



# Next generation of spin-orbitronics: a *topological* approach to flexible electronic and spintronic devices

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**Mafalda Moreira**

PhD Student in Physics | MAP-Fis Doctoral Program

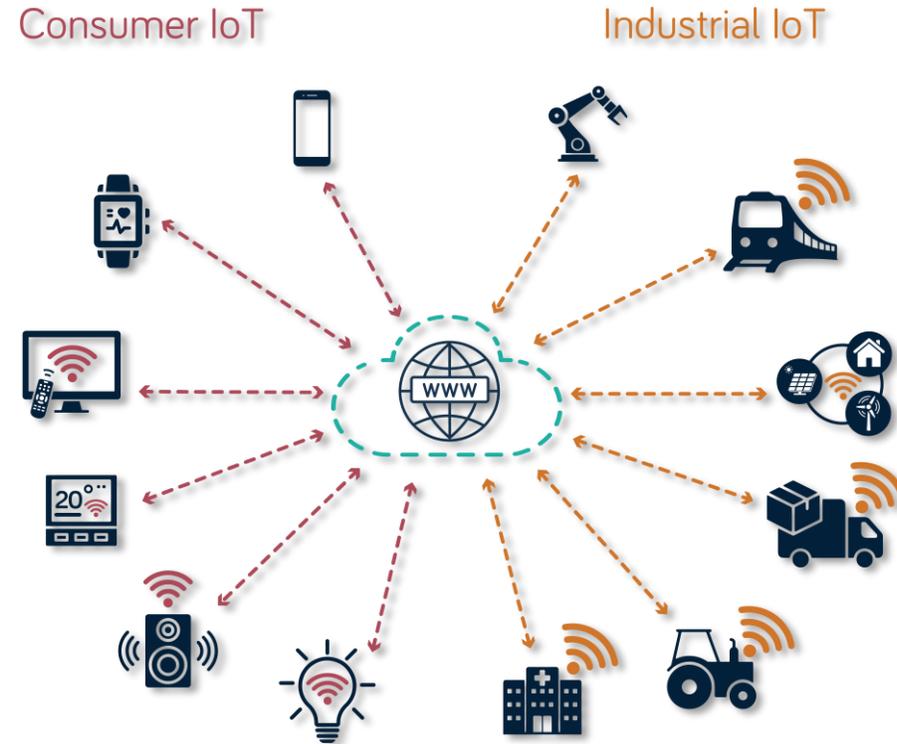
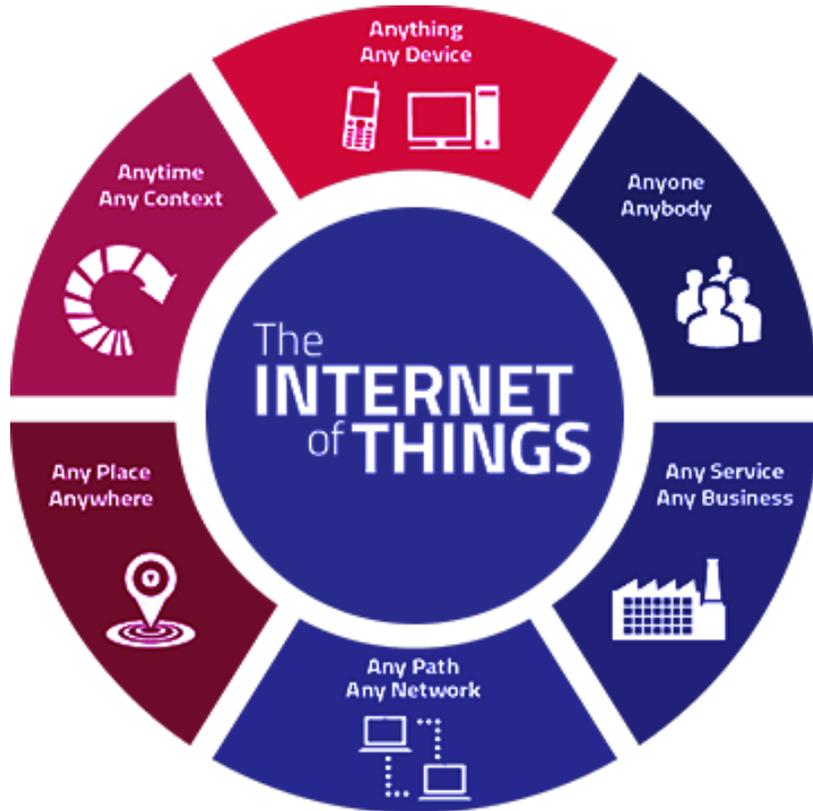
**Advisors:**

