Magnetic Vortex

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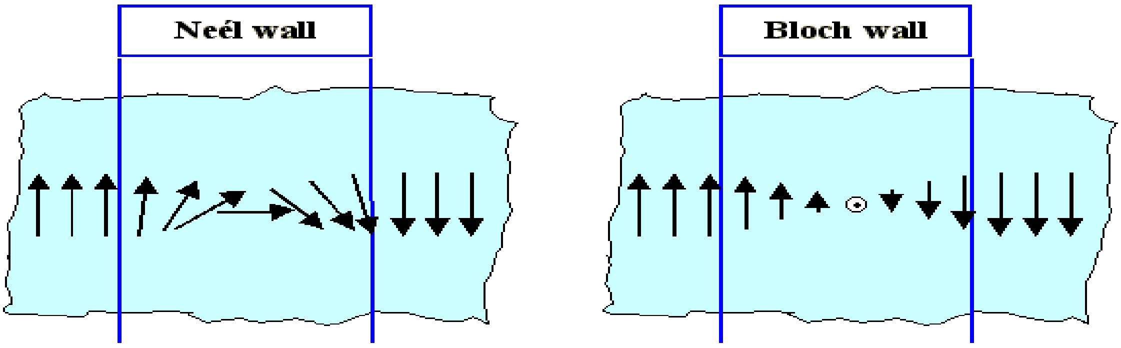
19 December 2008

Abstract

Direct observations of vortex structure only appear recently; in this essay we will examine these first observations. And then introduce experiments and theory about the dynamics of vortex core; meanwhile we will propose the principle of chirality conservation in vortex; and with this idea we present another explanation in Bussmann's experimental results. Finally, reveal the high possible application of vortex in MRAM.

Introduction:

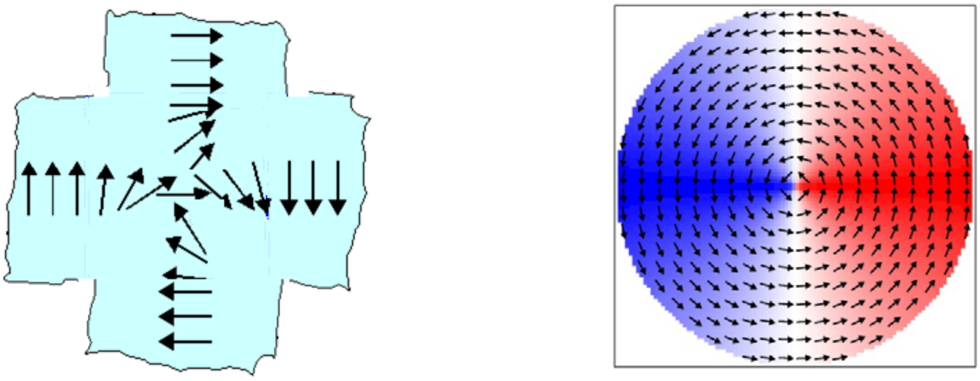
For ferromagnetic materials, they will form magnetic domains to reduce the energy. Naturally, a wall will appear between two domains which have different directions of magnetization. Generally, there are two types of domain wall: Bloch wall and Neel wall.



(a) (b)

Figure 1: domain wall. (a) Neel wall: magnetization vector must be in-plane. (b) Bloch wall: magnetization vector can be out-plane. [1]

Neel wall will replace the Bloch wall if the thickness of the sample is small, especially in the case of ferromagnetic films. An interesting phenomenon will occur when two Neel walls cross with each other. Magnetic vortex will come out in the intersection of Neel wall!



(a) (b)

Figure 2: magnetic vortex. (a) magnetic vortex at the intersection of Neel walls. (b) magnetic vortex. [2]

Obviously, crossing two Neel walls is not the only way to generate magnetic vortex; there also exists magnetic vortex in circular dot of ferromagnetic materials [5], when the dot thickness is much smaller than the dot diameter. This unique property of magnetic vortex yields several interesting application. One of them is data storage application [3]. Due to the dipole-free configuration, this magic structure will prevent cross-talk among adjacent vortices, and thus have high magnetic stability.

Furthermore, more interesting phenomenon will exhibit at the center of the magnetic vortex.

