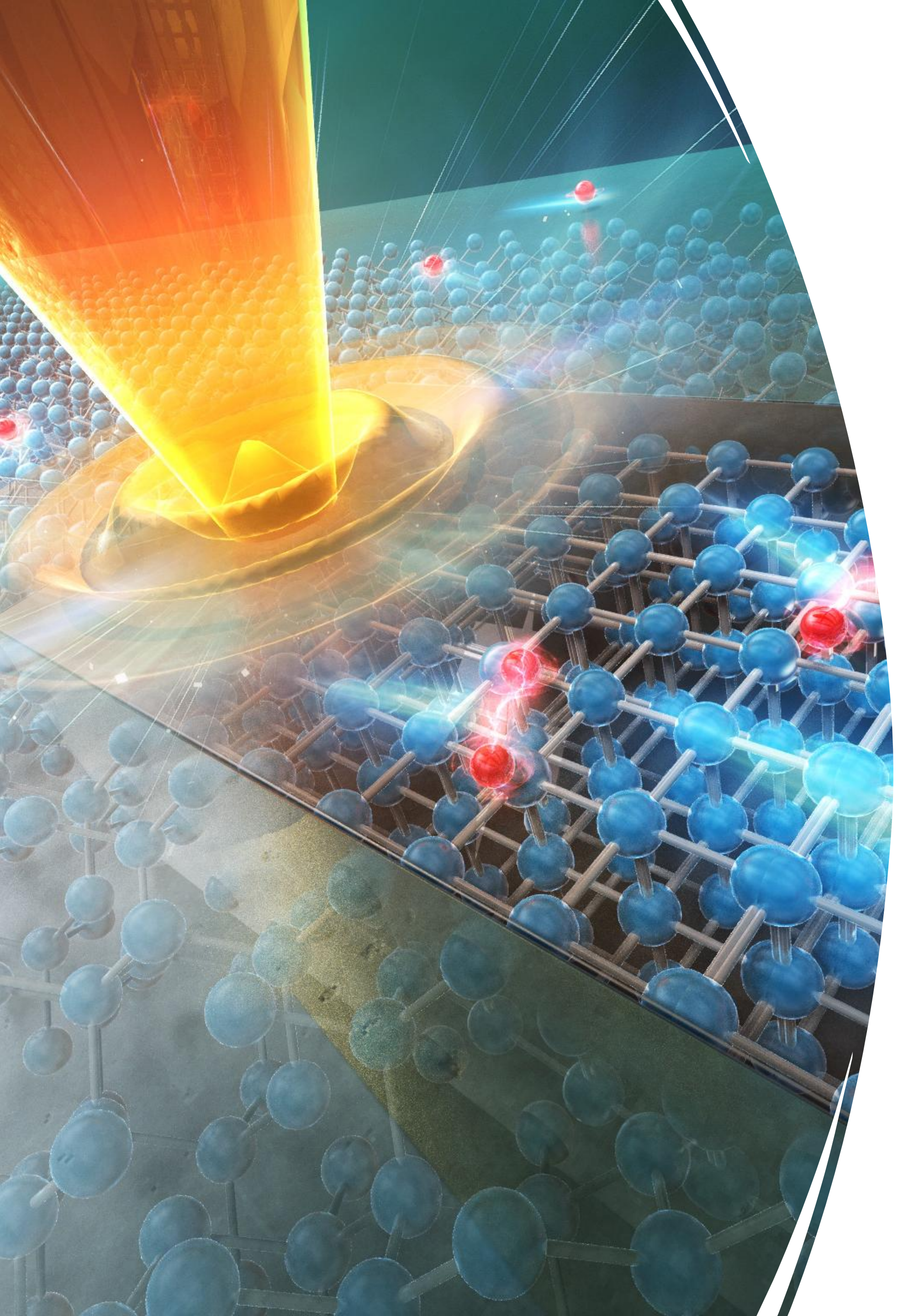

Sn-based quantum heterostructures: a platform for topological physics and devices

Le Duc Anh[1,2]

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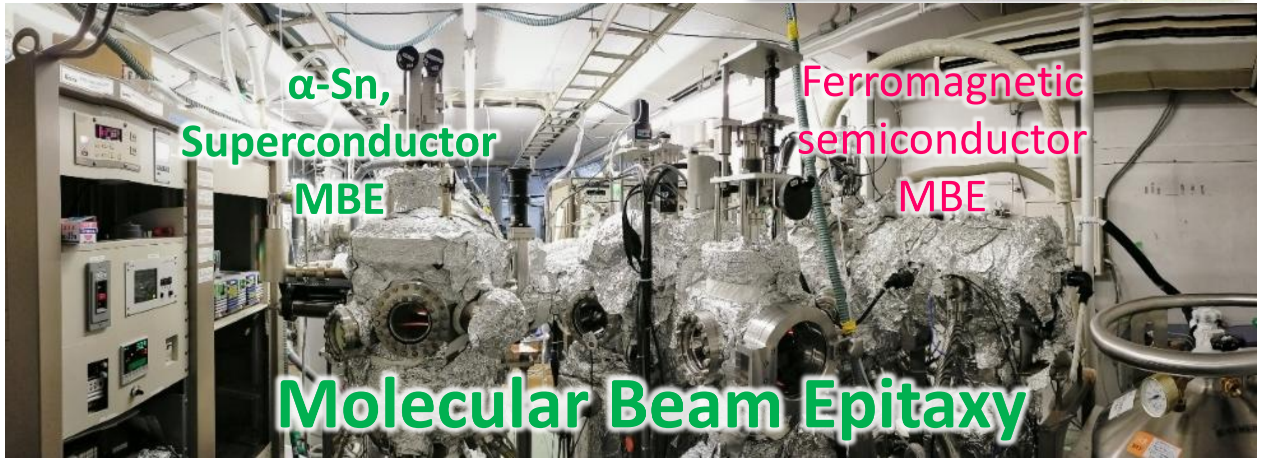
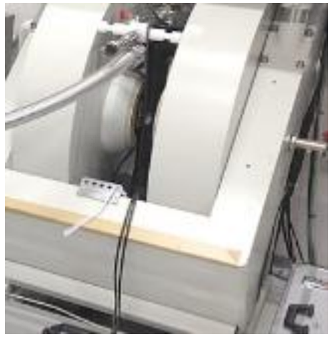
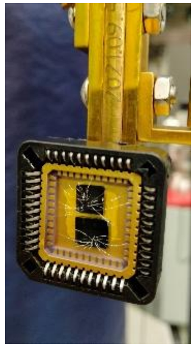
2. Center for Spintronics Research Network (CSRN), The University of Tokyo, Japan.

Our group in Utokyo: https://anh-lab.com



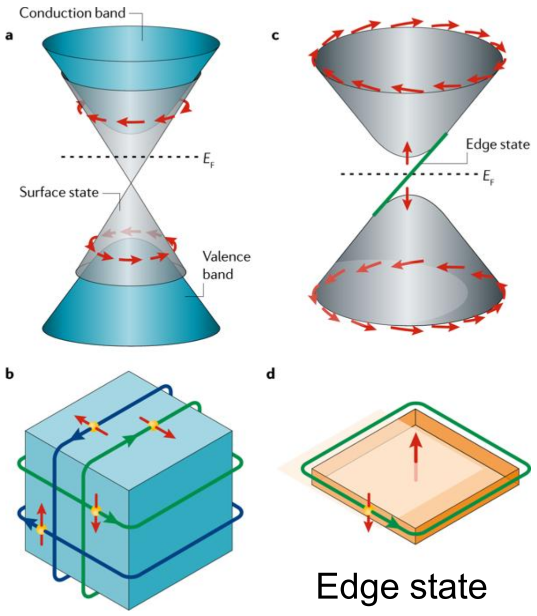




Topological materials

Topological Insulator (TI)

3-dimensional 2-dimensional



Surface state

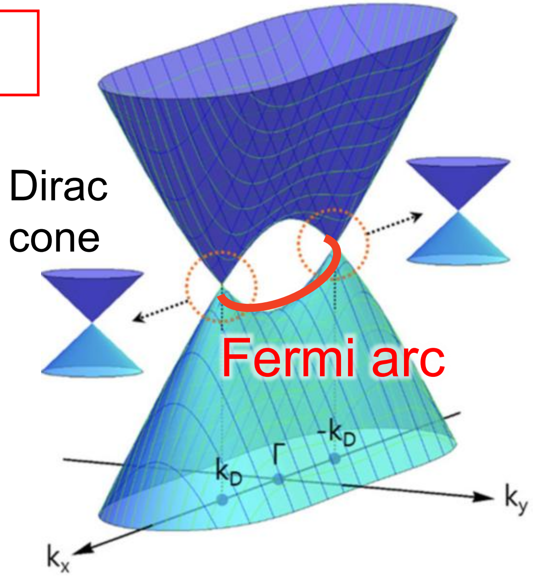
Spin-Momentum locking topological surface state (TSS)

Applications in Spin･Charge Conversion
Spintronics,Quantum information

Topological Dirac semimetal (TDS)

Dirac cones in the bulk band structure + **Fermi arcs**

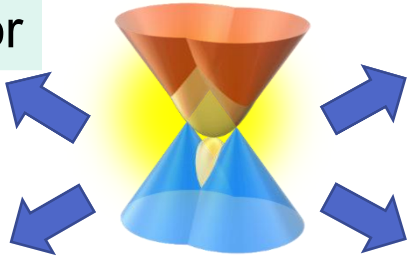
Requirements
- ✓Time Reversal Symmetry
- ✓Inversion Symmetry
- ✓New: Rotation Symmetry



Experimentally confirmed TDSs are rare: Na_3Bi, Cd_3As_2, α-Sn

Topological Superconductor

Weyl semimetal



Band Insulator

(TDS)
Parent state

Topological Insulator

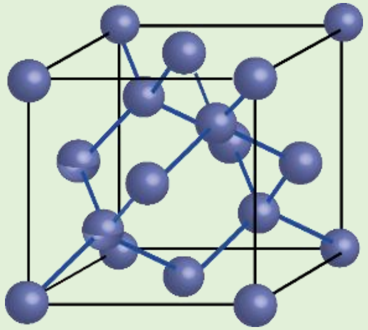
M. Z. Hasan, C. L. Kane, *Rev. Mod. Phys.* **2010**, 82, 3045.
N. P. Armitage, E. J. Mele, A. Vishwanath, *Rev. Mod. Phys.* **2018**, 90, 015001.
Z. K. Liu, et al., *Science* **2014**, 343, 864-867.
I. Crassee, et al., *Phys. Rev. Mater.* **2018**, 2, 120302.