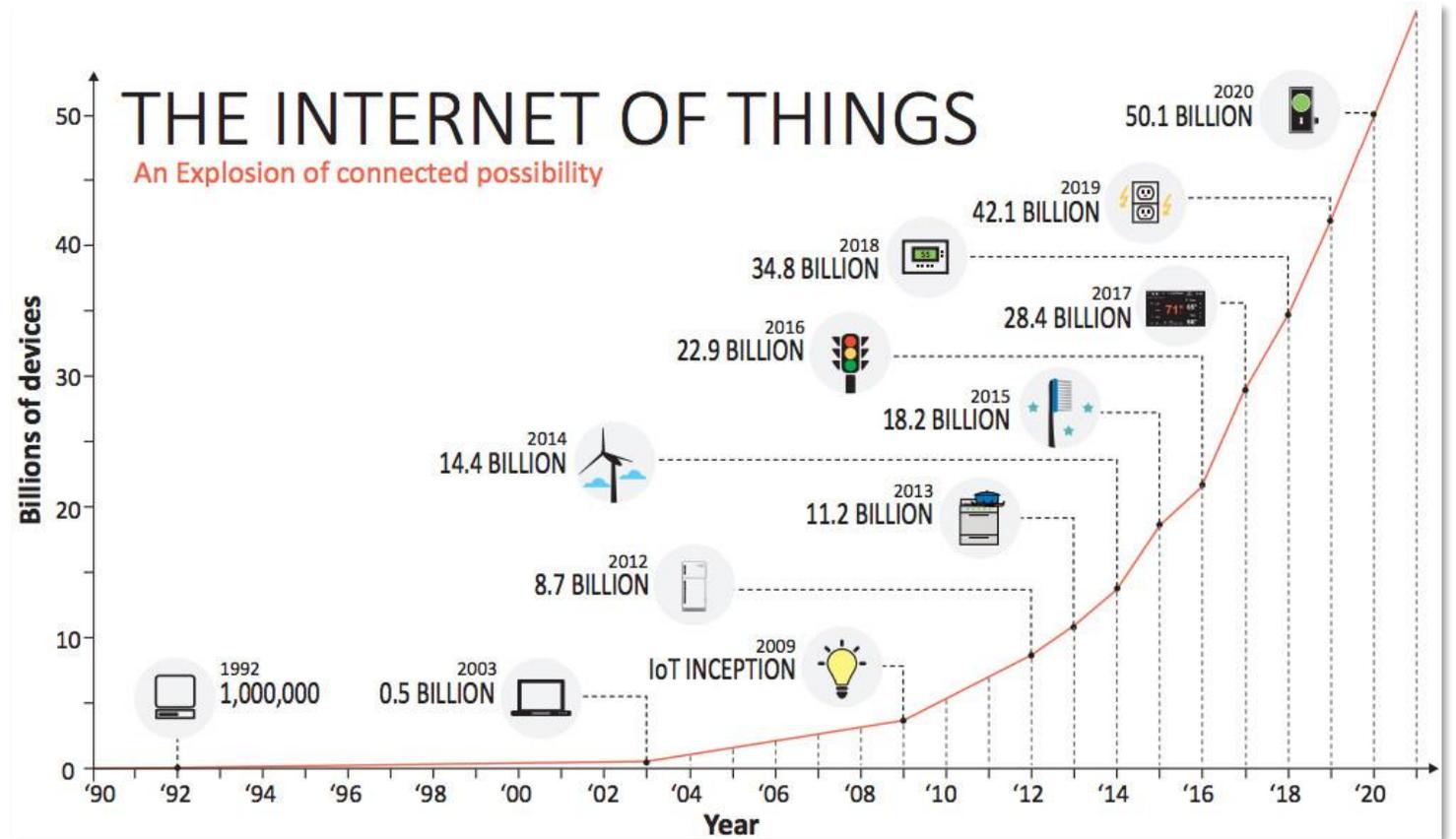
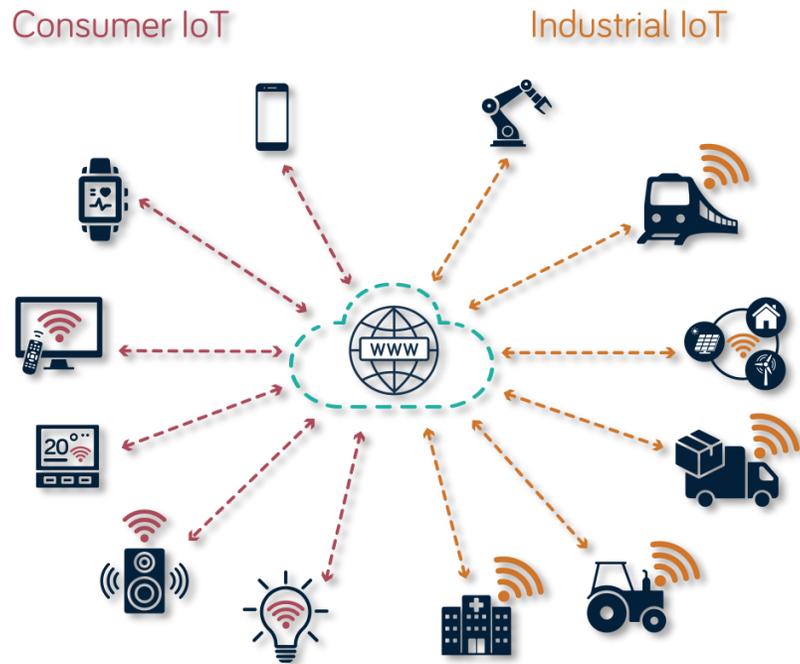
André M. Pereira | Eduardo V. Castro | Ana L. Pires