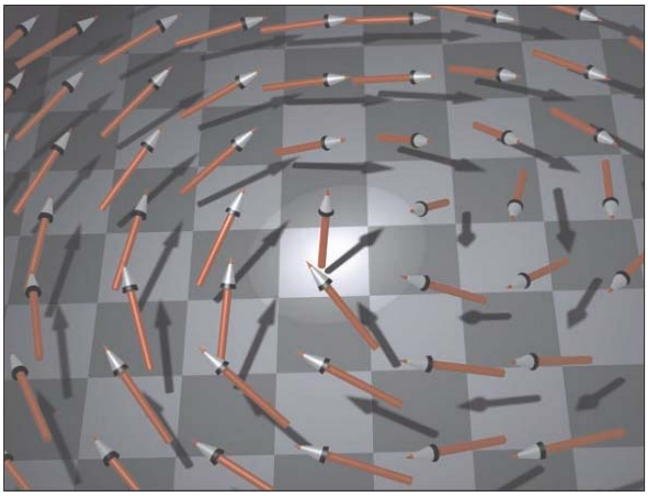


Figure 3: Schematic of a vortex core. Far away from the vortex core the magnetization continuously curls around the center with the orientation in the surface plane. In the center of the core the magnetization is perpendicular to the plane (highlighted). [4]

Out of core the direction of spin is in plane; however, in the core the direction of spin will turn out, not in plane!

Direct observation:

Although, the structure of magnetic vortex core has been predicted long before in theory, the experimental observation only appear recently [5][4]. Due to highly developed nanotechnology, we can now prepare samples in nano-scale. One experiment among the first observations of magnetic vortex core is just done in the circular dots of Permalloy, (Shinjo, 2000) which was prepared under the help of nanotechnology.

In Shinjo's experiment, they use magnetic force microscopy (MFM) to detect the core of the magnetic vortex. As the core has perpendicular magnetization, while the magnetization vector out of the core parallel the plane, thus, the force between the cantilever tip and the surface of the core is different from the force between the cantilever tip and the surface of out-of-core. Their results as follows:

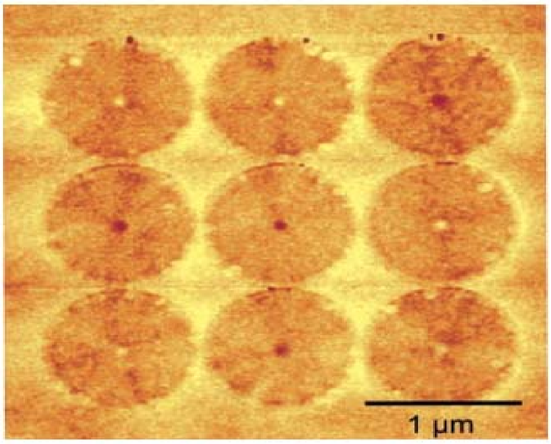
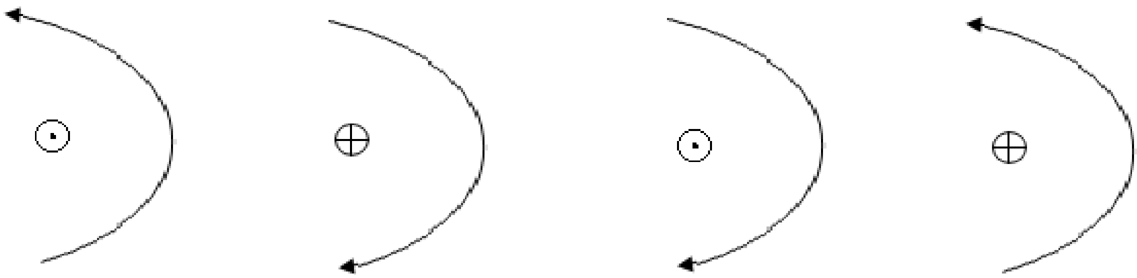


Figure 4: MFM image of an array of permalloy dots 1um in diameter and 50 nm thick. [5]

These images show clearly contrasted spot at the center of each dot. The authors of this experiment believe that this suggests each dot has a magnetic vortex structure and contrasted spot is just the core of the magnetic vortex; white and dark spots are believed to have opposite direction of magnetization.

Clearly, the ground state of this circular dot is degenerate. The out-of-core can have either clockwise or anti-clockwise curling configuration; meanwhile the core can also either have up or down magnetization direction. Their combination yields four different ground states but energetically equivalent.



