International Research School and Workshop on Electronic States and Phases Induced by Electric or Optical Impacts
L'Institut d'Etudes Scientifiques de Cargèse, Corsica, France
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Superconducting diode effect

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References

J. Magn. Soc. Jpn. 43, 2 (2019)
Nature 584, 373 (2020)
Jpn. J. Appl. Phys. 60, 060902 (2021)
Appl. Phys. Express 14, 073003 (2021)
Appl. Phys. Express 15 113001 (2022)
Nat. Nanotechnol. 17, 823 (2022)
Adv. Mater., 2304083 (2023)

Collaborators

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Outline

(1) Introduction: what is the superconducting diode effect (SDE)?

(2) Motivation & Finding of SDE in Rashba superlattice

(3) Possible scenarios of SDE

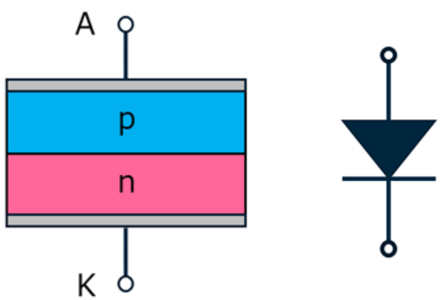
(4) Experimental results of SDE in Rashba superlattice

(5) SDE in superconductor/ferromagnet superlattice

(6) Summary

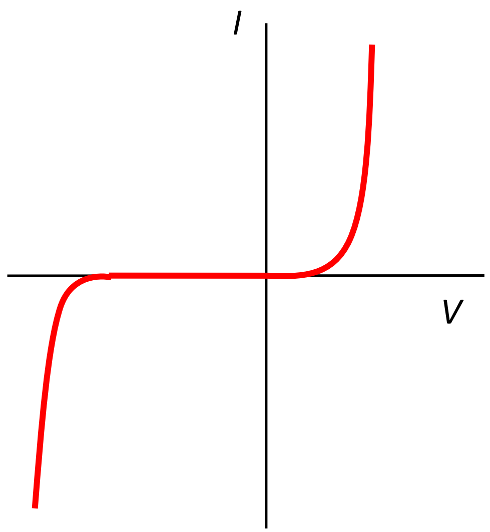
What is the superconducting diode effect?

Conventional diode



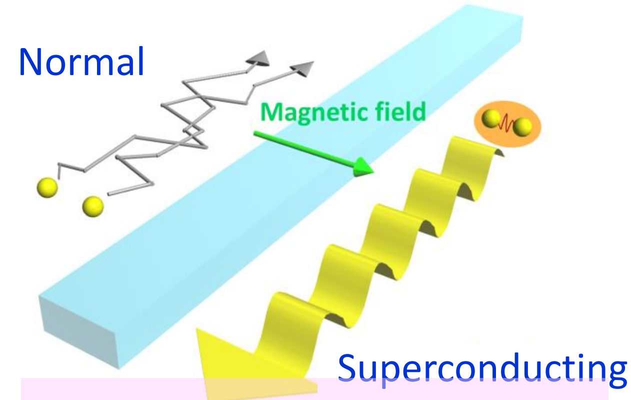
Low resistance (forward direction)
High resistance (reverse direction)

Structural asymmetry → diode

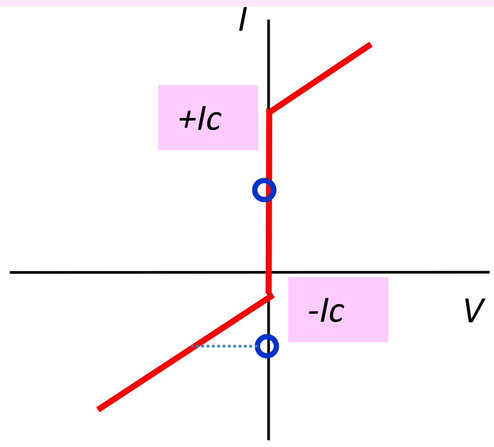


Joule heating

Superconducting diode



Is this possible?



Different I_c for forward and reverse directions

No Joule heating (forward)

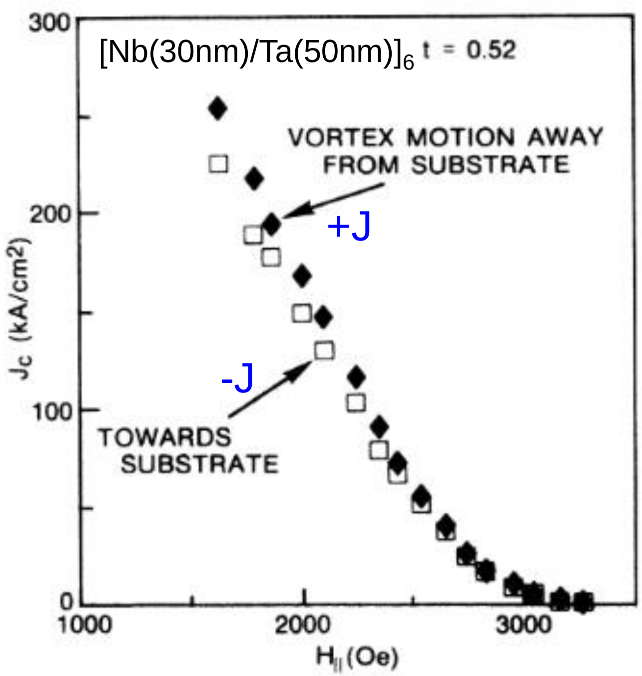
Possible mechanisms of superconducting diode effect

(1) Asymmetric vortex motion

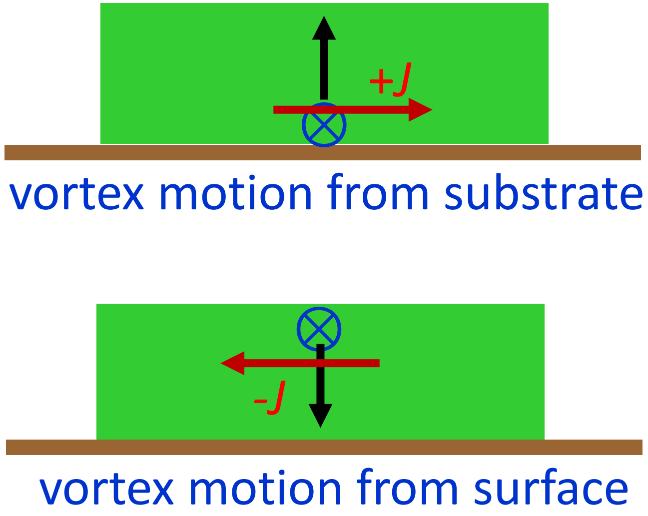
(2) Stray field from ferromagnet

Possible mechanism of superconducting diode effect (1) Asymmetric vortex motion

P. R. Broussard and T. H. Geballe, "Critical currents in sputtered Nb-Ta multilayers", Phys. Rev. B 37, 68 (1988).



Vortex motion breaks superconductivity.

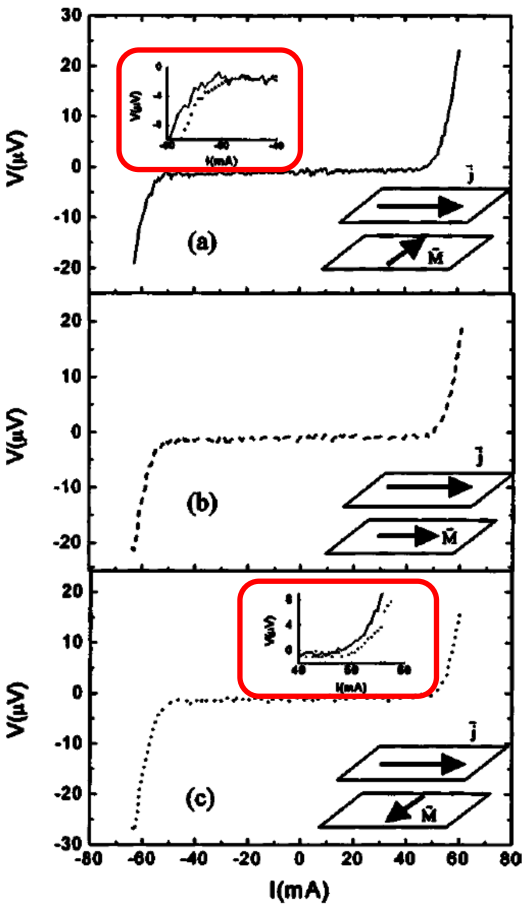


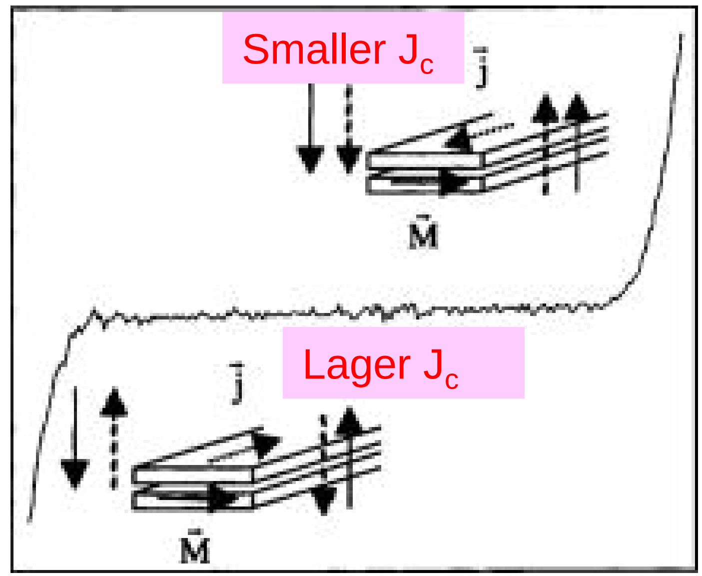
If vortex formation at the substrate surface is harder than on the surface side, superconducting diode effect can be obtained.

Possible mechanism of superconducting diode effect (2)
Stray field from ferromagnet

N. Touitou et al., “ Nonsymmetric current–voltage characteristics in ferromagnet/ superconductor thin film structures”, Appl. Phys. Lett. 85, 1742 (2004).

YBCO(40nm)/LSMO(100nm)





H from j is parallel to stray field from M : smaller J_c

H from j is anti-parallel to stray field from M : smaller J_c

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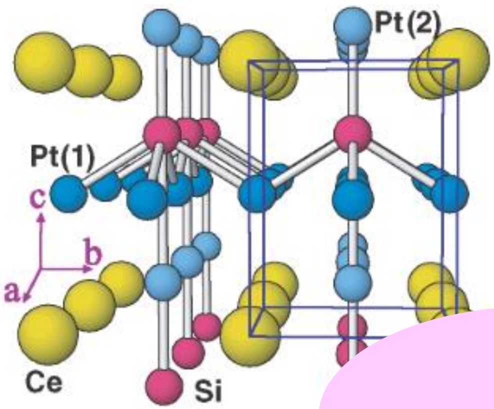
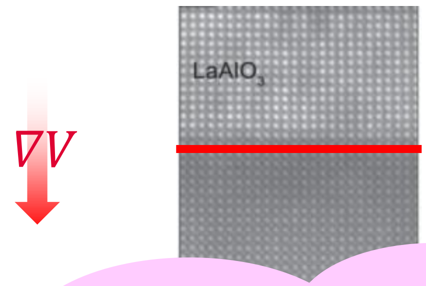
Superconductor without inversion symmetry

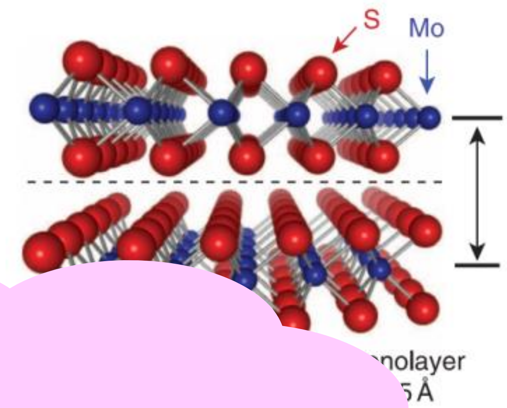
Bulk — Interface — 2D material



CeP

E. Bauer *et al*, *Phy*



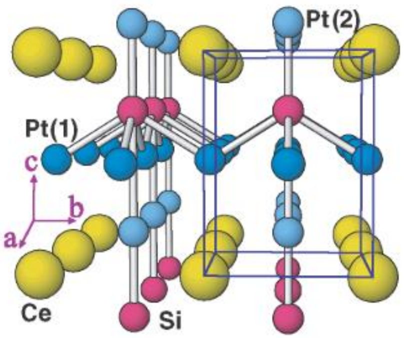


Superconductor without inversion symmetry is rare.

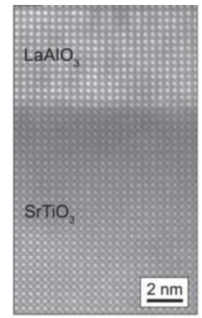
Unconvent nal superconductivity

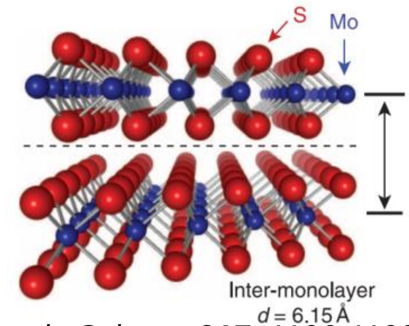
- Singlet-triplet pair mixing
- Spin current generation
- Magnet-chiral effect
- Topological superconductor
- FFLO state

Why not making artificial ABC superconductor?



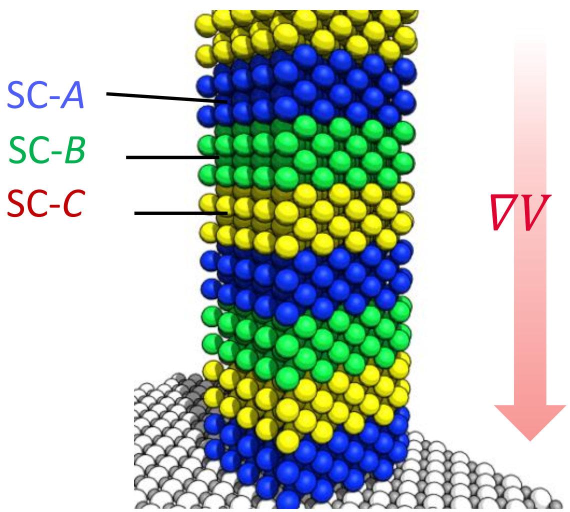
E. Bauer *et al*, *Phys. Rev. Lett*. **92**, 027003 (2004).





N. Reyren *et al.*, *Science* **317,** 1196-1199 (2007).
J. T. Ye *et al*, *Science* **338,,** 1193-1196 (2012).

ABC superlattice naturally breaks symmetry



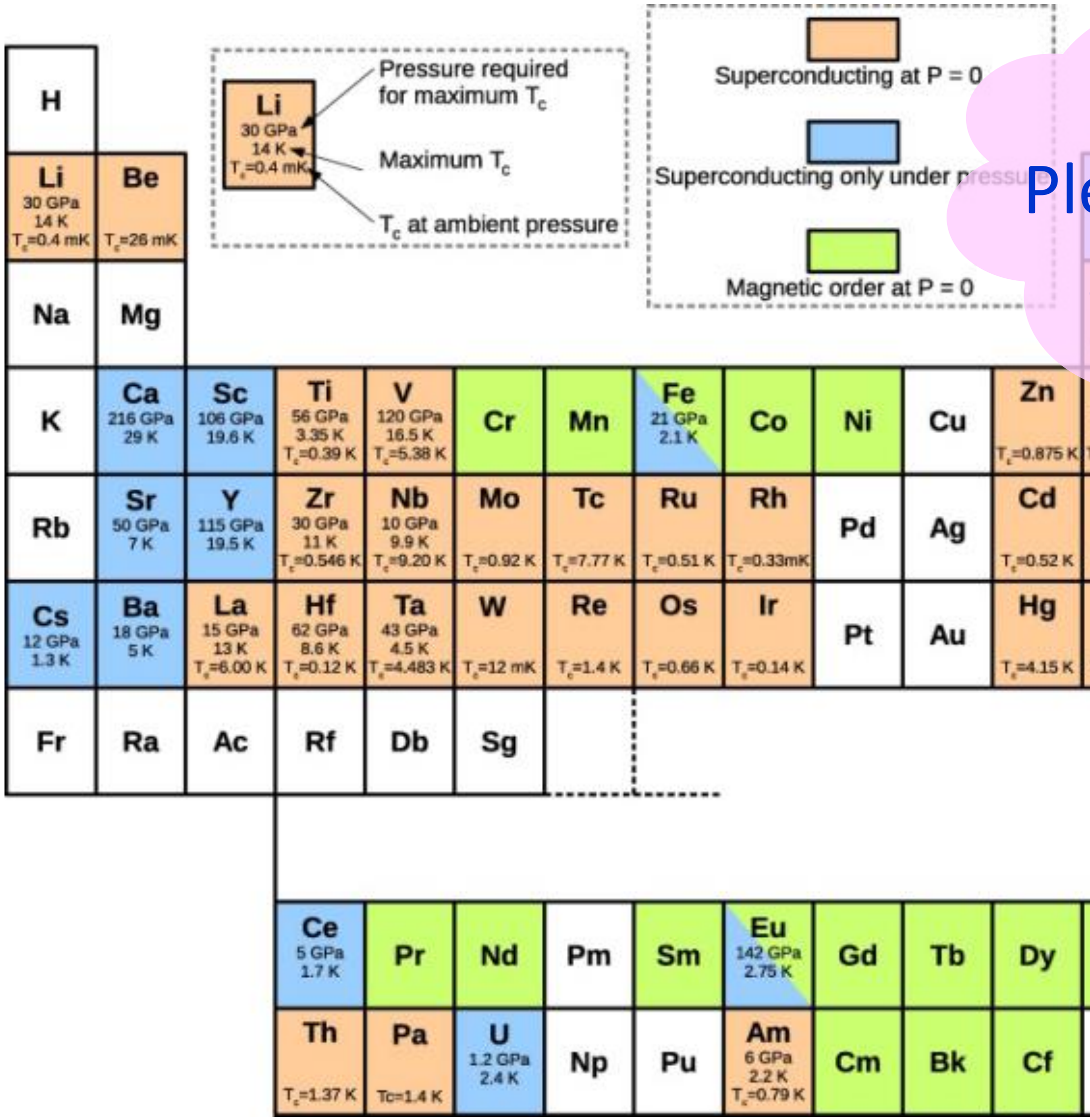
Furthermore,

- **Band structure engineering**
  by tuning elements, thickness, period

- **Hetero-structure, microfabricated device**
  →Josephson junction, Andreev reflection, spin-torque measurements

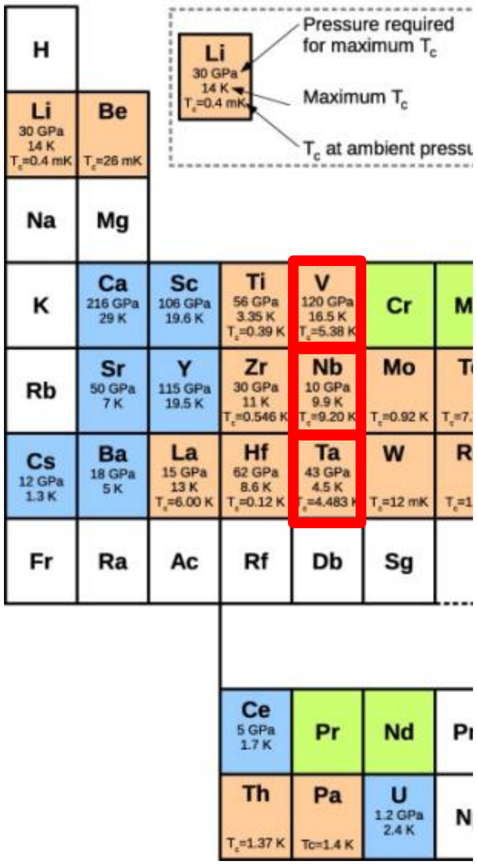
New platform for superconductivity study

Making ABC superconductor



Please choose 3 elements and make superlattice

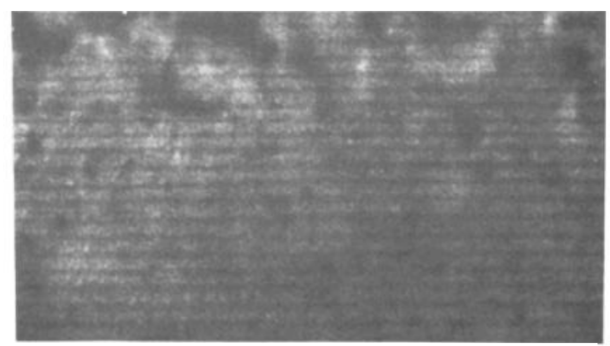
Making ABC Superconductor



Nb, V, Ta

1. Relatively high T_c
2. Reports on Nb/Ta superlattice

	Type	T_c (K)	H_c (Oe)	a (Å)	$\sqrt{2}\times$a (Å)
Nb (bcc)	II	9.50	1980	3.29	4.65
V (bcc)	II	5.38	1420	3.03	4.29
Ta (bcc)	I	4.48	830	3.30	4.67
MgO (fcc)				4.21	



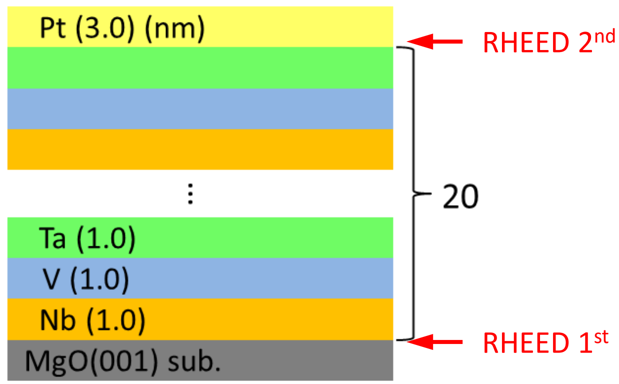
TEM image of Nb/Ta superlattice

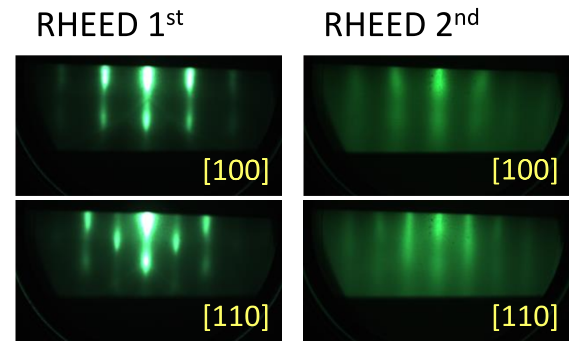
S. M. Durbin *et al.*, *J. Phys. F*, **11**, L223 (1981).

