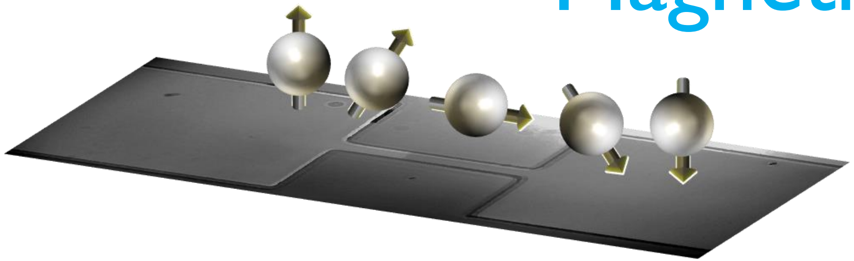
Ferrimagnetic Materials for advanced Magnetic Memories



Sina Ranjbar

Outline

- **Introduction**
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  3. Mechanism of Domain wall motion
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- **Mechanism for maintaining ultrafast domain wall mobility over a wide temperature range**
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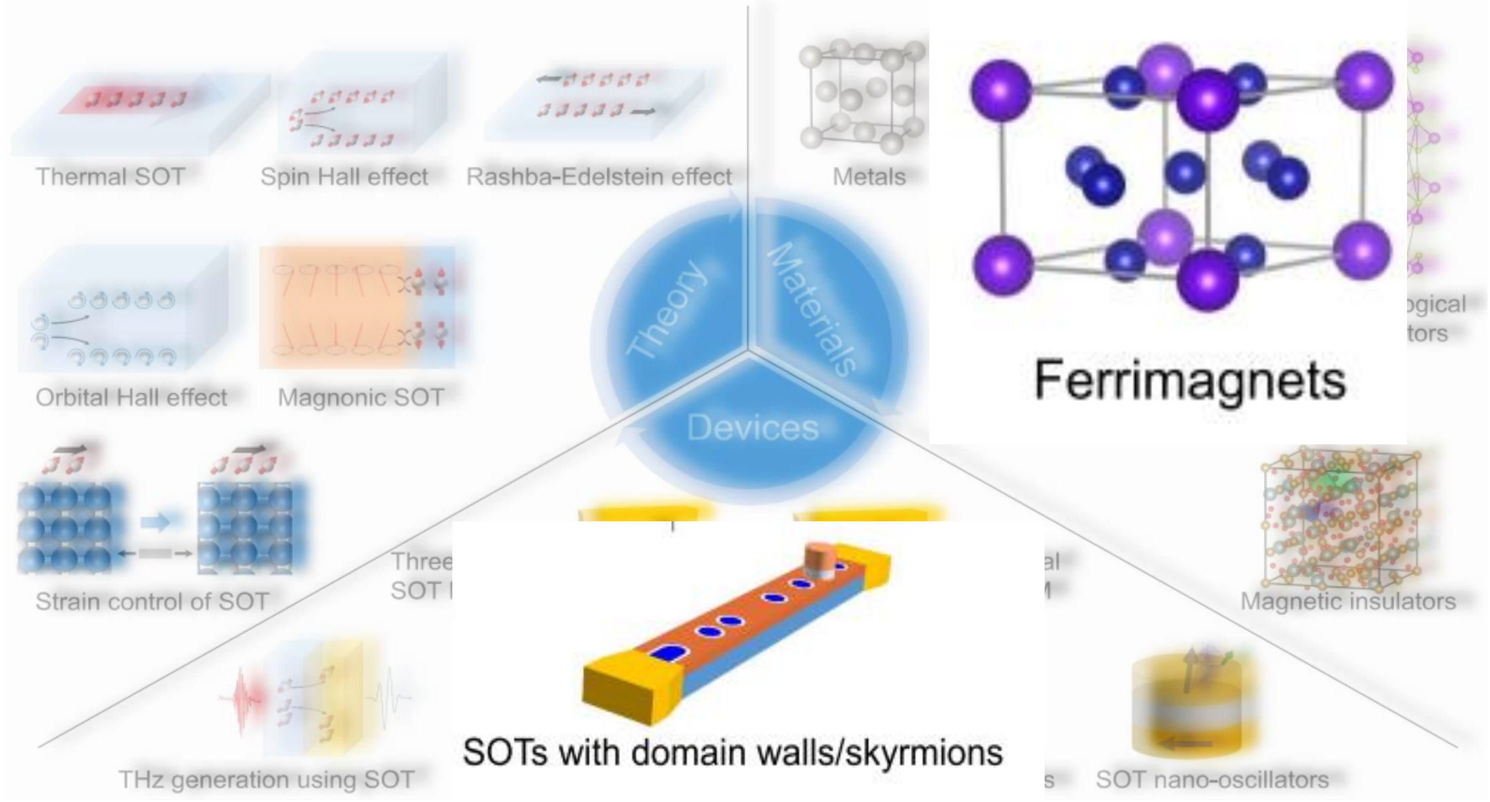
- **Controlling the multi-bits DWs driven by the electric current at an ideal position**
  1. Experimental method and Electrical setup for the domain wall motion measurement.
  2. Results and discussion
  3. Summary

- **Remain challenges and possible research using ferrimagnets**

Study potentials



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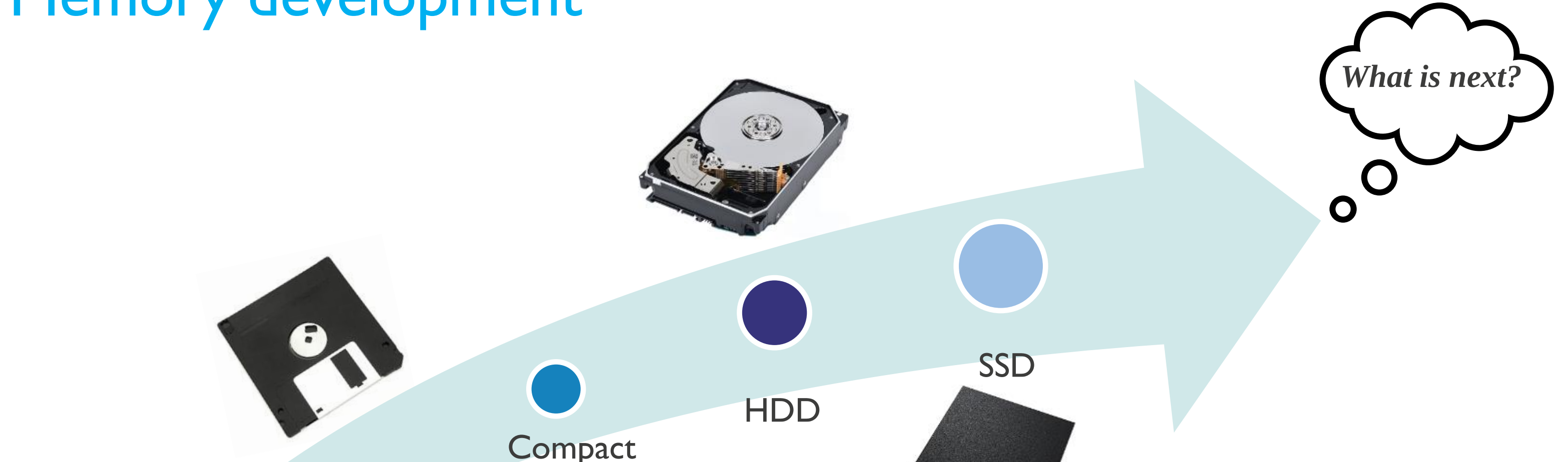
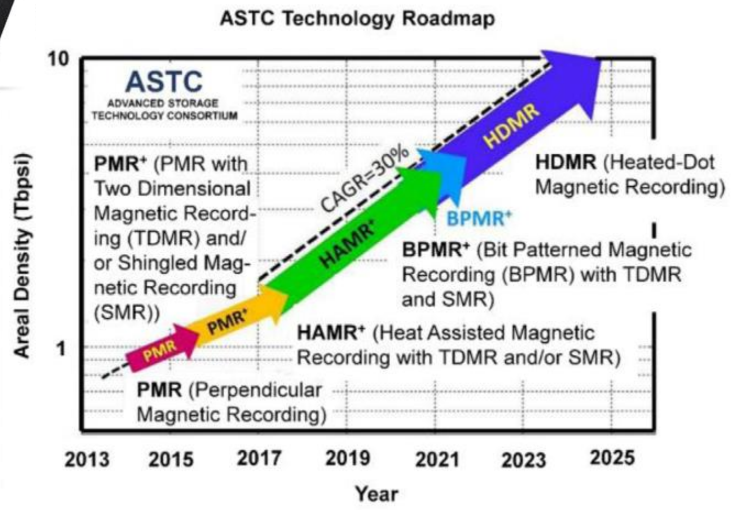
Memory development

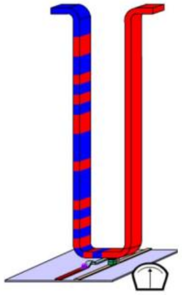




High data storage potential in Racetrack memory

- The magnetic HDDs have established an areal density ~1.5 Tb/in2
- With HAMR, it could go up to about 4 Tb/in2 .
- 12 platters, achieve about 40 TB in HDDs.