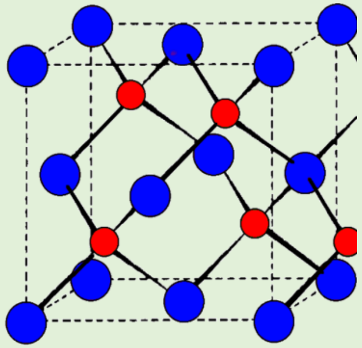
α-Sn: A rich elemental topological material

50 $4d^{10}5s^25p^2$
Sn
Tin
118.71

Advantages

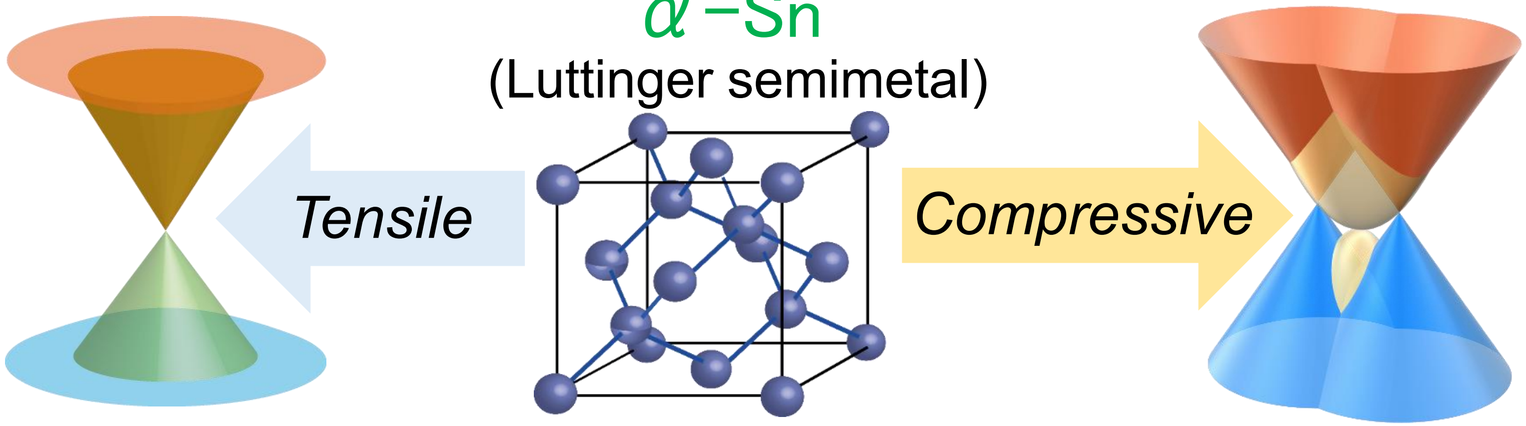
- Not toxic
- High quality film
- No off-stoichiometry or disorder issue



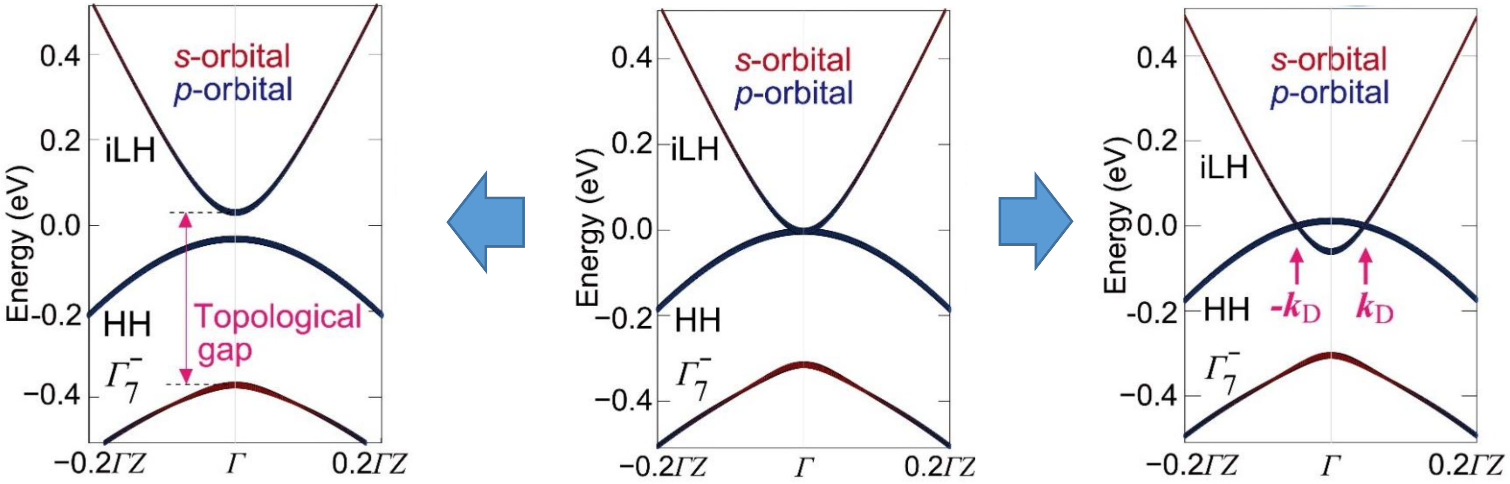


Elemental α-Sn can be grown nearly lattice-matched on InSb substrates (a = 6.489 Å)

α−Sn
(Luttinger semimetal)

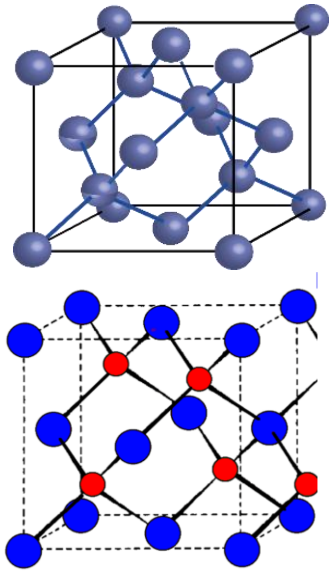


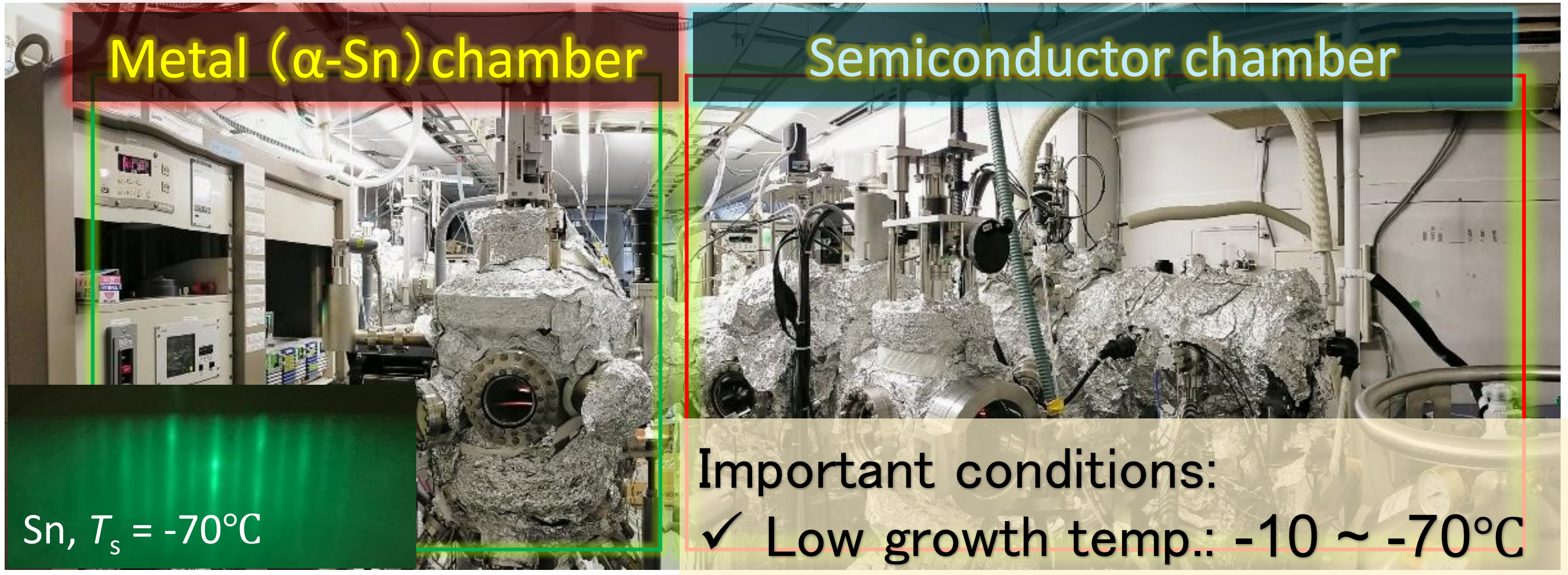
3D Topological Insulator (3D-TI) | **Bulk α-Sn** | **Topological Dirac semimetal (TDS)**

