of the interatomic distance to the domain wall width (the bigger the ratio, the deeper the Peierls potential). This limits us to using ferromagnetic materials with very narrow domain walls.

To tackle the problem of sensitivity, we used a ballistic Hall probe magnetometry technique, which proved itself as a very sensitive method for local measurements of tiny variations of magnetic flux (sensitivity up to $10^{-4}\phi_0$, where $\phi_0 = h/e$ is the flux quantum) [15]. It has been shown previously (both experimentally [15] and theoretically [16]) that the Hall response of the ballistic Hall probes is proportional to the average magnetic field in the central area of the Hall cross. Thus, unlike diffusive transport, ballistic transport allows a straightforward quantitative description of the detected Hall signal. We applied this technique to study sub-nanometer movements of domain walls in a garnet film. High uniaxial anisotropy of our film makes domain walls just a few lattice constant wide, which makes the observation of intrinsic pinning possible. In our experiments we have detected transitions of a domain wall between adjacent Peierls valleys as well as dynamics of a domain wall within a Peierls valley.

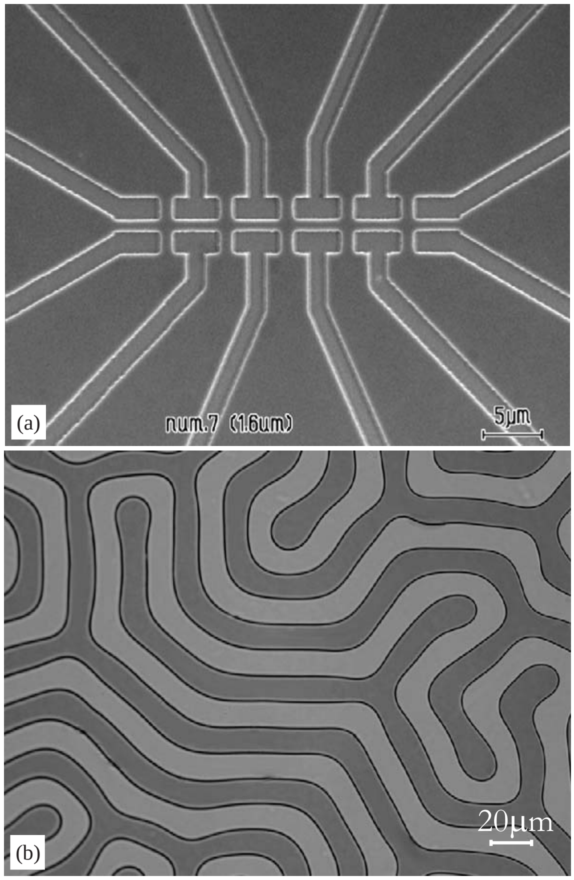

Fig. 1. (a) SEM micrograph of one of our devises with 5 Hall crosses, (b) a micrograph of a garnet film taken in transmitted polarized light. Domains of different orientations are visible due to Faraday effect.

2. Experimental technique and samples

Hall probes 2 μm × 2 μm in size, made from a high-mobility 2DEG (Fig. 1a), were used to study the propagation of domain walls in a uniaxial garnet film (Fig. 1b). One of the reasons for using a 2DEG is its large Hall coefficient ($1/ne$), due to a relatively low concentration of 2D electrons ($n \approx 3 \times 10^{11}$ cm^{-2}). However, what is even more important for using 2DEG in our studies is it's high mobility (3×10^5 cm^2 V^{-1} s^{-1}), such that electrons move ballistically inside the cross junction.

The garnet film was a single-crystal, multi-domain sample with magnetization perpendicular to the surface ([1 1 1] direction). The thickness of the garnet film is ≈10 μm, characteristic domain width ≈14 μm, the width of domain walls at helium temperatures is ≈10 nm. The film was pressed against the surface of the Hall probe, and the estimated distance between the surface of the garnet and the surface of the probe is less than 100 nm [17]. Most of our experiments were carried out at low temperatures (below 77 K).

When a magnetic field is applied perpendicular to the surface of the sample, domains of the preferable orientation start growing, and those with the unfavorable orientation start shrinking. This effectively causes domain walls to move, and eventually one of them can get right underneath of the Hall probe. As the domain wall passes underneath of the Hall probe, it changes the average magnetic field in the sensor area.

Domain walls in our garnet film always try to orient along $[1\ 1\ \bar{2}]$ or equivalent directions (it is the projection of $(1\ \bar{1}\ 0)$ easy plane on $(1\ 1\ 1)$ plane, which is the surface of the sample). When mounting the garnet film on the Hall probe we have made sure that one of $\{1\ 1\ \bar{2}\}$ crystallographic directions is parallel to the current lead of the Hall probe. It was also shown, that at low-temperatures domain walls in this material move as rigid planes by parallel shifts. Thus, taking into account that the Hall response of the ballistic Hall magnetometers is directly proportional to the average magnetic field in the central area—changes in the Hall signal can be translated into domain wall displacements.

3. Experimental results and discussions

A typical example of a domain wall propagating underneath the Hall probe is presented in Fig. 2. For $H < -18$ Oe and for $H > 8$ Oe the domain wall is far away from the cross, so only a linear signal from the external magnetic field is measured. However, as the domain wall passes underneath of the Hall probe (-18 Oe $< H <$ 8 Oe), a step-like signal is detected. This is usually called the Barkhausen jumps, which are due to pinning and de-pinning of the domain wall on individual pinning centers.