- If one can fabricate nanowires with a width, spacing, DW width, and domain length of 10 nm, one can obtain an areal density of ~2.9 Tb/in2 .
- No head-media spacing issue in racetrack memory, we can stack layers.
- If 128 layers are stacked in the form factor of 65 mm HDD (2.5 in HDD), we can achieve ~145 TB.



Thus, a higher storage capacity – rather than a high density – is the main advantage of DW racetrack memory.

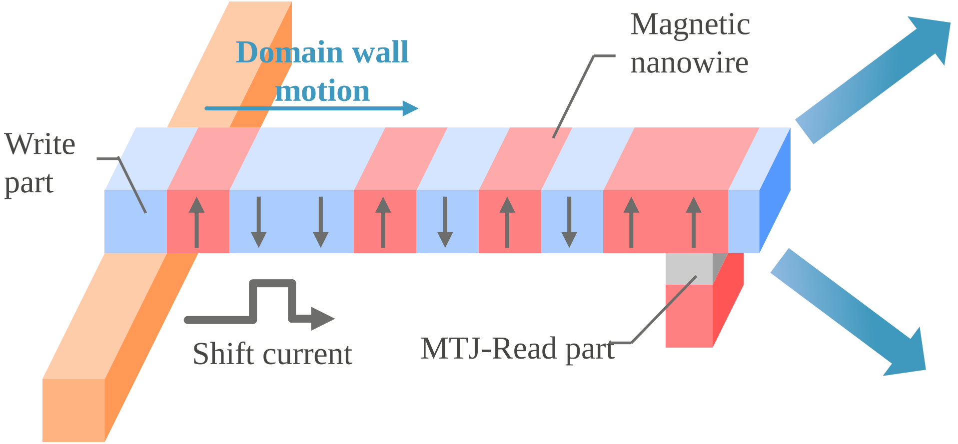
Requirements

- Being able to write information..
  - Being able to address and read the information.(TMR head)
    - Shifting DW by current induced or field driven.
      - Being able to store information.

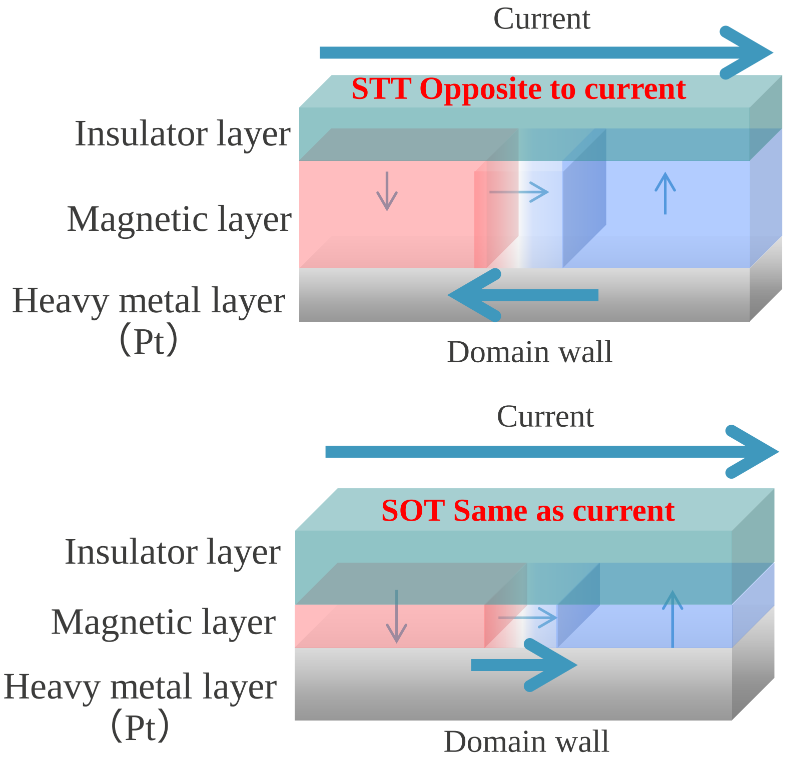
Mechanism of Domain wall motion

Racetrack memory

- One of the candidates for the future memory device.
- Non-volatile memory.



CIDWM is attributed to STT or SOT.



Every nanowire in a racetrack memory should have its reading and writing elements.
The size of the reading and writing element ≈ The size of the smallest domain.

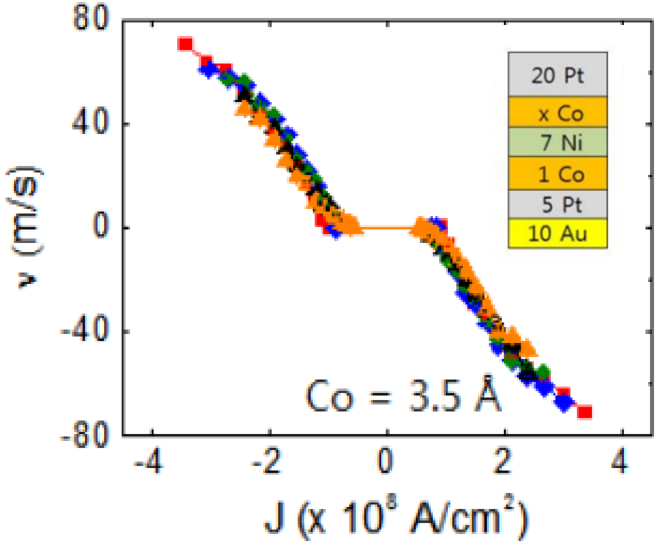
Domain wall memory challenges and Requirements

Challenges

- Fast DW motion.
  - DW stability.
    - Controlled motion of DWs are also challenges.
      - The domains have to be as small as possible.
        - Reducing the overall size of the nanowire devices
          - DW pinning and operation power consumption.

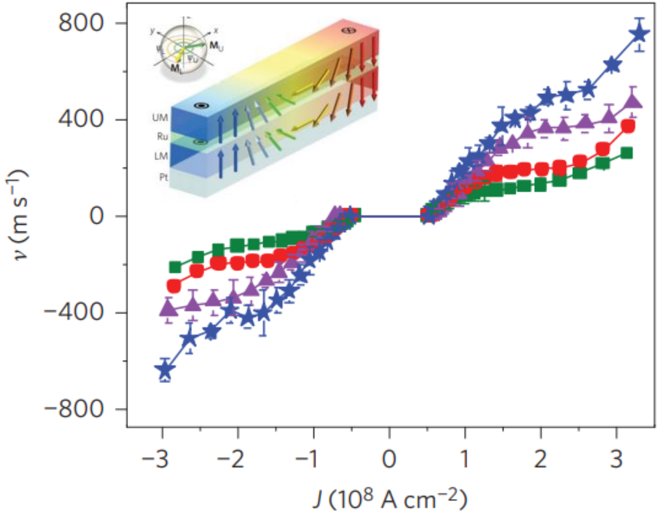
Domain wall memory background (FM and AFM DW speed)

RYU et al.: IEEE TRANSACTIONS ON MAGNETICS, VOL. 52, NO. 7, JULY 2016.



- Stray-field interactions limit the bit size.
- Precessional dynamics limit the operating speeds.