(a) (b) (c) (d)

Figure 5: four generate states. (a), (b): right-hand chirality. (c), (d): left-hand chirality. (a), (d): positive helicity. (b), (c): negative helicity.

However, external magnetic field will break this symmetry. One interesting question is what will happen if one applies an external magnetic field along the plane normal. Definitely, the magnetization in core will be aligned along the external magnetic field, thus parallel to the plane normal. But, how about the curling structure out-of-core i.e. the helicity?(definition of helicity is shown in Figure 5)
As showed in Figure 3, not just the central one has normal component magnetization but also ones near centre have non-zero normal component magnetization. Possible process as following:

When applying normal magnetic field, (assuming initial direction of magnetization of central one is opposite to the field) at first, the direction of magnetization of central one won't change at low strength field due to exchange coupling between adjacent ones; and the whole dot will be in a sub-stable state. As the strength of field increasing, the external field energy of the central one will be finally equal to the exchange coupling energy; then at this critical point the direction of the magnetization of the central one will reverse, and the adjacent ones will reverse, too. Finally, the direction of magnetization of all ones at the dot will reverse at this critical point, like physics transition.

In this process, helicity will change sign; however, chirality is conserved.(definition of chirality is in Figure 5) We will discuss a little more about this in the Application part of this essay.

In Shinjo's experiment, they use a relative high magnetic field (1.5T) to align the magnetization of all the cores along the external field.

Due to the limitation of MFM method, Shinjo's experiment cannot give the internal spin structure of magnetic vortex and the size of the core. Fortunately, the problem encountered by MFM method can be resolved by the method of spin-polarized scanning tunneling microscopy (SP-STM). (Wachowiak, 2002) [4]

The principle of SP-STM can be interpreted in the following formula:

$$\frac{dI}{dU}(\vec{r}, U_0)_{SP} = C(1 + P_T P_S \cos\theta)$$

The angle in this formula represents the angle between the directions of tip magnetization and the sample magnetization, C, P_T, P_S can be recognized as constant. Thus, this method can be used to determine the spin (magnetization) direction of the sample by measuring $\frac{dI}{dU}$ signals.

The primary results of this experiment as following:

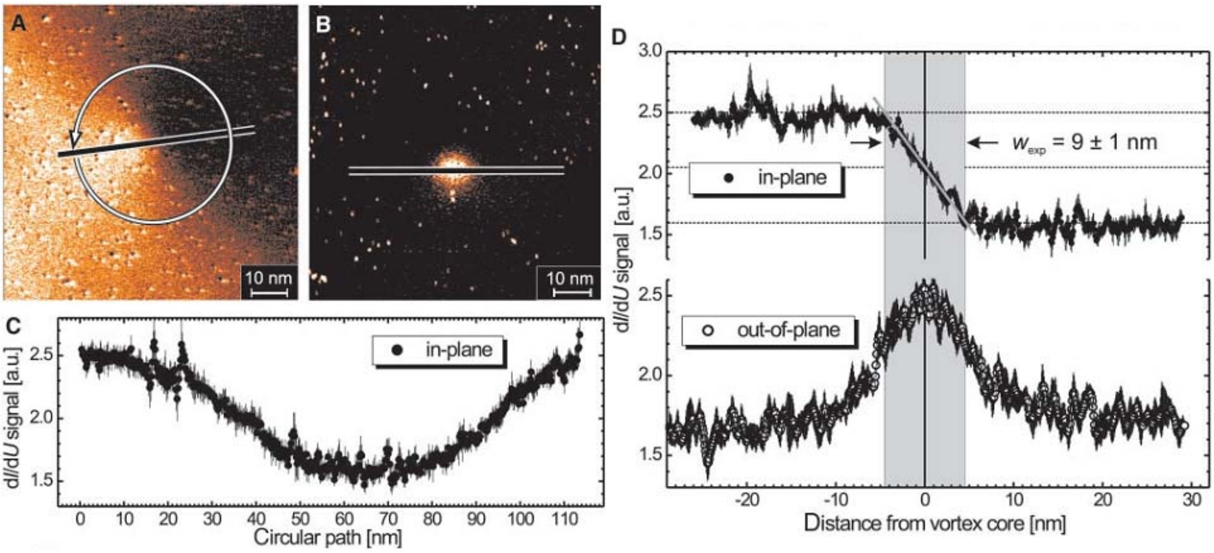


Figure 6: magnetic dI/dU maps as measured with an (A) in-plane and an (B) out-of-plane sensitive Cr tip. The curling in-plane magnetization around the vortex core is recognizable in (A), and the perpendicular magnetization of the vortex core at a distance of 19 nm [circle in (A)]. (D) dI/dU signal along the lines in

(A) and (B). The measurement parameters were (A) I=0.6 nA, U_0=-300mV and (B) I=1.0 nA, U_0=-350mV.[4]

The core size determined by this experiment is 9 nm. We will refer to this result in Application part of this essay.