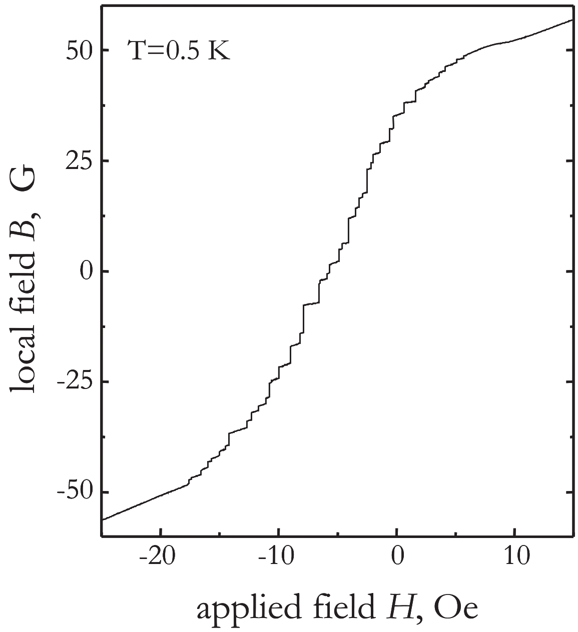

Fig. 2. Local magnetic field under one of the Hall crosses.

The jumps on Fig. 2 correspond to domain wall's propagation on the scale from 10 to 100 nm. However, if a domain wall was relaxed just before measurements by exposing it to AC magnetic field of decreasing amplitude, than even smaller jumps could be detected (Fig. 3). These jumps are of constant size 1.6 ± 0.2 nm, which corresponds with good precision to the distance between $\{\bar{1}\ 1\ 0\}$ atomic planes (1.75 nm) in garnet, which are the easy planes.

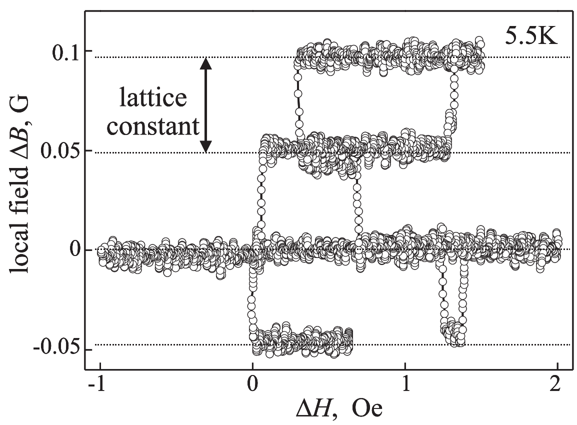

Fig. 3. Domain wall jumps between adjacent Peierls valleys.

The monoatomic steps like in Fig. 3 were detected routinely, independently of the specific place on our sample. We note that this is the first observation of the domain wall propagation between adjacent Peierls valleys.

To get a better physical insight into dynamics of the transitions between adjacent Peierls valleys, AC susceptibility for different excitation amplitudes was measured (Fig. 4a,b). Zero excitation corresponds to the relaxed state of a domain wall (located at the bottom of a Peierls valley). Any nonzero AC excitation causes the domain wall to oscillate inside the Peierls potential, and the oscillation amplitude increases as the excitation signal increases.

A number of characteristic features can be noticed on these curves. The amplitude of the AC susceptibility remains zero until the AC excitation amplitude

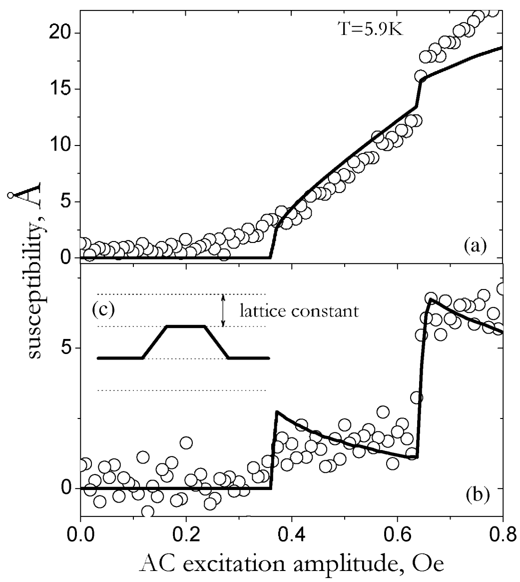

Fig. 4. Amplitude (a) and imaginary part (b) of AC-susceptibility vs. the excitation amplitude, measured in units of domain wall propagation. Schematic representation of kinks (c).

reaches a certain critical level H^* when a pronounced jump is detected in the imaginary part of AC susceptibility (imaginary part corresponds to energy dissipation in the system). The level of dissipation stays constant until the next jump occurs (both in real and imaginary parts of AC susceptibility). This jump corresponds to the domain wall moving to the adjacent Peierls valley.

These observations are consistent with a model of "kinks", topological excitations, which can arise in a system, with a periodic underlying potential. A kink is an object that consists of two parts of a domain wall shifted by one interatomic distance with respect to each other. A pair of kinks is shown in Fig. 4c. The bigger the size of the shifted part the higher the AC susceptibility signal. However, only kinks of a finite size are stable. Magnetic field H^* corresponds to the generation of stable kinks, which can then propagate along the domain wall. Propagation of a kink through the whole sample corresponds to a domain wall shift by one interatomic distance. We attribute the second jump in AC susceptibility to this transition.

4. Conclusions

For the first time, the motion of an individual domain wall in the Peierls potential was observed. The high sensitivity to local displacements of a domain wall was achieved due to low intrinsic noise of ballistic Hall probes. The dynamics of domain walls is discussed within a model of kinks, topological excitations, which gives good agreement with the experimental observations.

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