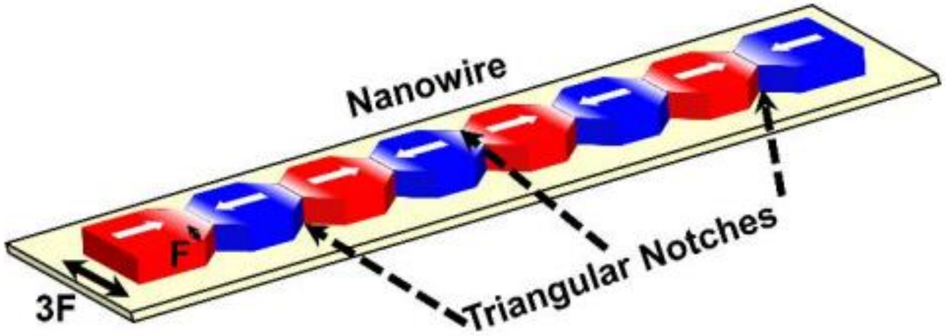
Yang, See-Hun, et al, *Nature nanotechnology* 10, no. 3 (2015).



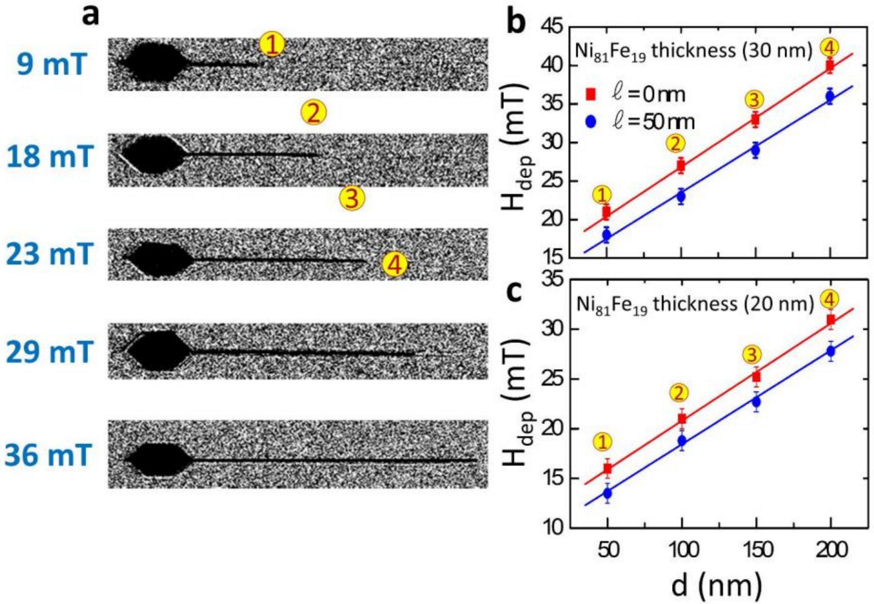
- Lack stray fields, allows for atomically thin domain walls with a high packing.
- Much faster dynamics than ferromagnets, with THZ switching speeds.
- Manipulating and detecting AFM spin textures is challenging.

Domain wall memory background (Accurate Control DW Position)

Durgesh Kumar, et al., IEEE TRANSACTIONS ON MAGNETICS, VOL. 55, NO. 3, (2019).



Al Bahri, et al. *Physical Review Applied* 11, no. 2 (2019).



- The artificial pinning, for example, by making notches, is necessary to control precisely the domain wall position.
- Complicated microfabrication technique.

This method is not practical because it is costly to manufacture and difficult to produce.

Why Ferrimagnetic?

- In ferrimagnets the opposing sublattices can fully compensate one another to achieve behaviors like those of antiferromagnets.
    - They remain individually detectible and addressable if the electronic or optical properties of the constituent elements are different.

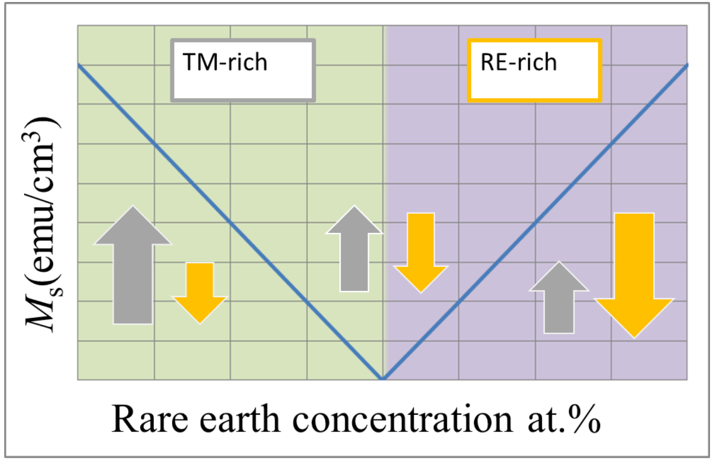
Compensated Ferrimagnetic systems

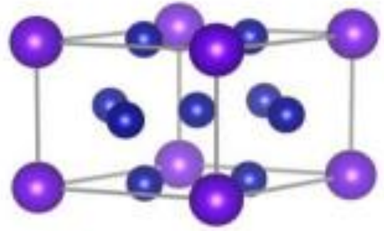
Net magnetization= $M_1(T)+ M_2(T)= M(T)$

Net angular momentum= $A_1(T)+ A_2(T)= A(T)$

At magnetic compensation point (T_M); $M(T)=0$ and $A(T)\neq 0$

At angular momentum compensation point (T_A); $M(T)\neq 0$ and $A(T)=0$





Ferrimagnets

$$M_{total}(T) = M_{Gd}(T) - M_{FeCo}(T) = \alpha_{Gd}(T_C - T)^{\beta_{Gd}} - \alpha_{FeCo}(T_C - T)^{\beta_{FeCo}} \quad \text{(Eq. 1)}$$

$$T_C - T_{MC} = T_C\left[\frac{M_{Gd}(0)}{M_{FeCo}(0)}\right]^{1/(\beta_{FeCo}-\beta_{Gd})} \quad \text{(Eq. 2)}$$

$$A_{total} = \left[\frac{M_{FeCo}(0)}{\gamma_{FeCo}(0)}\right]\left(1-\frac{T}{T_C}\right)^{\beta_{FeCo}} \quad \text{(Eq. 3)}$$

$$T_{AMC} = T_{MC} + T_C\left[1-\left(\frac{g_{FeCo}}{g_{Gd}}\right)^{1/(\beta_{FeCo}-\beta_{Gd})}\right] \quad \text{(Eq. 4)}$$

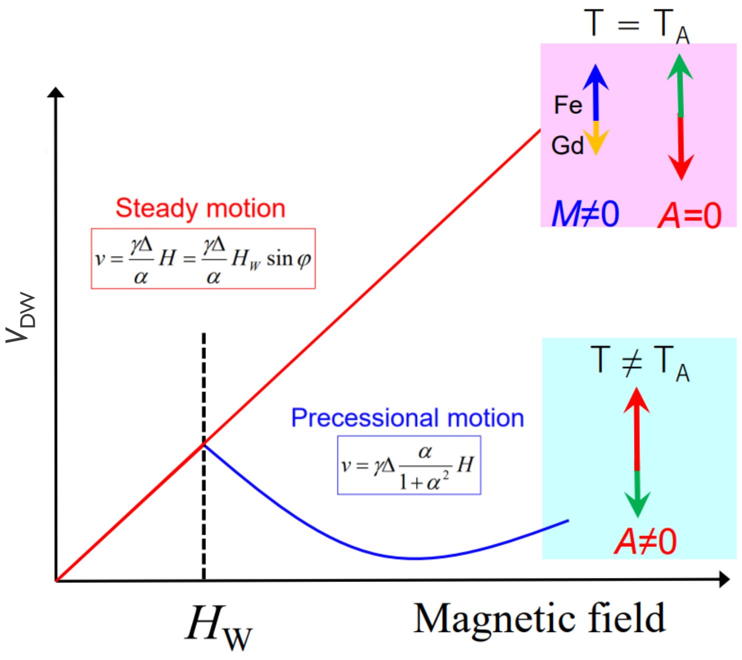
- g-factors are different.

T_M and T_A could be also be achieved by tuning the composition of the systems.