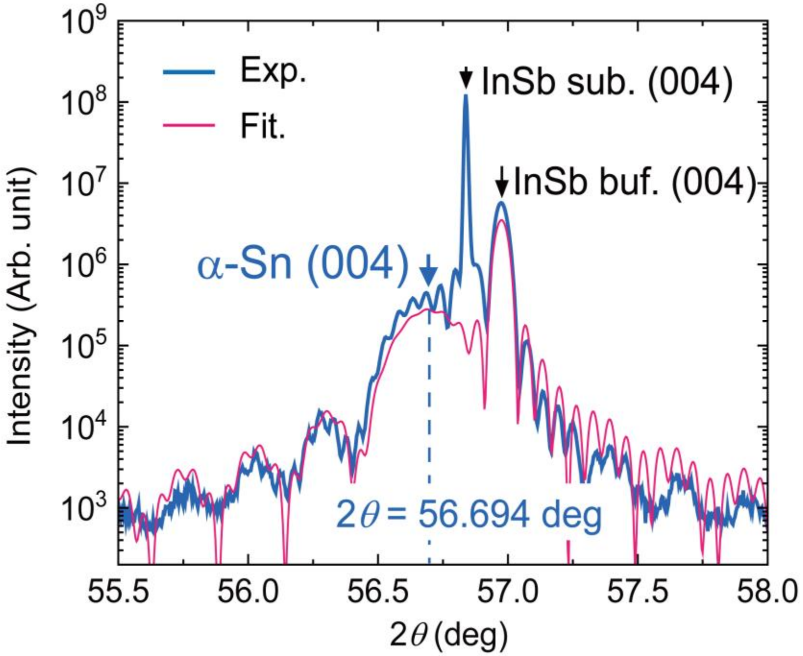


α-Sn is promising as a well-controlled material platform for topological physics that is compatible to mainstream semiconductors

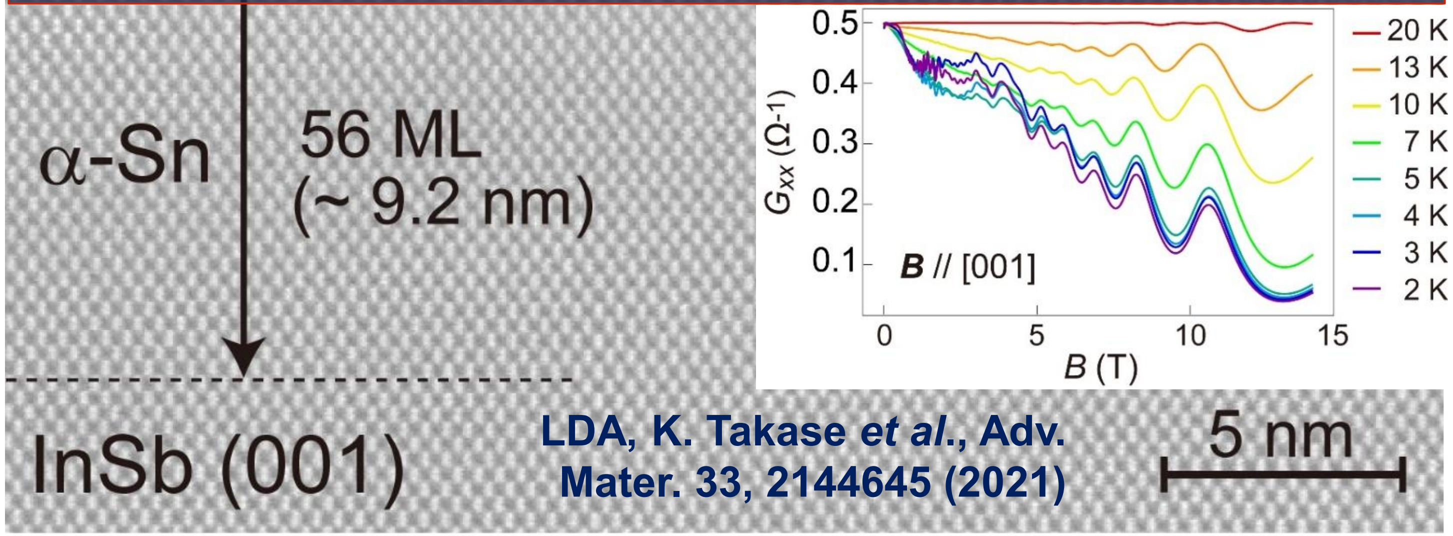
Epitaxial growth of α-Sn(001) on InSb





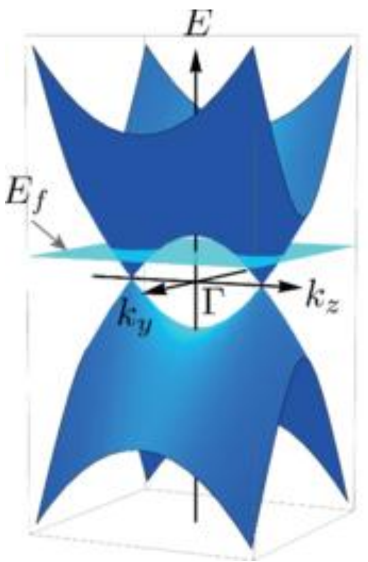


High-quality α-Sn on InSb(001) substrates



LDA, K. Takase *et al.*, Adv. Mater. 33, 2144645 (2021)

Spin-orbit-momentum coupling in Dirac semimetal



At the Dirac points, the basis set:

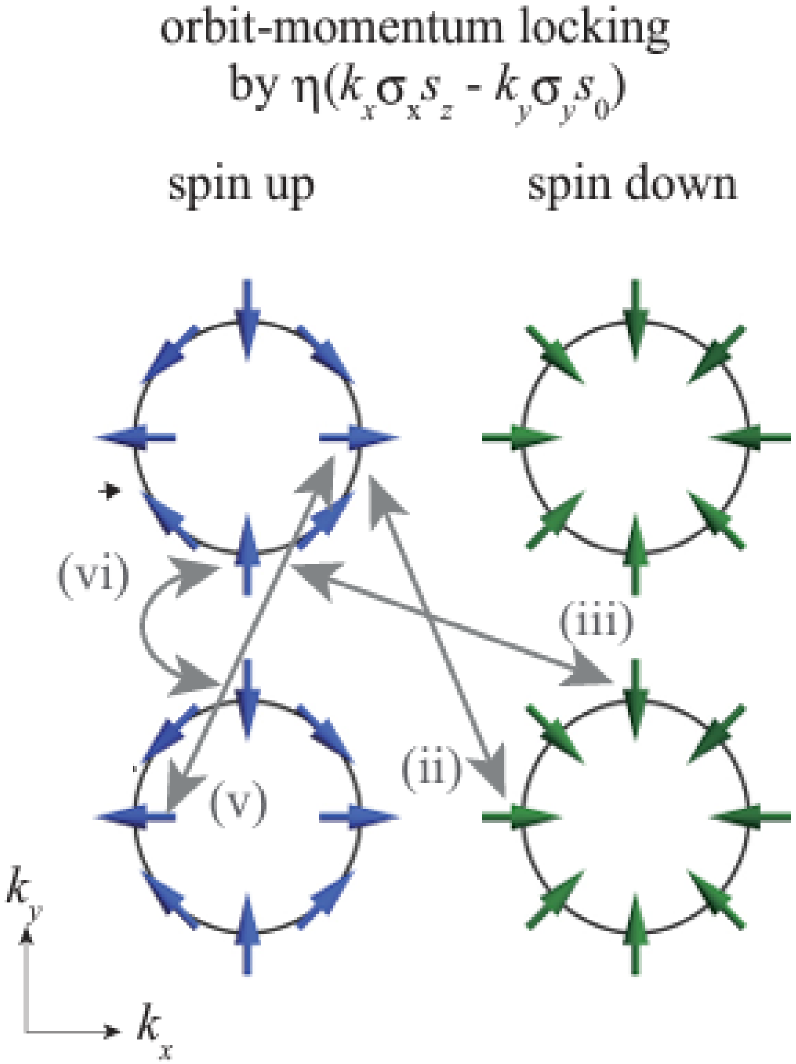
$$|\mathrm{s},\uparrow\rangle\ |\mathrm{s},\downarrow\rangle$$

$$|\mathrm{p}_x + i\mathrm{p}_x,\uparrow\rangle\ |\mathrm{p}_x - i\mathrm{p}_x,\downarrow\rangle$$

Orbital space operators $\sigma_0, \sigma_x, \sigma_y, \sigma_z$

Spin space operators s_0, s_x, s_y, s_z

Hashimoto et al., PRB, 94, 014510 (2016)



Orbital texture of Dirac semimetals

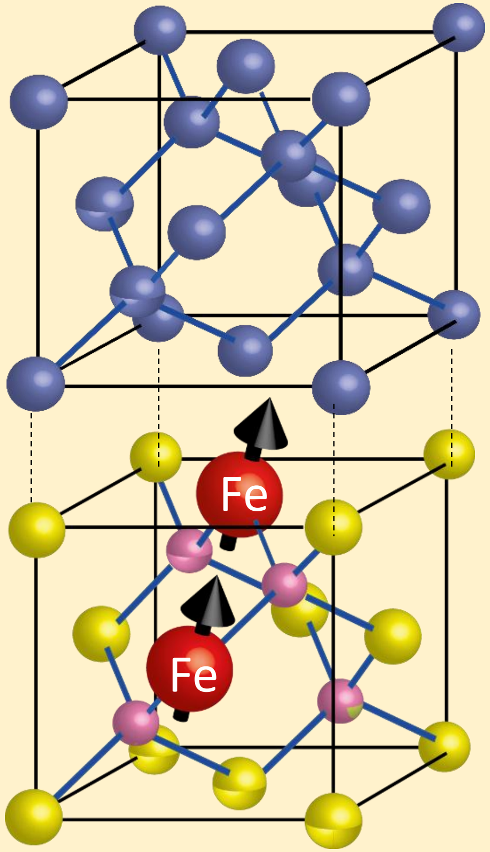
Up-spin: $$H_{n\uparrow}(\boldsymbol{k}) = a(\boldsymbol{k})\sigma_z + \eta(k_x\sigma_x - k_y\sigma_y)$$

