Controlled depinning of domain walls in a ferromagnetic ring circuit

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The authors have investigated dynamics of paired domain walls in a ferromagnetic ring circuit, driven by a variable pulsed magnetic field. The magnetic reversal accompanied by the propagations of the domain walls depends not only on the amplitude but also on the rise time of the applied pulsed magnetic field. The threshold of the rise time is found comparable to the propagation time of a domain wall along a half-path of the ring. This finding may be useful for the high speed operation of the magnetic logic devices based on the domain wall motion. © 2007 American Institute of Physics. [DOI: 10.1063/1.2748339]

Study on the manipulation of domain walls confined in a small ferromagnet is an important fundamental research topic for developing a future device based on a domain wall motion. A logic operation in a ferromagnetic circuit has been demonstrated as a counterpart of a semiconductor logic device. In the earlier studies, they focused on a domain wall motion under a slowly varying magnetic field. For future application, it is important to investigate a magnetic response under a faster operation inside a system with a number of domain walls. In the actual sample, the domain wall behavior is strongly affected by local defects such as edge roughness. This implies that the propagation of the domain walls cannot be perfectly synchronized. We thus expect that the magnetic response should be different when the time scale of the field sweep becomes comparable to the time of a domain wall displacement inside the artificially microfabricated ferromagnet.

In this work, we study a dynamics of domain walls confined in a ferromagnetic ring under a variable pulsed magnetic field. The ring structure is suited for an investigation for dynamics of domain walls since the so-called onion state consisting of paired domain walls, head to head (H-H) and tail to tail (T-T) domain walls, can easily be stabilized in the ring. When the paired domain walls collide with each other, annihilation of the walls leads to a vortex state, where the magnetic flux is closed in the ring. Therefore we can clearly distinguish the magnetic state according to the number of the domain walls after the application of the pulsed field.

The velocity of a domain wall in a ferromagnetic wire under an external magnetic field or a spin polarized current attracts a great attention in the recent decade. The domain wall velocity ranges from m/s to km/s. The time of the domain wall displacement in a ring with 1 μm diameter is on the order of nanoseconds. Under a slowly varying magnetic field, one domain wall starts to propagate while the other wall still stays at the initial position, and then the magnetic state becomes a vortex state after collision. The discrepancy between depinning fields of the paired domain walls is unavoidable since defects are not identical in the sample. We, however, expect that a steep ramp of the pulsed magnetic field compensates the time delay between the propagations. We here demonstrate that the switching behavior between the onion state and the vortex state can be tuned by choosing the rise time of the pulsed magnetic field.

We fabricated a NiFe ring (thickness: 30 nm, linewidth: 70 nm, diameter: 1 μm) on the surface of a Ti/Au wire (thickness: 50 nm, width: 2 μm). Figure 1(a) shows a scanning electron microscope (SEM) image of the prepared device together with a schematic diagram of the measurement setup. We can apply a static in-plane magnetic field $B$ along the directional angle $\varphi$ from the horizontal $x$ axis. We can also generate a pulsed magnetic field $B_p$ by injecting a pulsed current $I_p$ from a pulse generator through the Ti/Au wire. The amplitude of the current is given by $V_{os}/50 \Omega$, where $V_{os}$ is the transmitted voltage monitored by an oscilloscope (input impedance 50 Ω). The signal line between the pulse generator, the sample, and the oscilloscope is connected by a high speed oscilloscope with a 50 Ω input impedance.

![SEM image of the device. A pulsed signal is injected from a pulse generator through the sample and then transmitted into an oscilloscope.](image)

