Magnetic Domain-Wall Racetrack Memory

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outline

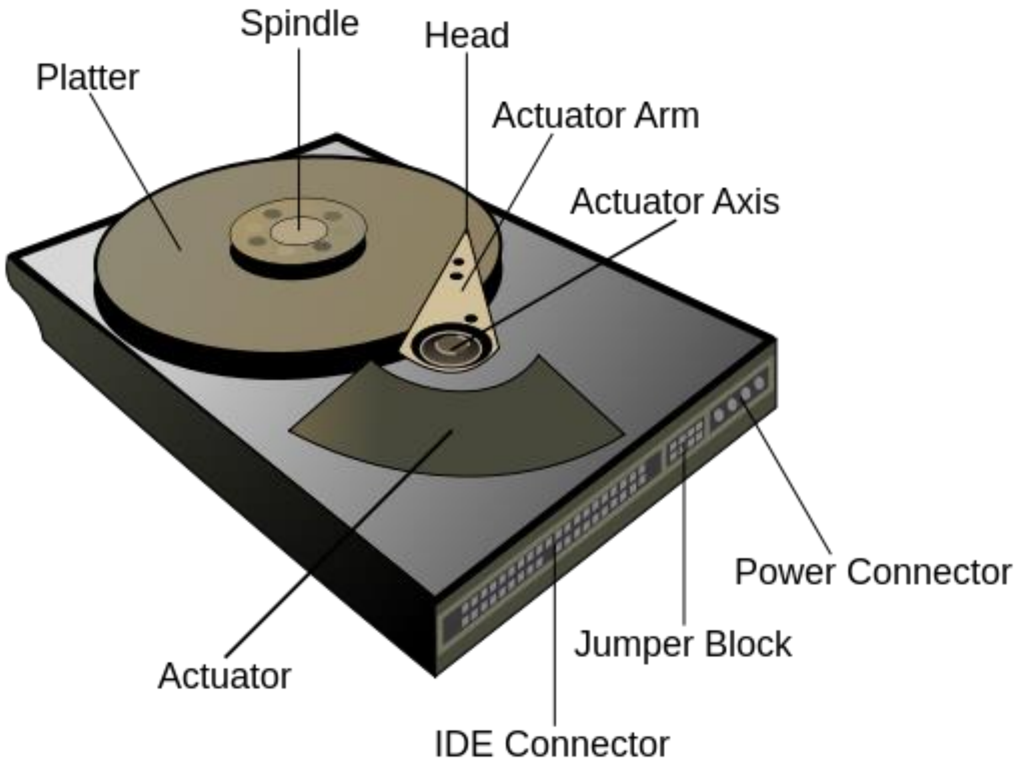
1、Background of Racetrack Memory

2、How it works?

