A new connection between electricity and magnetism

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A Viewpoint on "Universal Electromotive Force Induced by Domain Wall Motion," Shengyuan A. Yang, Geoffrey S. D. Beach, Carl Knutson, Di Xiao, Qian Niu, Maxim Tsoi and James L. Erskine. Physical Review Letters, LU12053

Electricity arises from the flow of electron charge, ferromagnetism arises from the ordering of electron spins; the interactions between them have been crucial to our technological development over the last centuries. The magnetic fields generated by electrical currents and the voltages generated by moving magnets are among the cornerstones of our modern lifestyle. Important applications range from the largest power plants, through electric motors, down to the nanoscale write heads in our laptop hard drives. In contrast, the physics of ordered electron spin transport has become important relatively recently. The new field of spintronics [1] is based on the ongoing prediction, discovery, and interpretation of additional interactions between electricity and magnetism that follow from the flow of ordered electron spins. Writing in Physical Review Letters, Shengyuan Yang, Geoffrey Beach, Carl Knutson, Di Xiao, Qian Niu, Maxim Tsoi and James Erskine from the University of Texas, Austin present a theoretical description and measurements of a new spintronic interaction: the voltage induced in a ferromagnetic wire by a moving domain wall [2].

The most studied spintronic interactions occur in layered ferromagnetic metal films and devices patterned from these films where the layers are thin enough that flowing electron spins carry magnetic information from layer to layer without drastic realignment. The most dramatic example is the large variation in electrical resistance depending on the magnetic orientation of the layers caused by spin flow between the layers. The discovery of this effect, called giant magnetoresistance [3, 4], led rapidly to the development of novel sensor and data storage technologies in turn leading to its recognition in the 2007 Nobel Prize in Physics.

A related effect, dubbed "spin transfer torque," occurs when spins flowing from one layer to another drive changes in magnetic orientation in the layers [5]. The effects of spin transfer torque, precession and switching of magnetism in small junction devices, have been measured under a wide variety of conditions. The complementary effect, spin pumping [6], occurs when the dynamics of the magnetization in the layers drives a spin current in the device. The consequences of spin pumping are more difficult to observe than those of spin transfer torques but are still well established experimentally [7, 8].

Analogous spintronic effects occur in magnetic nanowires. The analog of giant magnetoresistance is domain wall resistance, the additional resistance in a wire due to presence of a domain wall. Spin transfer torques also occur in magnetic wires [9–11], where current induced domain wall motion is analogous to the precession and switching observed in multilayers. As the electron spins flow through the domain wall, the magnetization in the wall exerts a torque on the spins that tends to align the spins with the local magnetization direction. A reaction torque on the magnetization tends to move its pattern in the direction of the electron flow. Several theoretical groups [12–15] have predicted the existence of a new effect, voltage or current induced by domain wall motion, an effect that is both complementary to current-induced domain wall motion, and also analogous to spin pumping in layered structures. The measurements of Yang et al. are the first observations of these effects.

The early predictions [12–15] of domain wall motion-induced voltage considered idealized domain walls, which lack the complicated structure found in domain walls in the wires of Yang et al. (See Fig. 1.) To address this disconnect, the authors developed a new approach to computing the domain wall motion-induced voltage, allowing them to compute it for the complicated structure of the walls. Interestingly, they find the same magnitude of the voltage as predicted earlier for the motion of idealized domain walls subject to the same applied magnetic field.

Conceptually, it is straightforward to measure this voltage: simply propagate a domain wall down a ferromagnetic wire while measuring the voltage difference between the ends of the wire, as illustrated in Fig. 1. In practice, however, the voltage induced by the moving domain wall is only one of several voltages arising from different effects, and the challenge to the experimenter is to sort out this one small signal from the competing signals.

In the technique devised by Yang et al., domain walls are generated and driven down the wire with an applied magnetic field generated by large alternating currents in a copper strip. In addition to creating and moving domain walls giving the domain wall motion-induced voltage, the magnetic field also introduces a competing voltage in the detection circuit, and possibly other voltages induced by changing magnetization in nearby ferromagnetic structures.

The authors separate the domain wall signal from the competing signals by a clever modulation scheme and by the unique symmetry of the domain wall signal, which is expected to be independent of whether the magnetization is switching from right to left or left to right.