**FIG. 1.** (Color online) (a) SEM image of the device. A pulsed signal is injected from a pulse generator through the sample and then transmitted into an oscilloscope. A pulsed magnetic field perpendicular to the direction of the pulsed current switches the magnetic state in the NiFe ring. The switching is monitored by measuring the bend resistance of the 2DEG cross. (b) Bend resistance traces as a function of external in-plane magnetic field $B$ in the $y$ direction ($\varphi=90^\circ$). The signal is obtained by a low frequency ac measurement technique with an excitation current of 5 μA. A pulsed magnetic field is applied under the fixed in-plane magnetic field $B_{os}=70$ mT. (c) Switching field distribution with the directional angle $\varphi$ of the in-plane magnetic field.
coaxial cables in order to avoid damping of the fast pulse. The ratio of the transmitted signal \( V_{OS}/V_{PG} \) is 0.7–0.8 in the experiment. A GaAs/AlGaAs two-dimensional electron gas (2DEG) cross lies below the Ti/Au wire in the depth of 65 nm for detecting the magnetic state in the NiFe ring\(^2\). The density \( n \) and the mobility \( \mu \) of the 2DEG before processing were \( 4.3 \times 10^{15} \text{ m}^{-2} \) and 77 m\(^2\)/Vs, respectively. The width of the active region in the 2DEG cross is about 1.5 \( \mu \)m. We measured a bend resistance of the 2DEG cross with the current and voltage configuration in Fig. 1(a) in a static in-plane magnetic field \( B \), which reflects a typical magnetization process of an individual ring as in Fig. 1(b).\(^3\) The measurements were carried out at low temperatures (−5 K) to obtain a large signal of the 2DEG cross and to avoid sample damage due to Joule heating.

The bend resistance magnetometry enables us to measure a precise angle dependence of two switching fields, which correspond to an onion-vortex transition and a vortex-reverse onion transition. The transition from the onion state to the vortex state is randomly distributed comparing with the other transition as in Fig. 1(c), which implies that the two switchings have different origins.\(^4\) In the case of the onion-vortex transition, the transition is accomplished by a propagation of one domain wall toward the other domain wall. The switching field is sensitive to a local pinning at the initial position of the domain wall. On the other hand, the vortex-reverse onion transition is determined by a nucleation field of domain walls inside a ring, which is less sensitive to defects and edge roughness.

When we set the static in-plane magnetic field \( B \) in the \( y \) direction (\( \varphi = 90^\circ \)), the switching fields are 80 mT (onion-vortex) and 130 mT (vortex-reverse onion), as shown in Fig. 1(b). We applied a pulsed magnetic field in the \( x \) direction while keeping the amplitude of the in-plane magnetic field \( B_{fix} = 70 \text{ mT} \), which is a little smaller than the switching field for the onion-vortex transition. Under the static field in the \( y \) direction, the magnetic state is energetically less stable than the reverse onion state. The paired domain walls are trapped at sample specific local pinning sites. The pulsed magnetic field in the \( x \) direction perpendicular to the static field depins the domain walls and well controls the rotational direction of the domain walls. The direction is counterclockwise, as schematically drawn in the inset of Fig. 2. The depinning events of the paired domain walls do not occur simultaneously since the pinning strength is different in different positions of the paired domain walls.

We applied a pulsed magnetic field \( B_p \) with a rise time \( t_R \) and a width of 100 ns. The magnetic state was identified after the application of the pulsed magnetic field by measuring the bend resistance of the 2DEG cross. Figure 2 shows the map of magnetic states stabilized after the application of the pulsed field as a function of rise time and amplitude, which is comprised of (1) no transition, (2) onion-vortex transition, and (3) onion-reverse onion transition. For lower amplitude of the pulsed fields (\( B_p < B_{g1} \)), the magnetic state remains an initial onion state since the pulsed field is not enough to depin both domain walls. For intermediate amplitude (\( B_{g1} < B_p < B_{g2} \)), the pulsed field depins only one wall, leading to an annihilation of the paired domain walls. In higher amplitude (\( B_p > B_{g2} \)), the transition depends on the rise time of the pulsed magnetic field. A pulsed field with a faster rise time switches the positions of the paired domain walls. The important point is that one domain wall is depinned faster than the other wall so that there is a time delay between the depinning events of the paired domain walls under a pulsed magnetic field. If one wall reaches the other before depinning, the magnetic state becomes a vortex state even under a larger pulsed magnetic field. Therefore the threshold of the rise time is given by the propagation time of the domain wall in the ring.