Down-spin: $$H_{n\downarrow}(\boldsymbol{k}) = a(\boldsymbol{k})\sigma_z - \eta(k_x\sigma_x + k_y\sigma_y)$$

This strong coupling leads to giant electromagnetic responses of TDS (α-Sn)

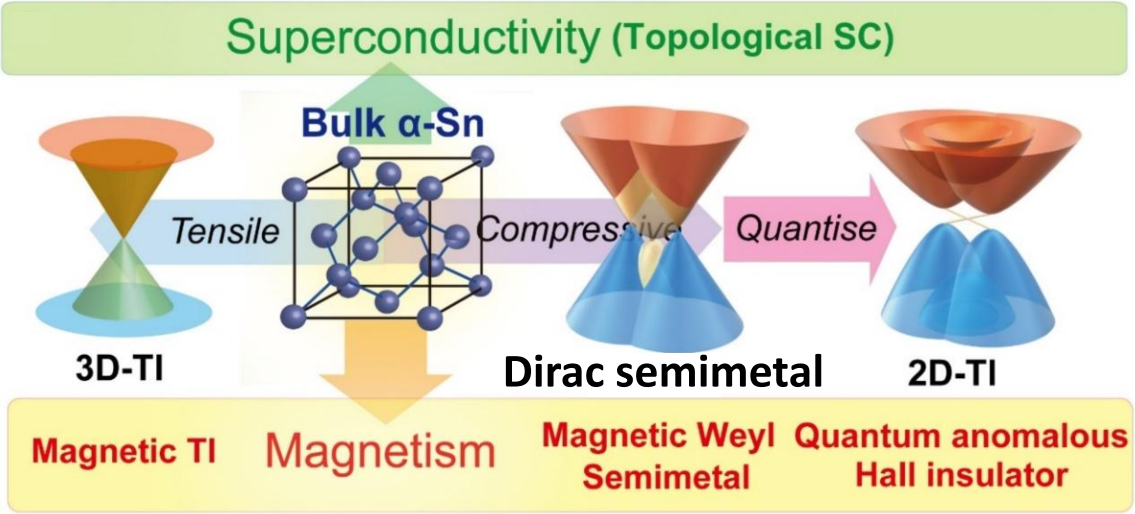
Perspective: Integration of "superconductivity" and "magnetism"

α-Sn
(zero-gap semimetal)



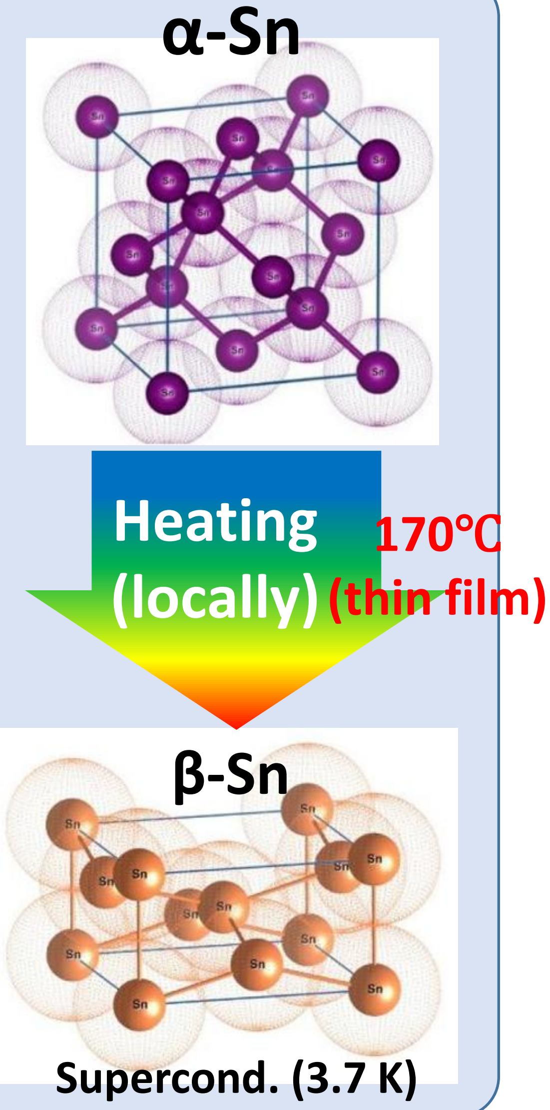
(In,Fe)Sb
(lattice-matched)

α-Sn: a zoo of topological phenomena

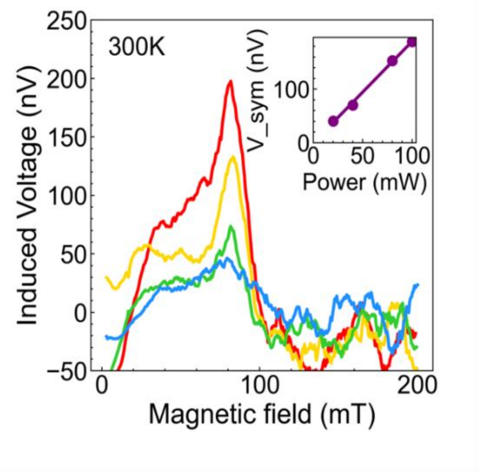


Magnetic proximity effect
Superconducting proximity effect
Control by Strain & Electrical gating

All of these novel topological phenomena can be realized in a single-element material

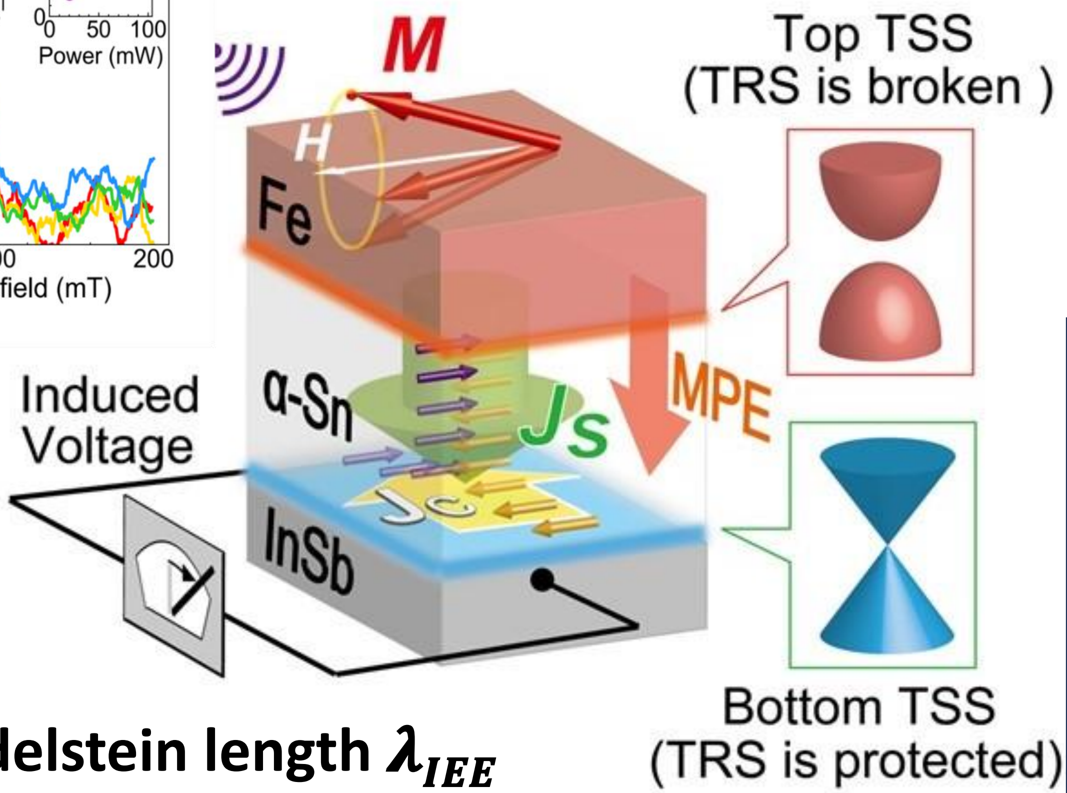


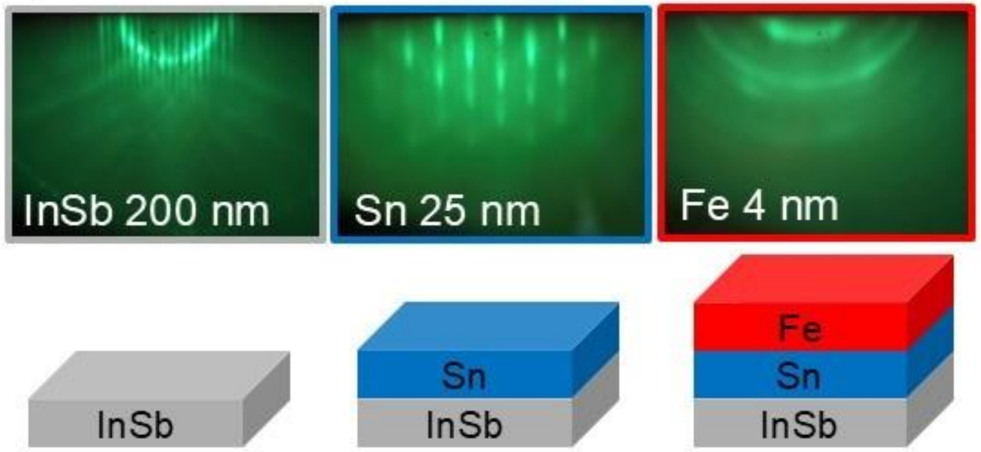
Ferromagnet/α-Sn as promising spintronic platform