Structure characterization

Nb/V/Ta superlattice was epitaxially grown on MgO(001) substrate at 700 ℃ by sputtering.

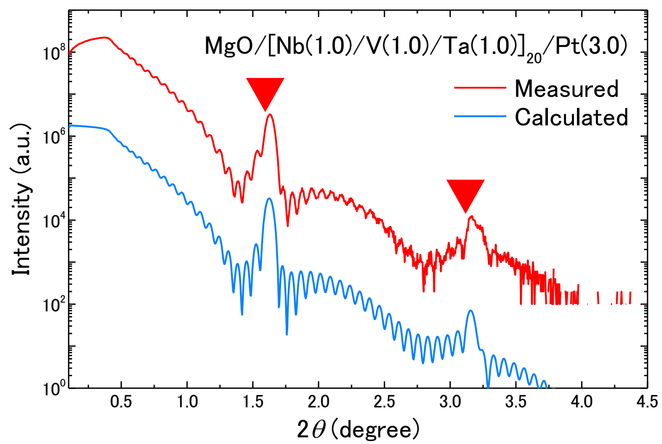
- RHEED observation



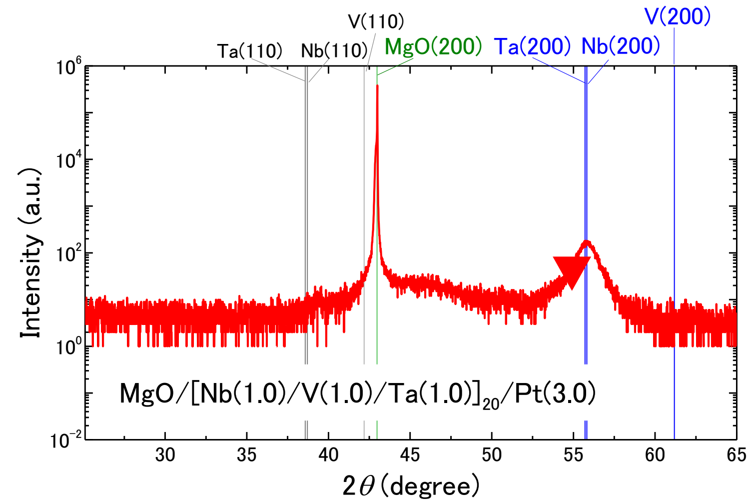


MgO[100] // Nb[110] // V[110] Ta[110]

- X-ray diffraction



Bragg peaks for superlattice period

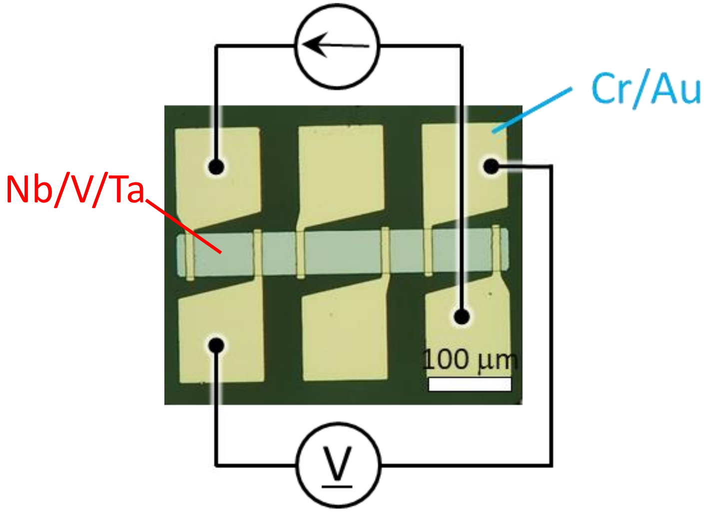


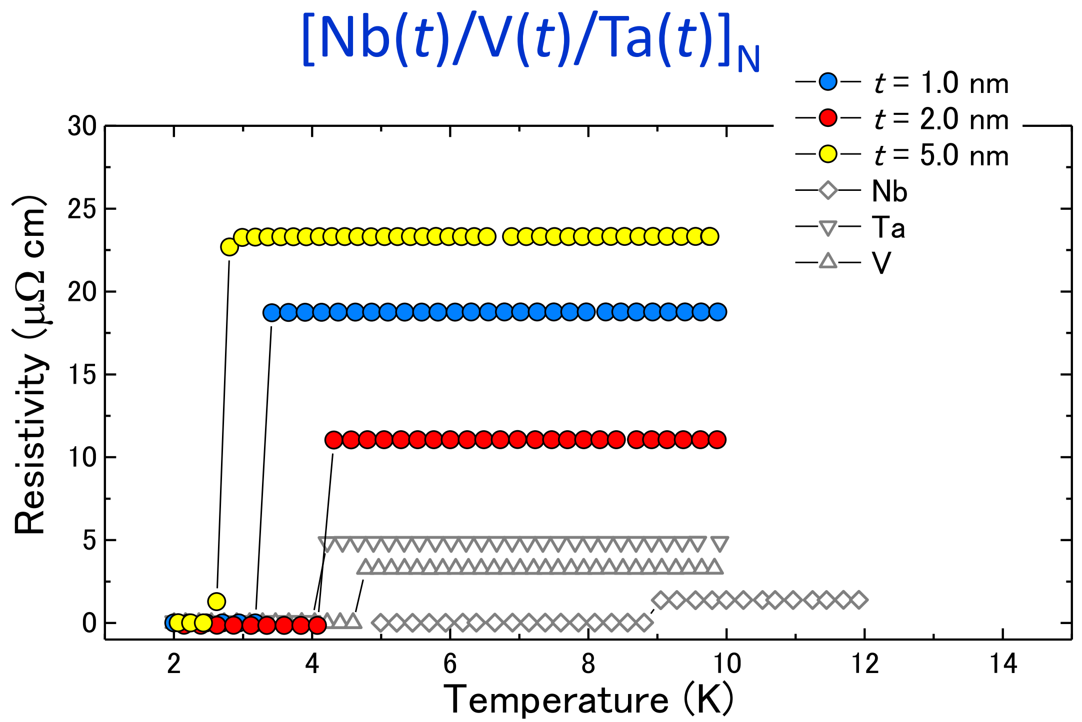
Growth along (001) direction

Superlattices are grown as designed.

F. Ando *et al*., J. Magn. Soc. Jpn. **43**, 2 (2019) .

Superconducting transition



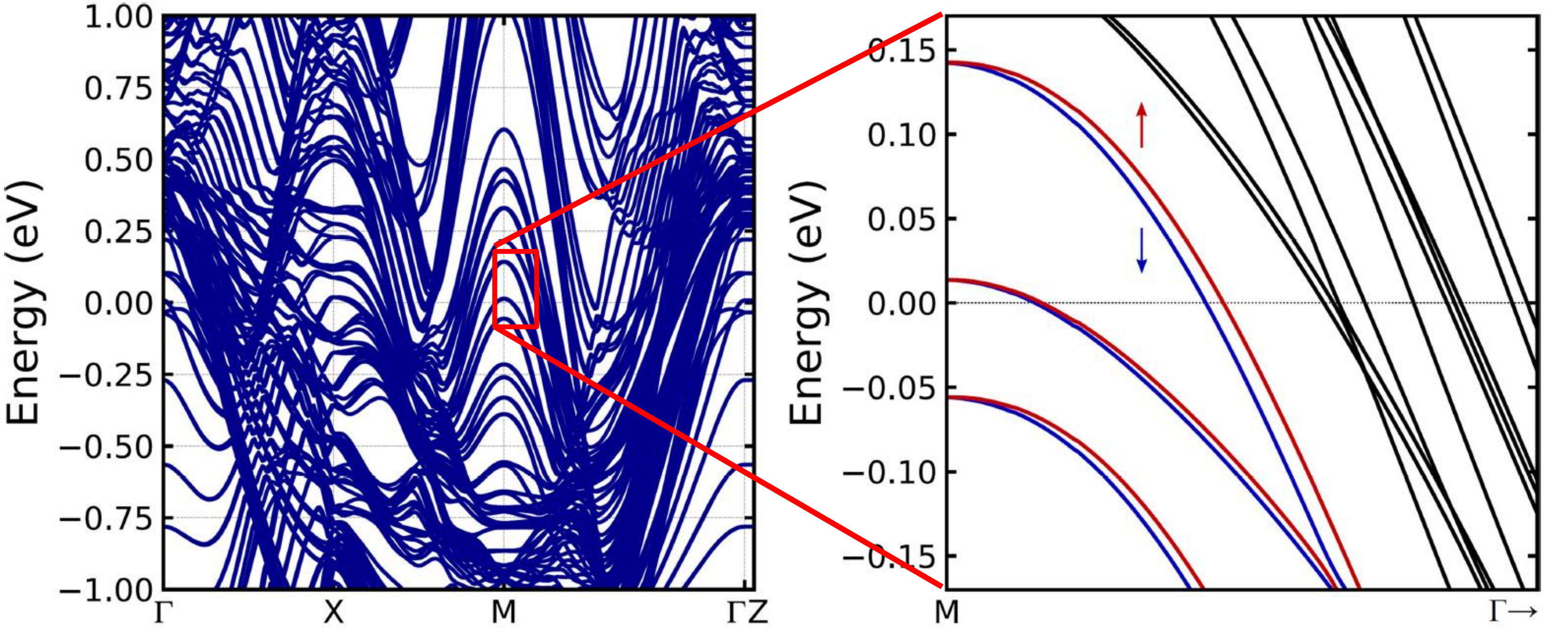


Nb/V/Ta superlattices show sharp superconducting transitions though Tc is a bit lower than in single element films.

F. Ando *et al*., J. Magn. Soc. Jpn. **43**, 2 (2019) .

Check band structure by first principle calculation

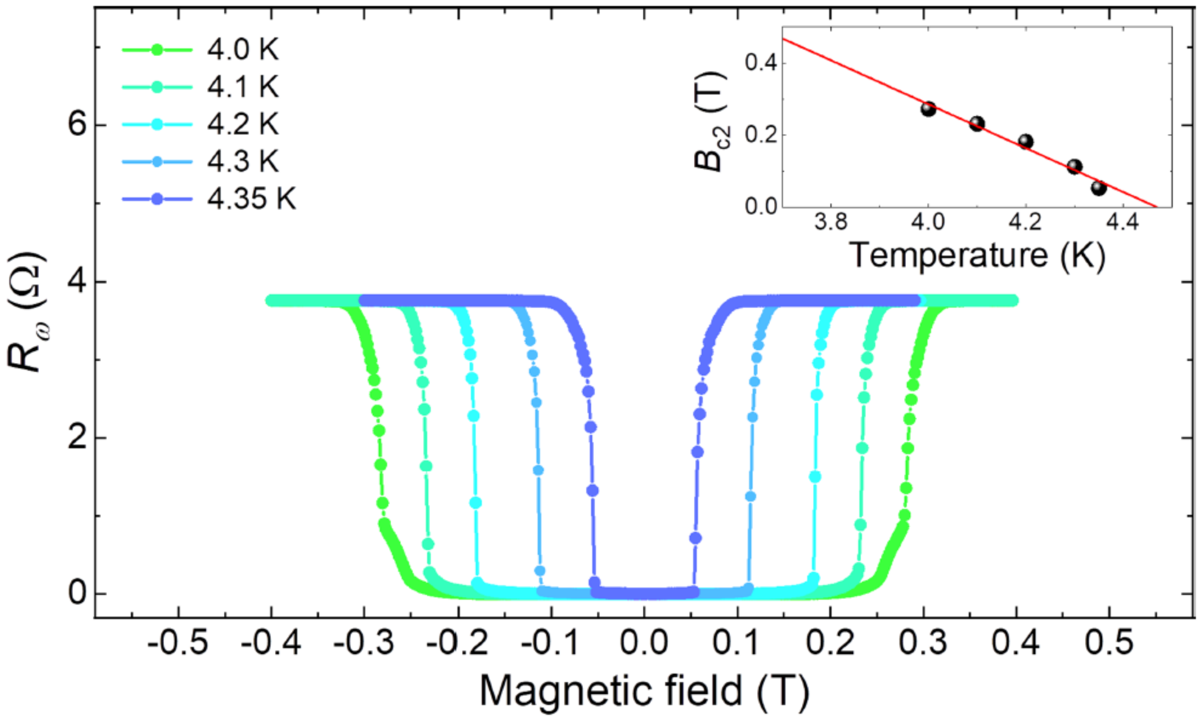
[Nb(2ML)/V(2ML)/Ta(2ML)]$_5$



Rashba spin splitting band at Fermi level.

Calculation by Prof. Ishizuka

Estimation of coherence length



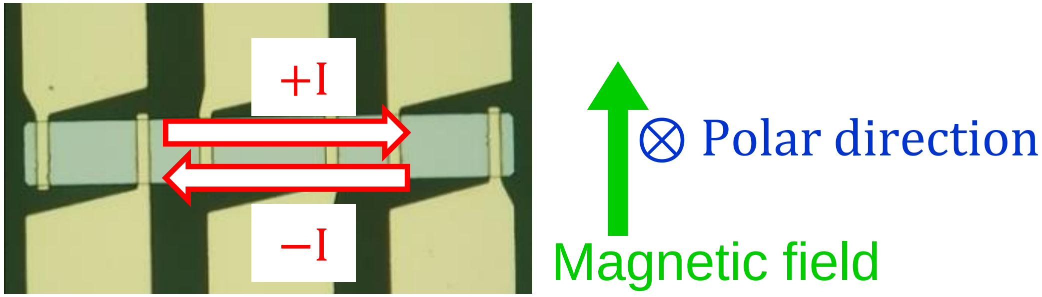
$$H_{c2\perp}^{\mathrm{orb}}(0) = -0.69T_c\left(\frac{dH_{c2\perp}}{dT}\right)_{T_c} = 1.9\ \mathrm{T}$$

ξ = 13 nm < film thickness (120nm)

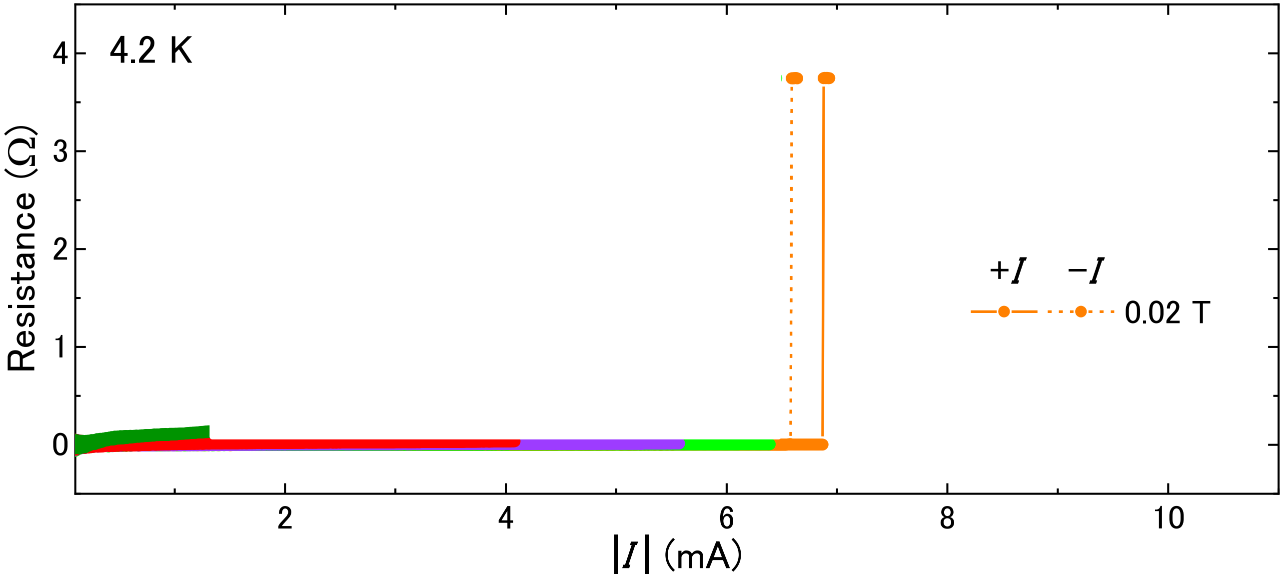
3D Rashba superconductor

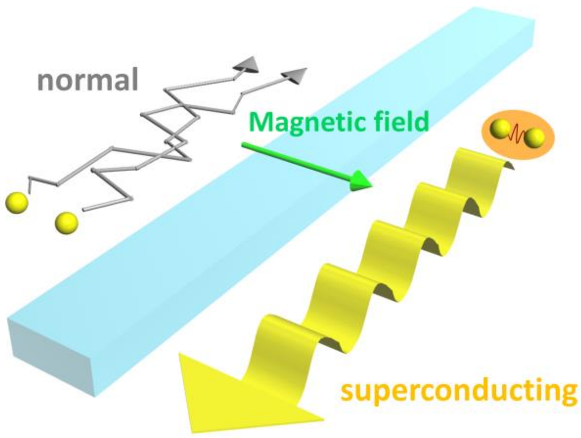
F. Ando et al., Jpn. J. Appl. Phys. 60, 060902 (2021)

Strange experimental results



[Nb(1nm)/V(1nm)/Ta(1nm)]$_{40}$





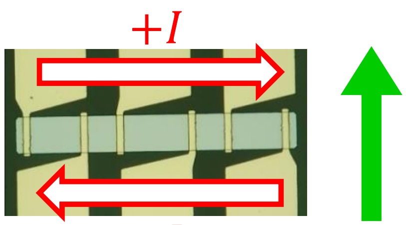
I_c depends on measuring current direction.

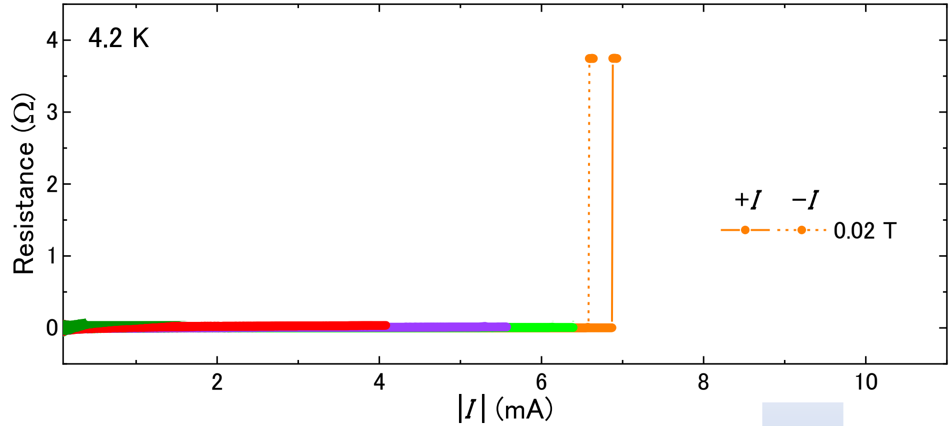
Superconductor in one direction, normal conductor in reversed direction!

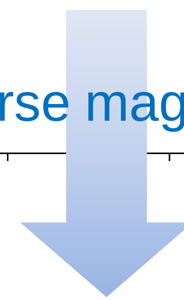
Superconducting diode!