3、**Domain Walls Motion**

4、Summary

Background of Racetrack Memory



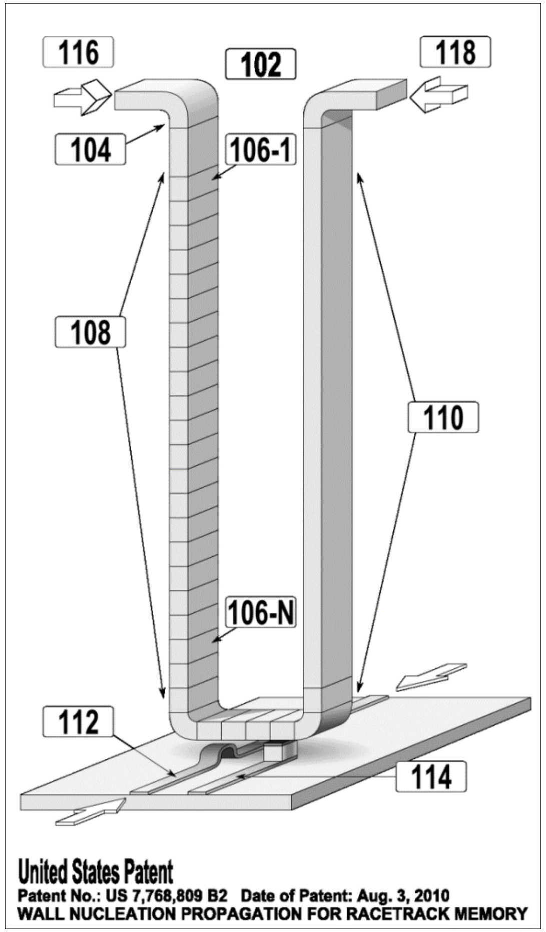
Hard Disk Drive

Slow but cheap

Solid State Drive

Fast but expensive

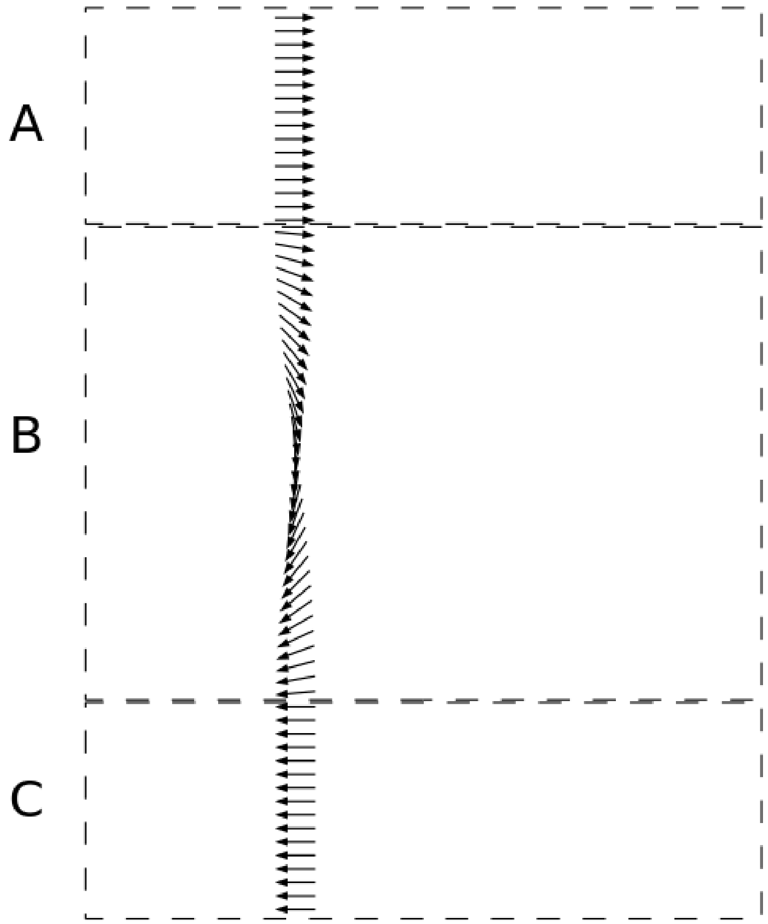
Racetrack Memory



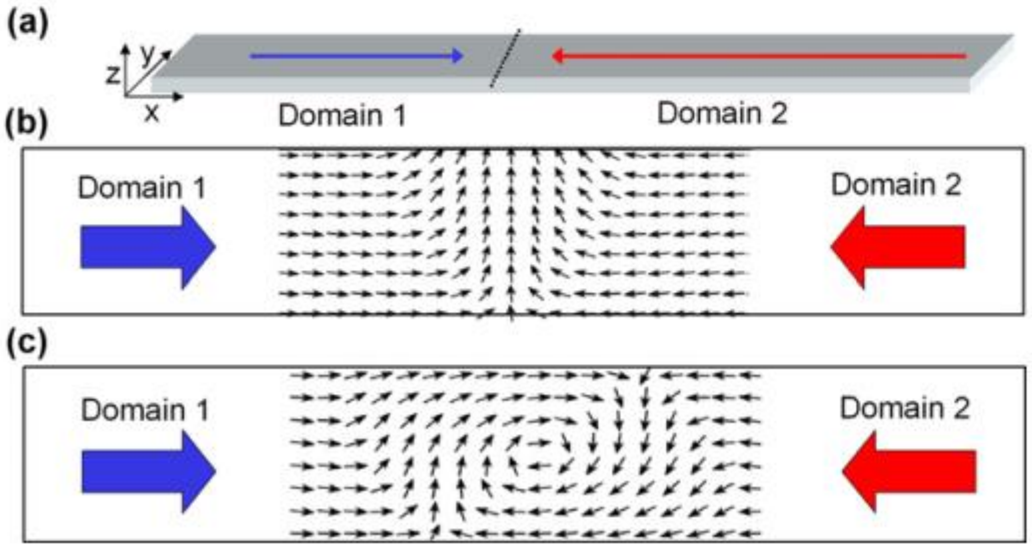
Racetrack memory or domain-wall memory (DWM) is an experimental non-volatile memory device under development at IBM's Almaden Research Center by a team led by physicist **Stuart Parkin**.

- Cheap
- 3D Storage
- Nonvolatile
- High performance

Domain wall



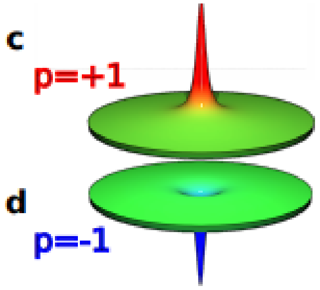
Head to Head



M Kläui 2008 J. Phys.: Condens. Matter 20 313001

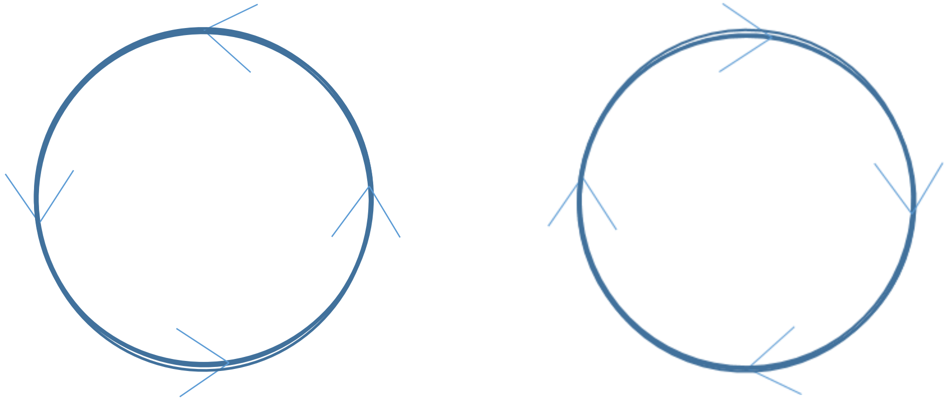
(b) Anticlockwise Transverse DM
(c) Clockwise Vortex DM

Polarity of Vortex DW (core)

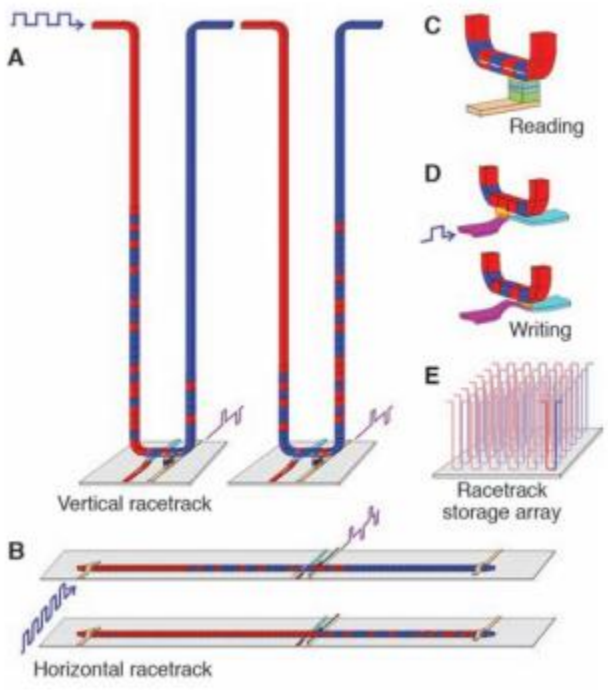


Affect the motion of DWs

Chirality of Vortex DM



How it works?