# Content Overview

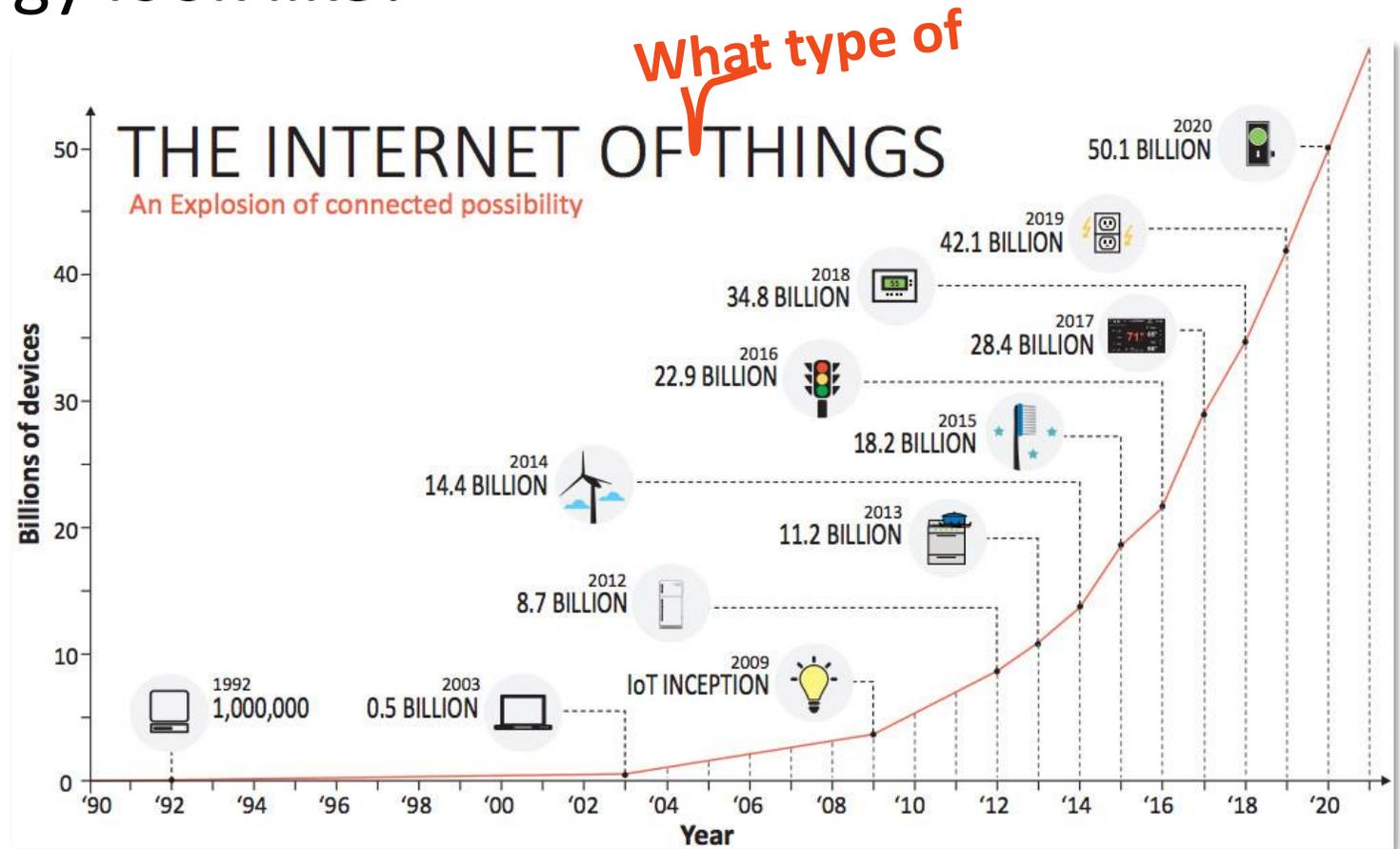
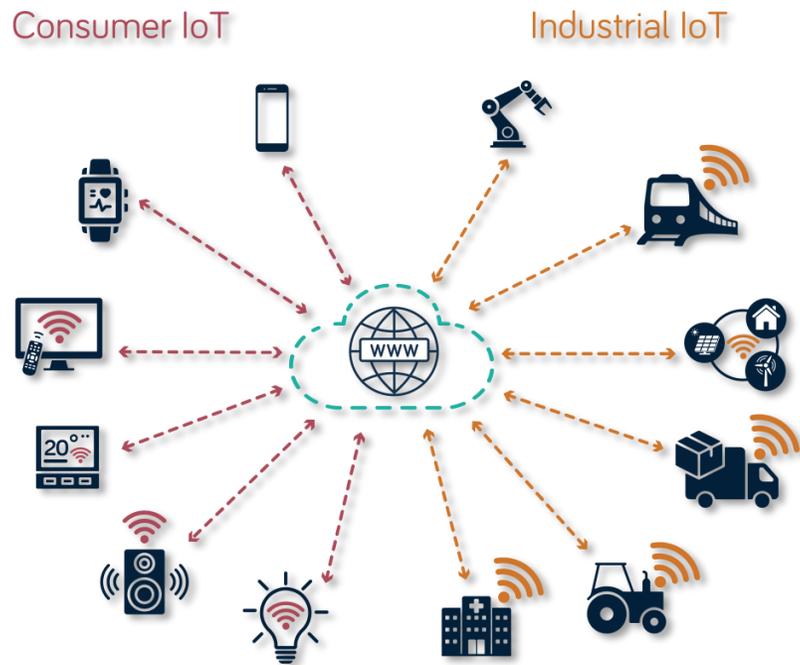
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- ↙ Motivation
- ↙ State-of-the art review
- ↙ Previous experimental results
- ↙ Research proposal
- ↙ Conclusion