Superconducting diode effect

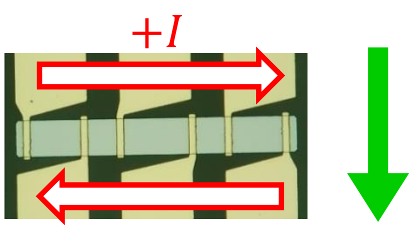
$[Nb(1nm)/V(1nm)/Ta(1nm)]_{40}$

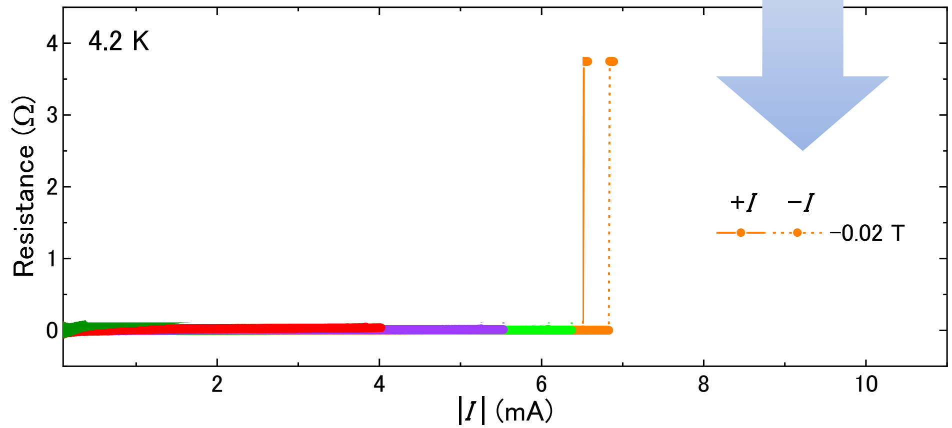






Reverse magnetic field





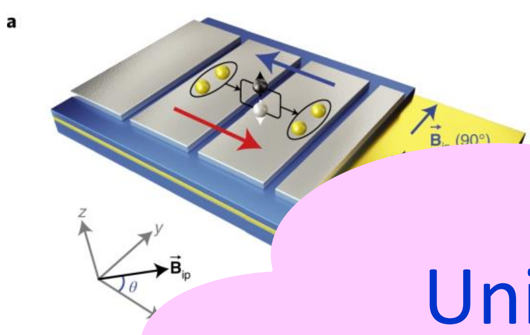
F. Ando et al., Nature 584, 373 (2020)

Polarity of superconducting diode can be switched by magnetic field.

Impossible with conventional diodes

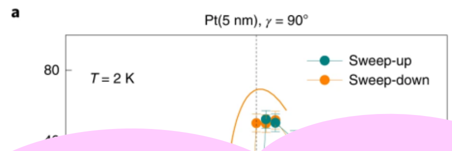
Boost of SDE research

SDE in Josephson junction

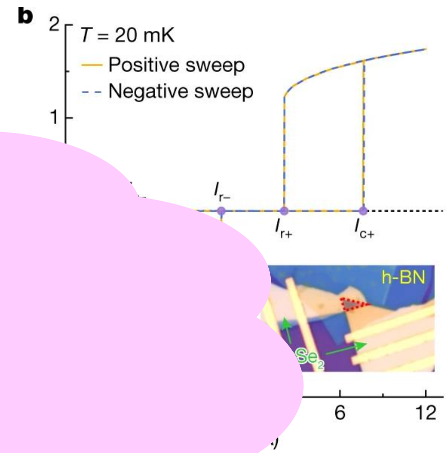


C. Baumga…
Nat. Nan…

Zero-field SDE in Josephson junction



Zero-field SDE in $NbSe_2$



…u et al., *Nature* **604**, 653 (2022)

Universal phenomena!

What is the mechanism?

- SDE by vortex motion
- SDE by stray field

Mechanism based on electronic band structure

(1) SDE in Josephson junction

(2) SDE in superconductor

J.J. Lin et al., *Nat. Phys.* **18**, 1221 (2022)

M. Trahms et al., *Nature* **615**, 628 (2023)

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(6) Summary

SDE in Josephson junction

Theoretical works

E.V. Bezuglyi et al., “Combined effect of Zeeman splitting and spin-orbit interaction on the Josephson current in a superconductor-two-dimensional electron gas-superconductor structure” Phys. Rev. B 66, 052508 (2002).

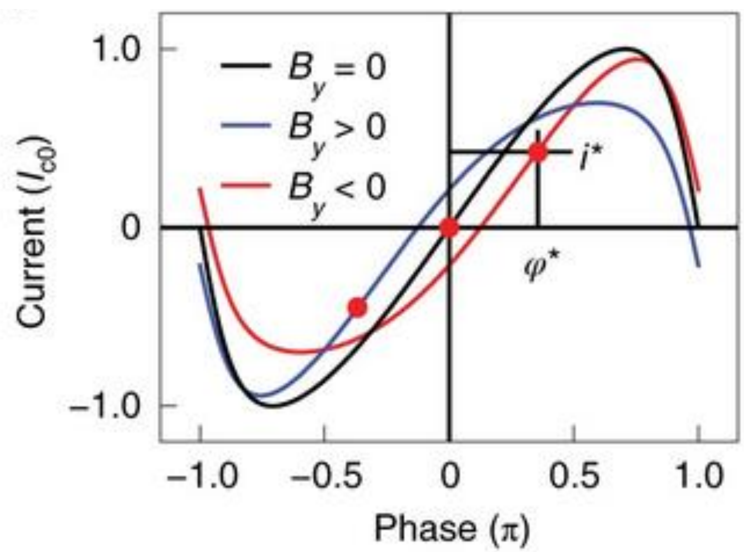
A. Buzdin, “Direct coupling between magnetism and superconducting current in the Josephson φ_0 junction”, Phys. Rev. Lett. 101, 107005 (2008).

Experimental works

C. Baumgartner et al. “Supercurrent rectification and magnetochiral effects in symmetric Josephson junctions”, Nat. Nanotechnol. 17, 39 (2022).

K-R. Jeon et al. “Zero-field polarity-reversal Josephson supercurrent diodes enabled by a proximity-magnetized Pt barrier”, Nat. Matter. 21, 1008 (2022).

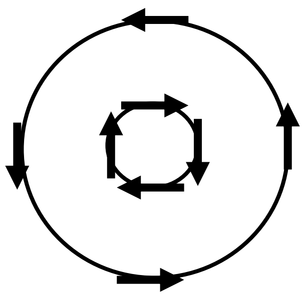
Distortion of current-phase relation



Nat. Nanotechnol. 17, 39 (2022)

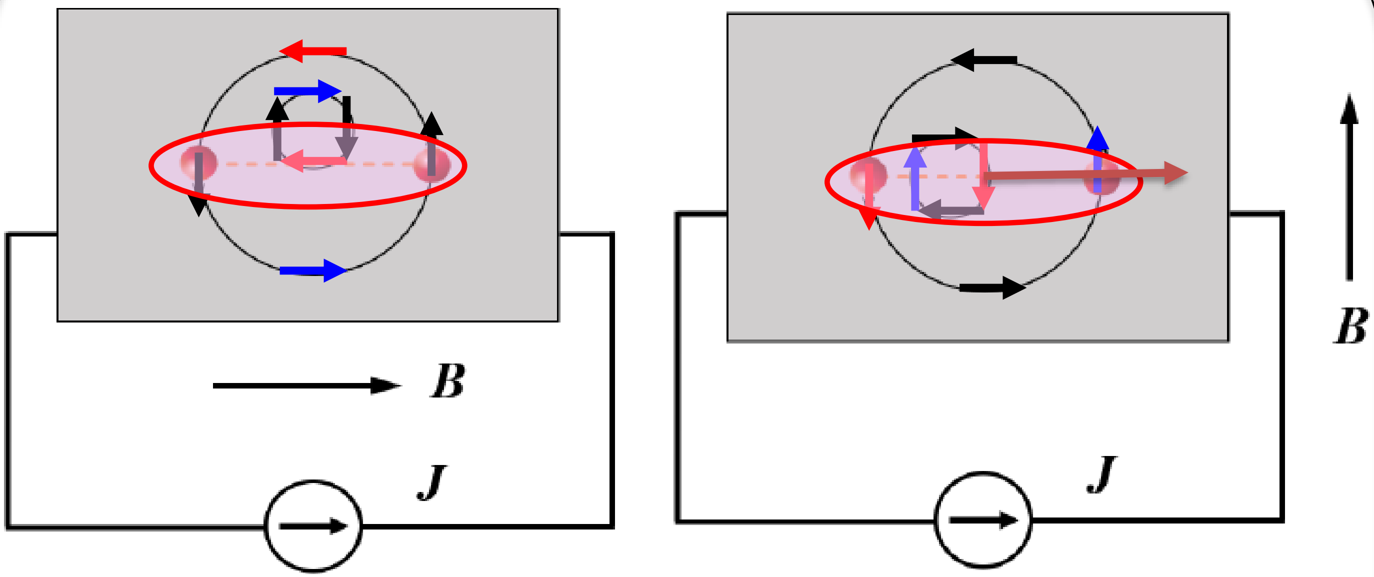
Possible scenario for bulk superconducting diode
- Rashba-split bands + Zeeman shift -

Rashba-split bands



Two bands with opposite spin-momentum locking

Zeeman shift of Rashba-split bands



Cooper-pair with zero momentum

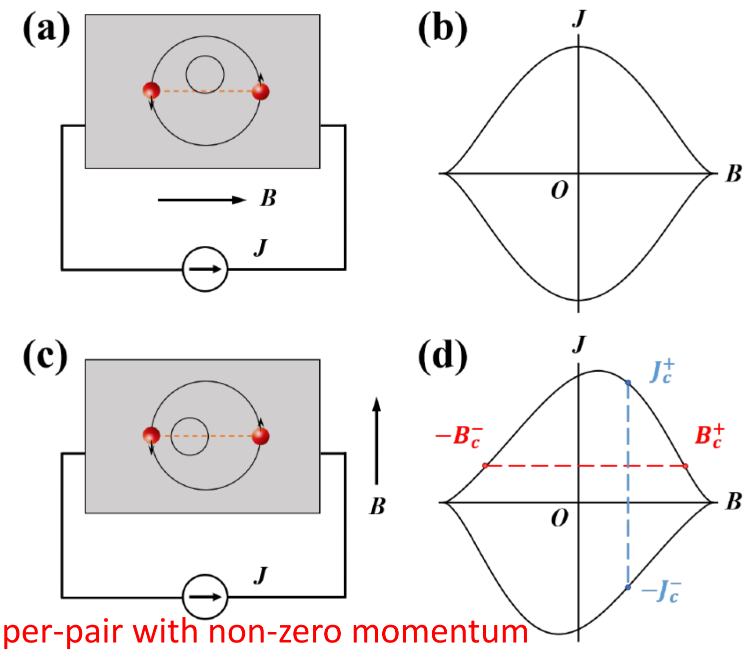
Cooper-pair with finite momentum

Different critical currents for q parallel to I, q antiparallel to I

N.F. Yuan, L. Fu, PNAS 119, e2119548119 (2022) .
A. Daido, Y. Ikeda, Y. Yanase, Phys. Rev. Lett. 128, 037001 (2022).
J. J. He, Y. Tanaka, N. Nagaosa, New J. Phys. 24, 053014 (2022).

Possible scenario for intrinsic superconducting diode

Zeeman shift + Rashba-split bands



Cooper-pair with non-zero momentum

FIG. 1: Supercurrent diode effect in a Rashba superconductor under in-plane magnetic field B and external current source J. Panels (a,c) are device plots with circles denoting normal state Fermi surfaces, and (b,d) denote schematic phase diagram in B-J plane. When $\boldsymbol{B} \parallel \boldsymbol{J}$ in (a), the phase diagram in (b) is symmetric with respect to both B and J axes. And when $\boldsymbol{B} \perp \boldsymbol{J}$ in (c), the phase diagram in (d) is skewed, indicating nonreciprocal critical current $J_c^+ \neq J_c^-$ and polarity-dependent critical field $B_c^+ \neq B_c^-$.

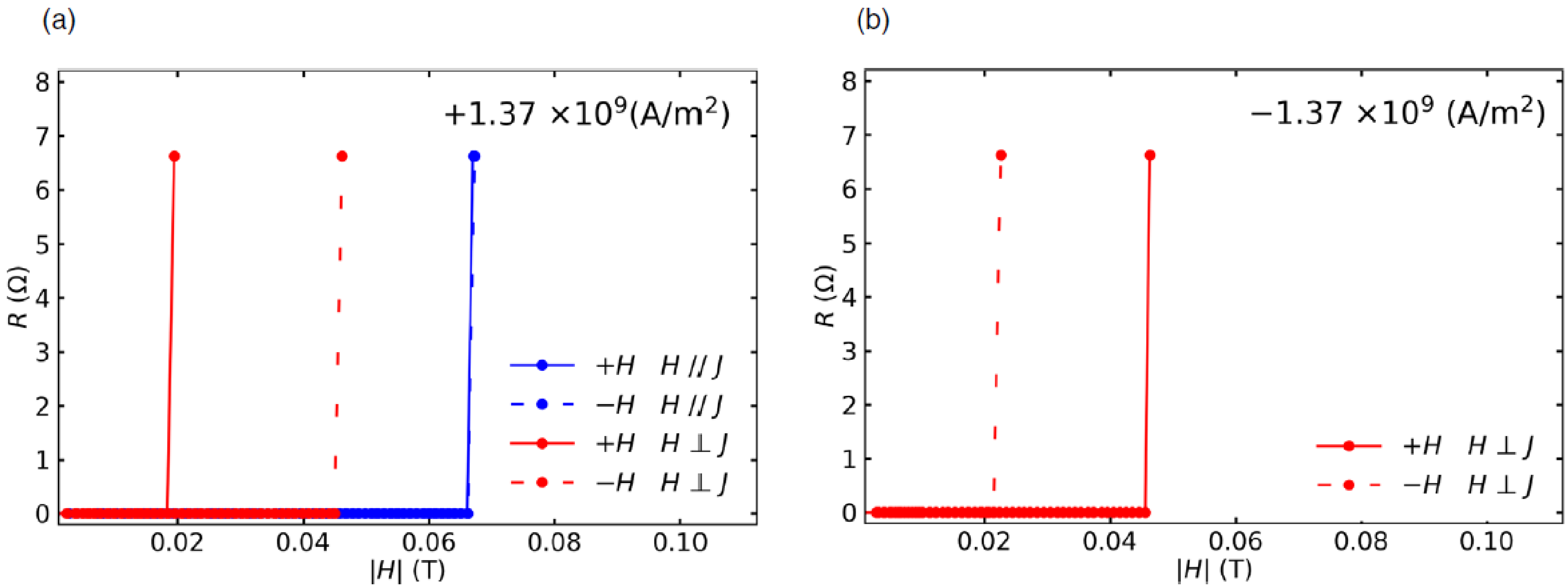
N.F. Yuan, L. Fu, PNAS 119, e2119548119 (2022) .

A. Daido, Y. Ikeda, Y. Yanase, Phys. Rev. Lett. 128, 037001 (2022).

J. J. He, Y. Tanaka, N. Nagaosa, New J. Phys. 24, 053014 (2022).

- Superconducting diode effect:
  Nonreciprocal superconducting critical current under B.
- Nonreciprocal superconducting critical field under I?

Observation of nonreciprocal superconducting critical field



Y. Miyasaka et al., Applied Physics Express 14, 073003 (2021).

We observed

✓ Nonreciprocal superconducting critical current under B (Superconducting diode effect)

✓ Nonreciprocal superconducting critical field under I

Ryo Kawarazaki

Yuta Miyasaka

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SDE in zero-field?

Preferable for application

Hideki Narita

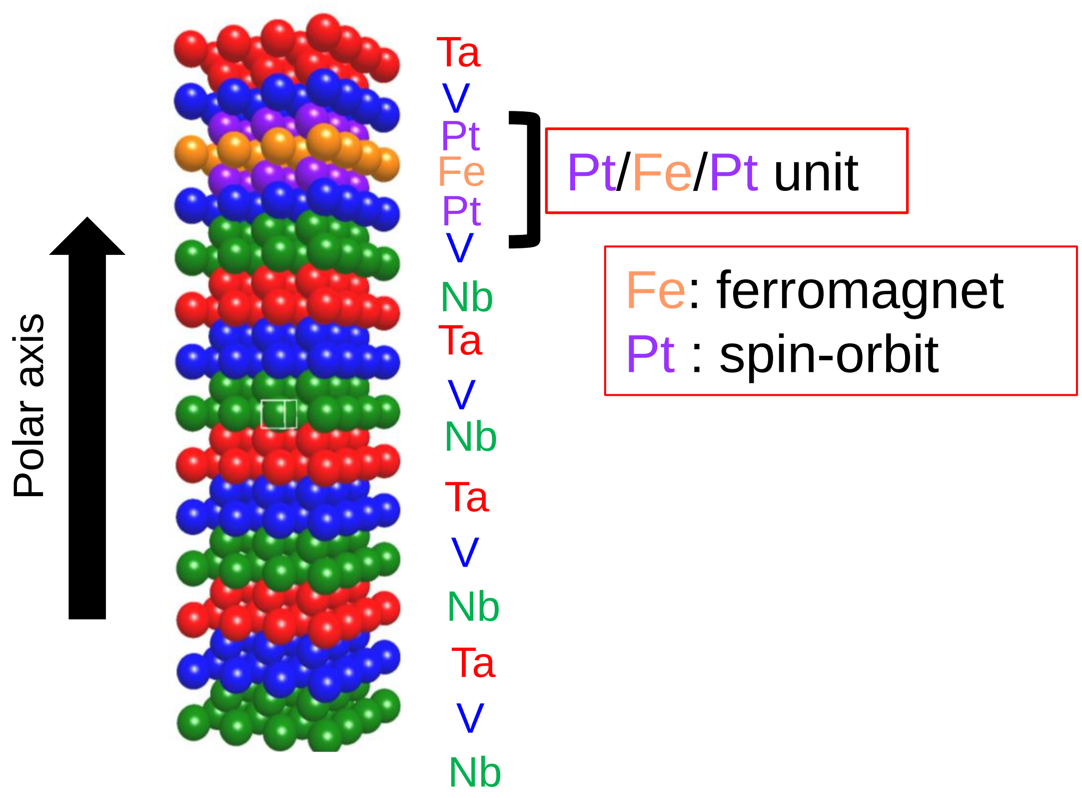
Nat. Nanotechnol. 17, 823 (2022)

Adv. Mater., 2304083 (2023)

Toward SDE in zero-field

Magnetic field → time reversal symmetry breaking → SDE

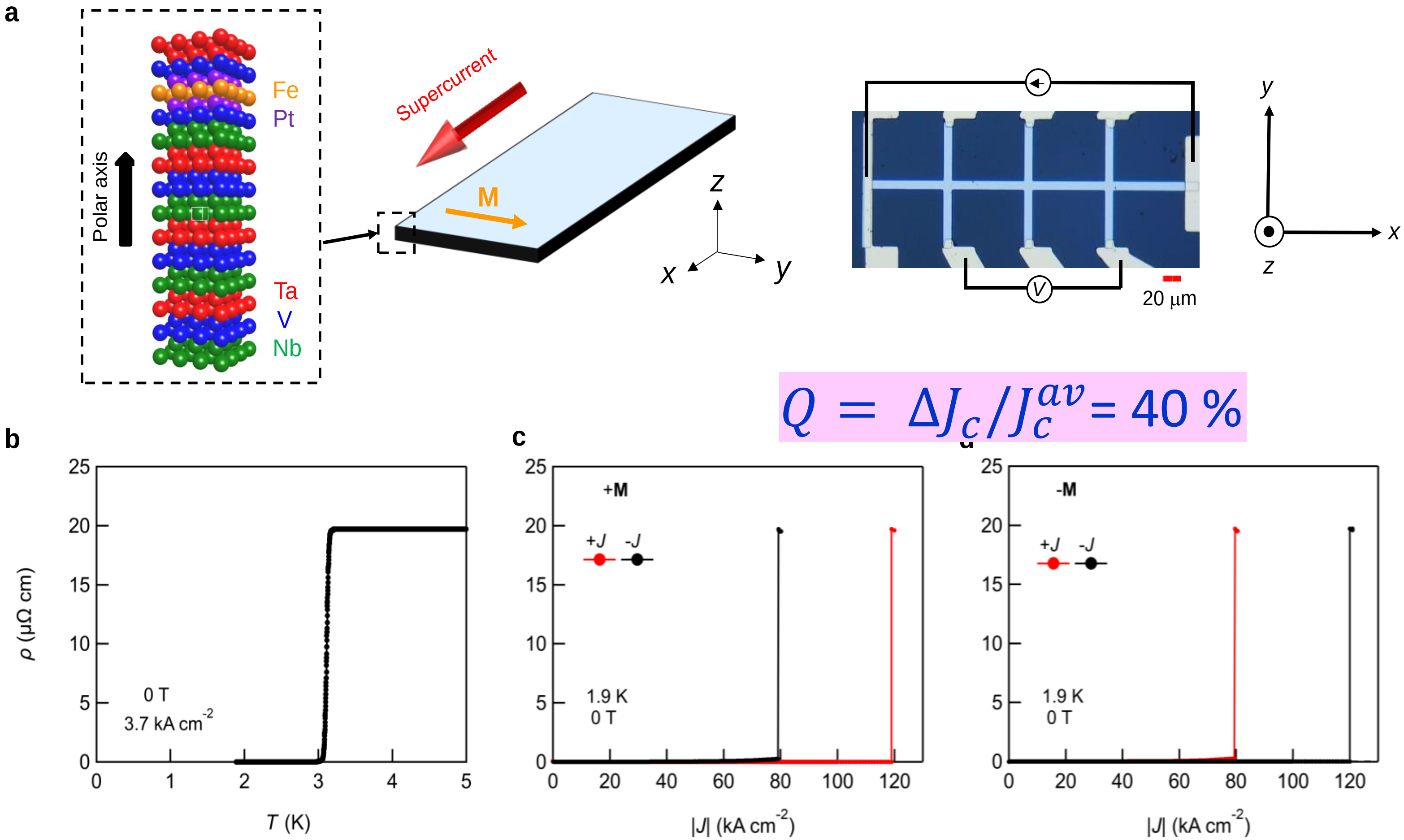
Using ferromagnet to break time reversal symmetry!