Dynamics of Vortex Core:

So far, experimental evidences have confirmed the existence of magnetic vortex and vortex core. In this part of essay, we will examine the dynamic property of vortex core.
We first consider the situation when applying an in-plane magnetic field, i.e. the direction of the external magnetic field parallel to the plane of dots. This experiment has been done by Schneider, 2000.

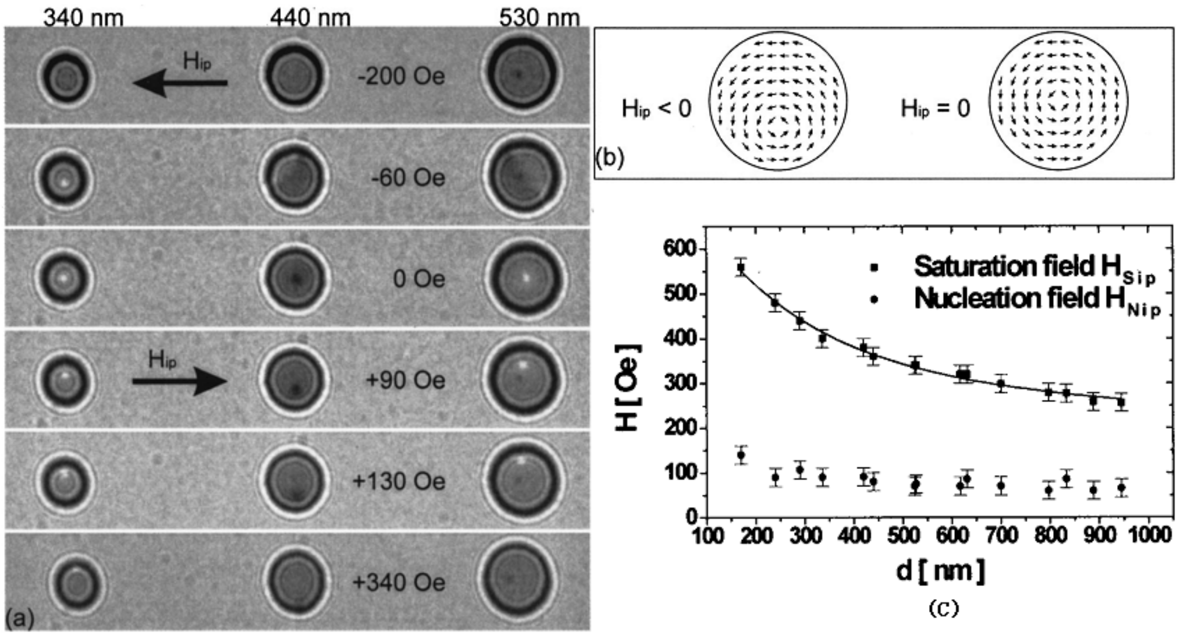


Figure 7: (a) Magnetization reversal in applied fields H_{ip} for nanodisks of diameter 340, 440, and 530 nm, respectively. Decreasing the applied field from saturation leads first in about half of the area of the structure to a deviation of the magnetization direction from the direction of the applied field. Field reversal shifts the vortex center to the disk border where it is annihilated at higher field values. (b) Schematic drawing of the vortices at remanent state and in an applied magnetic field. (c) Values of the saturation and nucleation fields $H_{S_{ip}}$ and $H_{N_{ip}}$, respectively, as a function of disk diameter d. The nucleation field $H_{N_{ip}}$ denotes the field value H_{ip} where contrast variations are first observed. The solid line is intended to guide the eye. [6]

Generally, this experiment proves that when applying an in-plane magnetic field, the vortex core will move perpendicular to the field direction towards the border of the disk where it is annihilated at the saturation field. However, this movement of vortex core is not observed in Shinjo's experiment [5], although they apply a relative high magnetic field (1.5 T) along an in-plane direction.