Bilayer Fe/α-Sn (9 – 35 nm)

(arXiv:2507.17639)



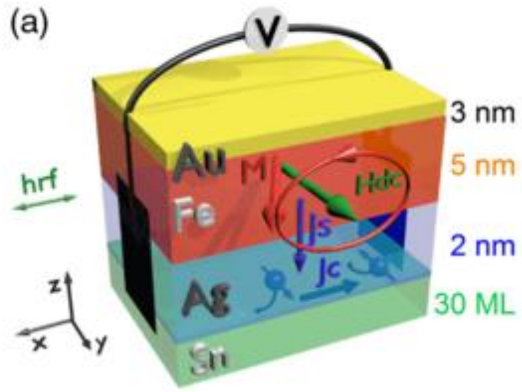


Previous results: [Rojas-Sanchez et al. PRL (2016)])

- **By inserting spacer layer (Ag),** good spin-charge conversion was realized

λ_{IEE} = 2.1 nm (300 K)

θ_{SHE} = 0.66 ~ 1.6 (300K)



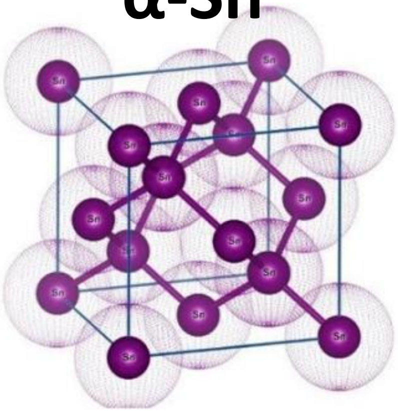
Inverse Edelstein length λ_{IEE}

$$\lambda_{IEE} = \frac{j_c^{2D}}{j_s^{3D}}\left(\frac{\hbar}{2e}\right) \sim 3.14\ \mathrm{nm}$$

Highest spin-charge conversion efficiency (λ_{IEE}) by TSS obtained at RT

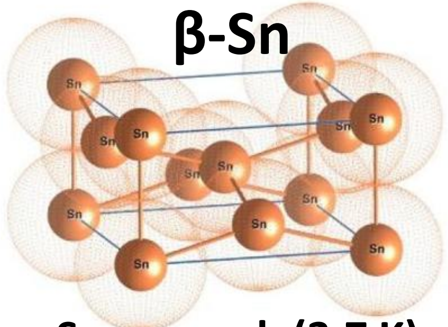
α-Sn/ β-Sn nanostructures: Superconductivity by proximity effect

α-Sn



Heating (locally)

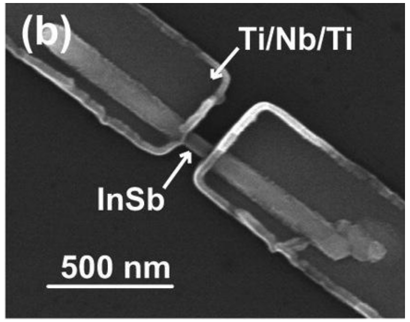
β-Sn



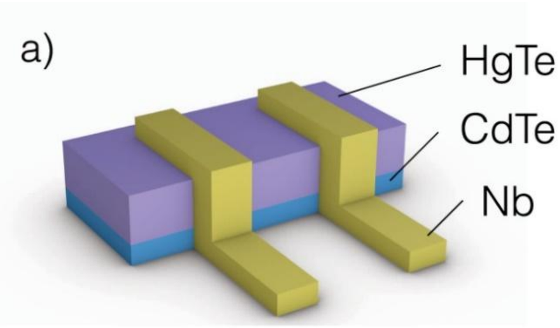
Supercond. (3.7 K)

Proximity effect at interfaces between superconductor and topological materials is promising for realizing Majorana physics

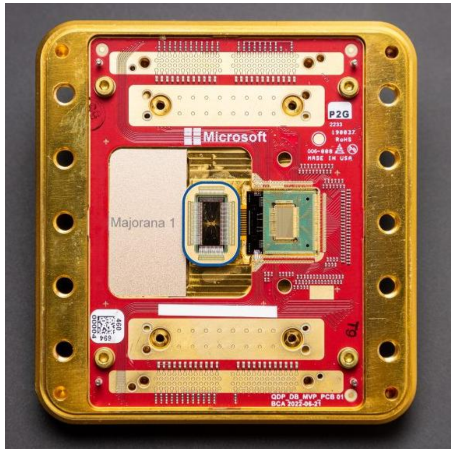
L. Fu and C. L. Kane, PRL (2008)



Gazibegovic et al, Nature **548**,434 (2017)



J. Wiedenmann et al.,
Nat. Comm. 7, 10303 (2016)



Majorana-1 (Microsoft)

To achieve a material platform for large-scale quantum computing, the critical challenges are

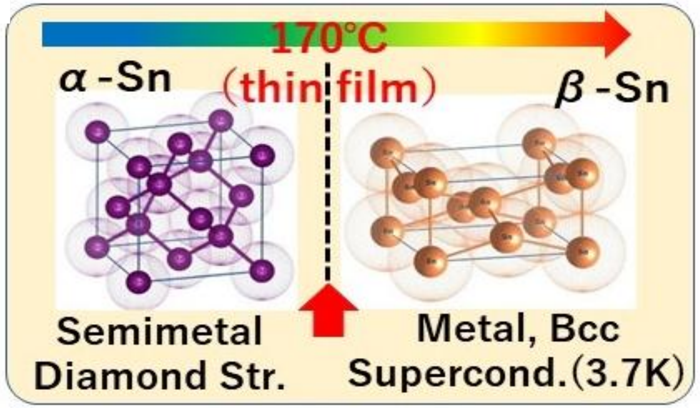
- **establishing high-quality interfaces**
- **utilizing cost-effective and scalable processes** for material growth and nanofabrication.

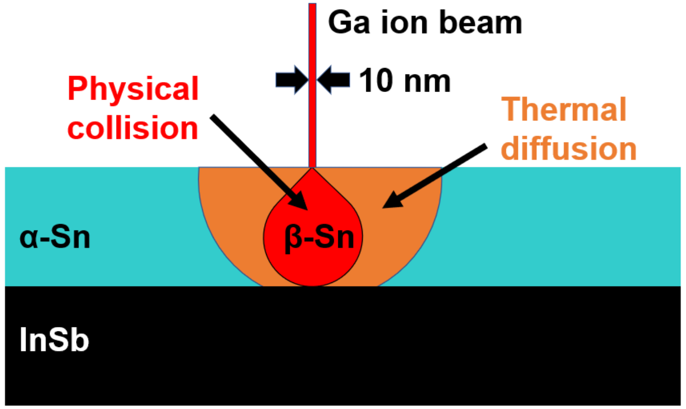
Sn-based SC/TDS heterostructure formed by ion beam irradiation

Our new method: β-Sn regions are formed by physical collisions and thermal diffusion.

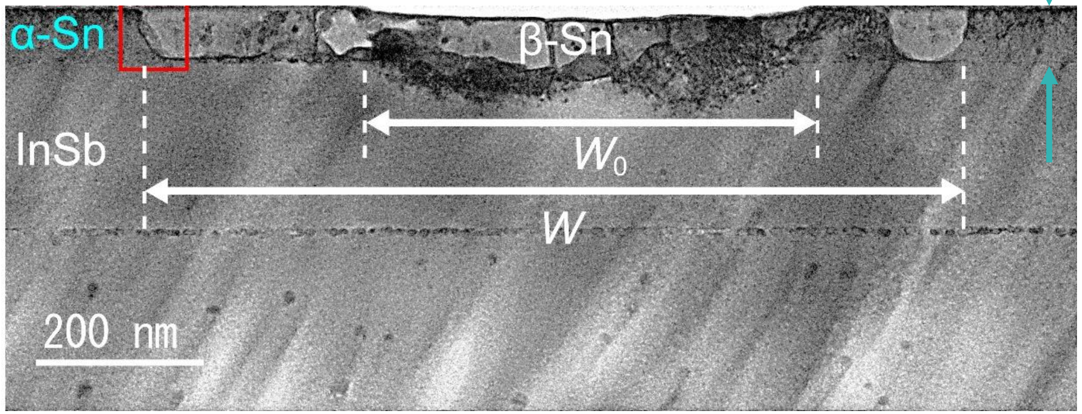
L. D. Anh et al, Nature Commun. 15, 8014 (2024)