SDE in [Nb/V/Pt/Fe/Pt/V/Ta] superlattice

By tuning Pt and Fe thicknesses, we can tune
the Rashba field strength and the exchange field strength on Cooper pairs.

[[Nb(1.8 nm)/V(1.8 nm)/Ta(1.8 nm)]$_3$/Nb(1.8 nm/V(0.9 nm)/Pt(0.9 nm)/Fe(1.0 nm)/Pt(0.9 nm)/V(0.9 nm)/Ta(1.8 nm)]]$_{10}$



$Q = \Delta J_c / J_c^{av} = 40\ \%$

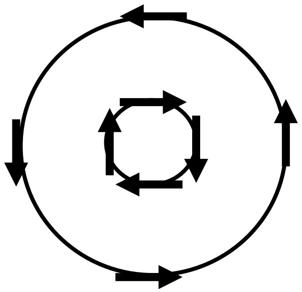
Large zero-field SDE

Adv. Mater., 2304083 (2023)

Mechanisms:
Intrinsic or Extrinsic?

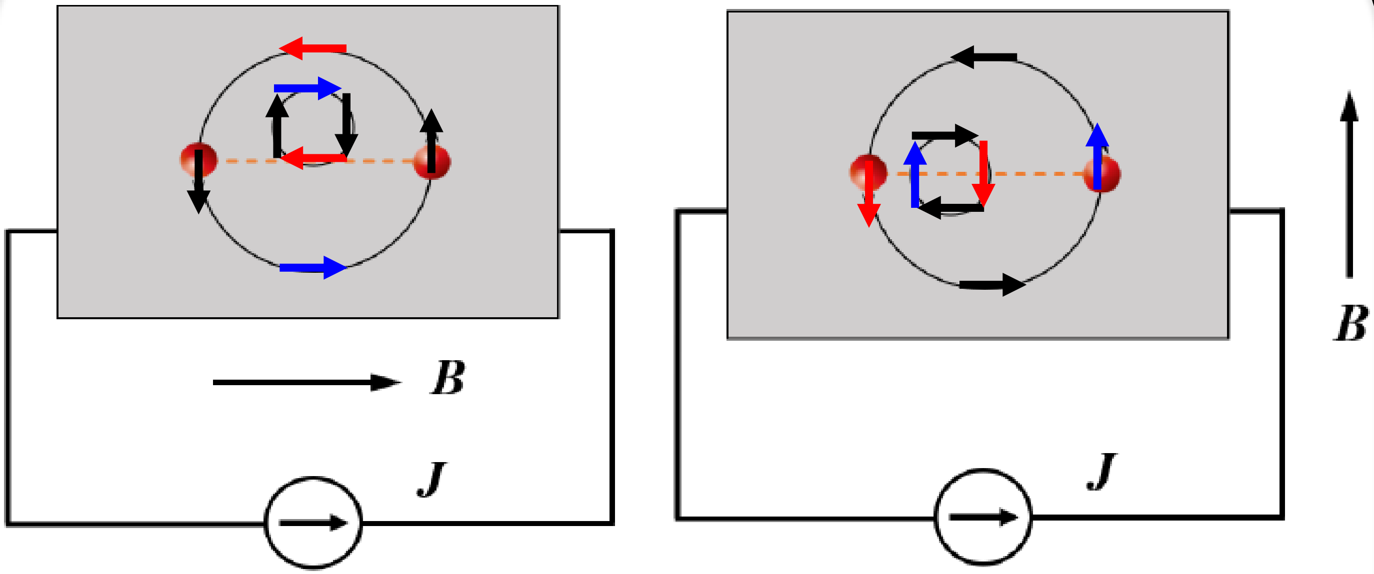
Intrinsic mechanism: based on electronic band structure
Rashba-split bands + Zeeman shift

Rashba-split bands



Two bands with opposite spin-momentum locking

Zeeman shift + Rashba-split bands



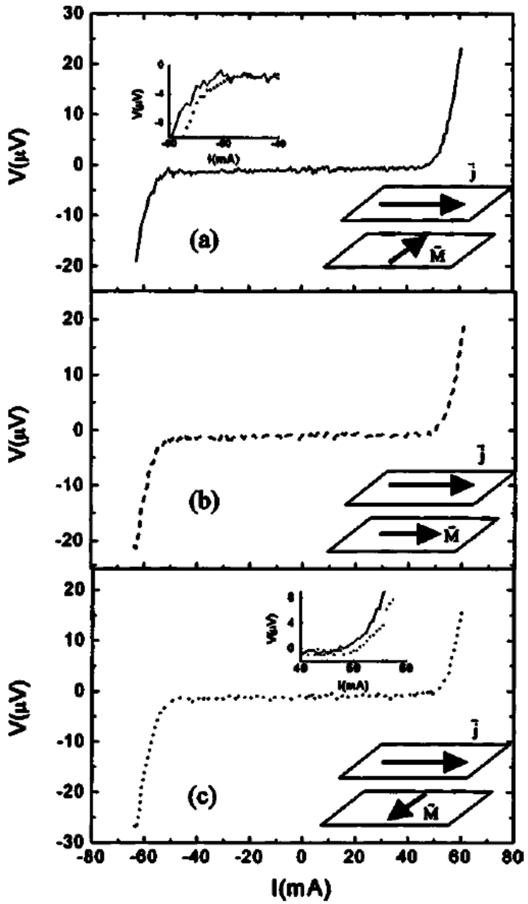
Cooper-pair with finite momentum

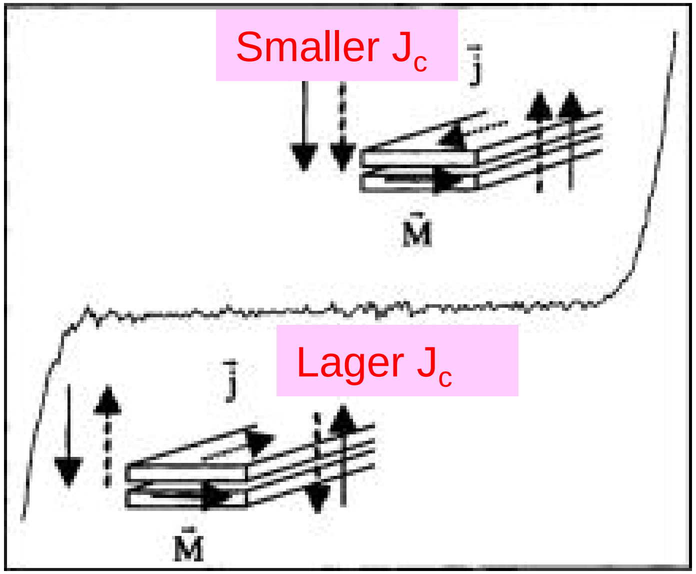
Superconducting diode effect is a manifestation of helical superconductors.
Cooper-pair with finite momentum

N.F. Yuan, L. Fu, PNAS 119, e2119548119 (2022) .
A. Daido, Y. Ikeda, Y. Yanase, Phys. Rev. Lett. 128, 037001 (2022).
J. J. He, Y. Tanaka, N. Nagaosa, New J. Phys. 24, 053014 (2022).

Extrinsic mechanism : Ferro/Super system

N. Touitou et al., " Nonsymmetric current–voltage characteristics in ferromagnet/ superconductor thin film structures", Appl. Phys. Lett. 85, 1742 (2004).





H from j is parallel to stray field from M : smaller J_c

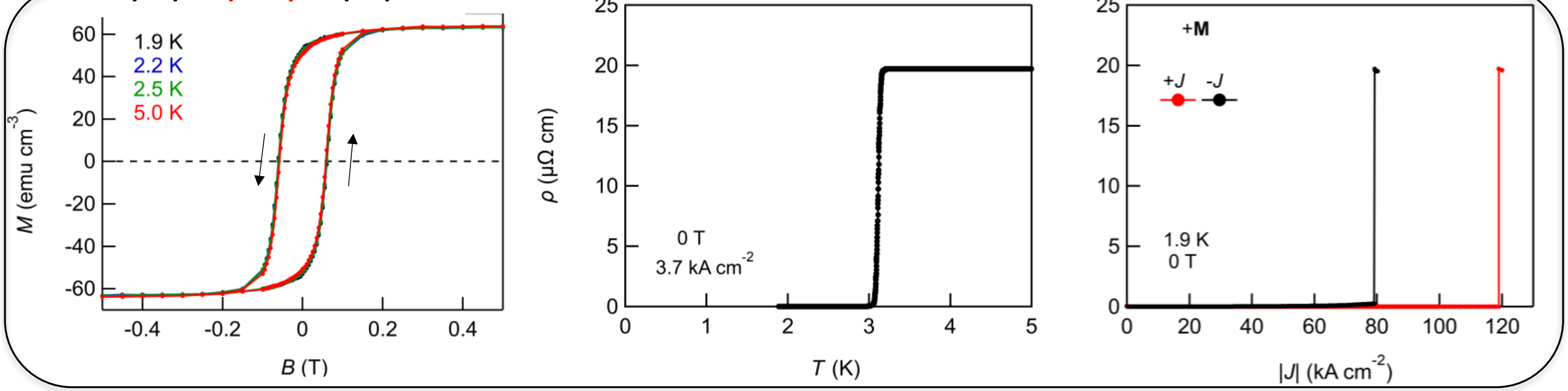
H from j is anti-parallel to stray field from M : smaller J_c

Magnitude of SDE depends on the stray field.

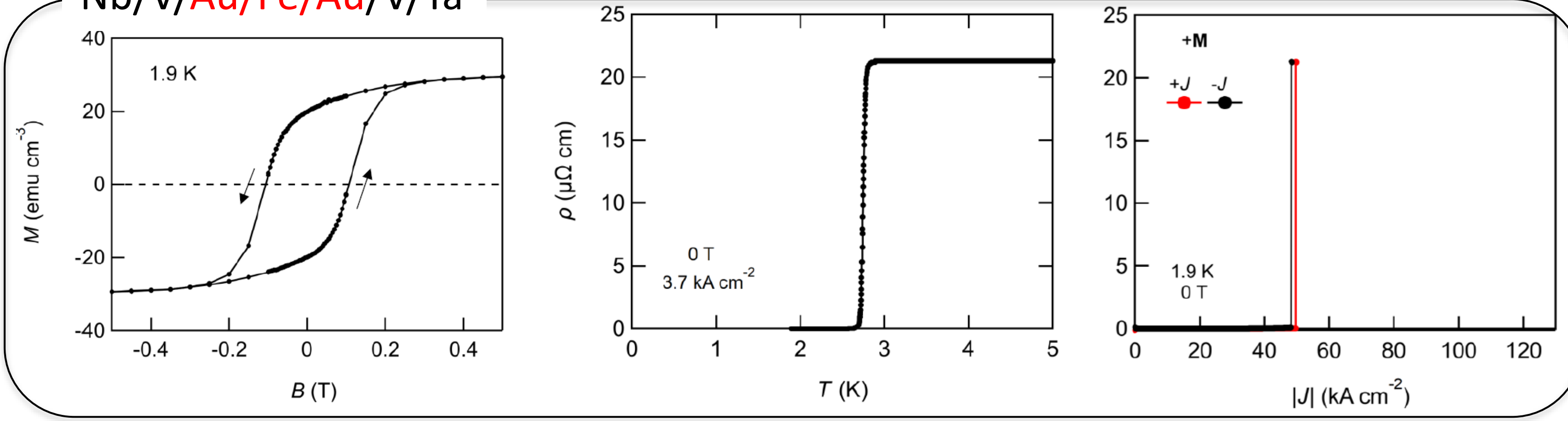
Comparison: [Nb/V/Pt/Fe/Pt/V/Ta] v.s. [Nb/V/Au/Fe/Au/V/Ta]

Adv. Mater., 2304083 (2023)

Nb/V/Pt/Fe/Pt/V/Ta



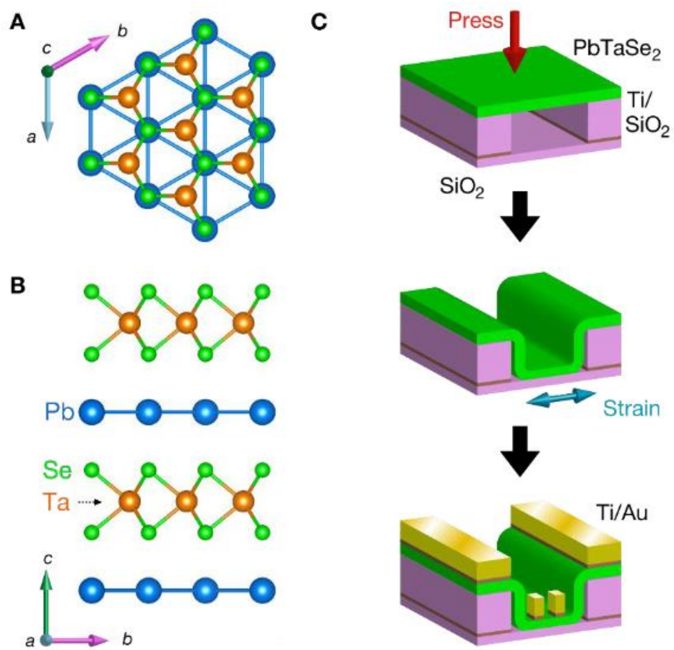
Nb/V/Au/Fe/Au/V/Ta

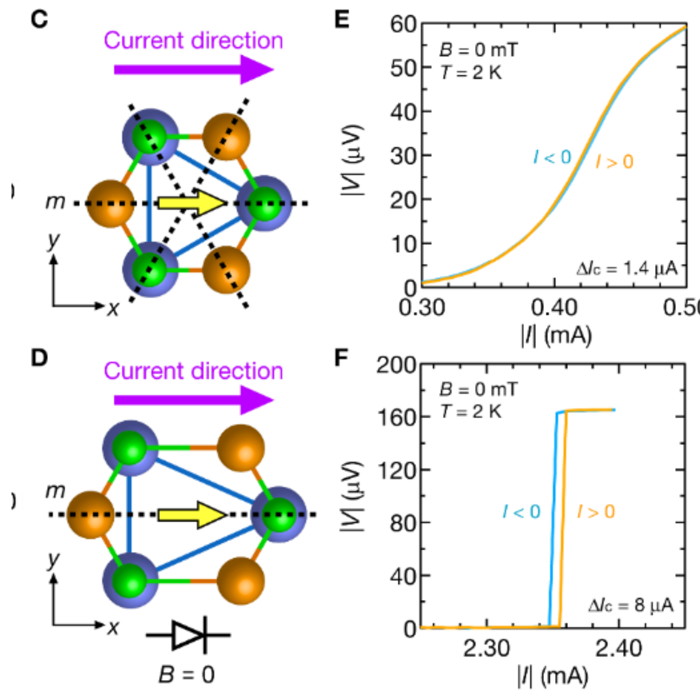


Two systems show quite different SDE magnitude though the stray fields should be the same order.

Extrinsic mechanism: Ferro/Super system
Superconducting diode due to stray field

Is the time reversal symmetry breaking necessary for SDE?





Zero-field SDE in strained $PbTaSe^2$ by current // polar axis

Possibility of SDE due to device structural asymmetry

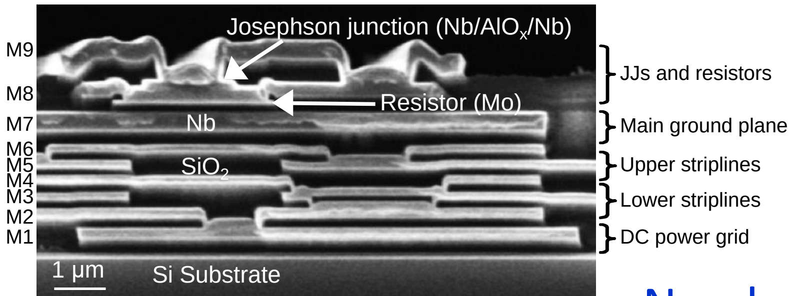
Y. Iwasa et al., arxiv.org/abs/2406.08157; Sci. Adv. accepted

Talk by Prof. Iwasa on Friday!

Possible applications of SDE

(1) Diodes in superconducting circuits

Single Flux Quantum microprocessor: High speed, low power consumption

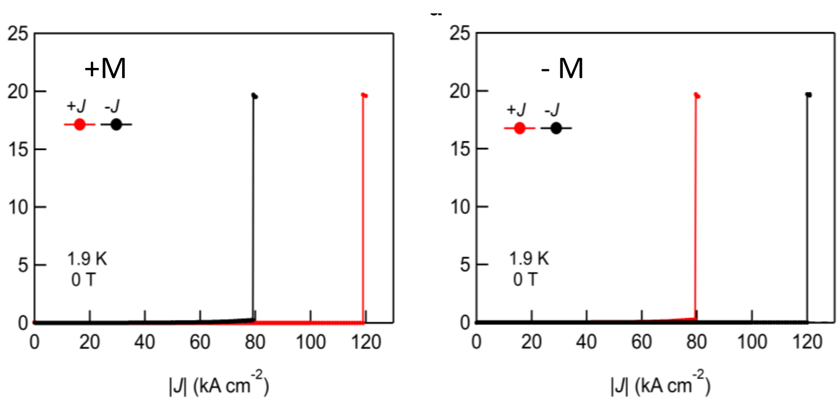


S. Nagasawa et al. *IEICE* **E97-C** (2014) 132-140.

Courtesy of Prof. Tanaka (Nagoya Univ.)

Need of SD with high current supply

(2) MRAM with single magnetic layer



Direction of M can be read out:

Appling +J (|-Jc| < |+J| < |+Jc|),

Superconducting -> +M

Normal state - > -M

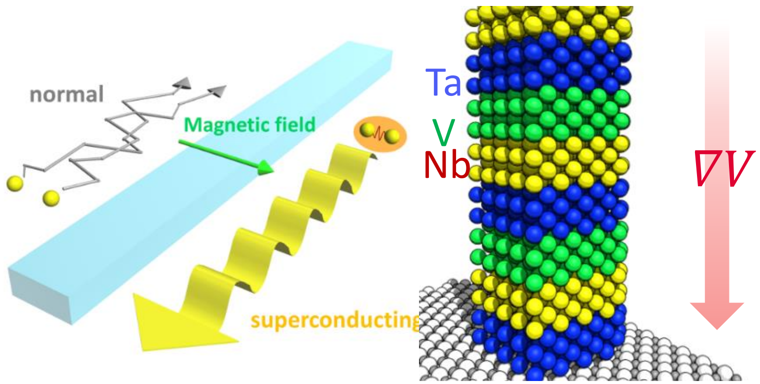
No need of reference layer

(3) Reconfigurable superconducting circuits

Summary

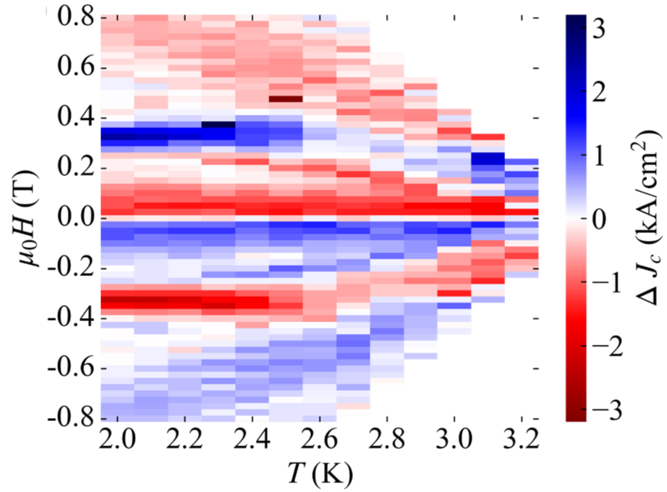
Superconducting diode effect

Nature 584, 373 (2020)



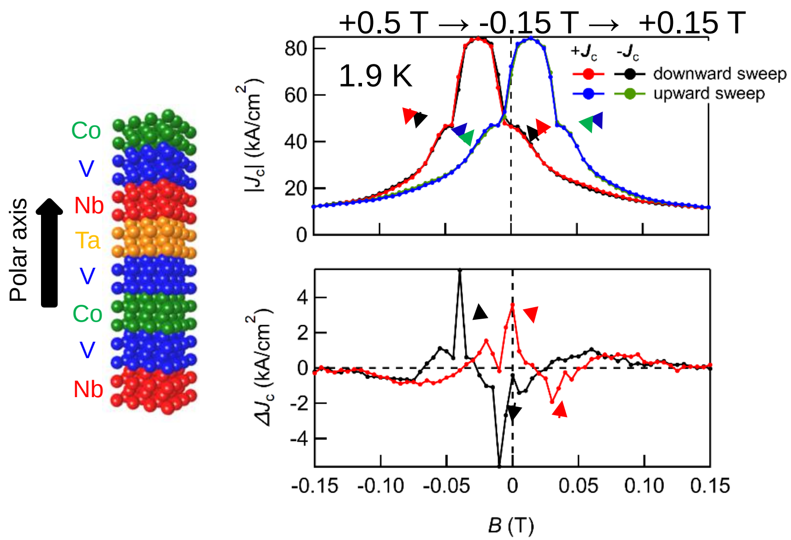
Polarity oscillation of SDE

Appl. Phys. Express 15 113001 (2022)