About the movement of the vortex core under an in-plane magnetic field, we can have an intuitive interpretation.

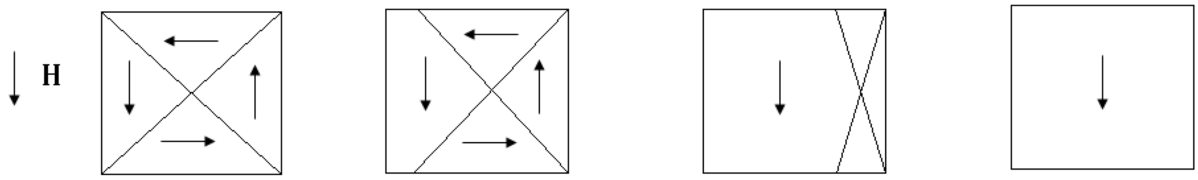


Figure 8: interpretation of the movement of vortex core.

Here, the four magnetic domains represent the vortex; their common vertex represents the vortex core. When applying an external magnetic field, the domain with magnetization along the field will grow; thus, common vertex (vortex core) will move perpendicular to the direction of the field; and finally disappear.

However, this intuitive argument is not valid when applying in-plane magnetic field pulse, as demonstrated in Choe's experiment [7]. They observed an initial motion along the field direction during the fast, subnanosecond field pulse.

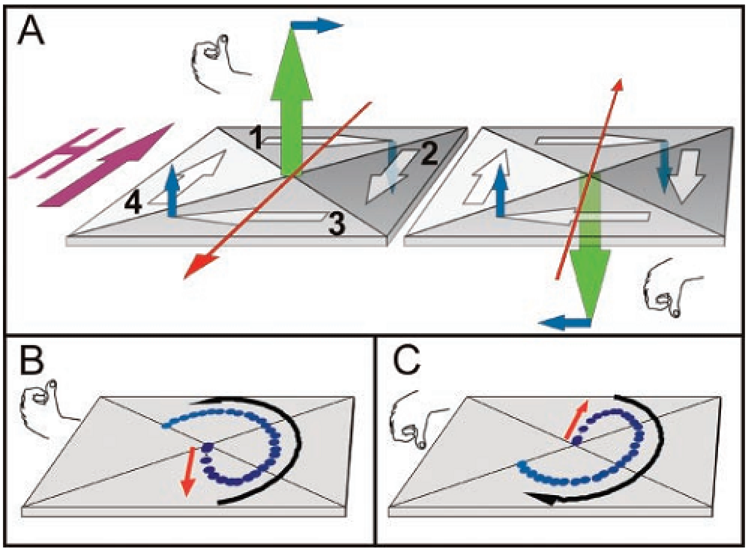


Figure 9: (A) spin structure (white arrows) of a left-handed (left side) and a right-handed (right side) square vortex. Blue arrows represent the precessional torque generated by the external magnetic field (purple arrow). Hands illustrate the vortex handedness, and a green arrow indicates the out-of-plane core magnetization. Red arrows indicate the acceleration direction in response to the field. (B and C) Simulated trajectory of the core of (B) a left-handed and (C) a right-handed vortex during and after a field pulse. [7]

The experiment results prove that vortex core will undergo a gyrotropic motion after the field pulse and the initial movement of vortex core either parallel or antiparallel to the field depends on the vortex chirality.

This gyrotropic motion of vortex core can be seen as the excitations of magnetic vortex. Guslienko also does the experiment about the magnetic vortex excitations; they probe circular dots and observe both core trajectories and eigenfrequencies. [8]