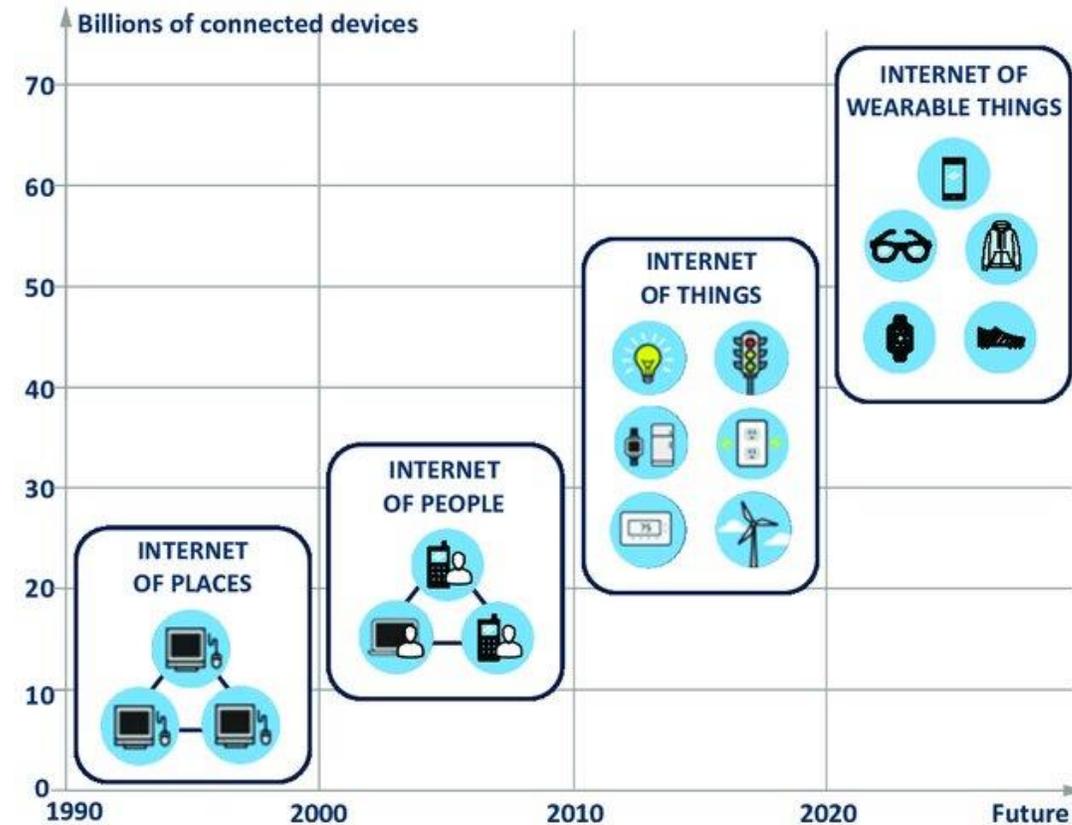
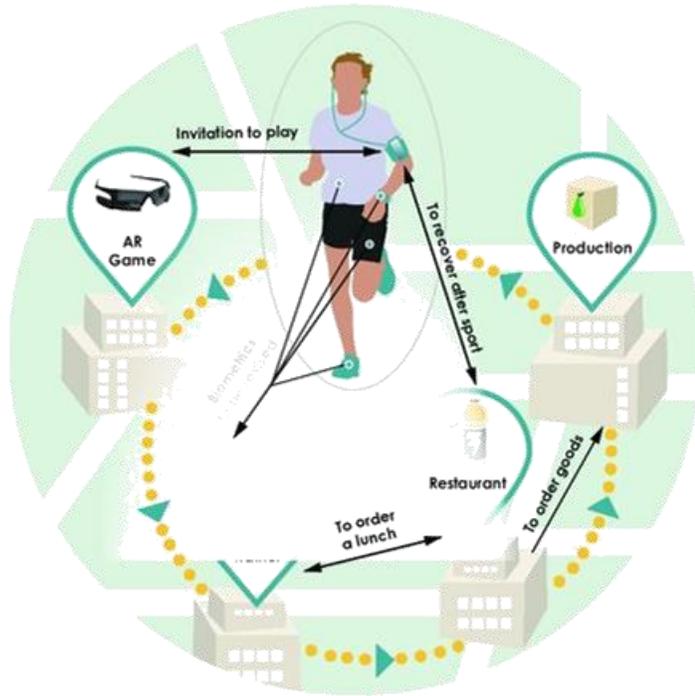