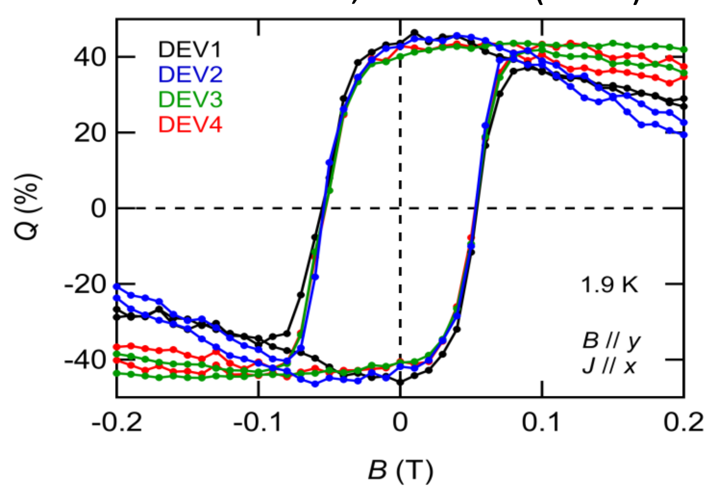
Zero-field SDE

Nat. Nanotechnol. 17, 823 (2022)



Non-volatile SDE in [Nb/V/Pt/Fe/Pt/V/Ta] system

Adv. Mater., 2304083 (2023)

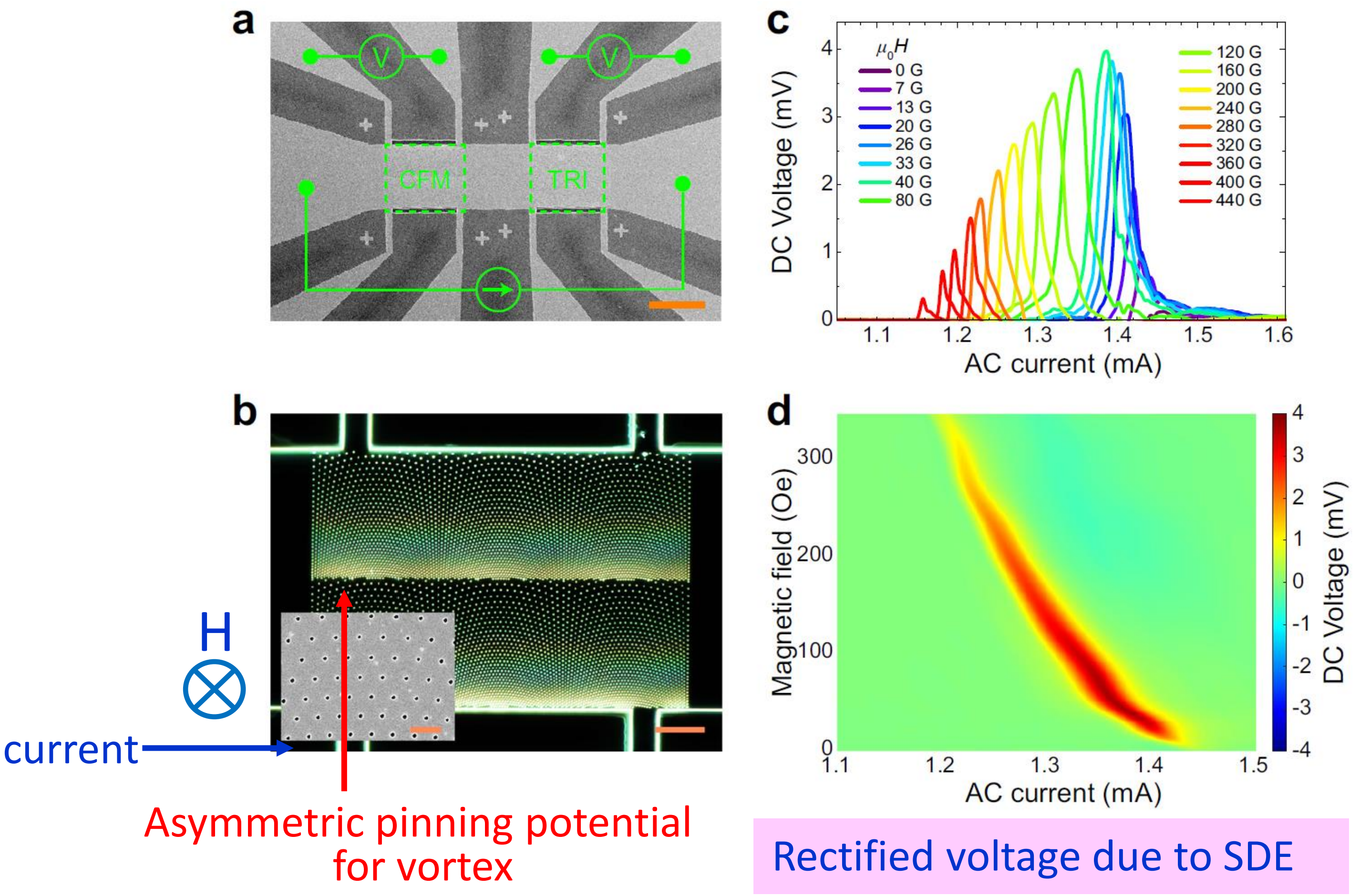


Asymmetric vortex motion in artificial pinning potential

https://doi.org/10.1038/s41467-021-23077-0 OPEN

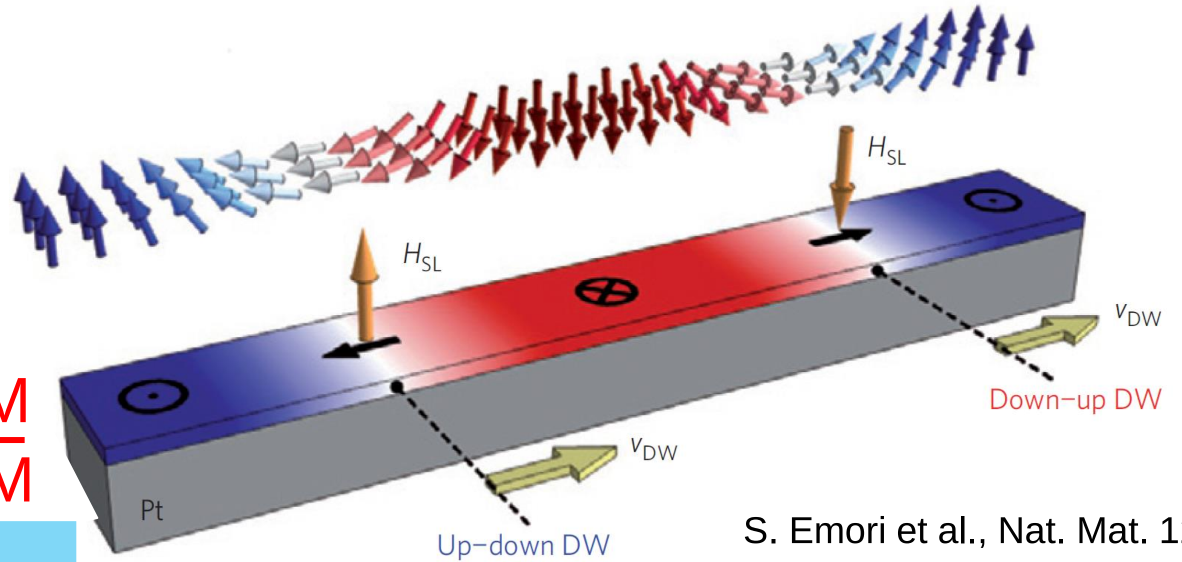
Superconducting diode effect via conformal-mapped nanoholes

Yang-Yang Lyu[1,2,8], Ji Jiang[3,4,8], Yong-Lei Wang[1✉], Zhi-Li Xiao[2,5✉], Sining Dong[1], Qing-Hu Chen[3], Milorad V. Milošević[4], Huabing Wang[1,6], Ralu Divan[7], John E. Pearson[2], Peiheng Wu[1,6], Francois M. Peeters[4] & Wai-Kwong Kwok[2]



Y.Y. Lyu *et al., Nat. Commun.* **12,** 2703 (2021).

Interface: important structure in spintronics



S. Emori et al., Nat. Mat. 12, 611 (2013)

FM
NM

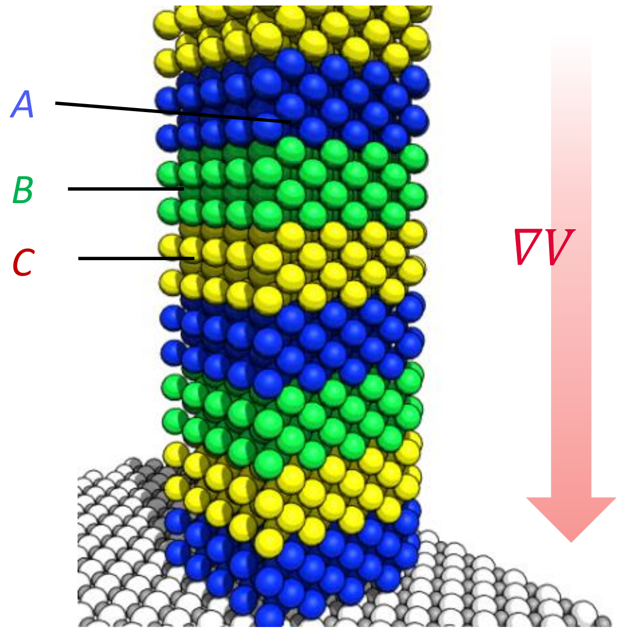
Inversion symmetry breaking

Only at the interface ?

Important spintronics properties

- Perpendicular magnetic anisotropy (PMA)
- Dzyaloshinskii–Moriya interaction(DMI)
- Spin orbit torque (SOT)

How about making tricolor ABC superlattice?



Naturally breaks inversion symmetry as a bulk structure

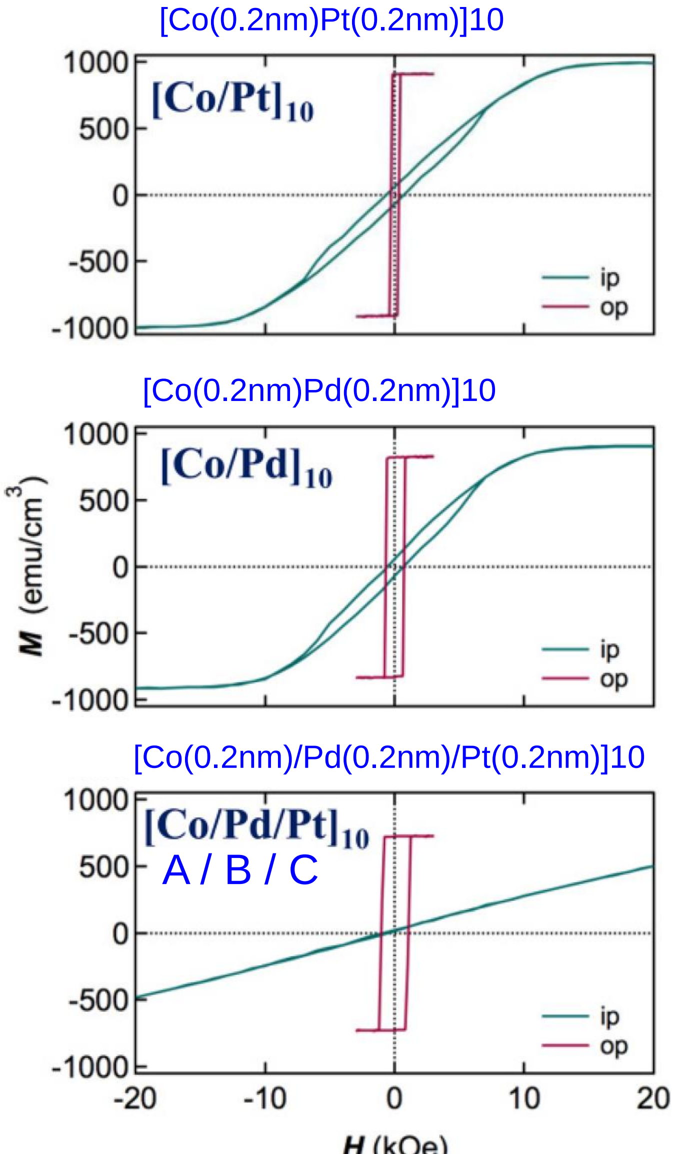
+

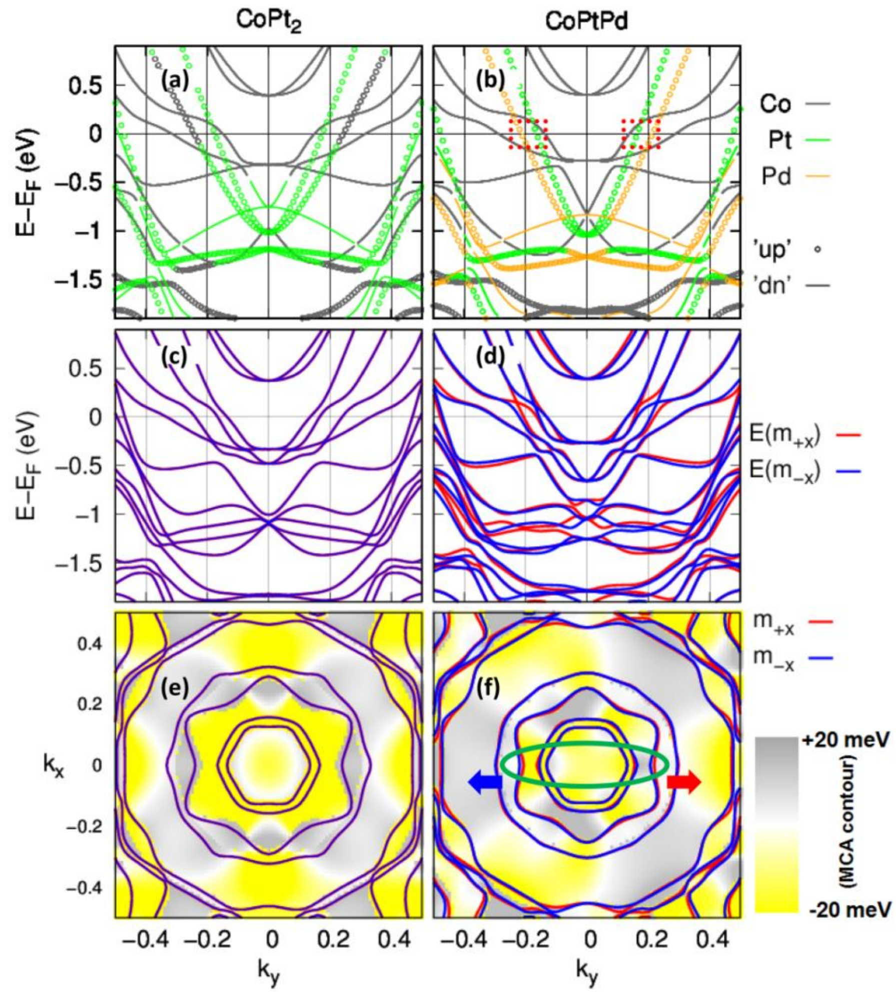
Band structure engineering

by tuning elements, thickness, period

Let us apply this idea to PMA, DMI, and SOT!

PMA enhancement in ABC superlattice





Phys. Rev. B 99, 180410(R) (2019)

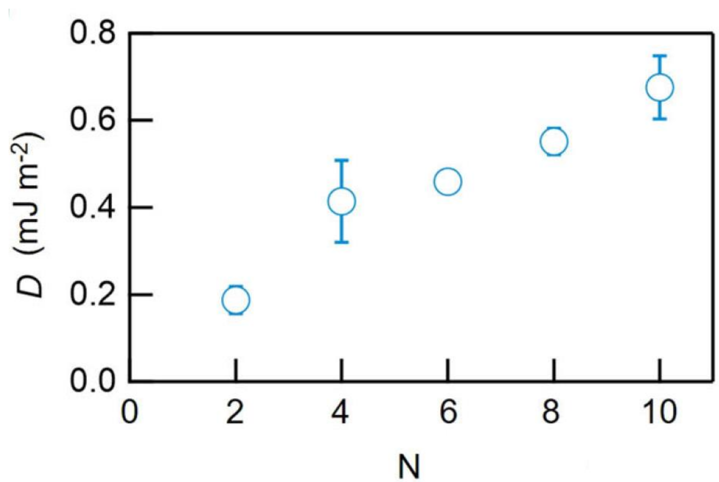
ABC structure doubles PMA!

Collaboration with Dr. Yakushiji (AIST) and Prof. Nakamura (Mie Univ.)

Bulk Dzyaloshinskii–Moriya interaction (DMI) in ABC superlattice

Experiment

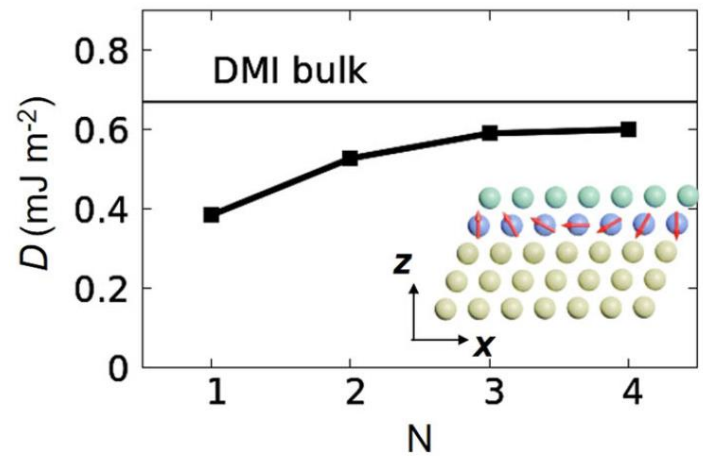
[Co(0.4nm)/Pd(0.4nm)/Pt(0.4nm)]N

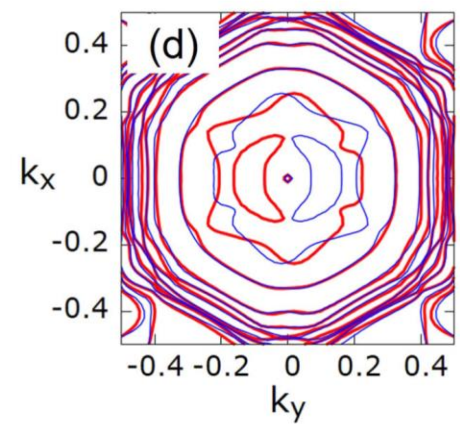


DMI should be constant
if it originates only from interfaces.

Band effect is there!

Calculation

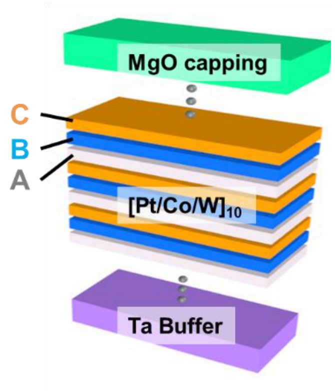


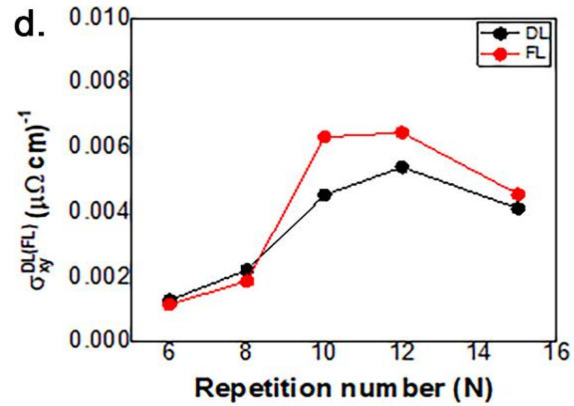


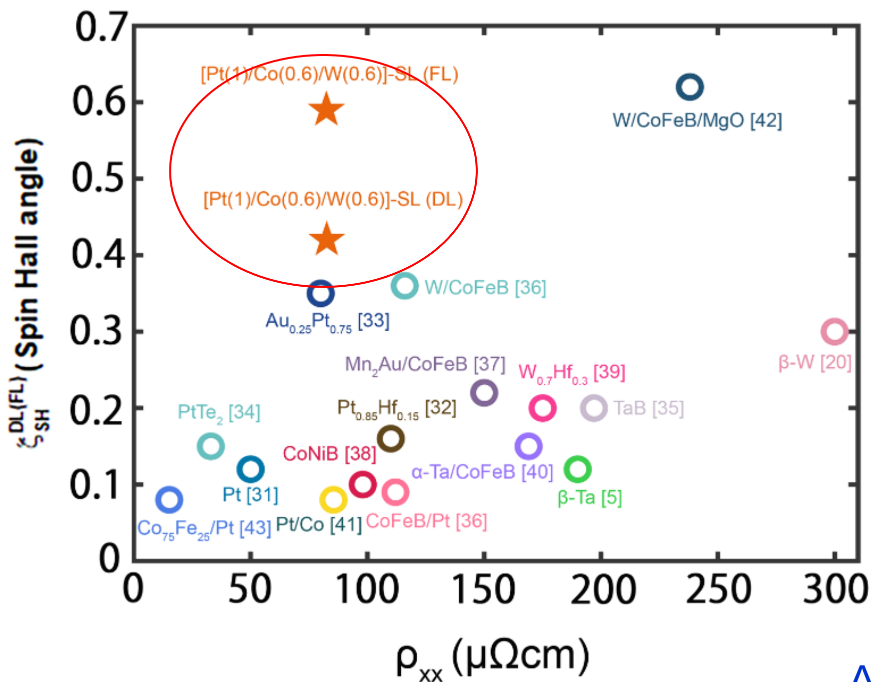
npj Computational Materials 7, 129 (2021)

Collaboration with Dr. Yakushiji (AIST) and Prof. Nakamura (Mie Univ.)