Lots of room to optimize ion beam conditions



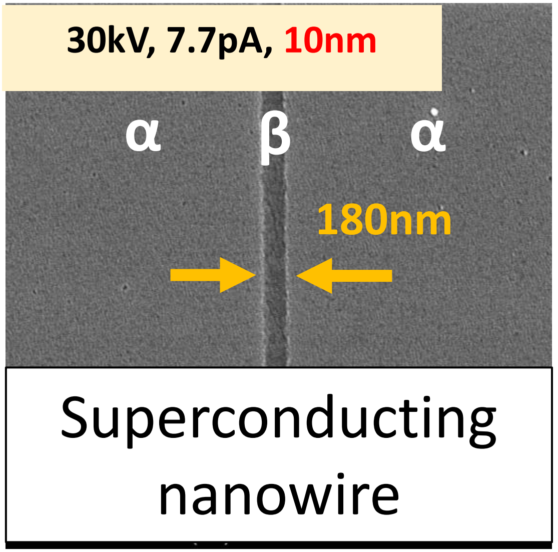


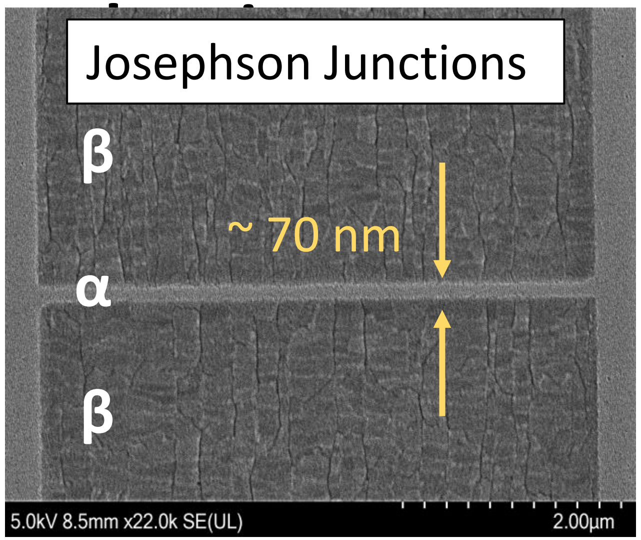
70 nm



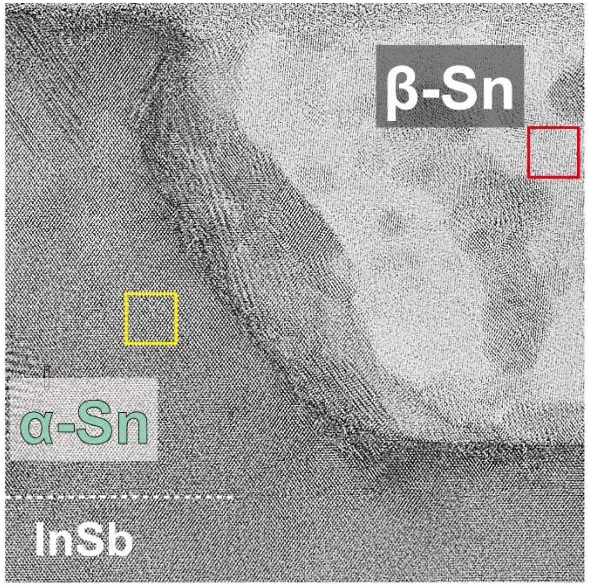
"Topological Circuit"

can be freely produced by Ion beam or laser

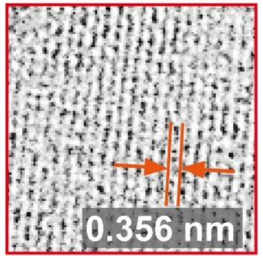




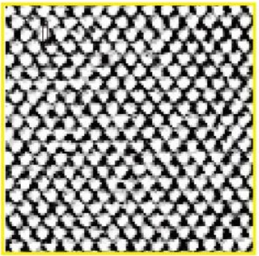
20 nm



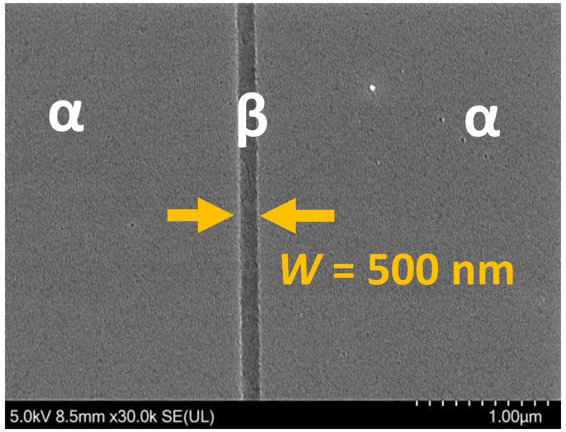
β-Sn (100)

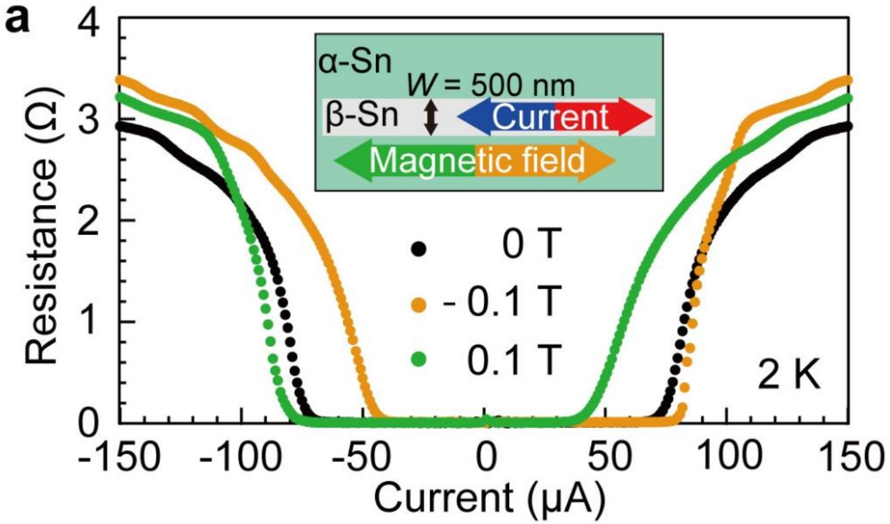


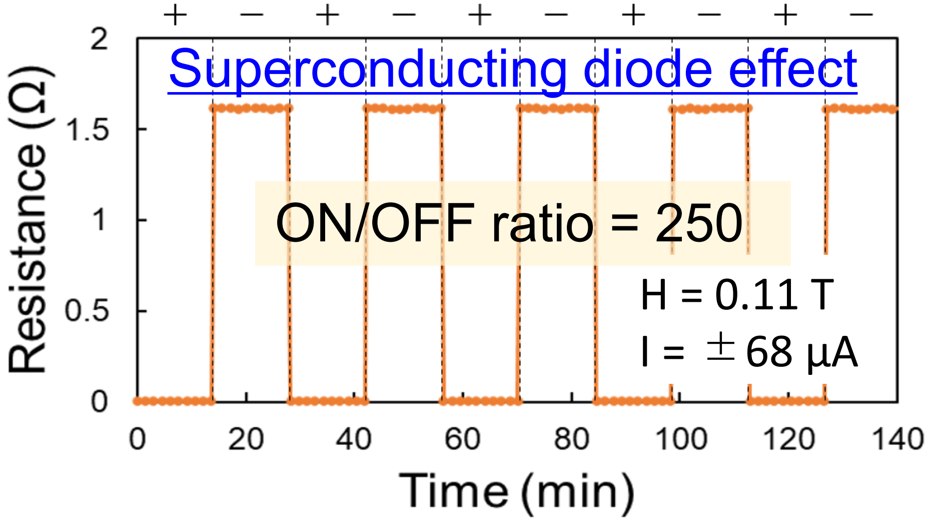
α-Sn 2 nm



Giant superconducting diode effect (SDE) in α-Sn/β-Sn SC NW



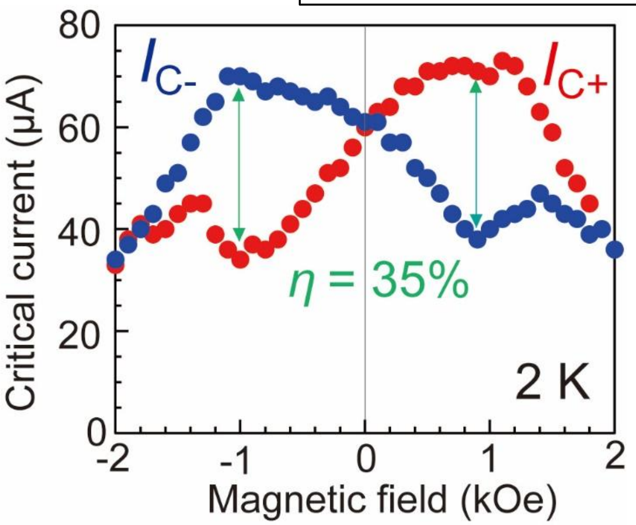


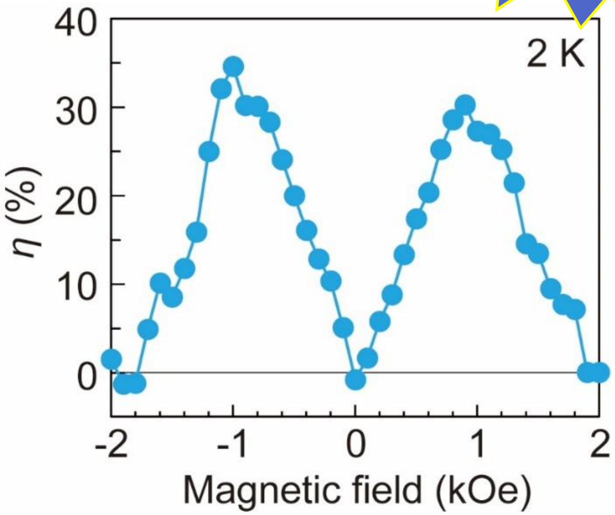


Non-reciprocal superconductivity in a β-Sn nanowire when H//I

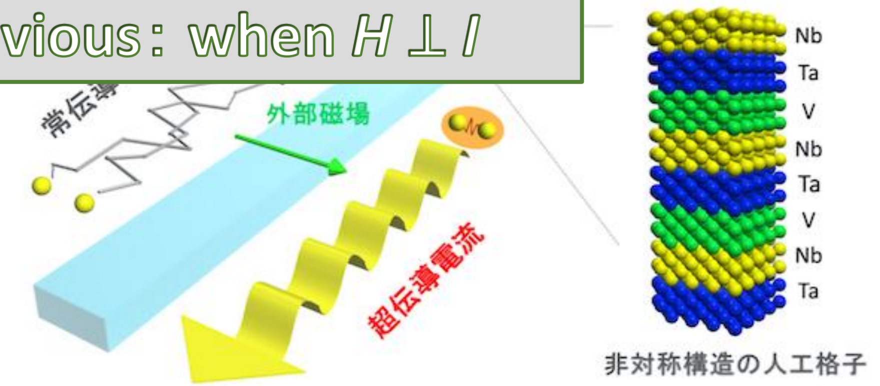
$$\eta = (I_{C+} - I_{C-})/(I_{C+} + I_{C-})$$

New !