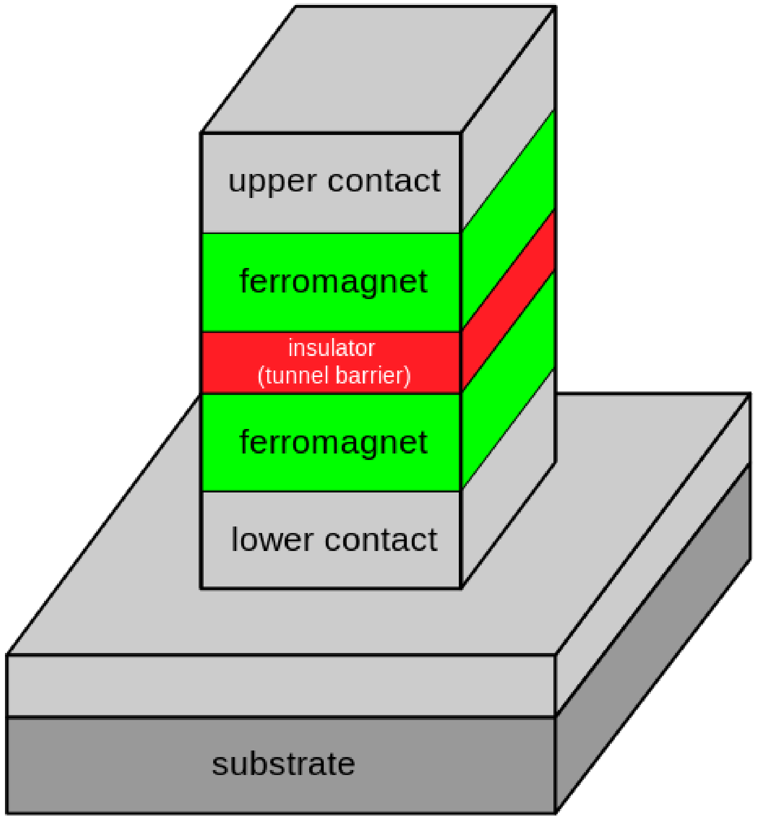
S. P. et.al *Science* **320** (5873), 190-194.

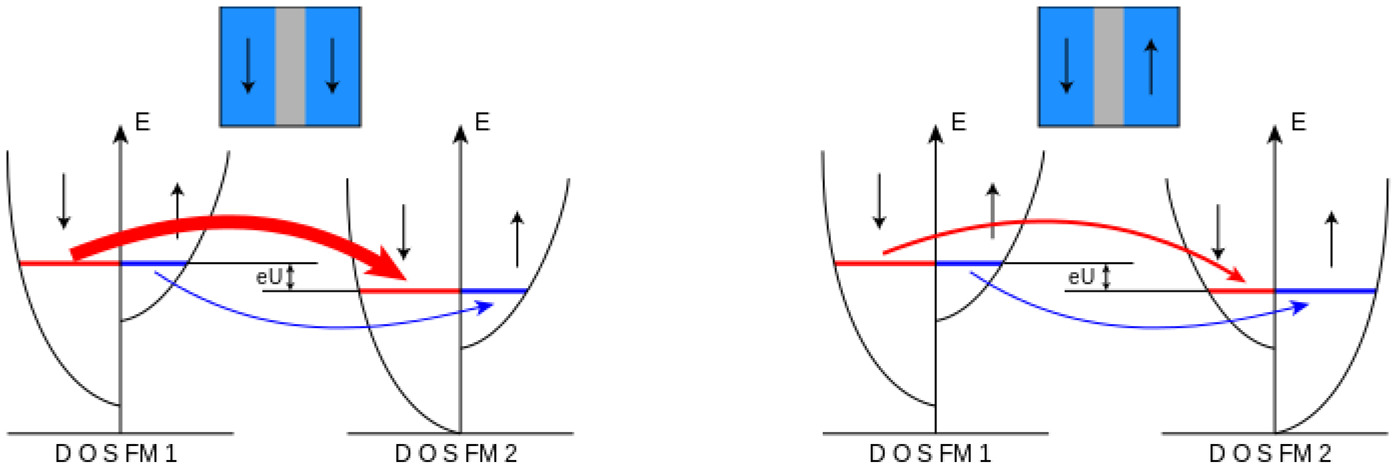
Structure: **magnetic nanowires** + **magnetic domains**

Read: MTJ

Write: self-field of current、spin-momentum transfer torque
fringing field

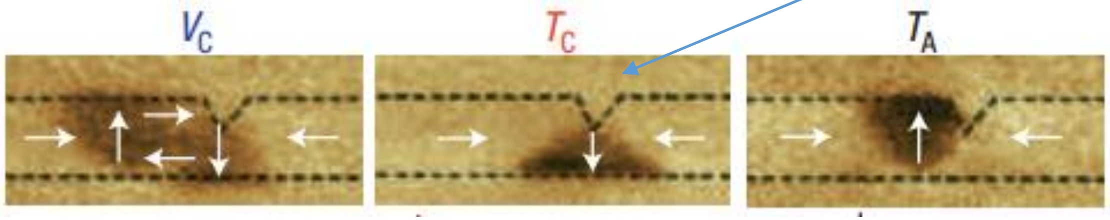
MTJ (magnetic tunnel junction)





Joulie model

Magnetic Nanowires



Hayashi, Masamitsu, et al. Nature Physics 3.1 (2007): 21-25.