Bulk spin-orbit torque (SOT) in ABC superlattice



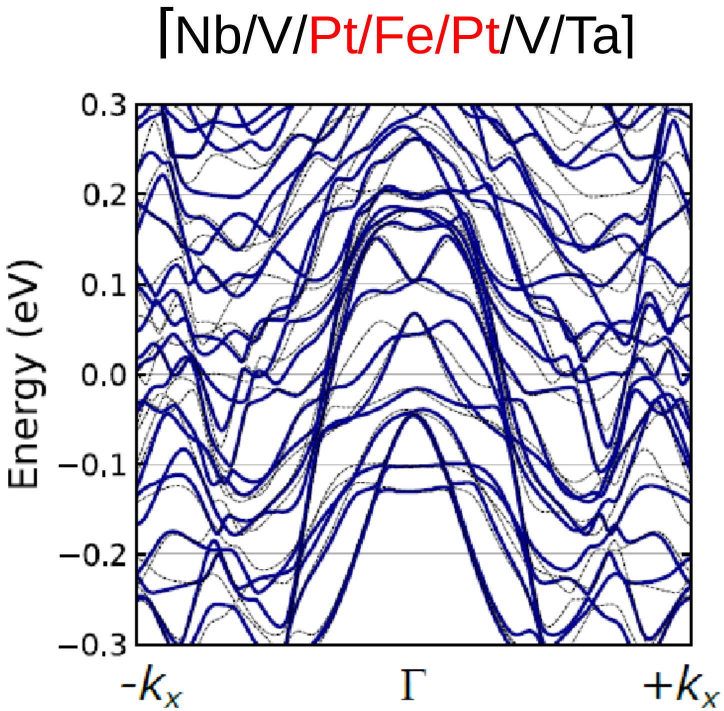


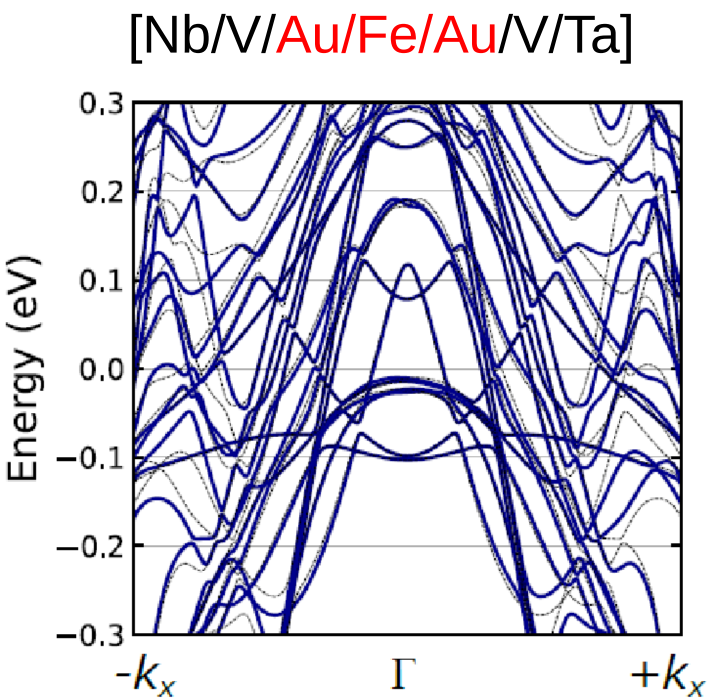


Adv. Sci.2023,10, 2206800

Collaboration with Prof. Sonny H. Rhim and Prof. Sanghoon Kim

First principle calculation

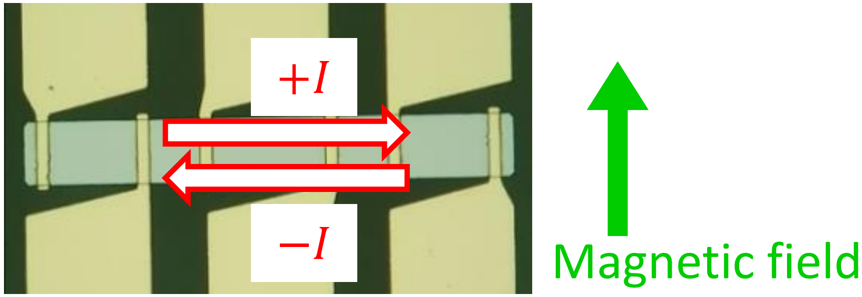


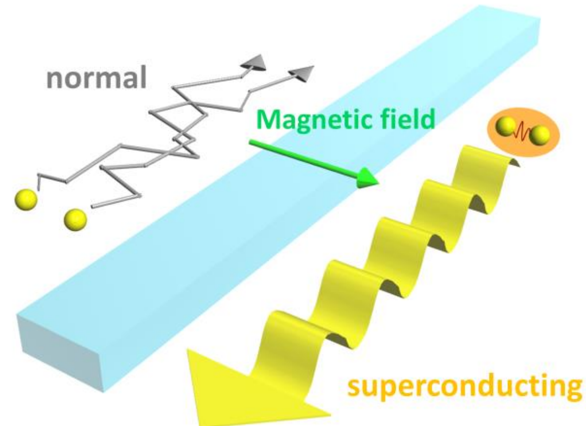


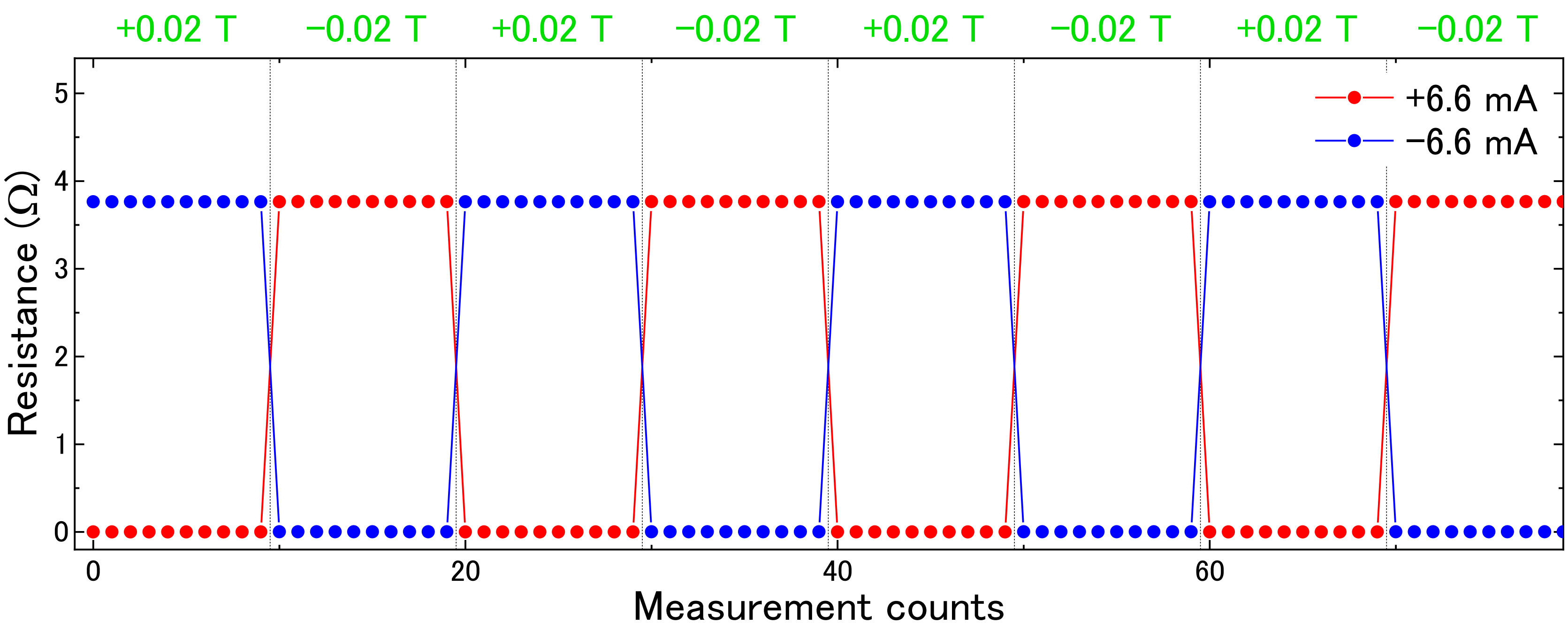
Rashba splitting	6.5 meV	6.5 meV
Exchange field	340 T	74 T

Adv. Mater., 2304083 (2023)

Switching of superconducting diode

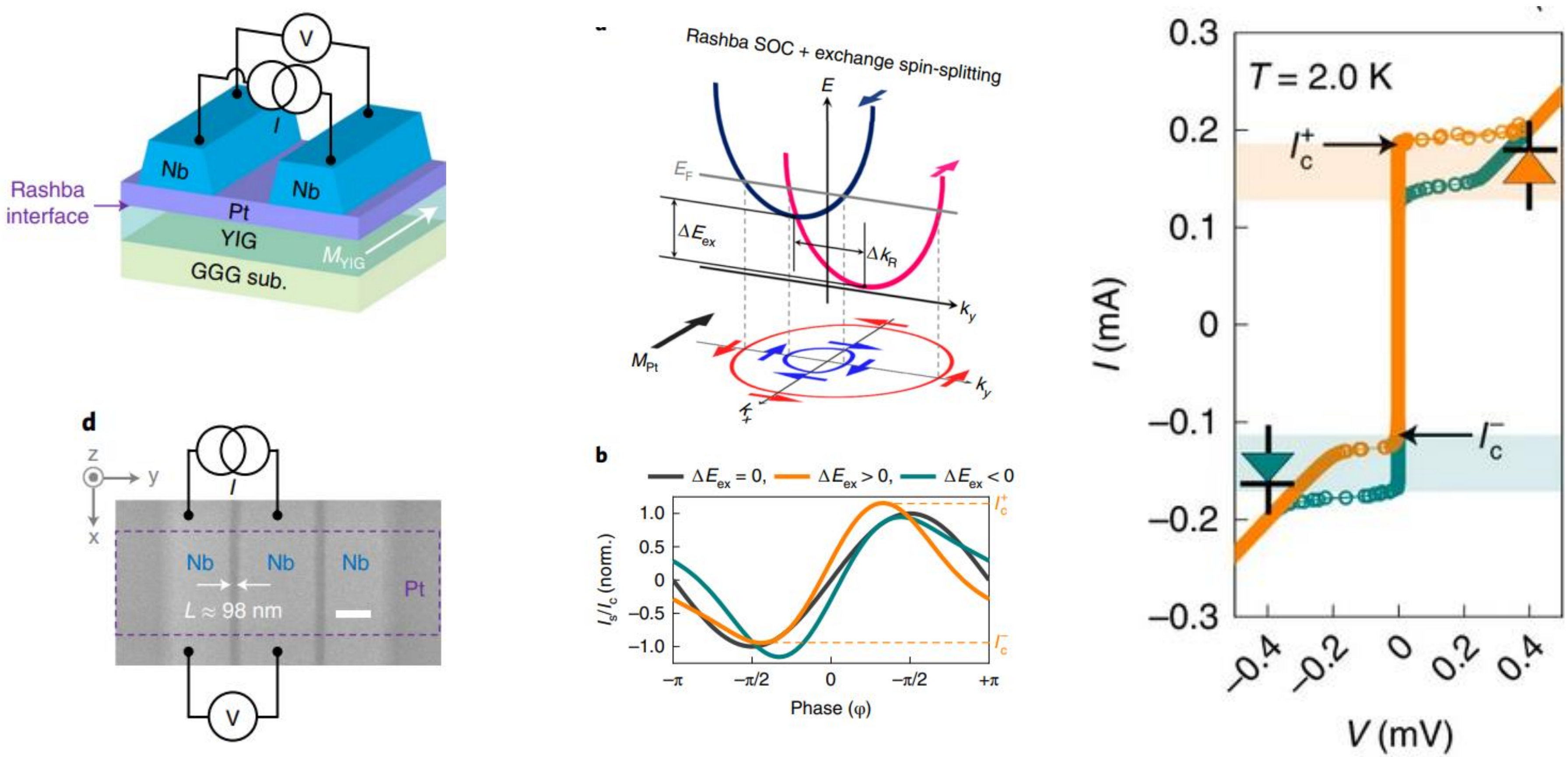






F. Ando et al., Nature 584, 373 (2020)

Josephson diode with Rashba + Exchange



Theory: ϕ_0 jucntion ($I_s(\phi) \approx I_{c1}\sin(\phi + \phi_0) + I_{c2}\sin(2\phi)$), distortion of current-phase relation

A. Buzdin, Phys. Rev. Lett. 101, 107005 (2008).

F. S. Bergeret & I. V. Tokatly, Europhys. Lett. 110, 57005 (2015).

F. Konschelle, I.V. Tokatly & F.S. Bergeret, Phys. Rev. B 92, 125443 (2015).

Experiment:

Kun-Rok Jeon et al., Naterue Materials 21, 1008 (2022).

Extrinsic mechanism for JJ-SDE: Vortex formation in JJ results in SDE

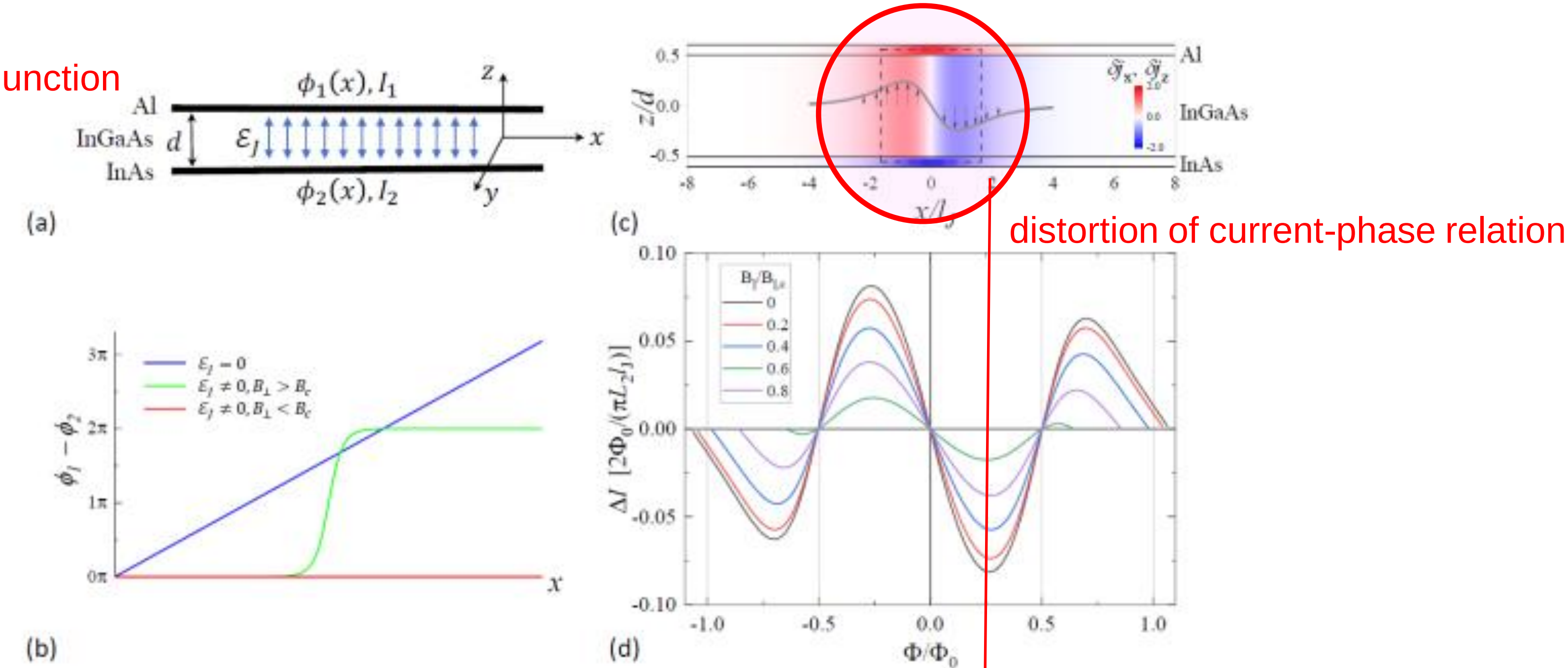
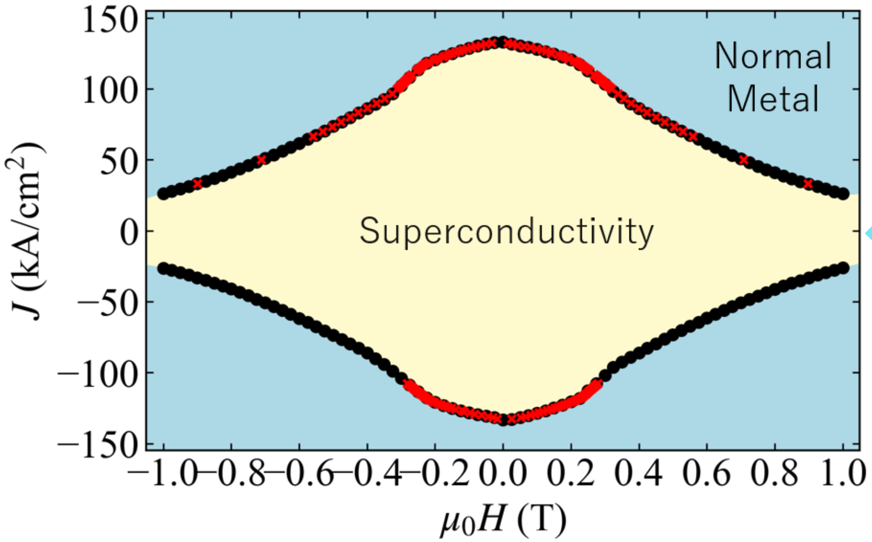
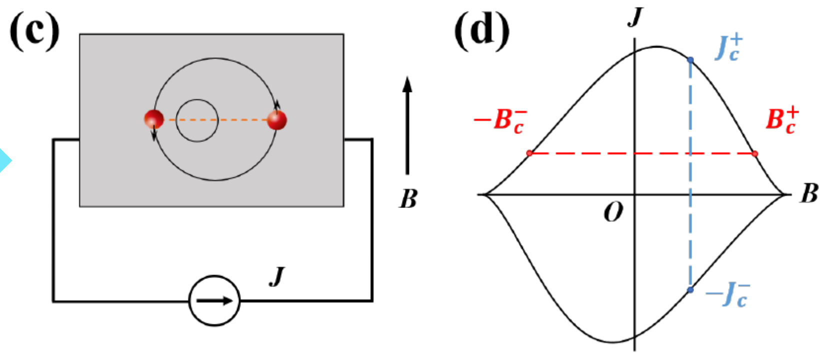


FIG. 4. **Two-wire model and vortex formation.** (a) Two one-dimensional superconducting wires separated by a tunneling barrier are coupled with a Josephson coupling $\mathcal{E}_J$. (b) Depending on the relative strength of kinetic $\mathcal{E}_K$ and Josephson energies phases in two wires can be locked ($\phi_1 = \phi_2$), vary independently or undergo a phase slip. (c) Circular currents due to the vortex formation (in units of $2\pi\mathcal{E}_J/\phi_0$). Dashed rectangle outlines an effective vortex area S_v. (d) NRS ΔI versus the flux $\Phi = S_v B_\perp$ is plotted for several $B_\parallel$, Eq. (S12).

Nature Communications (2023) 14, 1628 arXiv:2207.03633v1

Phase diagram in *H-I* plane





N.F. Yuan & L. Fu, PNAS 119, e2119548119 (2022).