Previous: when $H \perp I$



F. Ando et al, Nature 584, 373-376 (2020).

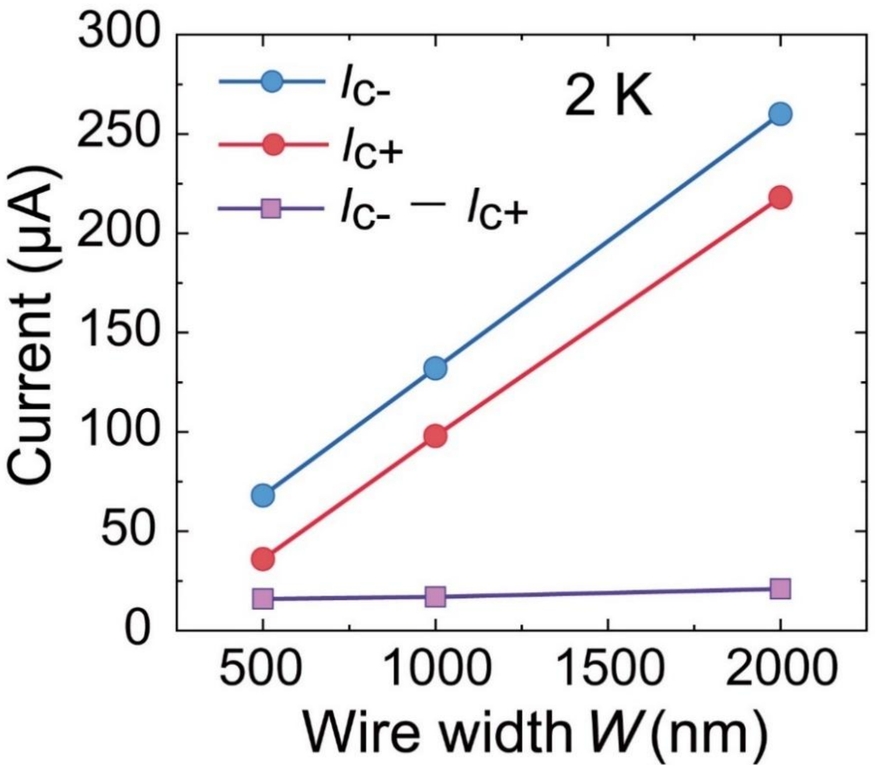
- Noncentrosymmetric SC (Intrinsic)

A. Daido et al., PRL 128, 037001 (2022). 他

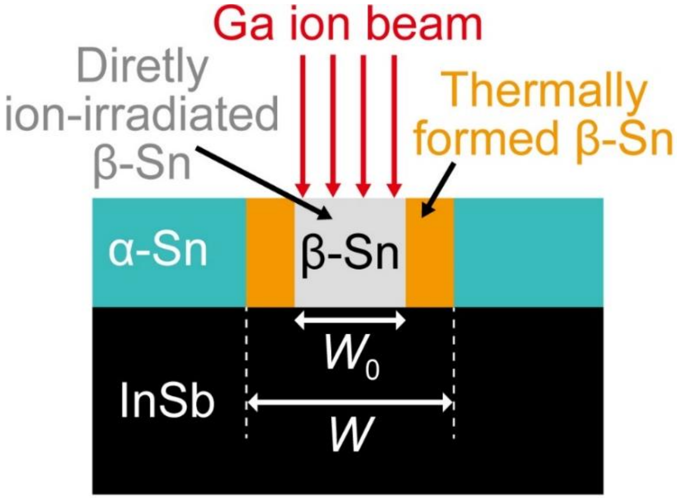
- Geometrical asymmetry, vortex pinning (Extrinsic)

Y. Hou et al, PRL (2023), D. Suri et al. APL (2023)

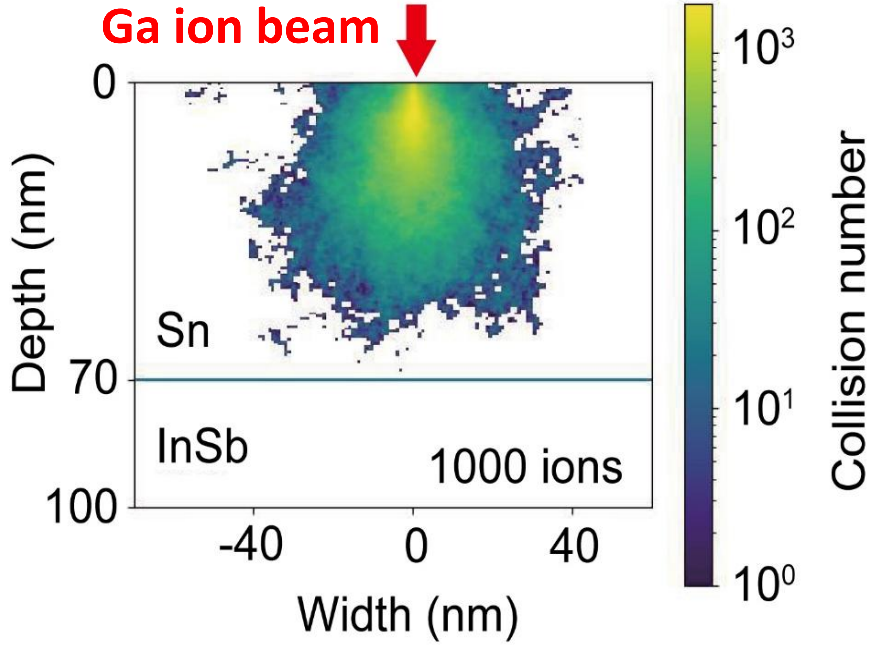
Width dependence of the SDE



W_0 (nm)	W (nm)
350	500
850	1000
1850	2000

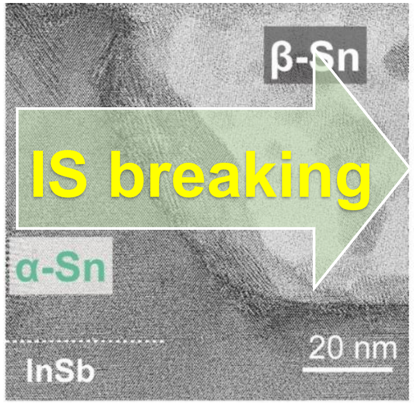


Thermally formed β-Sn part is 75 nm- wide in each side

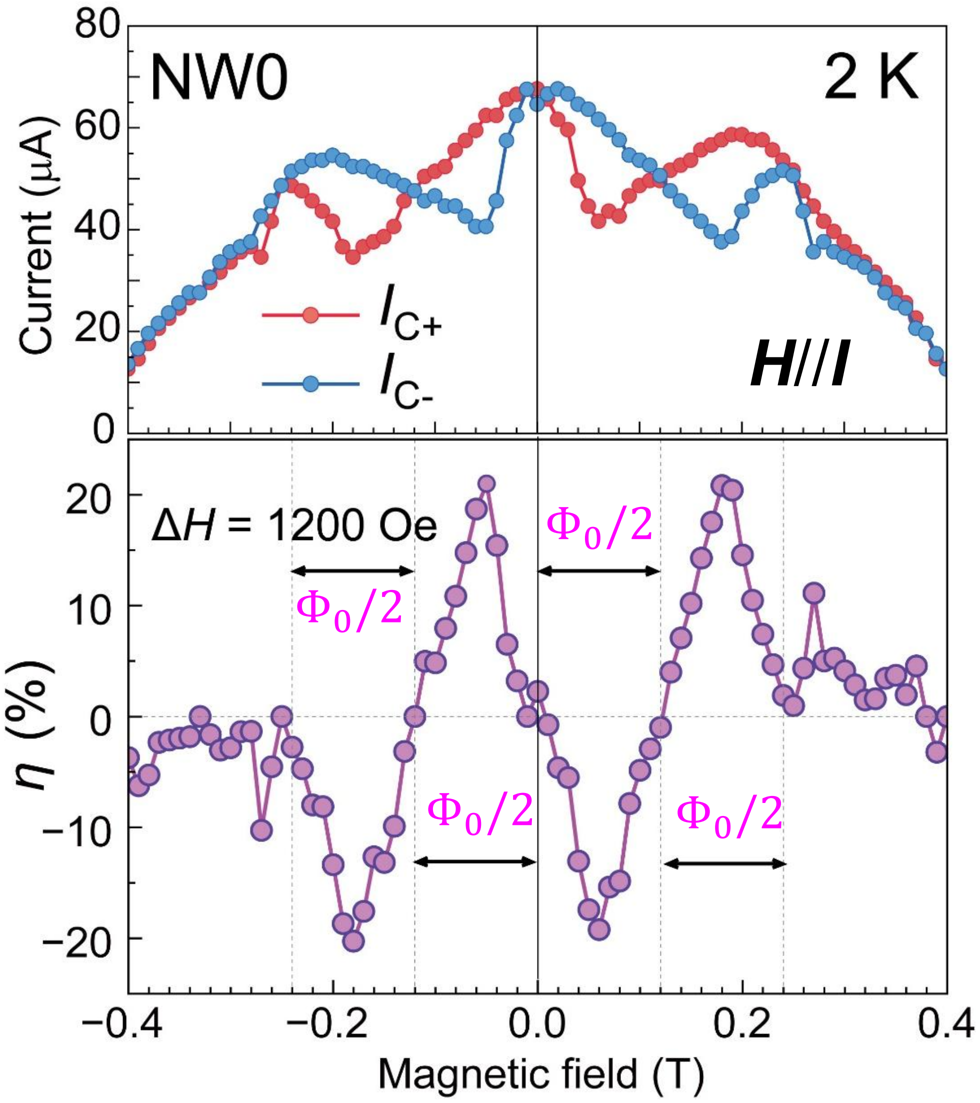


The odd-component (I_{C-} - I_{C+}) only weakly depends on NW width

- ☐ SDE occurs at the α-Sn/β-Sn interfaces, where **inversion symmetry is broken** (in *y* direction)
- ☐ α-Sn become superconducting due to a **proximity effect (~ 50 nm)**
  ⇒ ***TDS α-Sn affect the superconductivity of the nanowires***