Background study in compensated ferrimagnetic

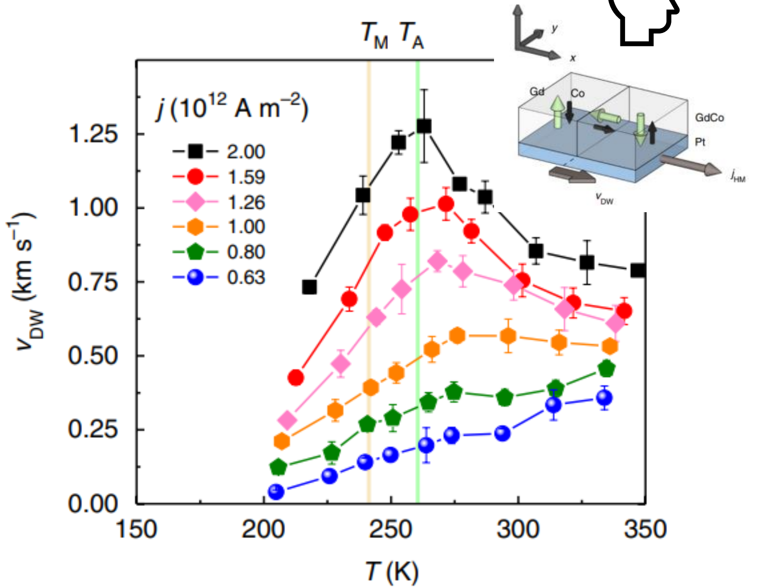
York TOHOKU KAISERSLAUTERN LEEDS Manchester spintec symposium

Field driven DW motion



Current induced DW motion

@ R.T



Sensitive to temperature fluctuations

L. Carreta. Et al, Nature Nanotechnology | VOL 13 | DECEMBER 2018

Objectives

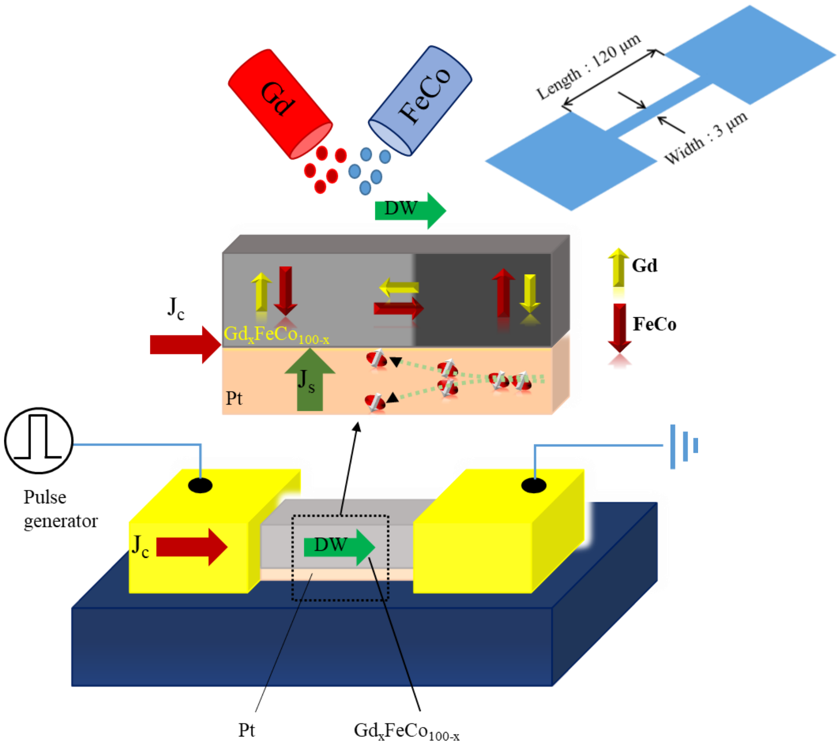
York TOHOKU KAISERSLAUTERN LEEDS Manchester spintec symposium

- Fast DW motion @ room temperature.
  - DW stability in a wide operating temperature range.
    - Controlled motion of DWs are also challenges.
      - Reduce Current density.

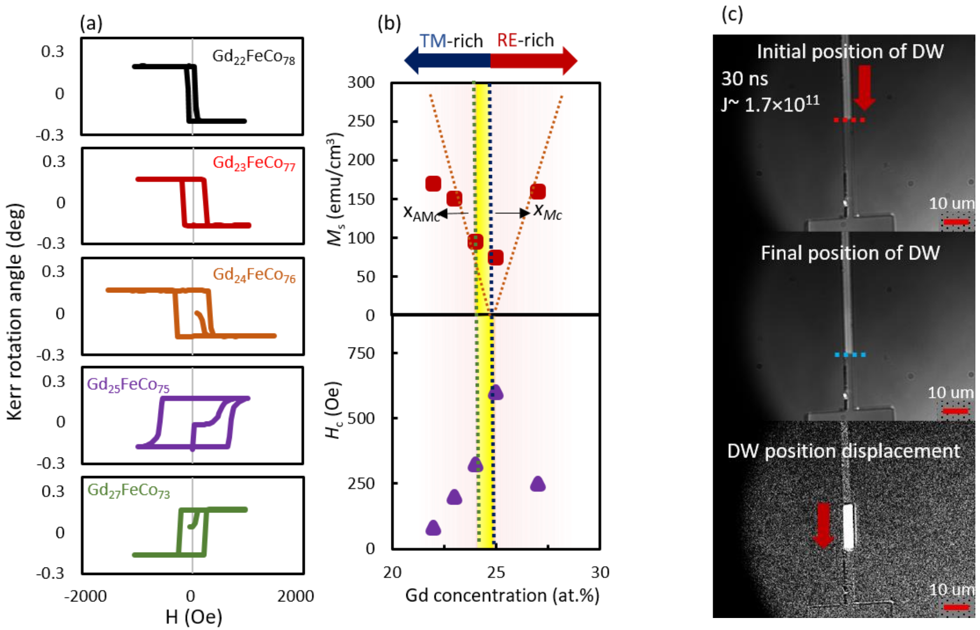
Ranjbar.S, et al, Mater. Adv., 2022, 3, 7028–7036

Elucidation of the mechanism for maintaining ultrafast domain wall mobility over a wide temperature range

Experimental method



Compensation @ RT?

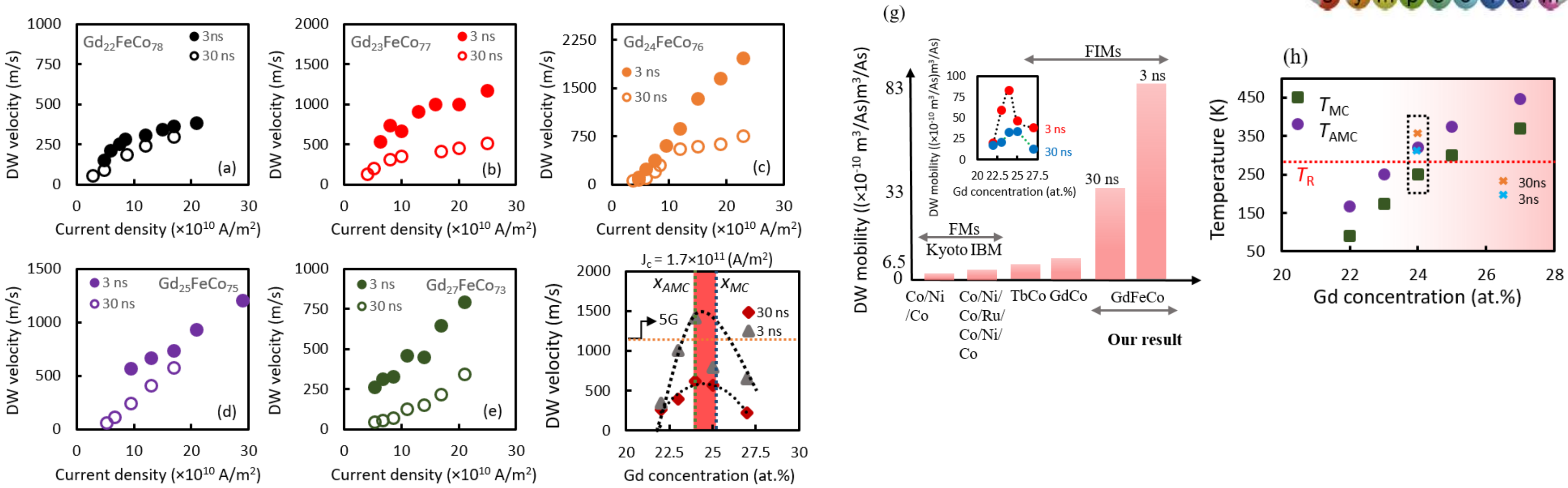


$$M = M_{Gd} + M_{FeCo}$$

$$A = A_{Gd} + A_{FeCo} = \frac{M_{Gd}}{\gamma_{Gd}} + \frac{M_{FeCo}}{\gamma_{FeCo}} = \frac{M_{Gd}}{\frac{g_{Gd}\mu_B}{\hbar}} + \frac{M_{FeCo}}{\frac{g_{FeCo}\mu_B}{\hbar}}$$

$g_{Gd} \approx 2.0$ $g_{FeCo} \approx 2.16$
x_{AMC} @ 23.