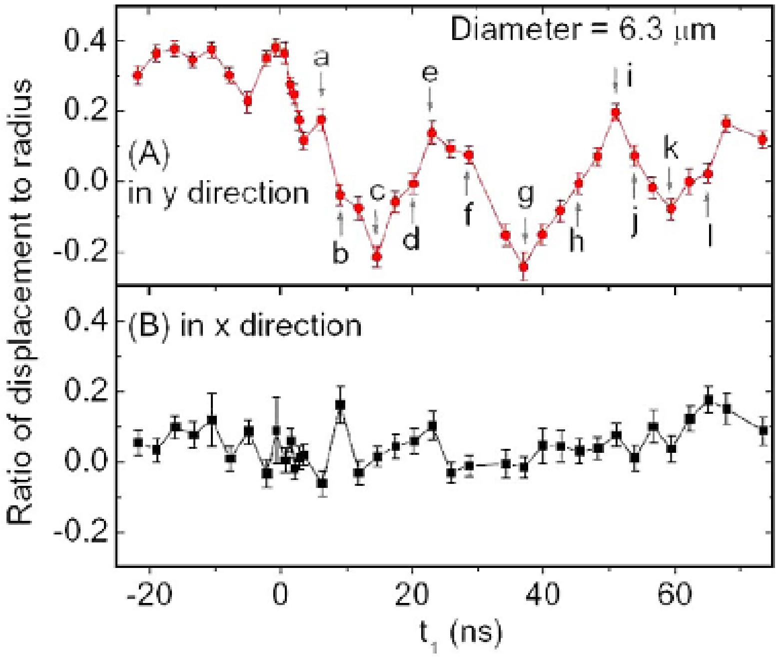


Figure 10: (A) and (B), respectively, show the time dependence of the ratio of the Y and X displacements of the vortex core to the radius of 6.3 um diameter dot with thickness 30 nm. [8]

They also observe that the oscillation frequency of the vortex core increases as the dot diameter decreases. Additionally, they provide a model to explain these experimental results.

Generally, in this model they regard vortex core as a particle described by coordinate, mass, momentum, etc. The equation of motion of vortex core is:

$$\hat{M}\,\ddot{\mathbf{X}} - \mathbf{G} \times \dot{\mathbf{X}} + \partial_{\mathbf{X}} W(\mathbf{X}) = 0,$$

Where X is the coordinate of vortex core, W(X) is the energy of the vortex shifted from its equilibrium position at the dot centre. M is the vortex mass that is a tensor. [8]

One of the consequences of this equation is that it can predicate the eigenfrequency of vortex core oscillation.

$$\omega_0 = 8\pi\gamma M_s F(\beta)$$

$\beta = L/R$ the aspect ratio of the cylindrical permalloy dots. If β is small $\beta \ll 1$, then:

$$\omega_0 = (20/9)\gamma M_s \beta$$

This means the eigenfrequency of vortex core is proportional to the aspect ratio of the dot.
This result can be easily understood if we assume the velocity of the core only depends on the thickness of the dot, particularly: $v \propto L$. And the eigenfrequency: $\omega_0 \propto \frac{v}{R}$ (core moves with uniform velocity in the dot). Finally, we get: $\omega_0 \propto \frac{L}{R} = \beta$

As mentioned the excitation of vortex, one question is why the ground state is the vortex state? Is there any other pattern which has lower energy than the vortex pattern? And, make analogy with the vortex in superfluid-Helium; does there exist many vortices state? Perhaps many vortices state can be realized in some kind of vortex excited state. All of these questions cannot be answered in the literature I have reviewd.

Application:

Traditional way in GMR experiments, the current used to sense the magnetoresistance is propagated parallel to the interfaces of the multilayered planar structure (CPP). However, an alternative approach is the direction of the current perpendicular to the plane, called CPP-GMR effect. Vertical GMR devices work in this CPP way; the first report for vertical GMR devices is due to Bussmann, 1999. [3] Their multilayer structure is
Si/SiN/40Ta/1500Cu/7Ta/20Cu/(23NiFeCo/40Cu/12NiFe/40Cu)$_5$/1000Cu/1500SiN
The diameter of this device is 0.3 um. The current propagates perpendicular to the plane.