We analyzed the domain wall dynamics under a pulsed magnetic field by using a micromagnetic simulator (OOMMF package\(^5\)). The actual sample has defects and edge roughness which act as domain wall pinning sites. In order to include the effect in the simulation, the linewidth in the ring varies with the position, as shown in Fig. 3(a). The width at the bottom is larger than at the top so that a domain wall at the bottom is easier to depin. We set the initial state in the onion state with a H-H domain wall at the bottom and a T-T domain wall at the top under a static in-plane magnetic field toward the upper direction. And then a pulsed magnetic field is applied while keeping the static magnetic field constant. Here, we show the simulations for three different pulsed magnetic fields. The time evolutions are shown in Fig. 3(b). The corresponding points in the experimental rise time-amplitude plane are marked with red stars in Fig. 2. The mesh size of the simulation and the damping constant \( \alpha \) are 4 nm and 1.0, respectively.

When the pulsed magnetic field is applied, the H-H domain wall at the bottom is depinned faster than the other and propagates toward the top. In all the cases (simulations A–C), it takes 5–6 ns for the wall to propagate from the bottom to the top, the propagation time \( t_{pr} \) is mainly determined by the static in-plane magnetic field since the pulsed magnetic field is much smaller than the static field in amplitude. In the experiment, the role of the pulsed field is to depin the domain walls in the desired direction. After the depinning the domain wall dynamics is dominantly controlled by the static magnetic field.

The simulation well reproduces the experimental results. The pulsed magnetic field with a large amplitude and a fast rise time corresponding to simulation A switches the mag-
of the paired domain walls results in the vortex state. The rise time under a static in-plane magnetic field
magnetic fields.
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domain wall at the bottom is easier to depin than the other wall at the top. The upper, bottom, and side widths are 68, 80, and 72 nm, respectively. The to induce a sample asymmetry, the ring has a position-dependent linewidth. to the top, the T-T domain wall at the top still
time of 8 ns and amplitude of 20 mT; and simulation C, rise time of
2, 5, and 8 ns
of the pulsed magnetic field with a small amplitude (simulation C) depins only the H-H domain wall at a bottom. The magnetic state becomes a vortex state regardless of the rise time.
Finally, we would like to remark that the onion-reverse onion transition is achievable in an elliptical ring only by applying a pulsed magnetic field. In the present study, the combination of the pulsed magnetic field and the static field controls the directional motion of the paired domain walls. In an elliptical ring, the stability of the domain walls depends on their positions, which determines the rotational direction of the paired domain walls.26
In summary, we find that a magnetic transition in a microfabricated NiFe ring excited by a pulsed magnetic field depends on the amplitude and the rise time of the pulsed field. The relation between the time scale of a varying magnetic field and the propagation time of the domain wall crucially effects the magnetization behavior in the artificial ferromagnetic structure.

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FIG. 3. (Color online) (a) Initial magnetic state in the OOMMF simulation under a static in-plane magnetic field $B_{\text{in}}=70$ mT in the y direction. In order to induce a sample asymmetry, the ring has a position-dependent linewidth. The upper, bottom, and side widths are 68, 80, and 72 nm, respectively. The domain wall at the bottom is easier to depin than the other wall at the top. (b) The time sequence of the pulsed magnetic field in the OOMMF simulation: simulation A, rise time of 4 ns and amplitude of 20 mT; simulation B, rise time of 8 ns and amplitude of 20 mT; and simulation C, rise time of 2 ns and amplitude of 10 mT. (c) Time evolution of the magnetic states (2, 5, and 8 ns) in the OOMMF simulation for the three different pulsed magnetic fields.

magnetic state from the onion state directly to the reverse onion state. The H-H domain wall is firstly depinned from the bottom and then the T-T domain wall is depinned before the H-H domain wall reaches the top. The rotational direction of the paired domain walls is counterclockwise. The threshold of the rise time $t_{R}^\text{th}$ is comparable to the time of the domain wall displacement $t_{p}$ of the H-H domain wall from the bottom to the top, $t_{p}\approx [B_{p}/(B_{d2}-B_{d1})]t_{R}$. In the case of a slow rise time (simulation B), the T-T domain wall at the top still remains at the initial position when the H-H domain wall reaches the position of the T-T domain wall. An annihilation of the paired domain walls results in the vortex state. The