Current induced domain wall motion



The maximum DW velocity v_{DW} = 1500 m/s (>20 Gbps) appears between x_{MC} and x_{AMC} point for $Gd_{24}FeCo_{76}$ with for short pulse duration width of 3ns.

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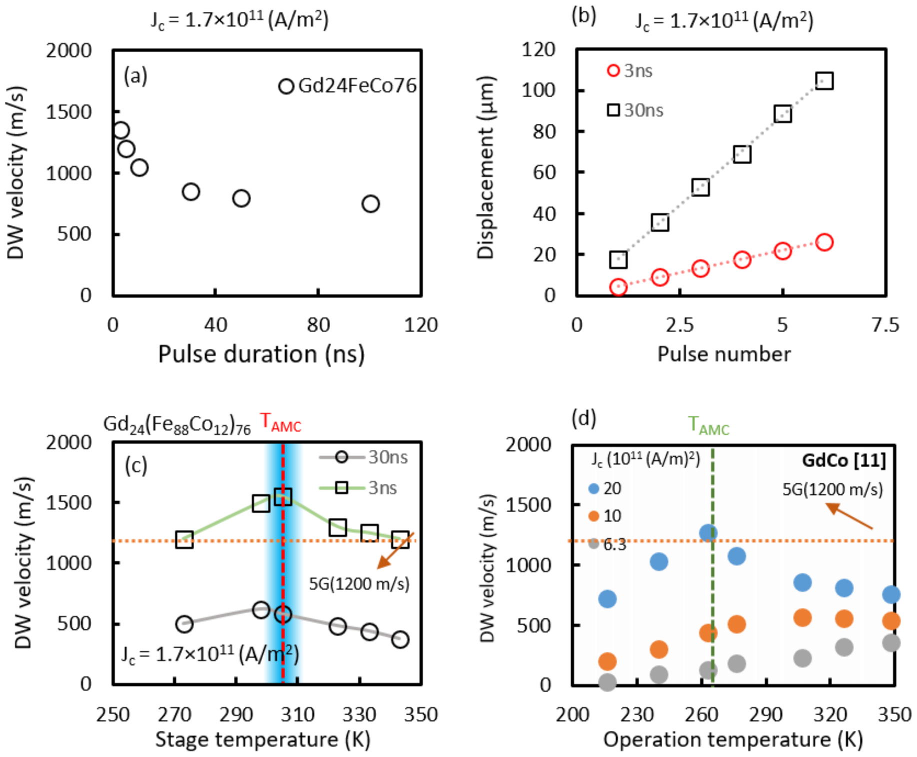
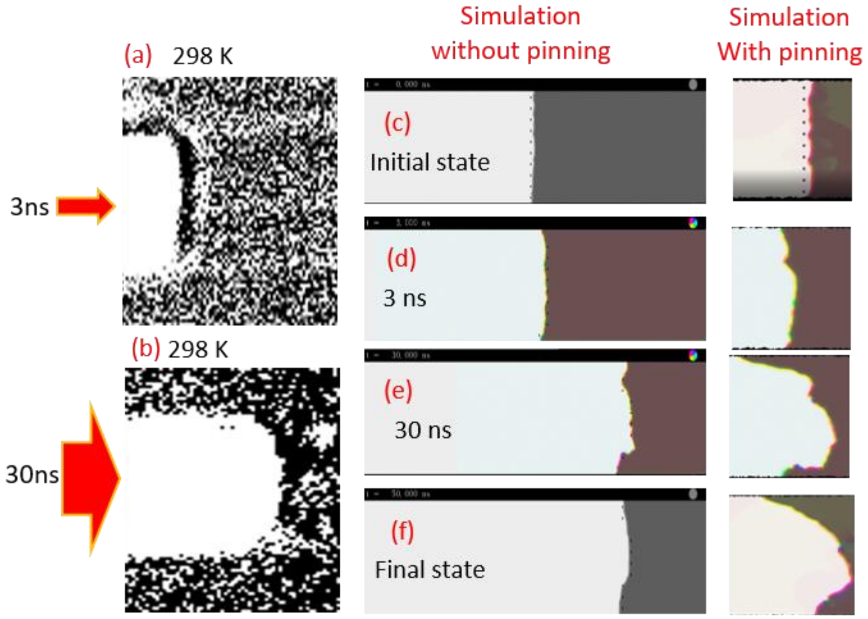
Pulse duration width dependence on the domain wall motion



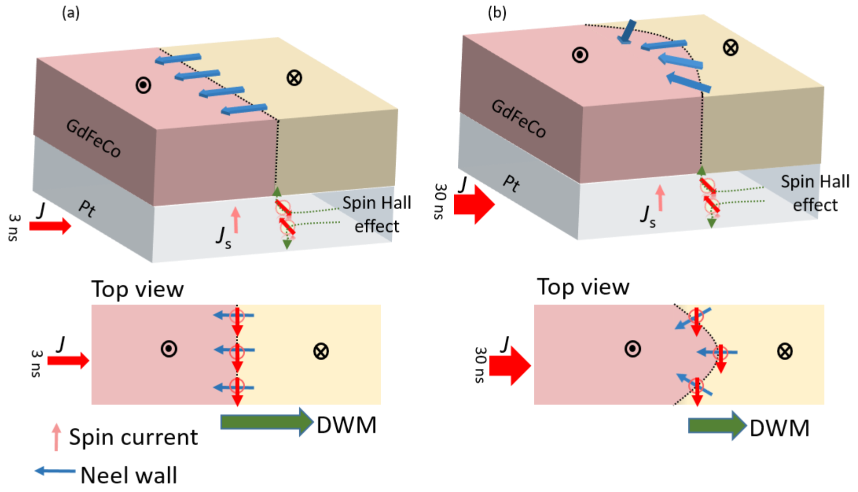
- ✓ The domain wall velocity became slower, when a short pulse duration width injected into the sample.
- ✓ The short pulse duration width of 3ns retains the sample temperature close to the T_{AMC}.
- ✓ A short pulse current of 3 ns with low input current density showed a broader and stable peak.