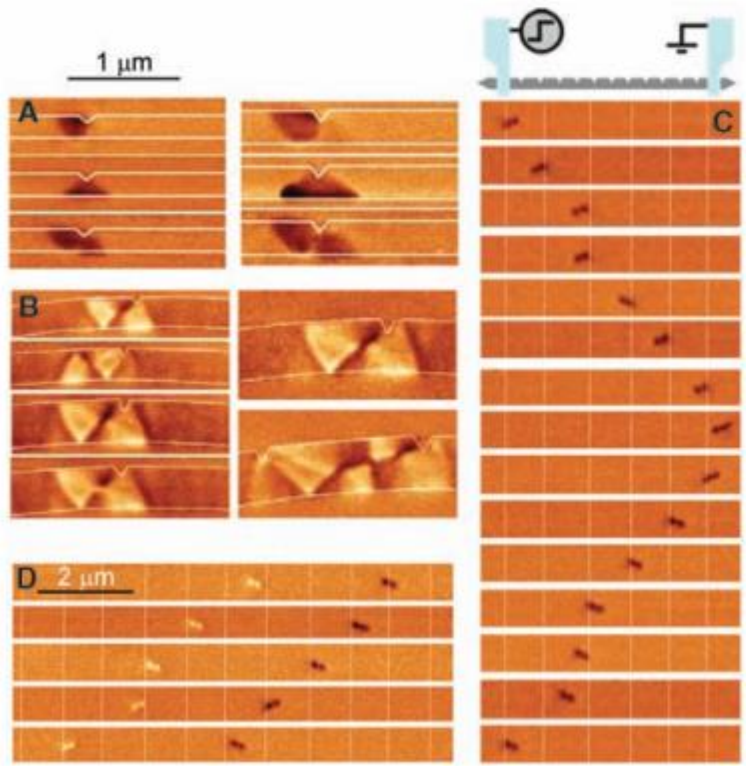
Pining sites

Control the domain walls' spacing

"V" or "T" DW depend on width and thickness

"V"is favored in thicker and wider nanowires

Domain Walls Motion



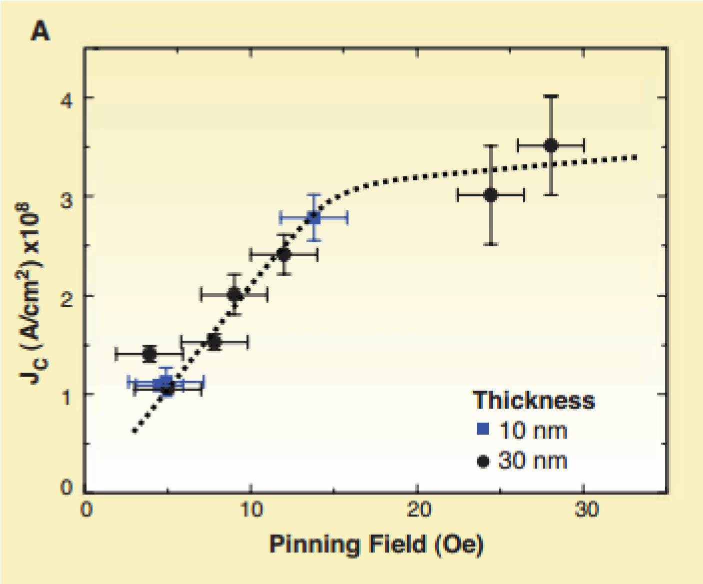
(C)
1、40-nm-thick, 100-nm-wide permalloy nanowire with 11 triangular notches located 1 mm apart ,
2、Single current pulses, **8V (26 mA)** and **14 ns** long, were applied between each image sequentially from top to bottom

(D)
The motion of two DWs in the same nanowire as (C).
Positive current pulses (**26 mA, 14 ns long**) were applied between successive images sequentially from top to bottom

the motion of the DWs is not reliable！

Critical curent is so high ($\sim 10^8 A/cm^2$), The Joule heating from current in 2~20ns can make temperature approach to curie temperature of permalloy (850K)

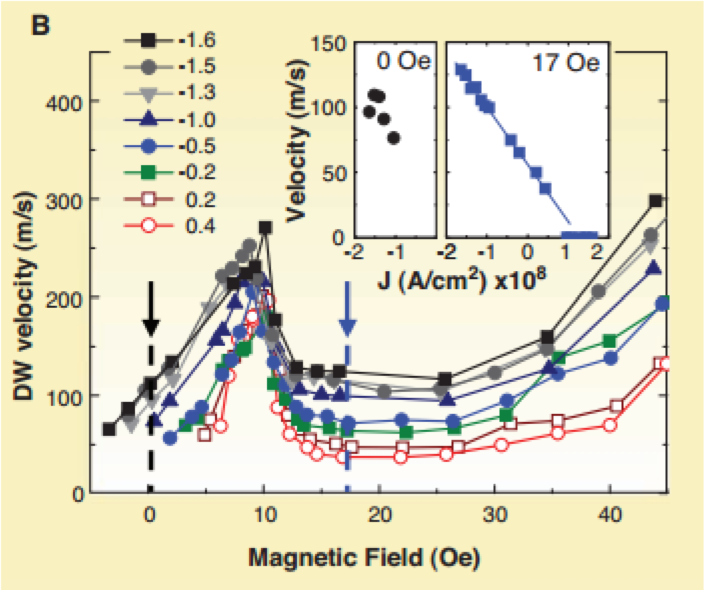
So can we reduce the critical current?



- For the lowest pinning strength (~5 Oe), the critical current is on the order of 10^8 A/cm^2.

- For relatively weak pinning (below ~15 Oe), the critical current density scales linearly with the pinning field.

- For stronger pinning (>15 Oe), the critical current appears to saturate and becomes independent of pinning strength .



Current densities indicated in the figure are in units of 10^8 A/cm^2

The DW velocity peaks at a relatively low magnetic field (~10 Oe)

This drop in the DW velocity is associated with a change in the DW propagation mode and is known as the **Walker breakdown**

The velocity exhibits a maximum value of ~110 m/s at a current density of ~1.5 $\times$ $10^8 A/cm^2$

Walker breakdown

The motion of 180° domain walls in uniform dc magnetic fields

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Bell Laboratories, Murray Hill, New Jersey 07974
(Received 29 April 1974)

The equations of motion of a 180° domain wall in an infinite uniaxially anisotropic medium which is exposed to an instantaneously applied uniform dc magnetic field H_0 have been integrated numerically. Below the critical field $H_c = 2\pi\alpha M_0$ (α is the Gilbert loss parameter and M_0 the saturation magnetization), where a steady-state solution is known to exist, it is shown that the wall motion tends smoothly to this solution. Above H_c, the magnetization precesses about the field and a periodic component appears in the forward motion of the wall. Analytic solutions for the wall motion have been found based upon approximations suggested by the computed behavior; these reproduce the computer results very accurately.