# What will future technology look like?



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Adaptable

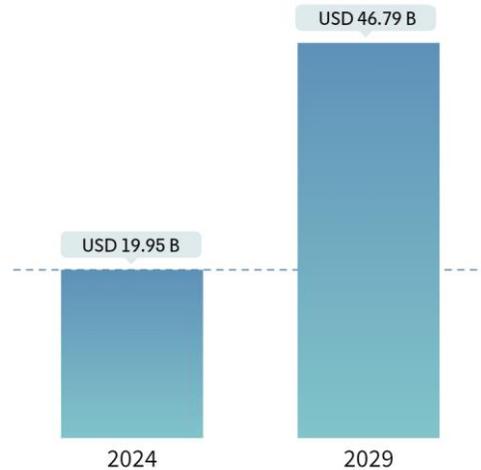


# What will future technology look like?

## Adaptable

Roll To Roll Flexible Electronics Market

Market Size in USD Billion  
CAGR 18.59%

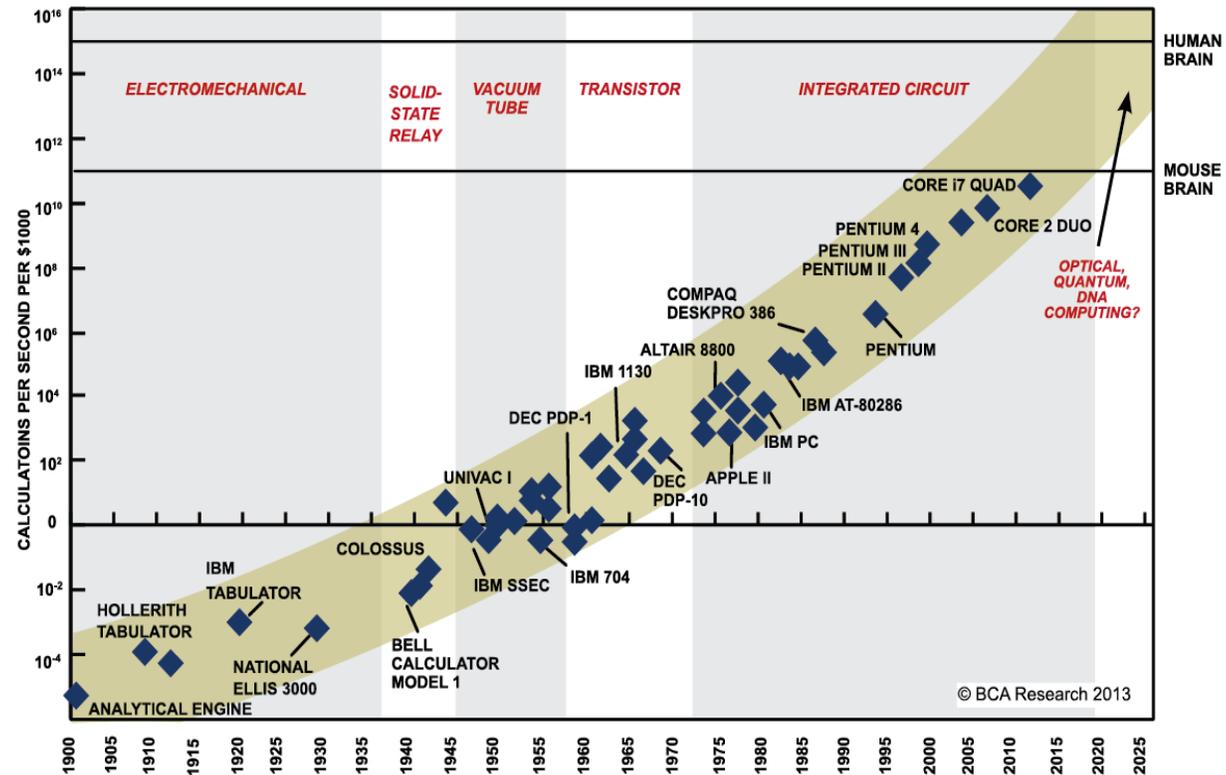


in Website. MOKOSmart. *Wearable IoT for All Industries* (2023) <https://www.mokosmart.com/wearable-iot-for-all-industries/>  
Mordor Research & Ltd *Roll to roll flexible electronics market size and share analysis - growth trends and forecasts (2024 - 2029)* (2024).