Discussion 1



$v_{DW(30ns)}=0.6v_{DW(3ns)}$

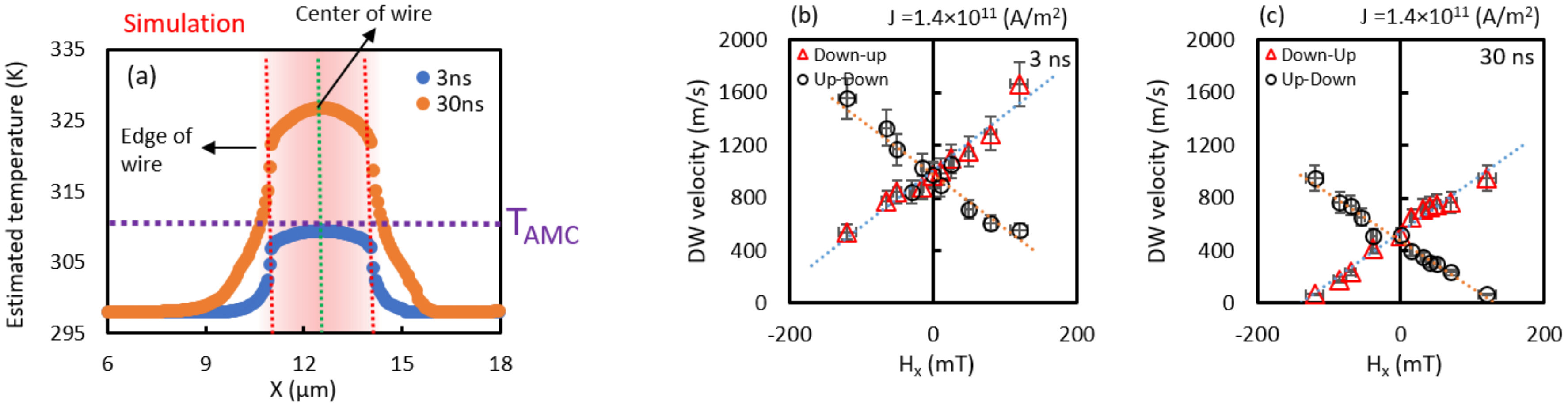
DW velocity with a pulse width of 30 ns is about 60% lower than that with 3 ns.



The spin currents flowing from the Pt layer and the Neel wall were orthogonal to each other.

SOT was efficiently generated and a high DW speed was achieved.

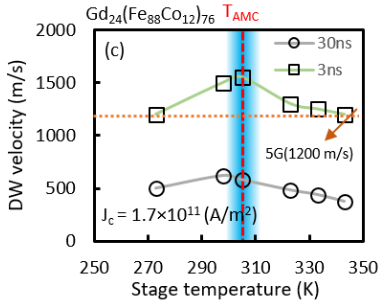
Discussion 2



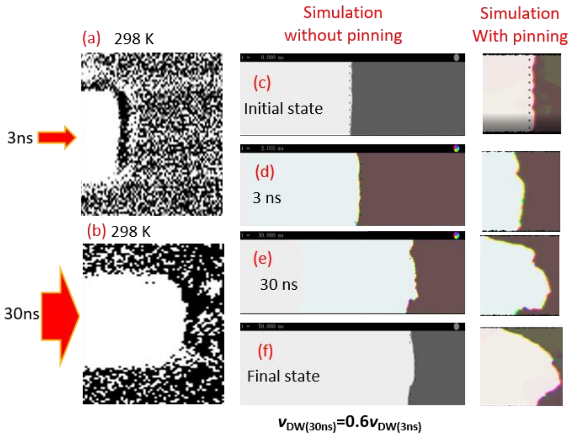
- ✓ The temperature difference between the center of the magnetic wire and the wire edge has been observed.
- ✓ The decisive difference is due to DMI, and this difference is thought to come from the shape of the domain wall driven by current.

Summary

1. Domain walls velocity up to 1500 m/s at J ~ 1.7×10^{11} (A/m^2) was found for both edges of DWs in GdFeCo nanowire.

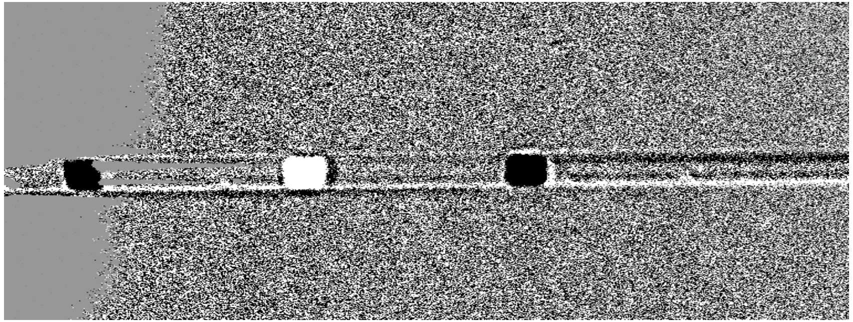


2. The mechanism of difference in DW speed was clarified by an experimental observation of the DW shape with the inclusion of DMI effects.

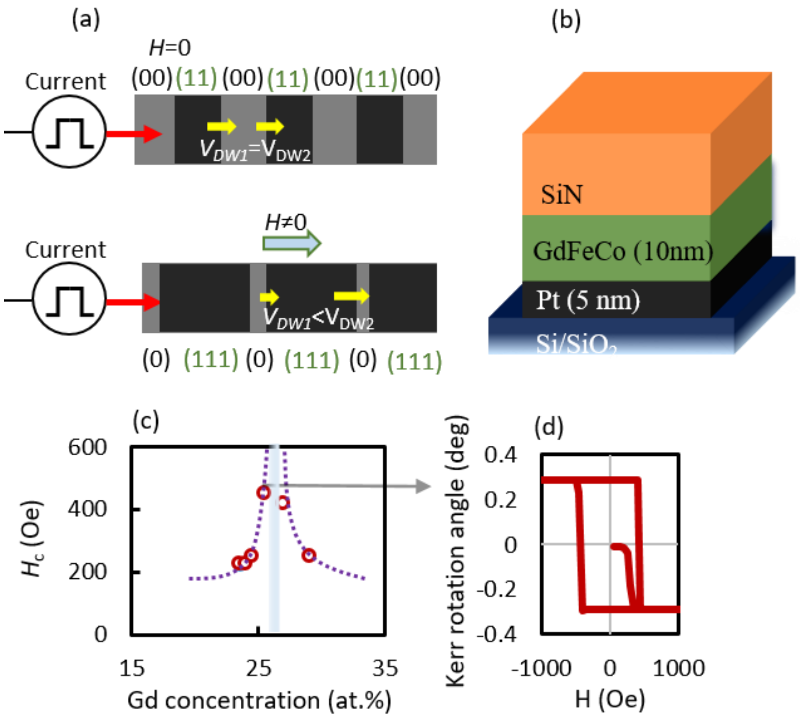


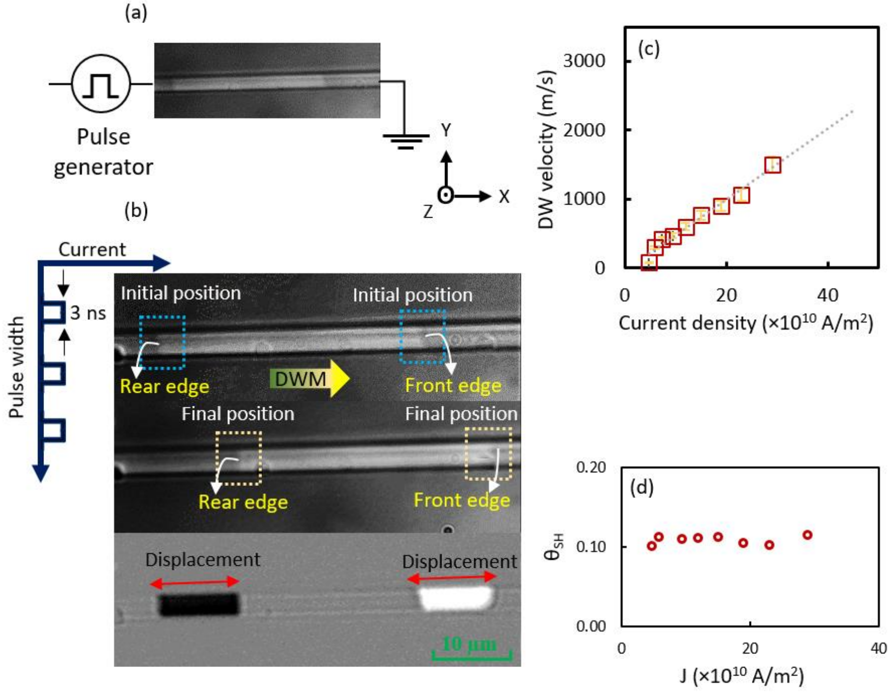
Ranjbar, S., et al. *APL Materials* 10.9 (2022).