Because the domain wall motion-induced voltage is measured at frequencies one thousand times lower than the domain wall launching frequency, it may be helpful to think of the domain wall motion-induced voltage signal as arising from a continuous stream of domain walls. The domain wall motion-induced voltage signal is modulated by periodically interrupting the stream of domain walls using an additional, slowly varying field. The DC component of this additional field determines whether the domain wall stream is switched on in phase or out of phase with the oscillating part.

Yang et al. offer two checks that the measured signal is the domain wall motion-induced voltage: its dependence on the domain wall launching frequency, and its dependence on the applied field. The signal voltage decreases as the launch period increases, or alternatively stated, the signal is proportional to the launching frequency over much of the measured range. Over this range, the measurement cannot be convincingly distinguished from an inductive signal. However, at high launch frequencies (short drive field period), the signal drops as the frequency increases, as one would expect if the field were reversed before domain walls were able to complete their trip down the wire. An inductive signal would not show such a decrease.

The second check is the dependence of the domain wall motion voltage on the drive field. In the theoretical analysis, the domain wall voltage is closely coupled to the transverse velocity of the vortex. While the longitudinal velocity is measured independently as a function of applied field, the transverse vortex velocity is related to the applied field indirectly by equating the domain wall oscillation frequency to the time required for the vortex to complete a round trip across the wire and by citing empirical results that place the domain wall oscillation frequency near the Larmor precession frequency. The result is a good agreement between the measured domain wall motion voltage and the theoretically predicted value.

As the first measurement of the voltage induced by domain wall motion, the experiment described by Yang et al. fills an important entry in the matrix of spintronic relationships between magnetic and electrical properties in magnetic metals.

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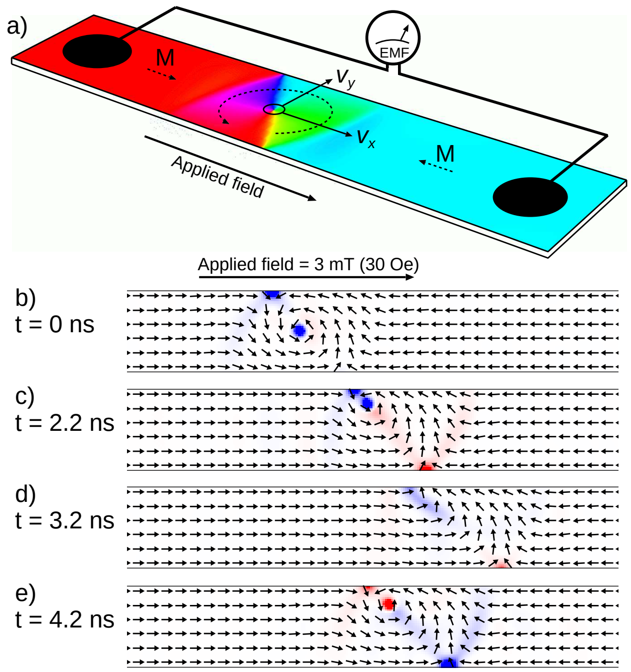

FIG. 1: a)A vortex-type domain wall being driven down a magnetic wire by an applied magnetic field. In a nanowire the magnetization tends to lie along the long direction of the wire except at domain walls, where it changes direction. For a range of wire geometries, these domain walls have a complicated structure known as a vortex wall. In a vortex wall, the magnetization circulates around a vortex core. At the vortex core, the magnetization tilts out of the plane, whether it tilts in a positive or negative direction determines the polarity of the domain wall. At the edges of the wires, there are two half anti-vortices, where the magnetization also tilts out of plane. In panel (a), the color indicates the in-plane angle of the magnetization, and approximate magnetization directions are indicated by the dashed arrows. The same wall is shown in panel (b) where the arrows indicate the in-plane direction of the magnetization and the color indicates the z-component of the magnetization: blue for negative polarity and red for positive polarity. As a magnetic field is applied, the vortex moves toward one side or the other depending on the direction of the field and the polarity of the wall. Above a critical applied field, the vortex core gets pushed to the wire edge, reverses its polarity, then moves toward the other side, starting a side-to-side oscillation as illustrated in b) to e). Starting from a position in the center of the wire (b), the vortex core approaches upper edge of the wire with negative polarity (c), reflects off of the edge (d) and returns with both v_y and the polarity changing sign (e). The predicted and measured voltage drop do not change sign because they are proportional to v_y *and* the vortex core polarity.