# What will future technology look like?

Adaptable

Efficient

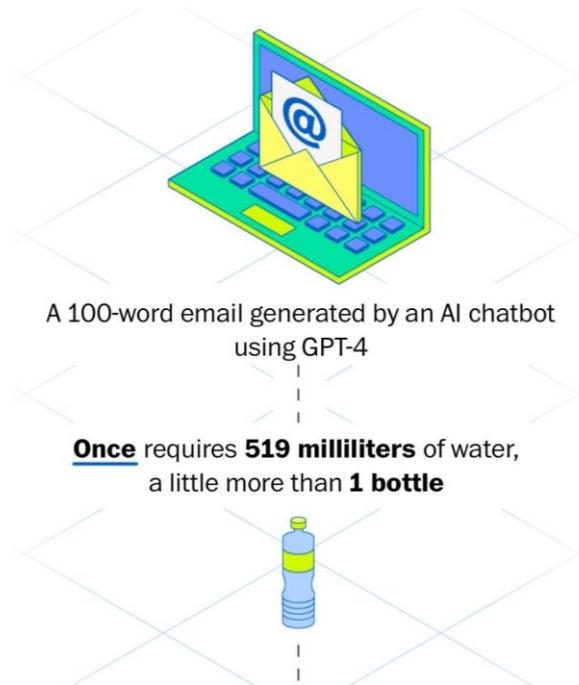


**Moore's law:** the number of transistors in a dense integrated circuit (IC) doubles about every two years.

# What will future technology look like?

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Efficient



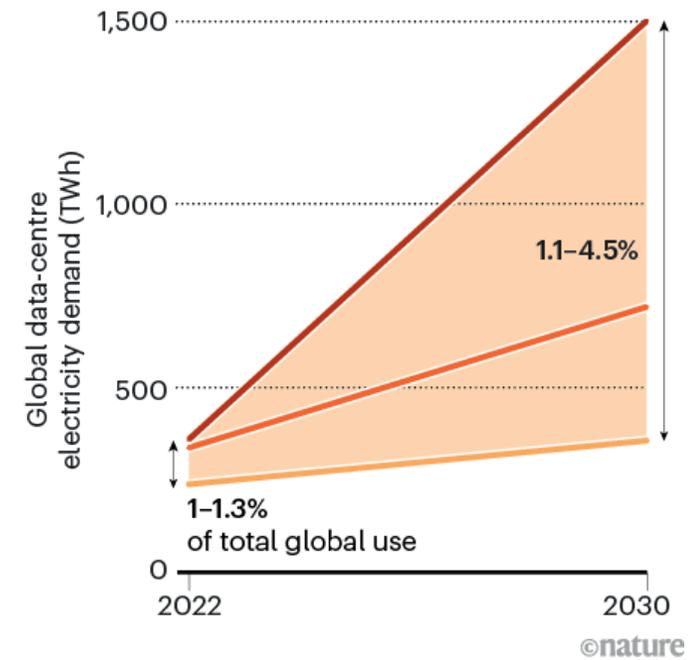
## DATA CENTRES' MODEST GLOBAL IMPACT

Data centres currently use 1–1.3% of the world’s electricity. But as more are built to supply artificial-intelligence models, they are expected to use up to 4.5% by 2030. The wide range shows the uncertainty in projections.

### Data source

- SemiAnalysis 2024 (base case)
- IEA 2024 (high projection)
- IEA 2024 (low projection)

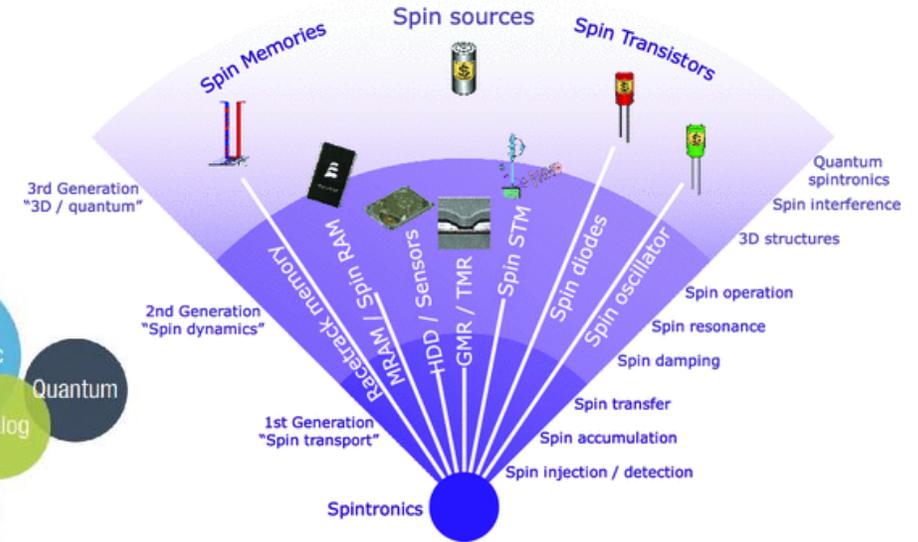
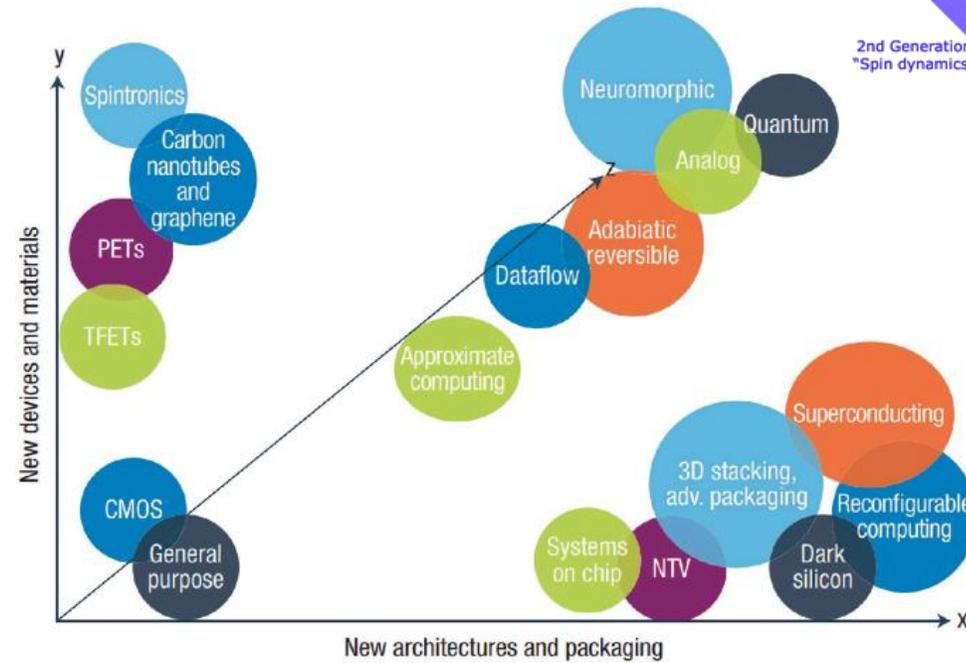
\*IEA: International Energy Agency, *World Energy Outlook 2024*. The agency says it will release new figures in April 2025.