Controlling the multi-bits DWs driven by the electric current at an ideal position

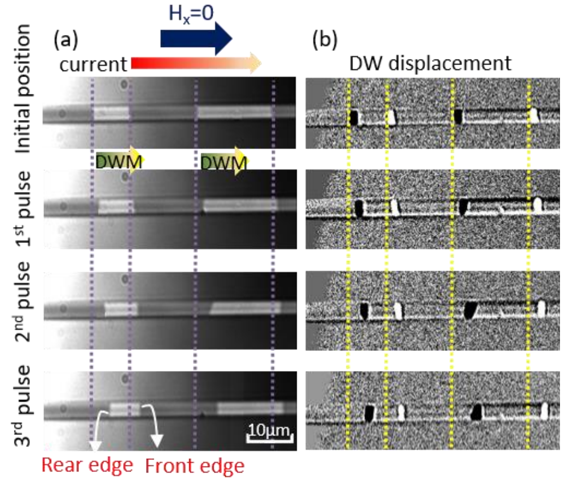


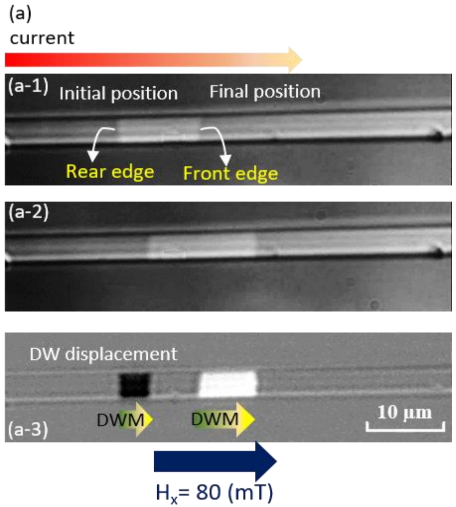
Experimental method and Electrical setup for the domain wall motion measurement.



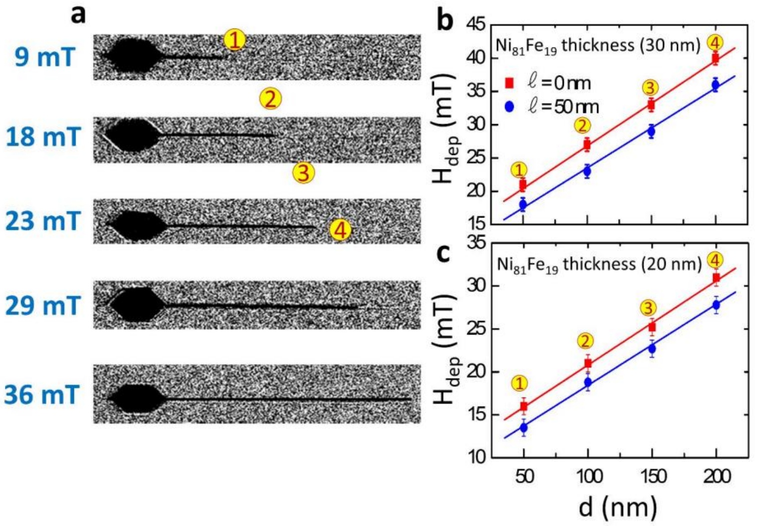


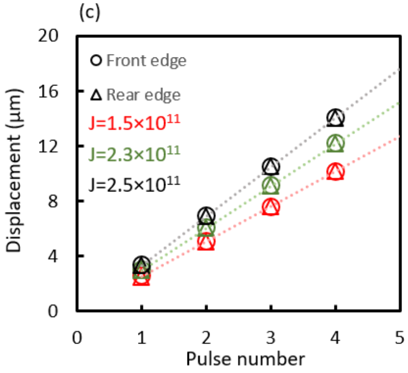
Results and discussion

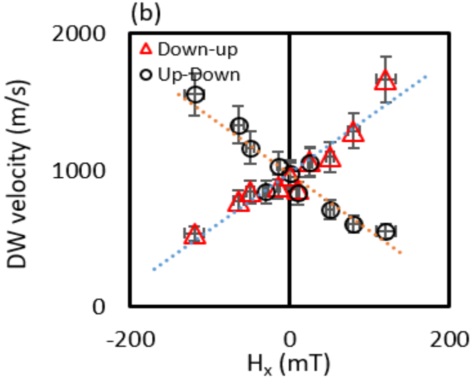




Al Bahri, et al. *Physical Review Applied* 11, no. 2 (2019).

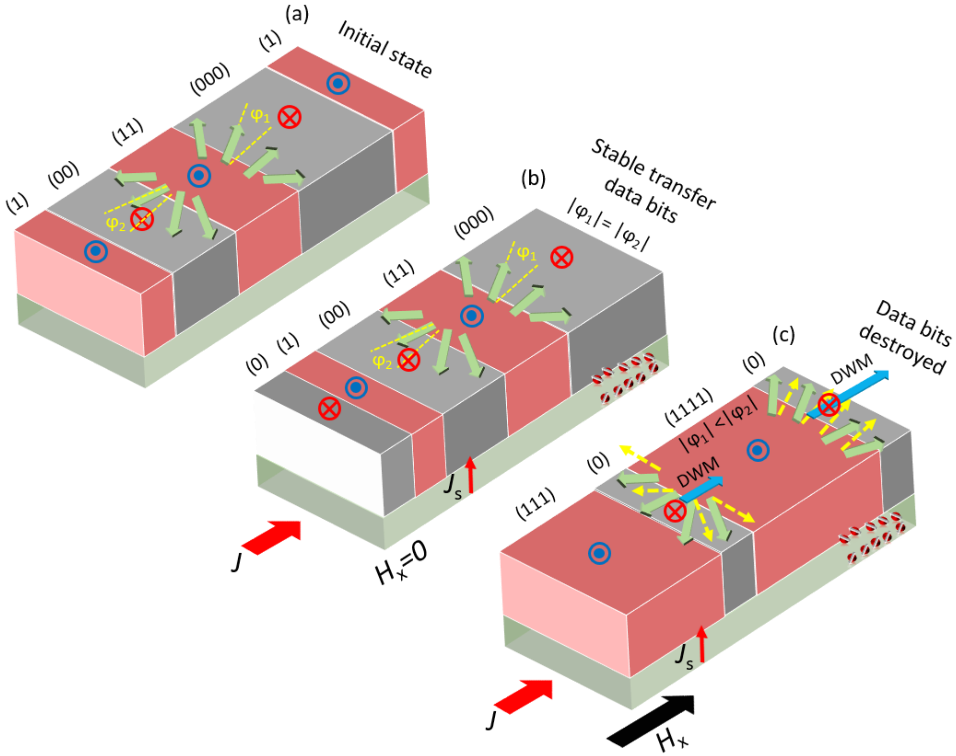






DW precisely controlled without notches.

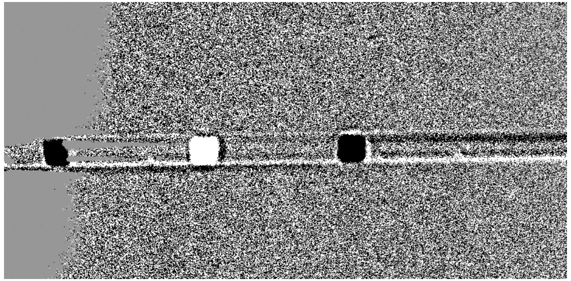
Results and discussion



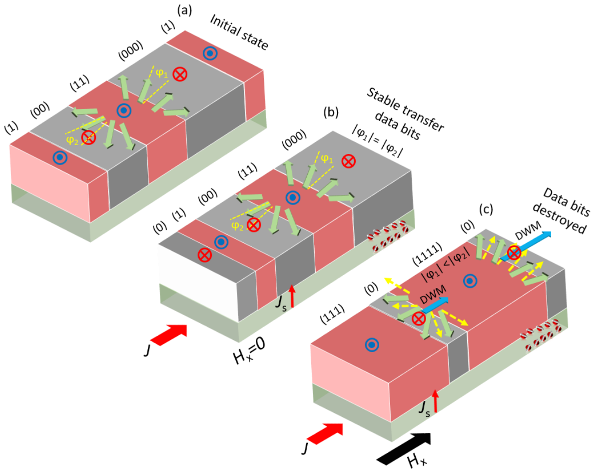
- $v \propto J \cos \phi$.
- ϕ is the angle of the internal DW magnetization.
- The Néel ($\phi = 0$) or Bloch ($\phi = \pi/2$) configuration, and the precession induced by SOT, which increases ϕ.
- By employing the GdFeCo without an external magnetic field, we can drive DWs with fast and stable motion.
- However, a further detailed examination of jitter, eye pattern, and the error rate are required to verify its practical application.