Observation

Direct observation of the coherent precession of magnetic domain walls propagating along permalloy nanowires

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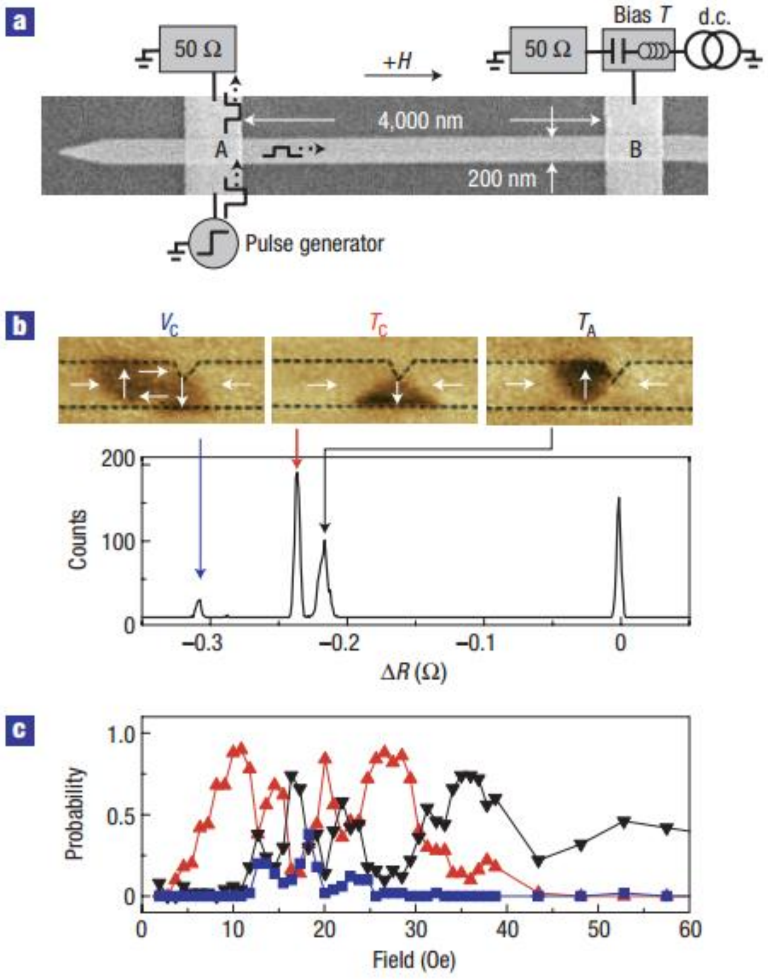


Figure 1 Experimental set-up and structure of injected DWs at a notched

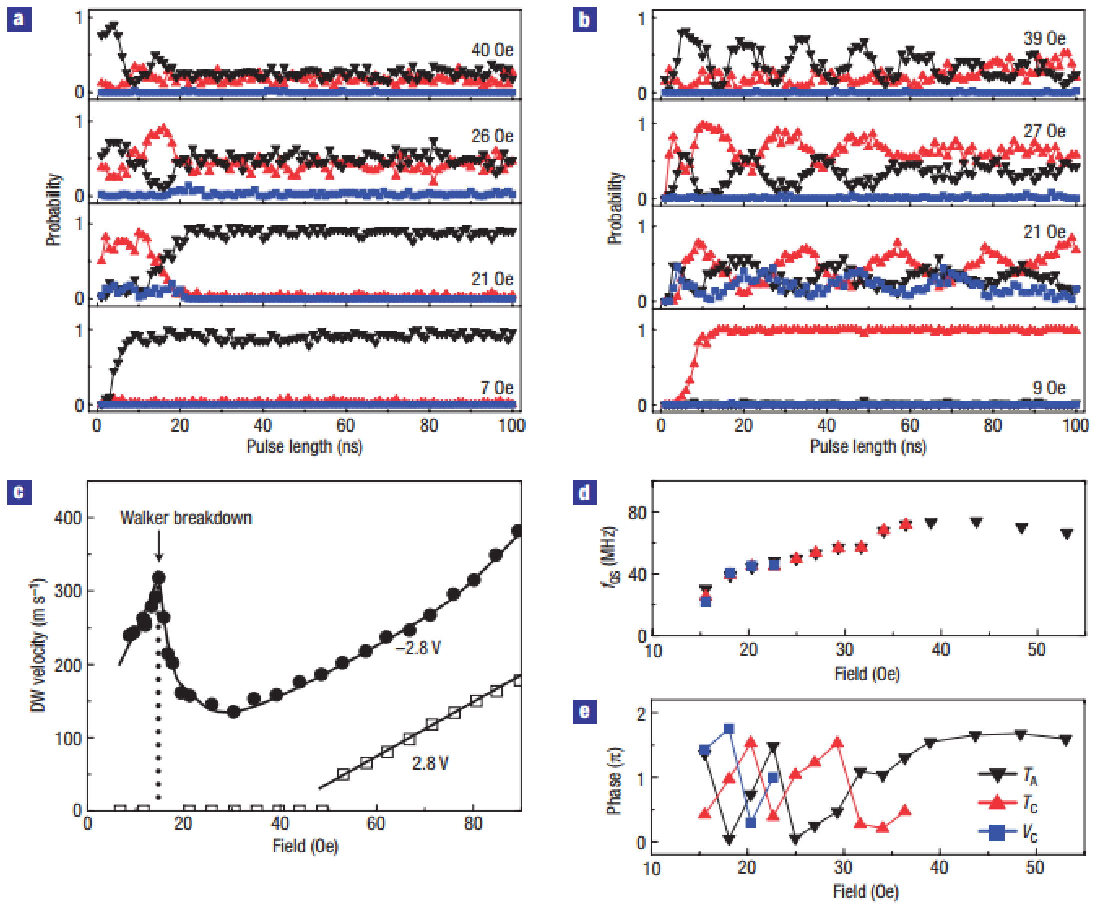


Figure 2 Probability of trapping DWs with different structures at a pinning site: field dependence. a,b, Probability of trapping a DW, V_C (blue), T_C (red) and T_A (black), at a notch plotted against the voltage pulse length at several different fields, when −2.5 V (**a**) and 2.5 V (**b**) pulses are used to inject a DW, respectively. **c**, DW velocity versus