Y. Miyasaka et al., Applied Physics Express 14, 073003 (2021).

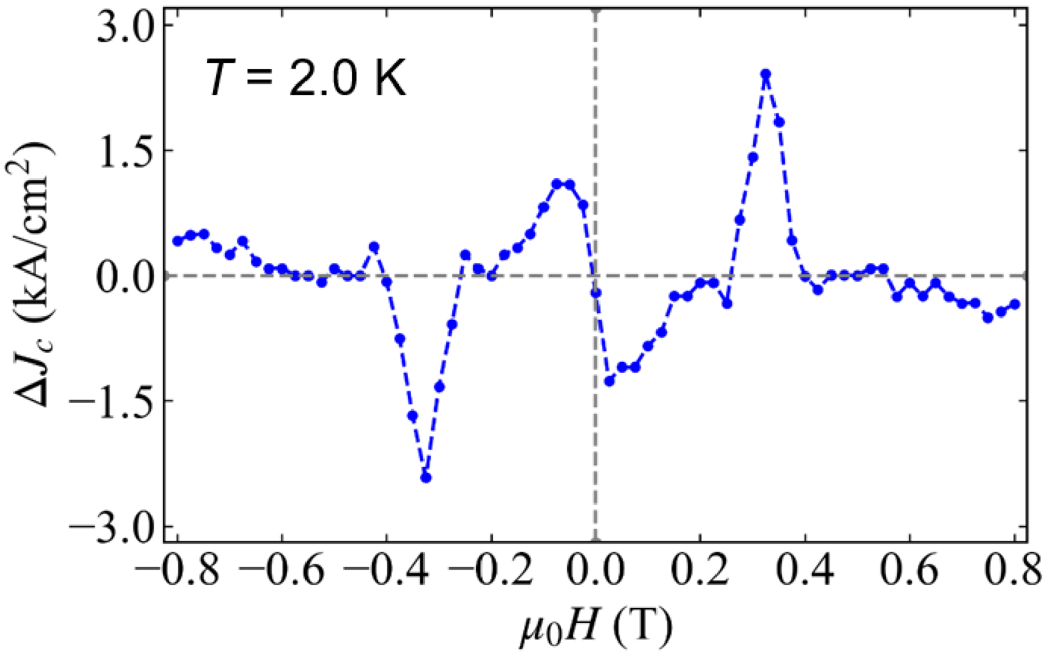
- Critical current as a function of applied magnetic field (red circles)
- Critical magnetic field as a function of applied current (black circles)

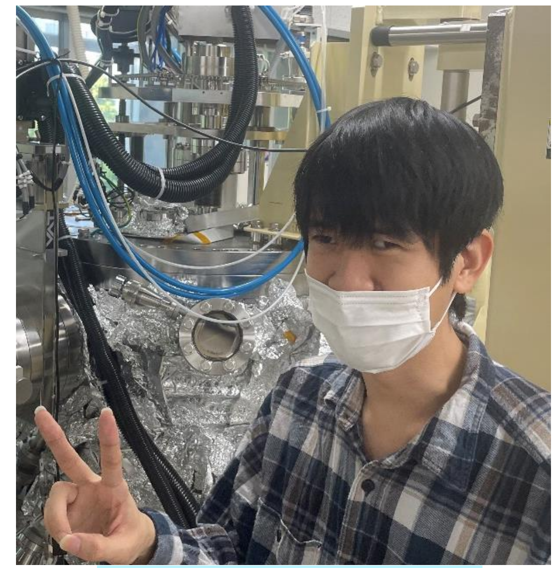
No difference between
the magnetic field dependence of the critical current
and
the current dependence of the critical magnetic field

Both nonreciprocal effects have the same origin.

Polarity oscillation of superconducting diode effect with magnetic field

$$\Delta J_c = |+J_c| - |-J_c|$$



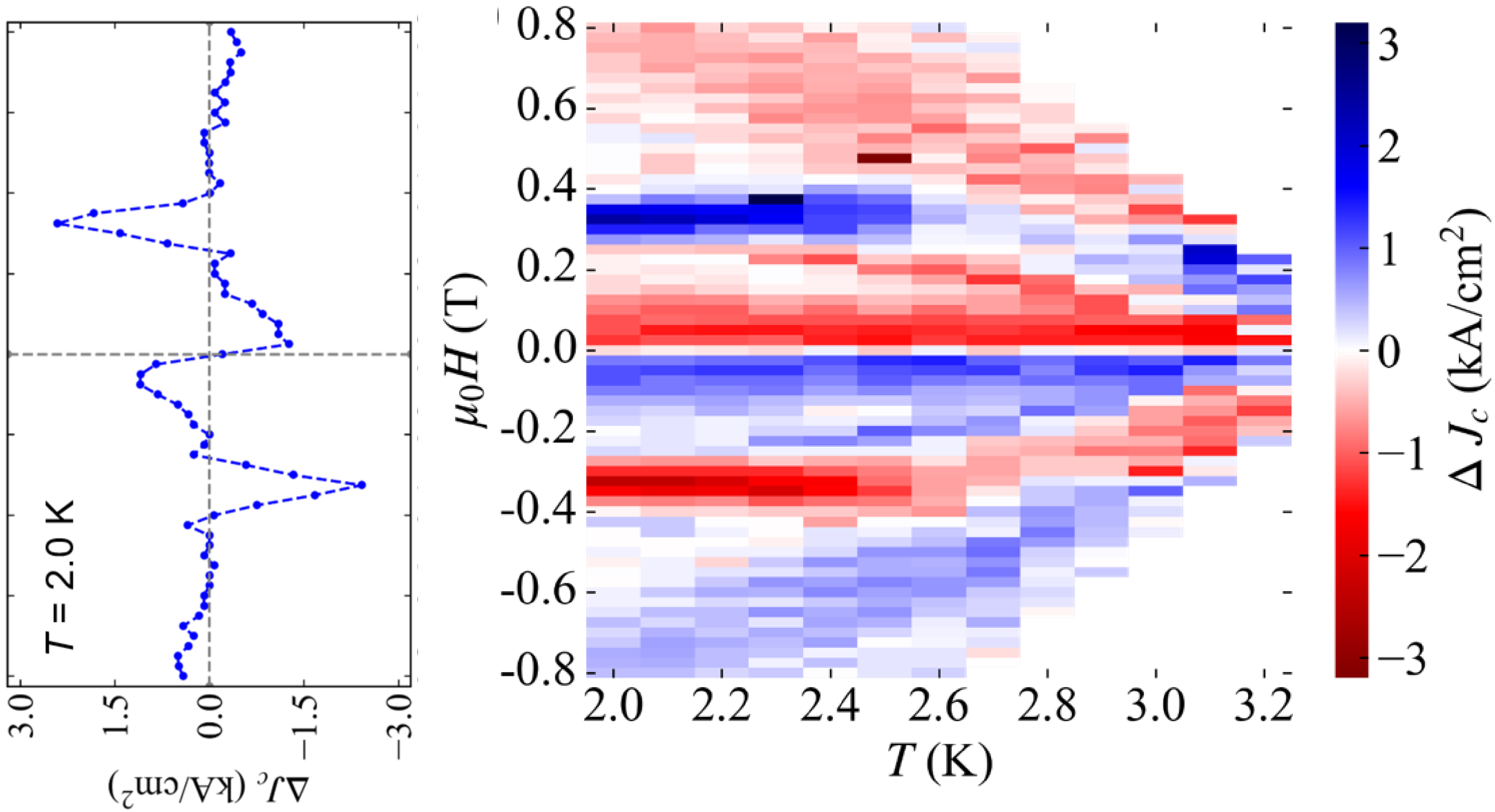


Ryo Kawarazaki

SDE shows sign reversal with magnetic field !??

Appl. Phys. Express 15 113001 (2022)

Color plot of ΔJ_c with respect to temperature and magnetic field



- Amplitude and period of the oscillation decrease with temperature.
- ΔJ_c vanishes at T_C.

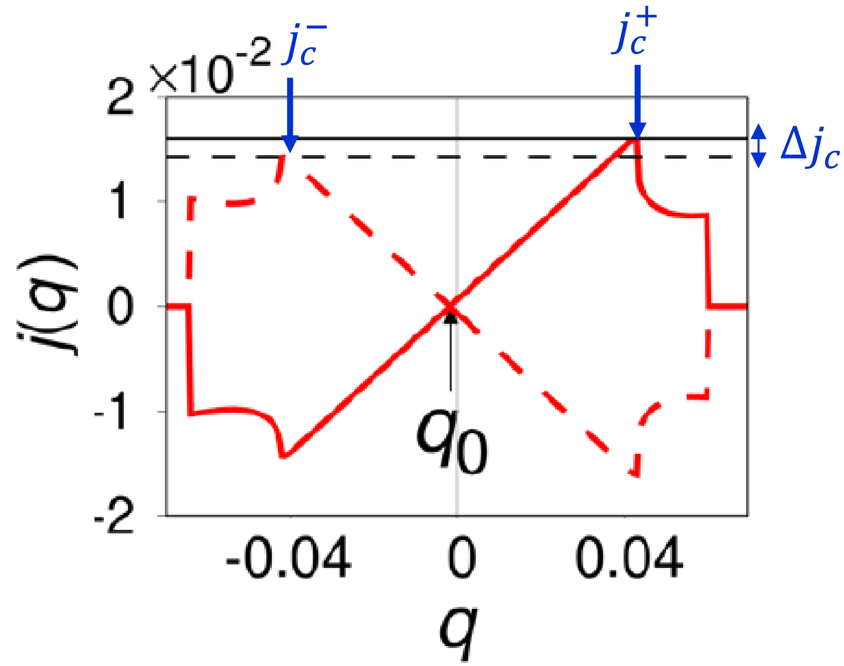
Appl. Phys. Express 15 113001 (2022)

Calculation of critical current

Set the model Hamiltonian
(Rashba SOI + Zeeman)

Calculate condensation energy: $F(q)$
q: momentum of Cooper pair

Current : $j(q) = 2\partial_q F(q)$



When an electric current $j_{\rm ex}$ is applied,
the superconducting state with q satisfying $j_q = j_{\rm ex}$ should be realized.

However, no superconducting state can sustain $j_{\rm ex} > \max j_q$

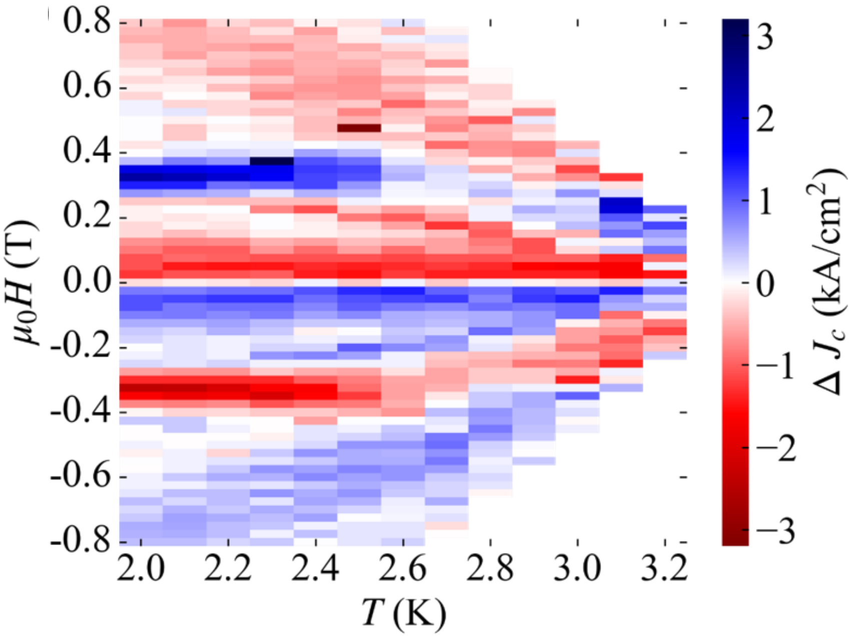
Critical current = $\max j_q$

$j(q_0) = 0$ for helical superconducting state with $q = q_0$

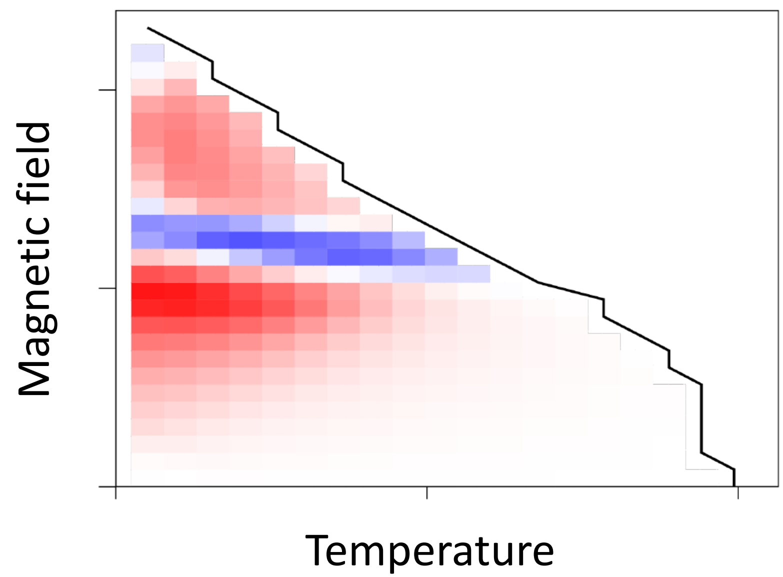
A. Daido, Y. Ikeda, Y. Yanase, Phys. Rev. Lett. 128, 037001 (2022).

Sign reversal: comparison to theory

Experiment



Calculation



$$\hat{H} = \sum_{\boldsymbol{k}\sigma\sigma'} \left[\xi(\boldsymbol{k})\delta_{\sigma\sigma'} + \boldsymbol{g}(\boldsymbol{k}) \cdot \boldsymbol{\sigma}_{\sigma\sigma'} - h(\sigma_y)_{\sigma\sigma'}\right] c^\dagger_{\boldsymbol{k}\sigma} c_{\boldsymbol{k}\sigma'}$$

$$- \frac{U}{V} \sum_{\boldsymbol{k}_1+\boldsymbol{k}_2+\boldsymbol{k}_3+\boldsymbol{k}_4=0} c^\dagger_{\boldsymbol{k}_1\uparrow} c^\dagger_{\boldsymbol{k}_2\downarrow} c_{\boldsymbol{k}_3\downarrow} c_{\boldsymbol{k}_4\uparrow}.$$

Daido, A., Ikeda, Y. & Yanase, Y. Intrinsic Superconducting Diode Effect. Phys. Rev. Lett. 128, 037001 (2022).

The theory suggests that sign change is the crossover between two helical states. But the crossover field should be around the Pauli limiting field 1.84 Tc ~ 6 T, which is much larger than the observation.

Orbital effect on the intrinsic superconducting diode effect

Kyohei Nakamura,* Akito Daido, and Youichi Yanase
Department of Physics, Graduate School of Science, Kyoto University, Kyoto 606-8502, Japan

(Received 2 June 2023; revised 5 February 2024; accepted 7 February 2024; published 1 March 2024)

The past few years have seen an increased interest in nonreciprocal phenomena in superconductors, especially the superconducting diode effect (SDE) characterized by the nonreciprocity of the critical current ΔJ_c. Contrary to the fundamental and practical significance of the SDE, the precise underlying mechanism remains unclear. In this paper, we investigate the impact of an orbital effect on the intrinsic SDE in a bilayer superconductor with Rashba spin-orbit coupling and an in-plane magnetic field. We show that a small orbital effect leads to the sign reversal of ΔJ_c and a crossover of the helical superconducting state at a lower magnetic field than the monolayer superconductor. On the other hand, a large orbital effect induces a decoupling transition, stabilizing a finite momentum Cooper pairing state called the orbital Fulde-Ferrell-Larkin-Ovchinnikov state, and results in the drastic change of the SDE. Owing to the orbital effect, the field dependence of the SDE may show oscillations several times. The results shed light on the mechanism of the SDE in atomically thin multilayer superconductors.

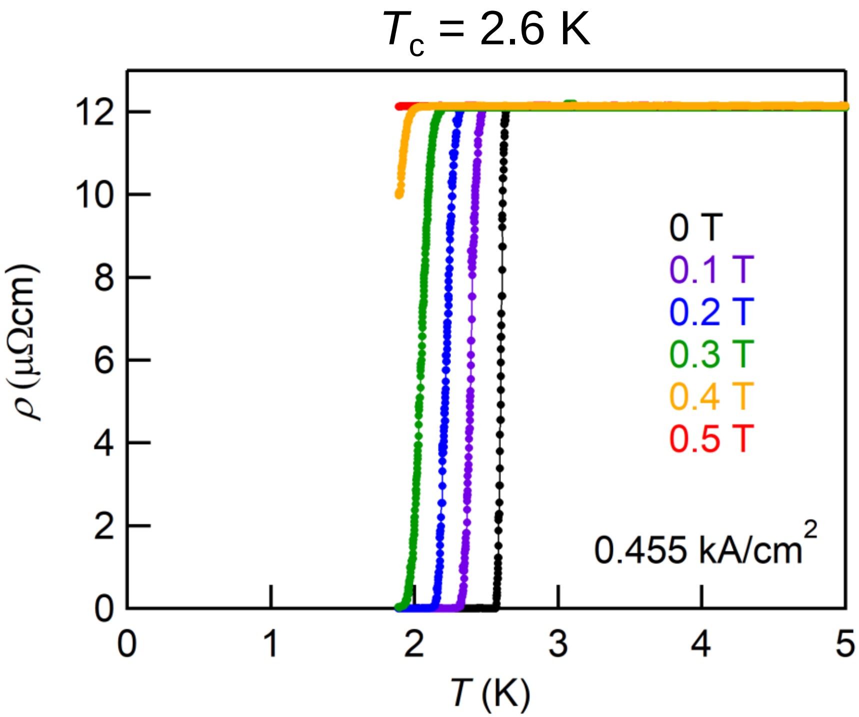
DOI: 10.1103/PhysRevB.109.094501

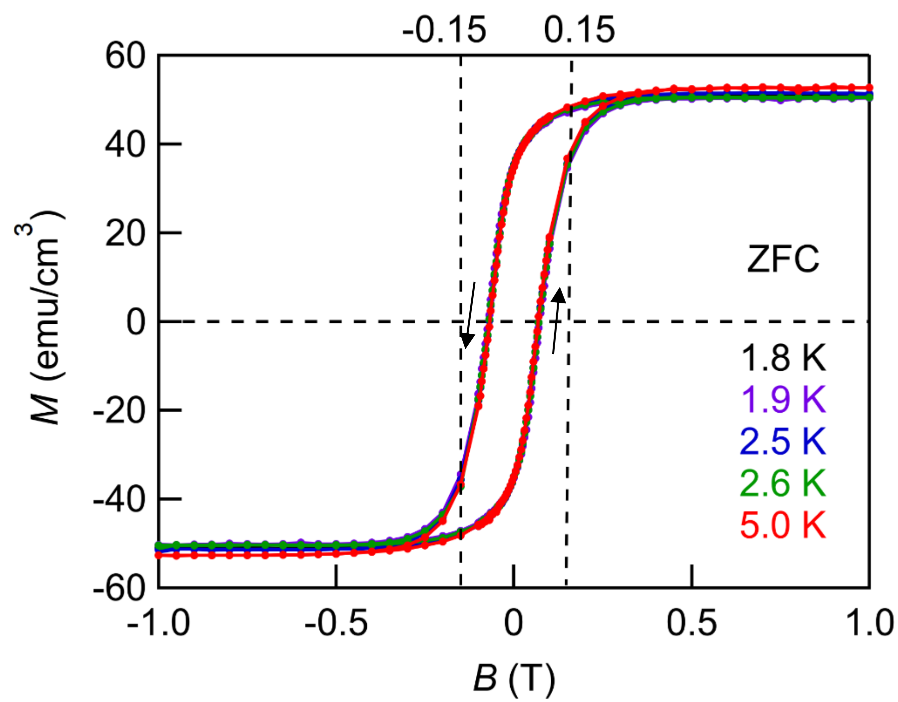
- Bilayer superconductor with Rashba SOI and magnetic field
- Josephson vortex

Orbital effect due to the Josephson vortex causes a sign reversal of the SDE at field much smaller than the Pauli limit,
which is consistent with the experimental results.

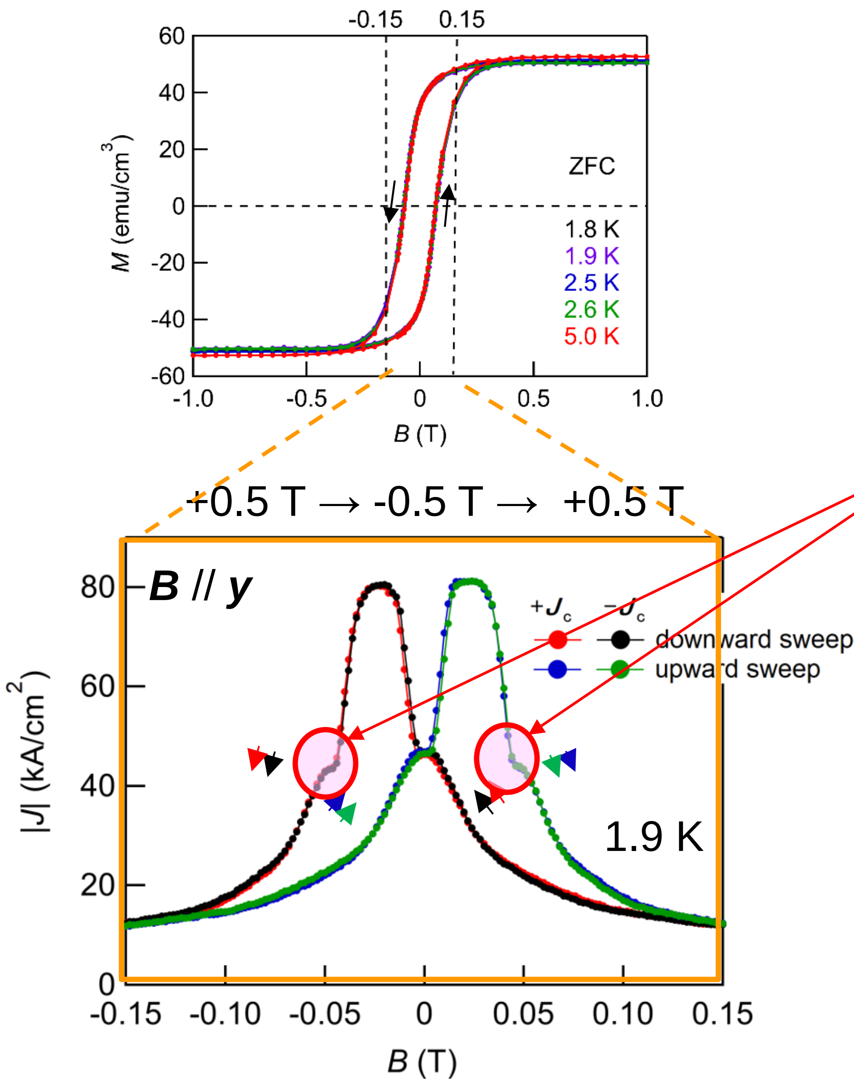
Coexistence of superconductivity & ferromagnetism

[Nb(4.5 nm/V(4.5 nm)/Co(1.7 nm)/V(4.5 nm)/Ta(4.5 nm)]$_{20}$





J_c as a function of magnetic field

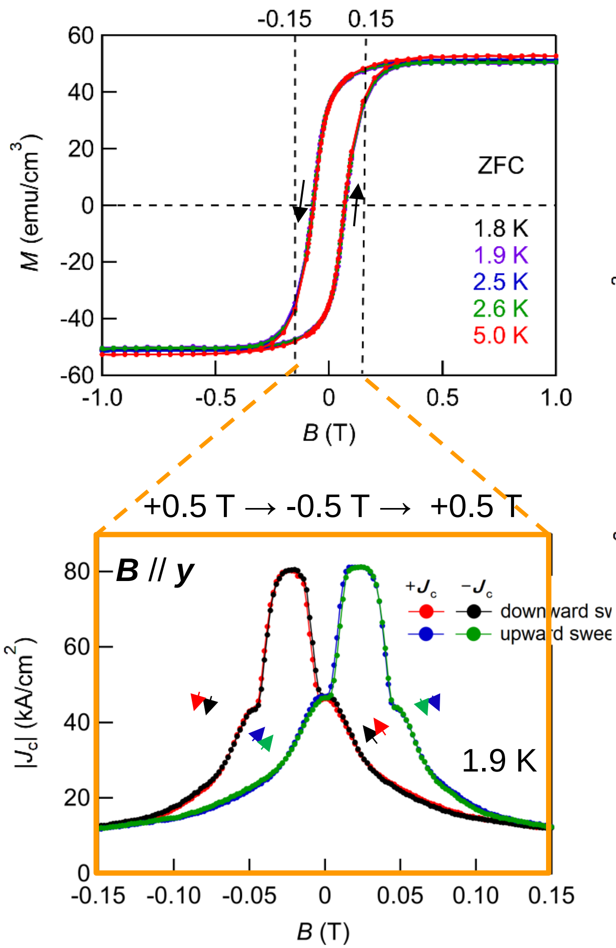


Shoulder structures in J_c that are not observed in MH curve

Supercurrent stabilizes domain structure?
Interaction between supercurrent & M?
Possibility of controlling M by supercurrent?