Summary

1. Here, we have demonstrated fast and controllable multi-bit domain wall motion without an external magnetic field in a Pt/GdFeCo nanowire system.



2. We have demonstrated that the external magnetic field rotated the angle of the internal DW magnetization closer (farther) to the Néel configuration for the front edge (rear edge) of DW.



Remain challenges and possible research using ferrimagnets

- Reducing the overall size of the nanowire devices
- The domains have to be as small as possible.
    - New materials Ferrimagnetic insulators
    - Synthetic ferrimagnets

REVIEW ARTICLE
https://doi.org/10.1038/s41563-021-01139-4
nature materials
Check for updates

Ferrimagnetic spintronics

Se Kwon Kim[1], Geoffrey S. D. Beach[2], Kyung-Jin Lee[1,3,4], Teruo Ono[5,6], Theo Rasing[7,8] and Hyunsoo Yang[9]

Table 1 | List of possible research directions using ferrimagnets

Research directions	Specific topics
New materials	Ferrimagnetic insulators Synthetic ferrimagnets Non-collinear ferrimagnets Ferrimagnets with strong spin–orbit coupling Ferrimagnets with ultrasmall damping Ferrimagnets with room-temperature compensation points
Fundamental studies	Dynamics of spin textures (DWs, skyrmions, vortices, Bloch points and stripes) faster than those in ferromagnets Spin waves with distinct handedness Interaction between spin textures and spin waves Interplay of charge, spin and heat in ferrimagnets Transport phenomena (spin torque, magnetoresistance and various Hall effects) Sperimagnetism
Practical applications	Ultrafast magneto-optical recording Soliton-based racetrack memory Wave-based computing with spin waves of distinct handedness Quantum information processing Neuromorphic computing

Acknowledgments

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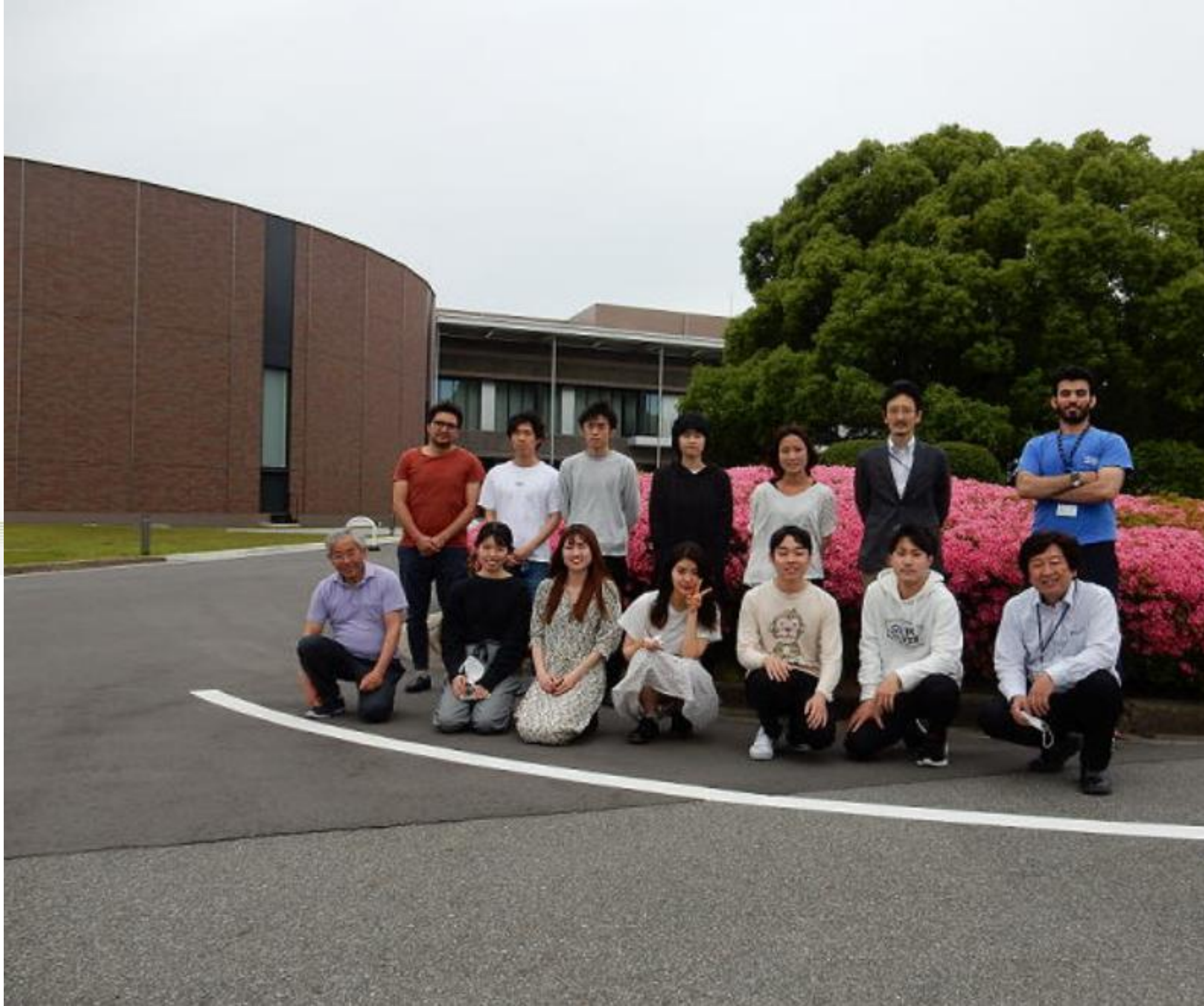
Grants-in-Aid for Scientific Research 科研費 <KAKENHI>



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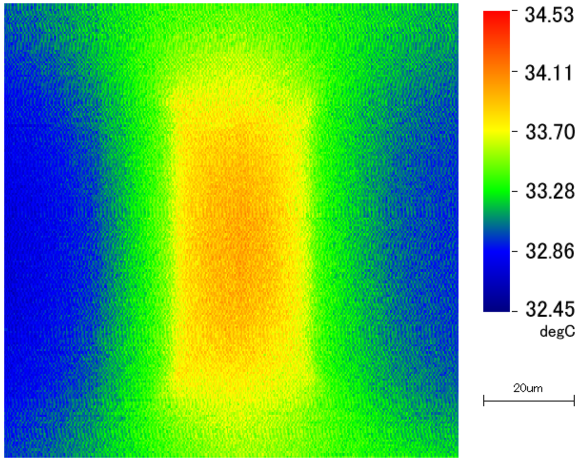
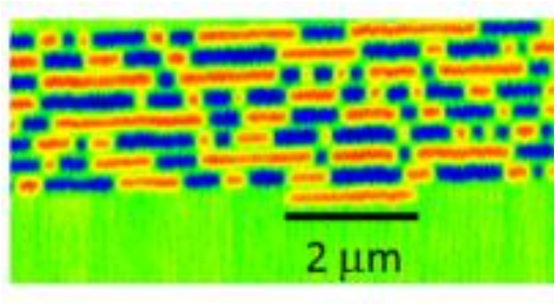
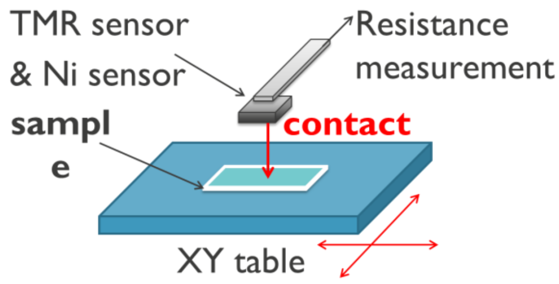
Nano MDS (Nano Magnetic Domain Scope)







Item	Property
TMR sensor	Size : 30 × 30 nm^2 Sensitivity : 0.02 mV/mT
Ni sensor	Size : 120 × 20 nm^2
Frequency band	~ 1 GHz (-6 dB)
XY table	Resolution : 1 × 5 nm^2

Memory development