$$A exp\left(-\frac{t_p}{\tau_D}\right) Sin(2\pi f_{QS}\, t_P + phase)$$

TA and *TC* walls are 180◦ out of phase with each other and the *VC* wall is 90◦ out of phase from the transverse walls.

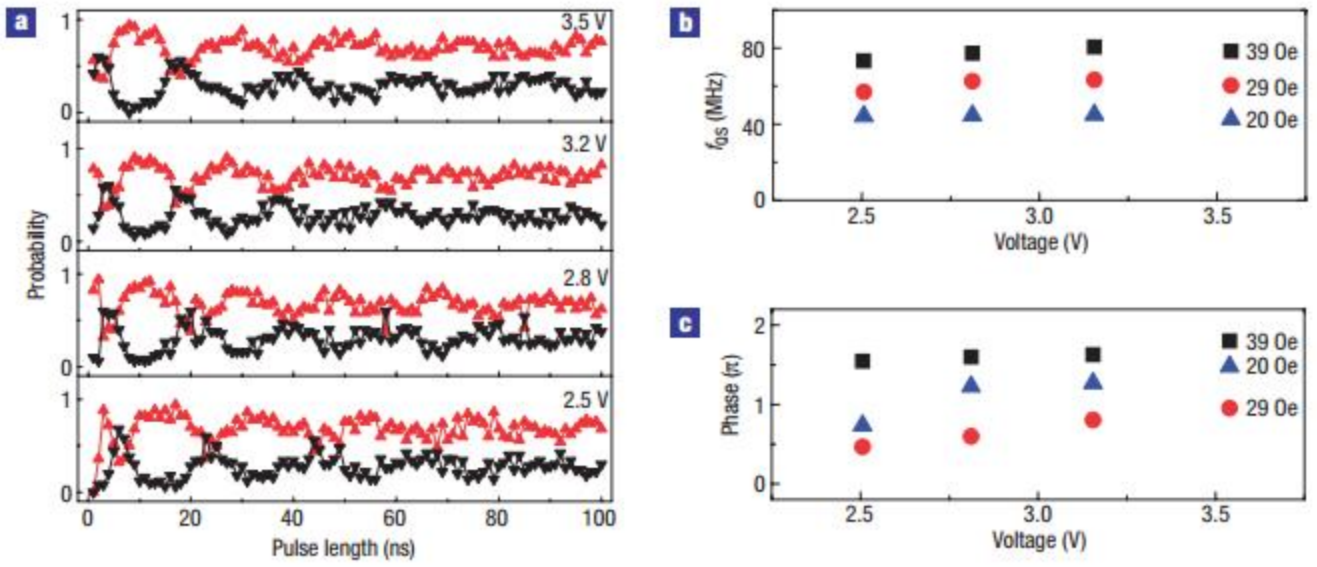


Figure 3 Probability of trapping transverse DWs with different chiralities at a pinning site: voltage pulse dependence. **a**, Probability of trapping a transverse wall, (red) and T_A (black), at a notch plotted against the voltage pulse length for various pulse amplitudes. The applied magnetic field is 25 Oe. **b**,**c**, Dependence of the frequency f_{OS} (**b**) and the phase shift (**c**) of the oscillations of the trapping probability on the pulse amplitude. The method of deducing of f_{OS} and the phase shift are described in the Fig. 2d caption. The corresponding magnetic fields used during the injection of a DW are shown in the panels.