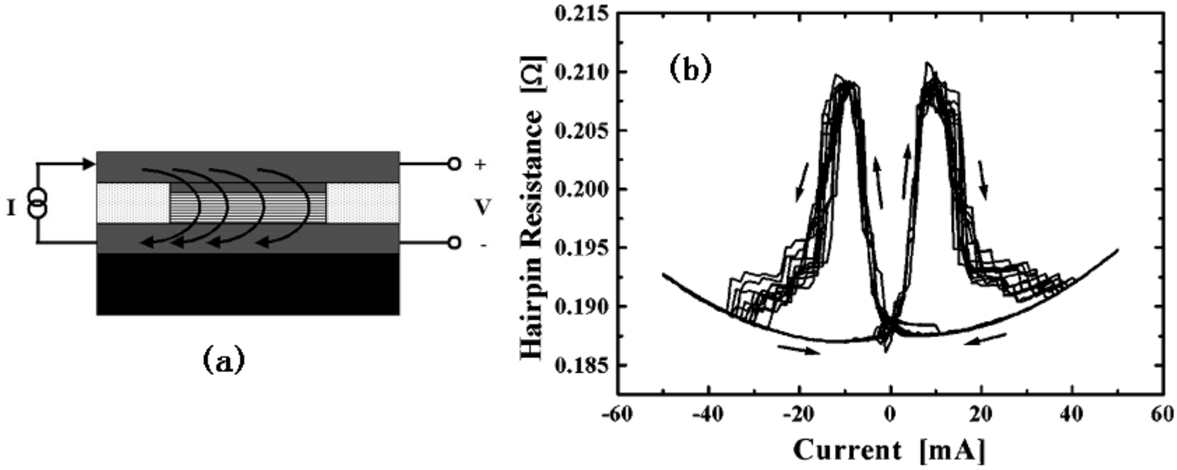


Figure 11: (a) Measurement setup and geometry used in determining device resistance. (b) Measured resistance of a multilayered device of 0.3 um diam repeated ten times. [3]

The most notable features about this result are the significant resistance changes (~11%).
They attribute the resistance changes to the reorientation of the magnetization configuration in the multilayer device caused by the rotational field generated by the current passing through the

device. They conclude that the magnetic layer will have vortex pattern; if the vortices of different layers have the same helicity, the device will be in the low-resistance state; if the vortices of two different types layers have opposite helicity, the device will be in the high-resistance state.

However, this explanation only considers the influence of out-of-core of vortex i.e. helicity. They neglect the effects of the vortex core. The core size is on order of 10 nm, discussed in Direct Observation part of this essay [4]; and the device size is on order of 100 nm. Just from these data we can not ignore the factor of vortex core. We will provide another explanation: the core will be responsible for the resistance change, as confirmed in Bussmann's paper that cross-section area plays an important role in vertical GMR devices.

Here, again, we will describe similar process as discussed in Direct Observation part about the magnetization reorientation induced by magnetic field.

Curling magnetic field induced by the current will change the spin (magnetization) direction out of core, making the out-of-core curling structure has the same helicity with the curling magnetic field; and the exchange coupling will reverse the direction of spin in the core.

We can conclude that either in the case of normal magnetic field or curling magnetic field, the chirality is conserved; the helicity of out-of-core and the magnetization direction of core will both change sign.

In Bussmann's experiment by passing current they can change the helicity of out-of-core, and thus change the direction of magnetization of core (due to the chirality conservation). So, the low-resistance state is corresponding to the same magnetization direction of cores of all layers; the high-resistance state is corresponding to different magnetization direction of cores of different layers.

One deduction of this explanation is that Bussmann's experimental result will only occur when all magnetic layers have the same chirality. There should exist other phenomena such as the device will always stay at high-resistance state due to non-uniform chirality of all layers.

Due to such property of vortex, we can consider vortex as basic elements for the magnetoelectronic random access memory (MRAM). The turn-up and turn-down direction of magnetization in the core can represent 0 and 1.

We can change 0 or 1 by directly passing current through the vortex; the magnetic field induced by the current can change the helicity of vortex, and thus change the magnetization direction of the core. If all vortices are in the same chirality(we can realize this by applying both normal and curling magnetic fields), right chirality for example, the positive direction current will generate 0 state; the negative direction current will generate 1 state.

And if the magnetization of substrate are all parallel to the normal of the plane, then the 0 state of vortex is just corresponding the low-resistance state; the 1 state of vortex is corresponding the high-resistance state. By measuring the resistance of vortex, we can read the information stored in vortices.

Conclusion:

In this essay, we first examine the experiments on vortex observation; the first experiment gives the evidence of vortex core, the second experiment gives more accurate results which can determine the size of the core. And then introduce experiments concerning dynamics of vortex core; the vortex core movment in static magnetic field and then vortex core response after the magnetic field pulse, additionally, a theoretical model about the vortex excitement. Meanwhile, we proposed the idea of chirality conservation in vortex magnetization process. With the idea of chirality, we present another explanation in Bussmann's experimental results. Finally, we exhibit the high possible application of vortex in MRAM.

Reference:

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