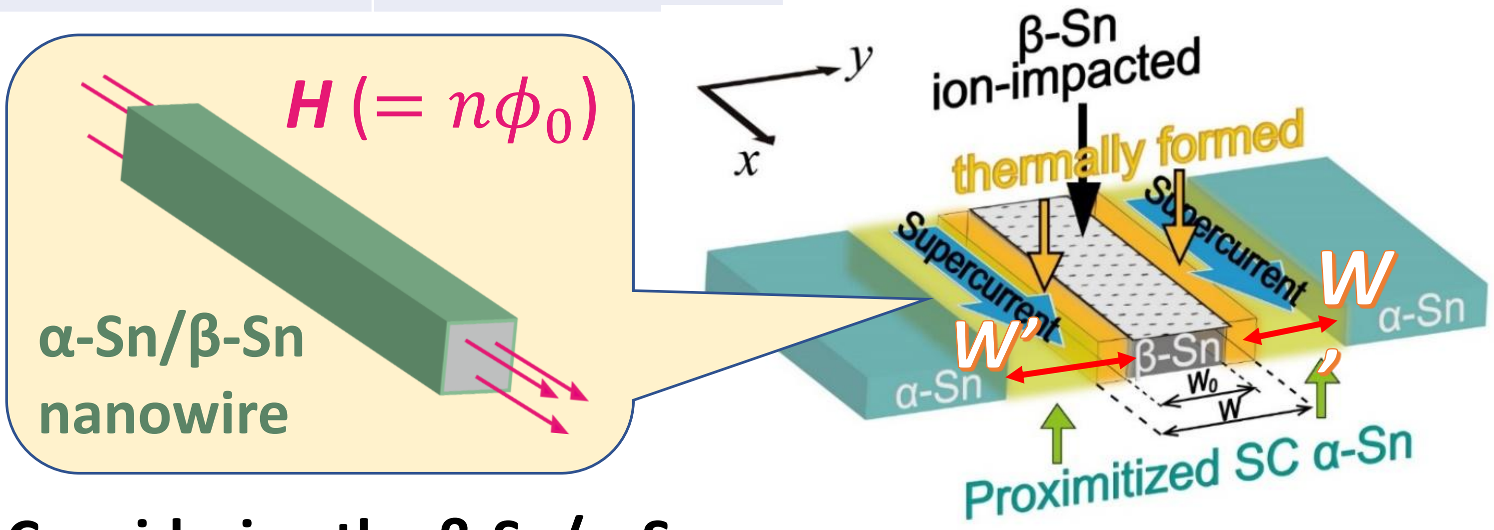
Oscillating magnetic field dependence of the SC rectification



Parameters	Values
W’ (nm)	75 + 50 ≈ 125
t (nm)	70

$\Delta H = 2400\ \mathrm{Oe} \cong \Phi_0$

1 flux quantum penetrating Sn nanowires



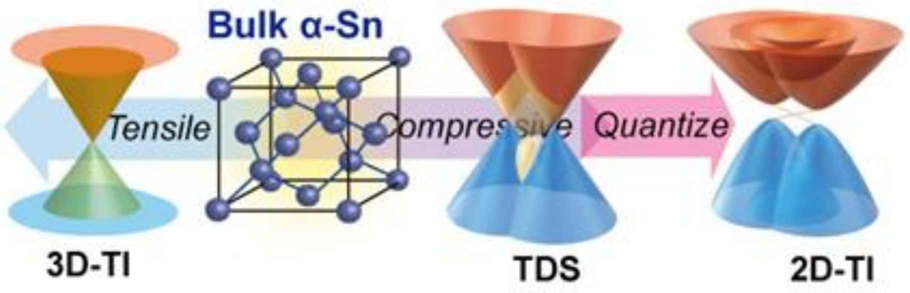
Considering the β-Sn/α-Sn superconducting nanowire model formed on both sides

- η oscillates with H = 2400 Oe (= Φ_0)
- η changes sign at H = 1200 Oe $\left(= \frac{\Phi_0}{2}\right)$

Very good controllability compared to other superconducting diode material systems

Conclusion remarks

L. D. Anh et al, Adv. Mater. 33, 2104645 (2021)



▶**Giant Superconducting Diode Effect**

L. D. Anh et al, Nat. Commun. 15, 8014 (2024)

▶**Giant Odd-parity Magnetoresistance**

T. Hotta, LDA, et al. arXiv:2507.23166

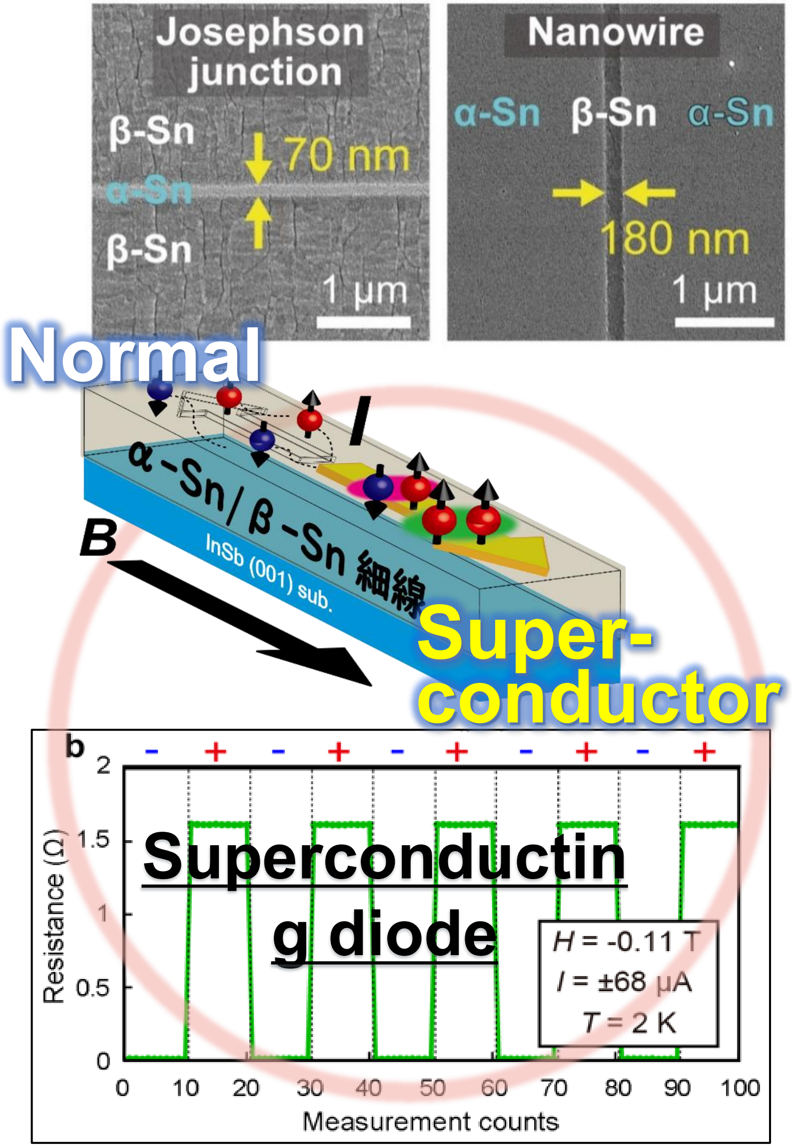
▶**Giant Spin to Charge Conversion**

M. Ishida, LDA, et al., arXiv:2507.17639

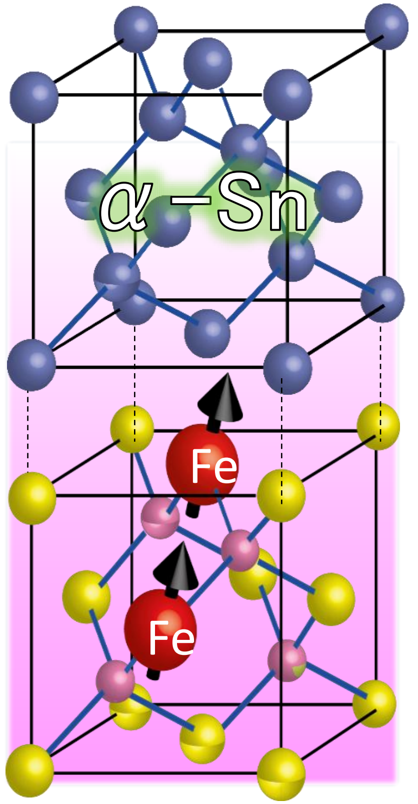
All of these novel topological phenomena can be realized in a single-element material

α-Sn: a zoo of topological phenomena

SC/TDS topological circuits



Magnetic proximity effect



(Ferromagnetic)

Acknowledgements

■ CSRN, UTokyo

- Prof. Masaaki Tanaka
- Kengo Takase
- Keita Ishihara
- Tomoki Hotta
- Daiki Nishigaki
- Soichiro Fukuoka
- Takahiro Saeki

Takase
(Nomura Res. Inst.)

Ishihara
(Rapidus)

Hotta
(Sandisk)

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- Dr. Takahiro Chiba (theory)
  (*now at Tohoku univ.)
- Prof. Yohei Kota (theory)

■ Photoemission spectroscopy (UTokyo)

- Prof. Masaki Kobayashi
- Kohdai Inagaki

科研費 KAKENHI

JST

CSRN Center for Spintronics Research Network
Graduate School of Engineering, The University of Tokyo

Spin-RNJ スピントロニクス学術研究基盤と連携ネットワーク拠点
Spintronics Research Network of Japan