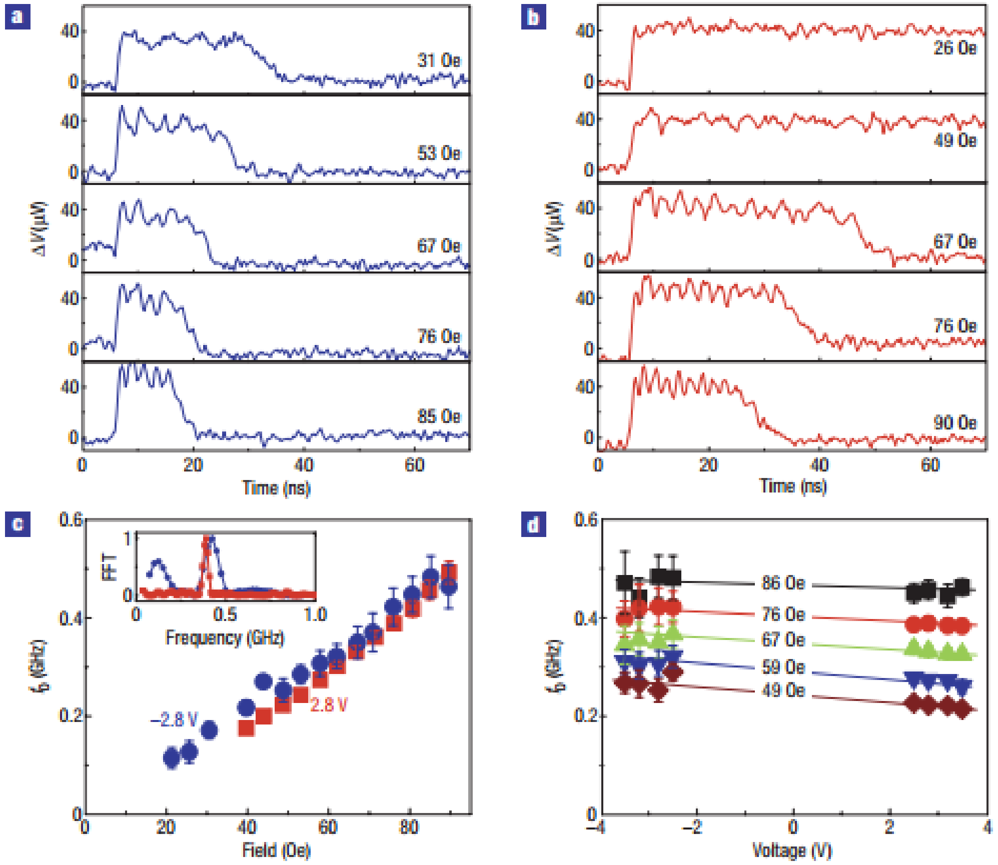


Figure 4 Time-resolved resistance measurements of a propagating DW along a permalloy nanowire. a,b, Real-time measurements of the DW propagation along the nanowire obtained by averaging the temporal evolution of the nanowire resistance 16,000 times. Signal traces ΔV obtained by using -2.8 V (**a**) and 2.8 V (**b**) voltage pulses to inject a DW. Representative signal traces are shown at various fields indicated in each panel. **c**, Dependence of the frequency of the oscillations in resistance observed in the signal traces (ΔV) plotted versus field. The data shown are when ± 2.8 V voltage pulses are used to inject a DW. Oscillation frequency f_0 is determined by taking the FFT spectra of each trace. Error bars correspond to the width of a gaussian to which the peak structure in the FFT spectra is fitted. The inset shows normalized FFT spectra of the signal traces taken at 76 Oe. Note that the lower-frequency feature simply corresponds to $1/\Delta\tau$. **d**, Dependence of the oscillation frequency f_0 on the amplitude of the voltage pulse in various magnetic fields. The definition of the error bars is the same as in **c**. The solid lines are guides to the eye.

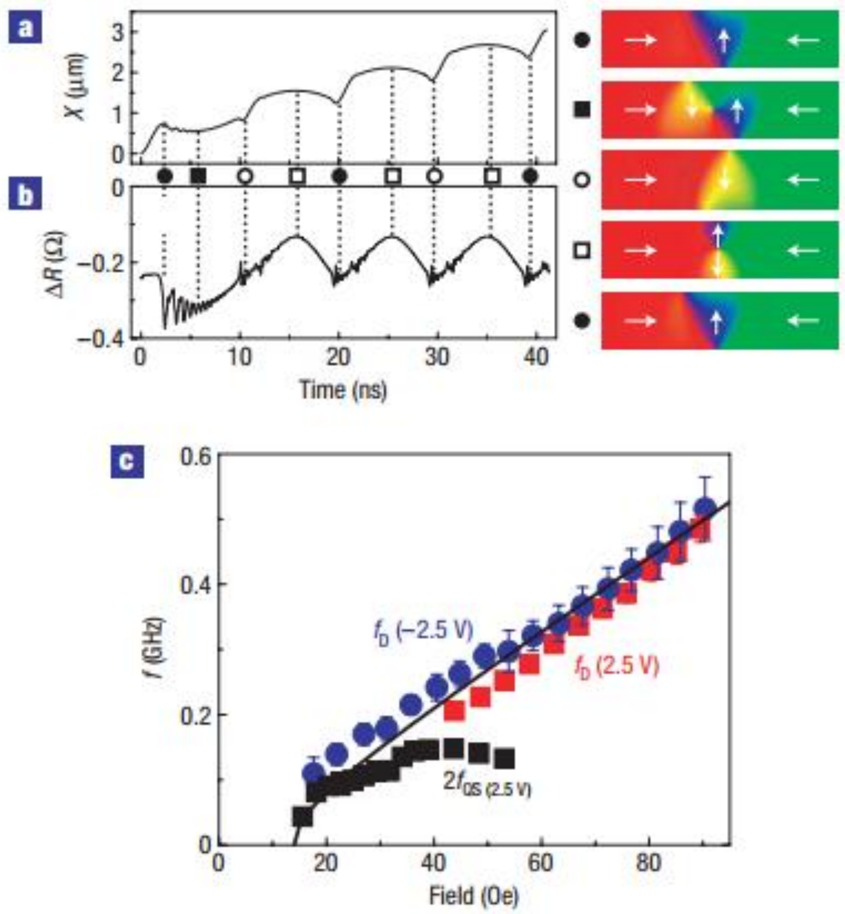


Figure 5 Micromagnetic simulations of the field-driven motion of a DW and comparison of calculated and measured frequency of periodic DW motion.