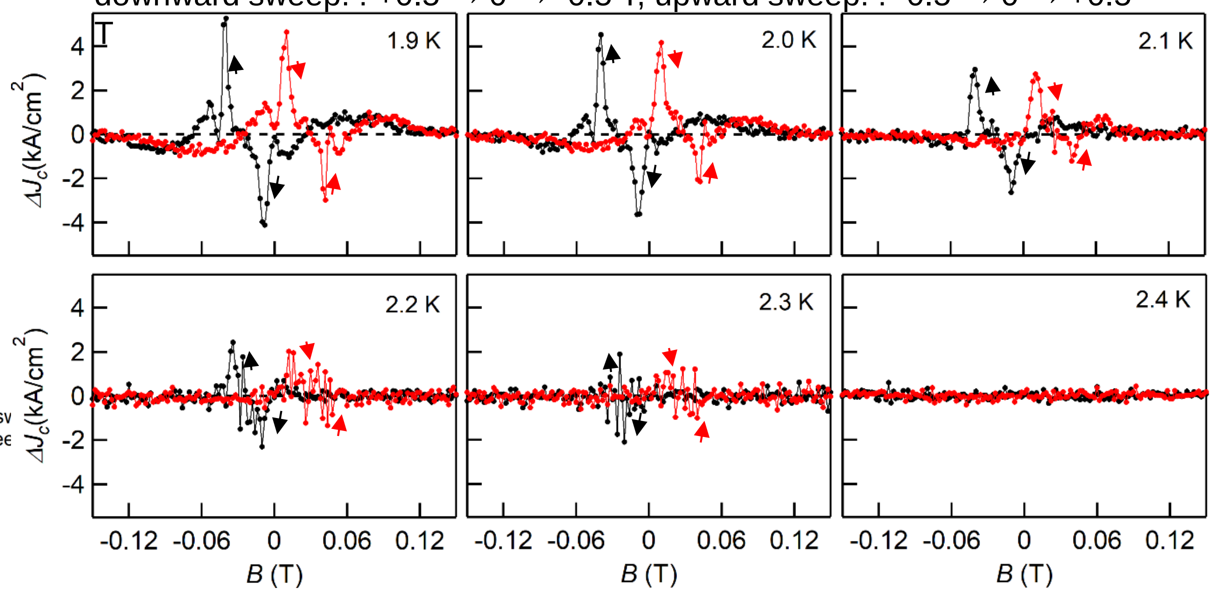
Nat. Nanotechnol. 17, 823 (2022)

SDE as a function of magnetic field



$$\Delta J_c = |+J_c| - |-J_c|$$

downward sweep: : +0.5 → 0 → -0.5 T, upward sweep: : -0.5 → 0 → +0.5 T

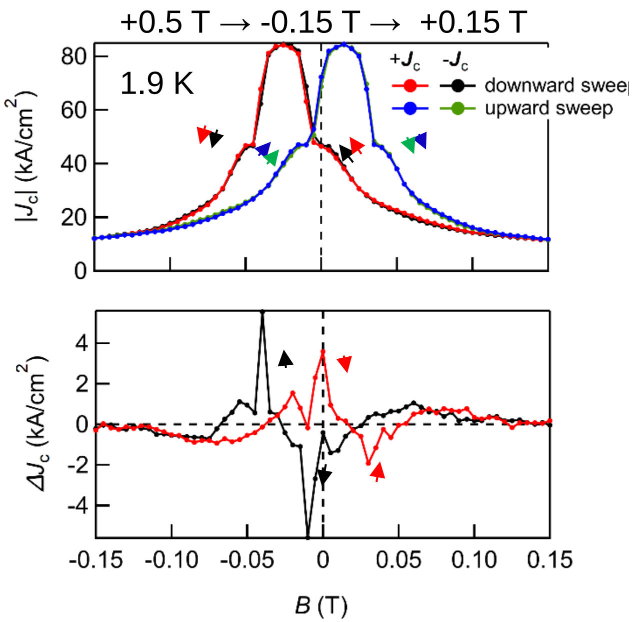


- Magnetic field dependent SDE
- No SDE in zero-field (TiT)…

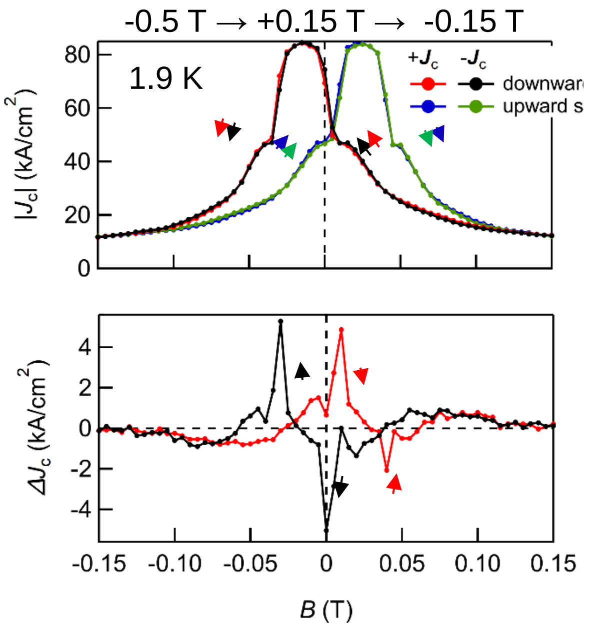
Multi-domain state at zero field?

Nat. Nanotechnol. 17, 823 (2022)

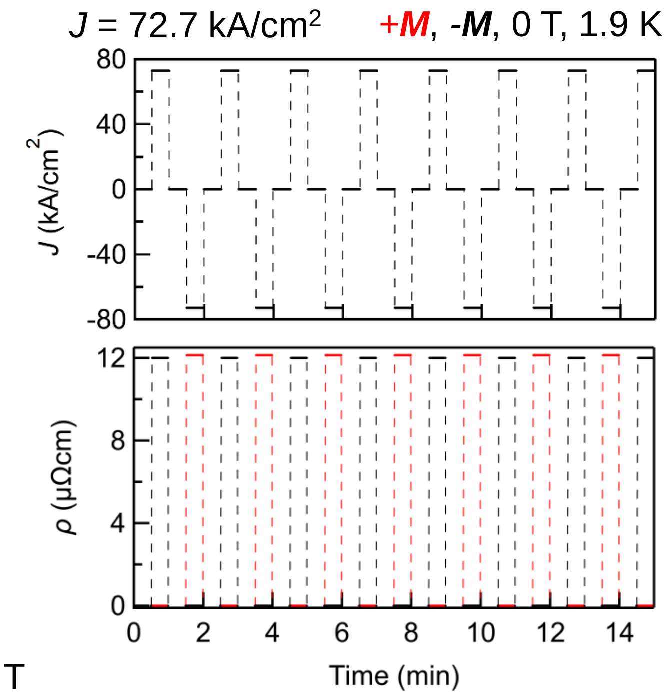
SDE in minor hysteresis loop



downward sweep : +0.5, 0, -0.15 T
upward sweep: -0.15, 0, +0.15 T



downward sweep : +0.15, 0, -0.5 T
upward sweep: -0.5, 0, +0.15 T



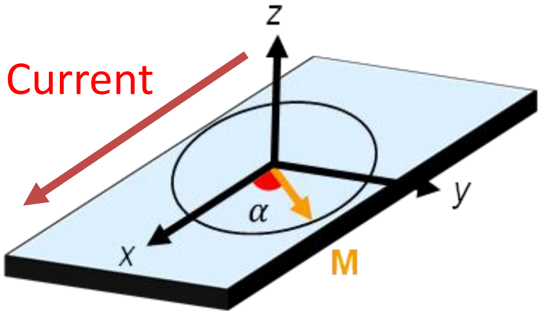
+M state : +0.5, 0, -0.15, 0 T
-M state : -0.5, 0, +0.15, 0 T.

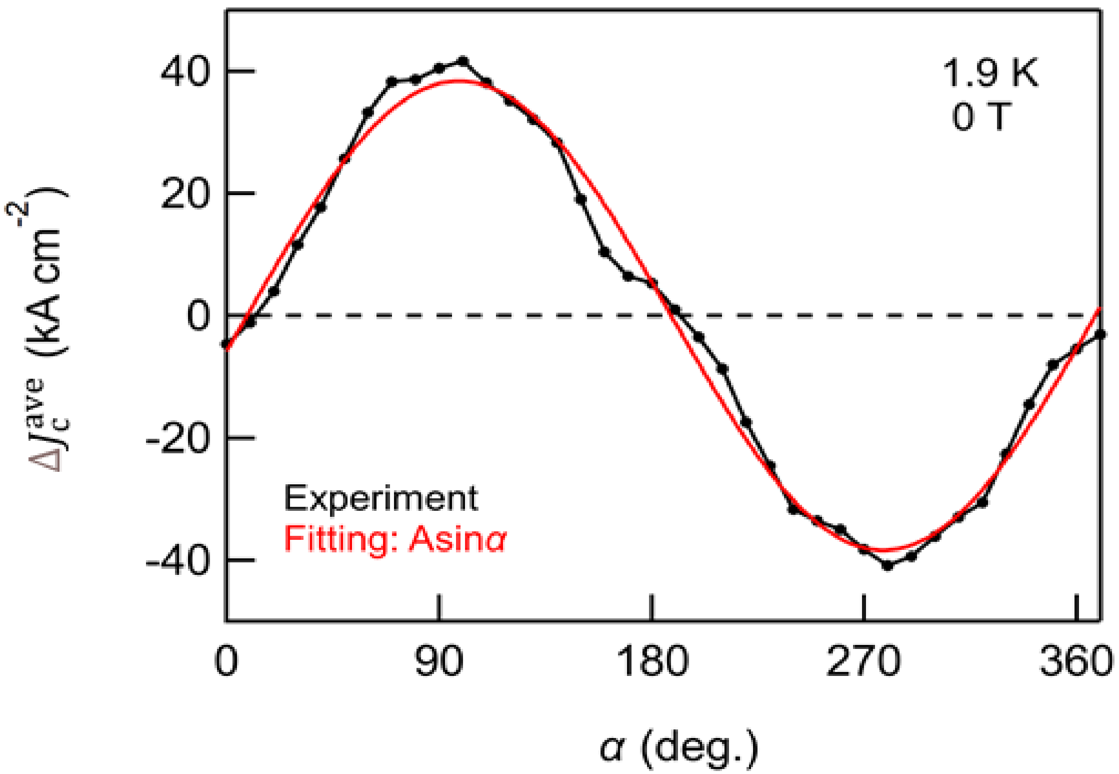
Zero-field SDE !

However we need the minor loop field sweep, and the effect is small.

Nat. Nanotechnol. 17, 823 (2022)

Angle dependence of zero-field SDE



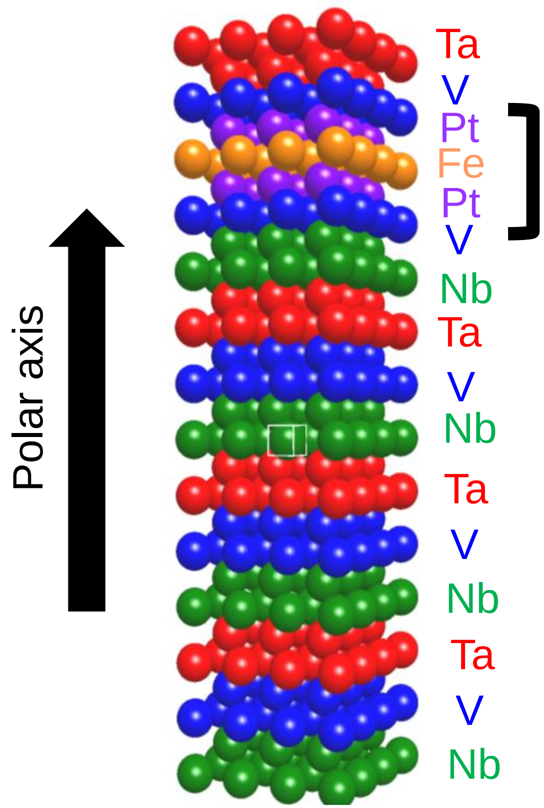


SDE shows sinα dependence

Exchange field from Fe to Cooper pairs

Adv. Mater., 2304083 (2023)

Toward bigger SDE in zero-field

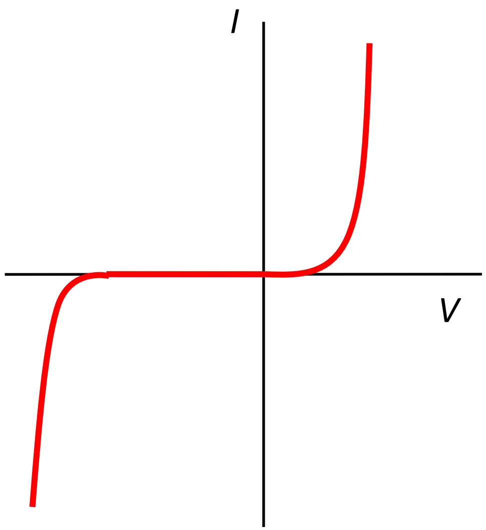


Pt/Fe/Pt unit

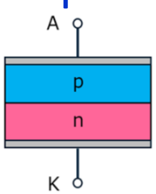
Fe: ferromagnet
Pt : spin-orbit

Comparison with conventional diode

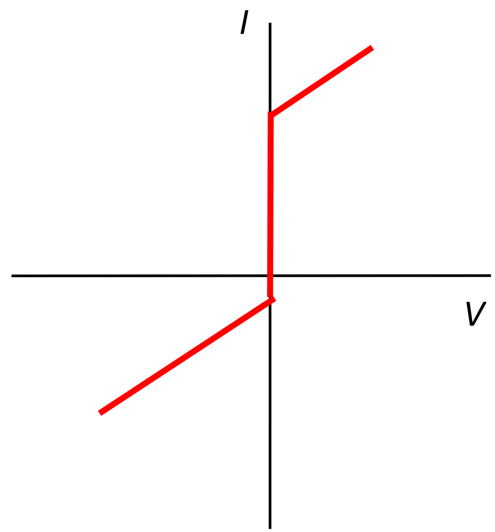
Conventional diode



Joule heating
Fixed polarity



Superconducting diode

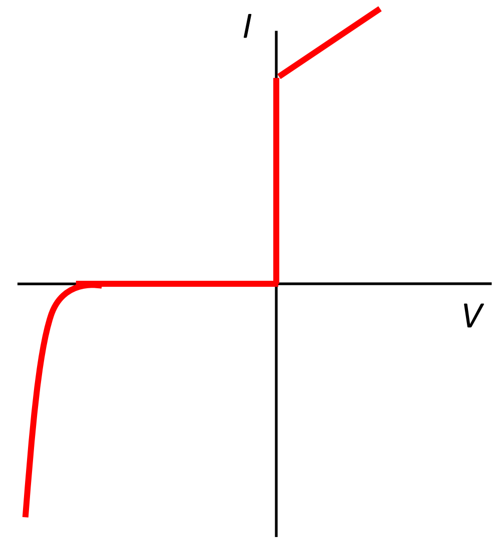


Superconducting (forward)
Normal state (reverse)

No Joule heating (forward)

Polarity control by H or M

Ultimate diode

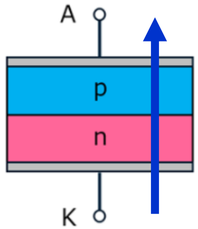


Superconducting (forward)
Insulating (reverse)

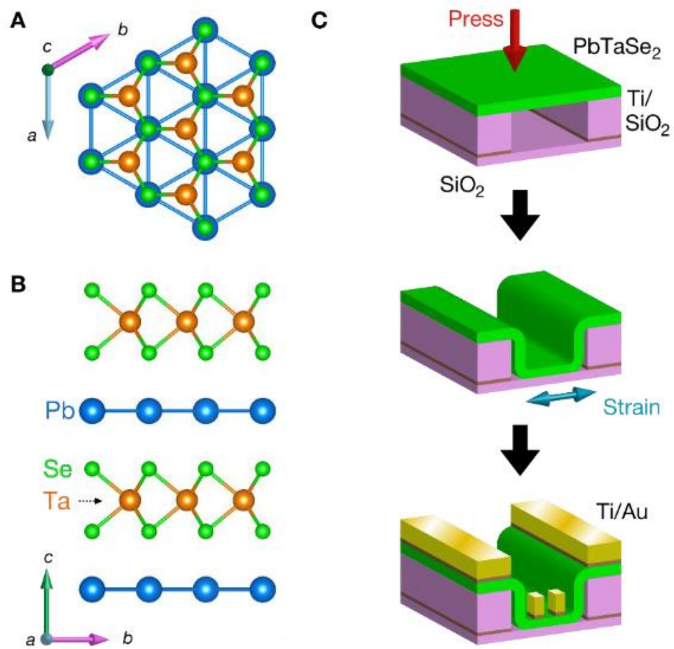
No Joule heating

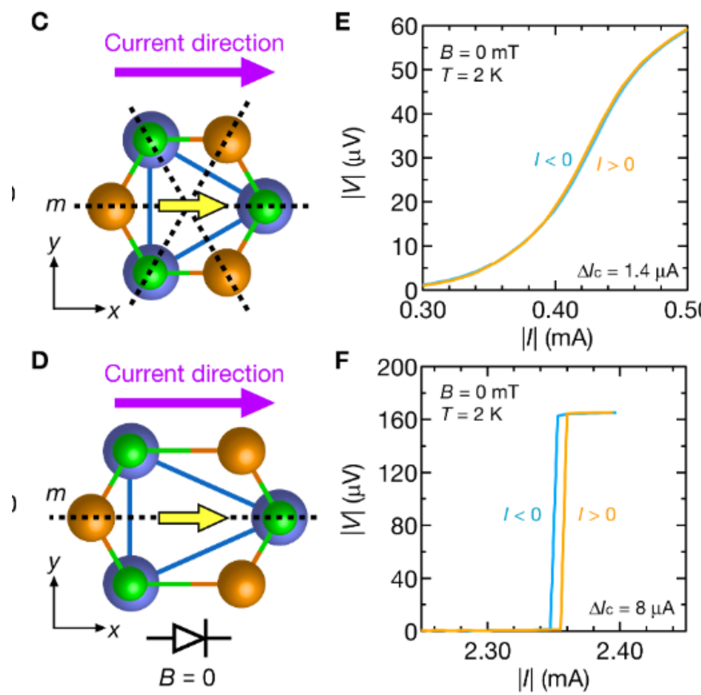
Polarity control

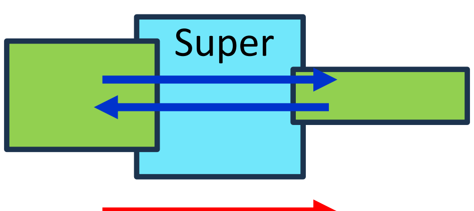
Is the time reversal symmetry breaking necessary for SDE?



Current // polar axis
-> Diode without the time reversal symmetry breaking







Current due to ΔT

Zero-field SDE in strained $PbTaSe^2$ by current // polar axis

Possibility of SDE due to device structural asymmetry

Y. Iwasa et al., arxiv.org/abs/2406.08157; Sci. Adv. accepted