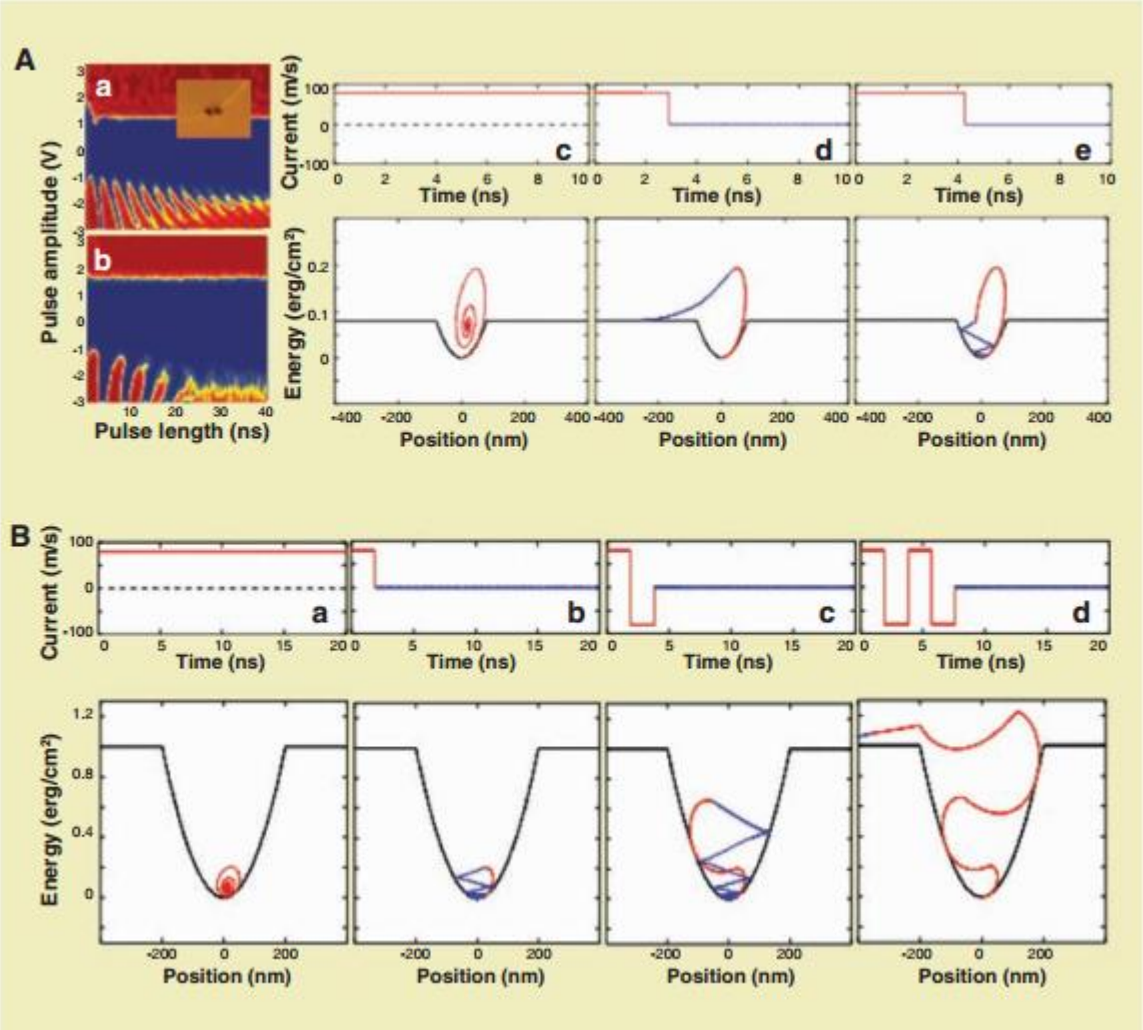
Conclusion:

- oscillations are observed only when the field exceeds the Walker breakdown field (~14 Oe)

- The DW state oscillates periodically from a transverse wall of one **chirality to a transverse** wall of the opposite polarity via a vortex wall or an anti-vortex wall state

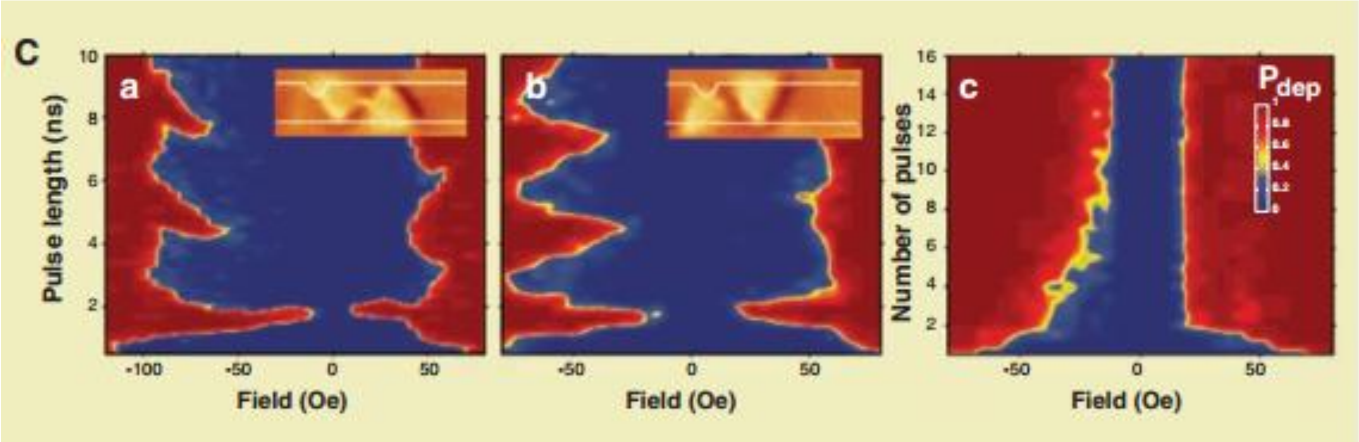
- the oscillations seen in the real-time measurements of the DW motion represent periodic variations in the DW structure as the DW propagates along the nanowire

Resonant Amplification of DW Motion



A novel method for lowering the critical current density of pinned DWs was recently demonstrated, which involves using short current pulses with particular lengths, matched to the innate **precessional frequency** of the pinned DW

When the current pulse length is matched to approximately a half integer of the DW's precessional period tp (such as 1/2, 3/2, 5/2, etc.), the DW can have sufficient energy to be driven out of the pinning site.



When the pulse length equals 1/2 t_p(~2 ns), the DWs are depinned with greater probability

The shorter the current pulse, the more efficient is the phenomenon.

Summary

1、3D Racetrack Memory may overcome the limitations of the further scaling of complementary metal oxide semiconductor transistors.

2、RM has great performace, the average access time of RM will be 10 to 50 ns, as compared to 5 ms for an HDD and perhaps ~10 ns for advanced MRAM .

3、There are also many challenges such as, interaction of spin-polarized current with magnetic moments...

Reference

- Parkin S S P, Hayashi M, Thomas L. Magnetic domain-wall racetrack memory[J]. Science, 2008, 320(5873): 190-194.
- Hayashi M, Thomas L, Rettner C, et al. Direct observation of the coherent precession of magnetic domain walls propagating along permalloy nanowires[J]. Nature Physics, 2007, 3(1): 21-25.
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Thanks for your attention!