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Adaptable

Efficient

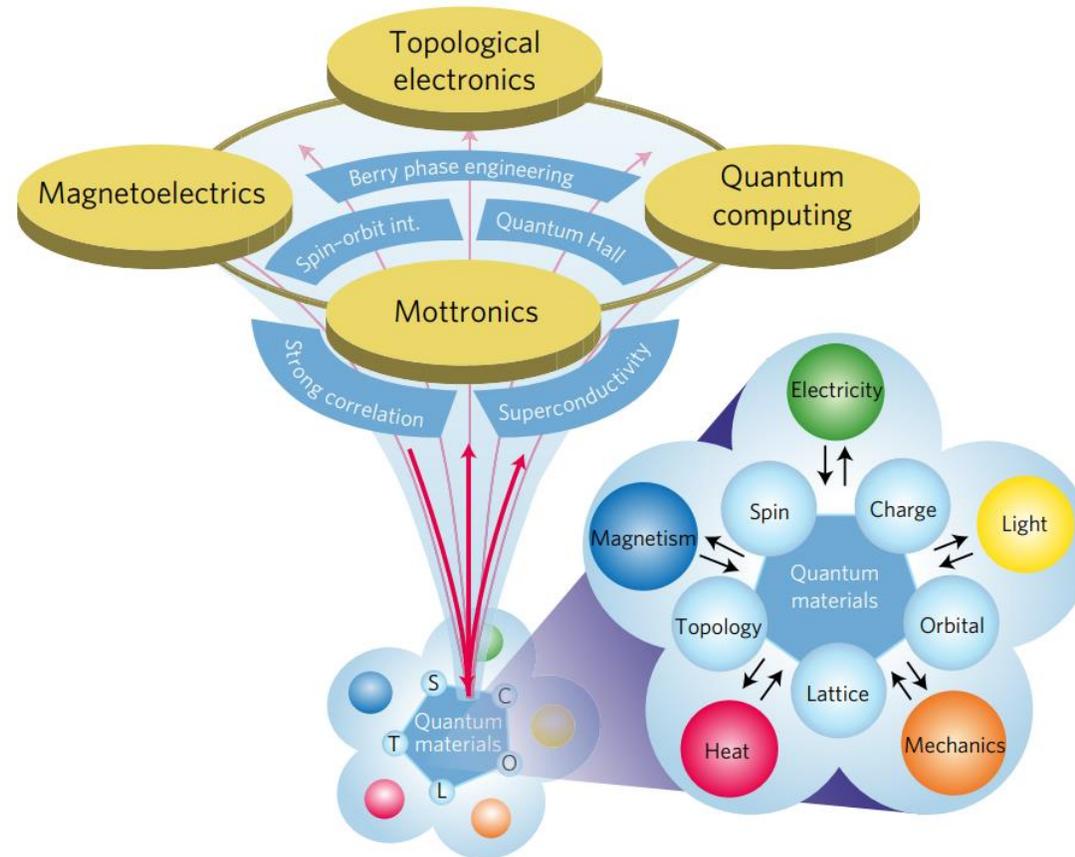


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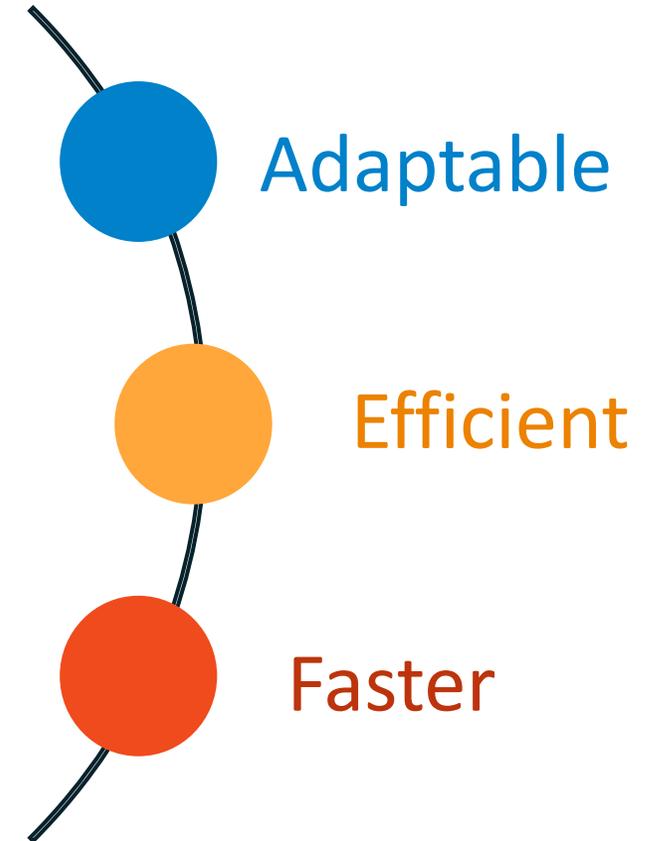
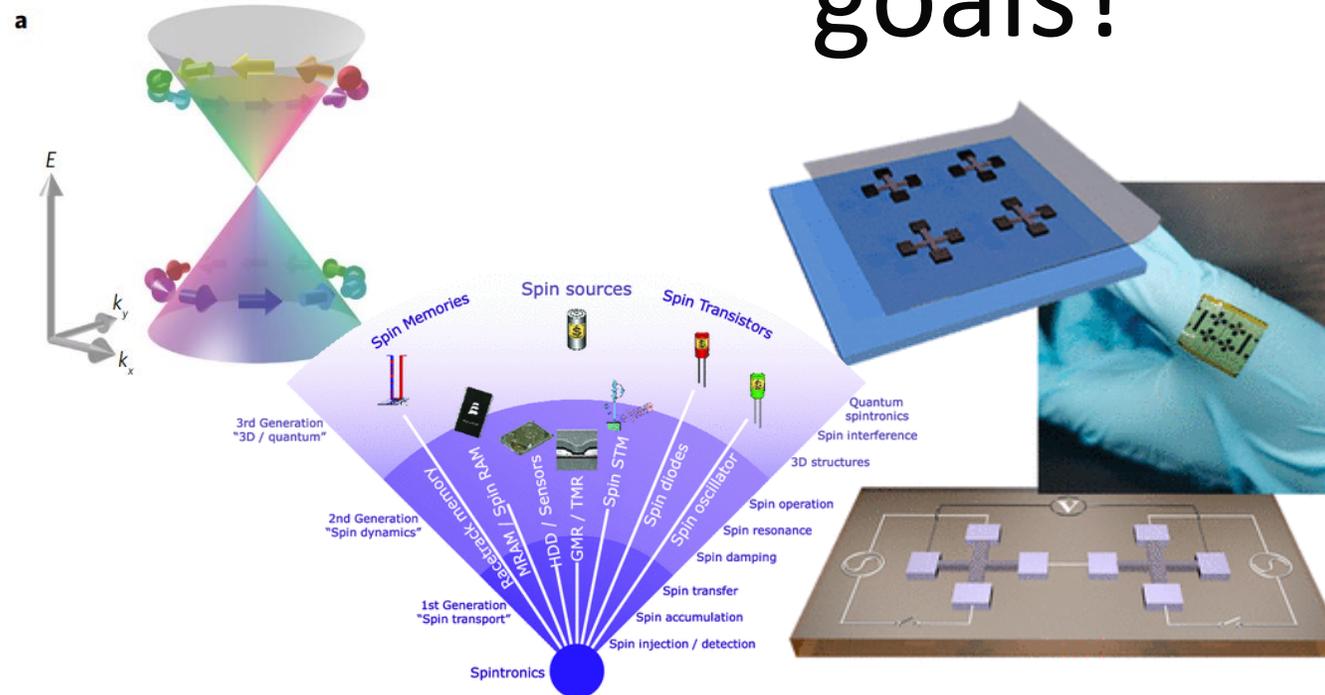
Adaptable

Efficient

Faster



# How can we combine these goals?



- The roadmap to Topological insulator materials



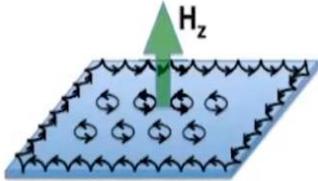


1980

## Quantum hall effect

Nobel Prize in Physics (1985) ✦

Klaus von Klitzing, G. Dorda, M. Pepper



$$\sigma_{xy} = n \frac{e^2}{h}, n = 0, 1, 2$$

in H. Weng, X. Dai, Z. Fang, Adv. Phys. 64, 227 (2015)

1980s

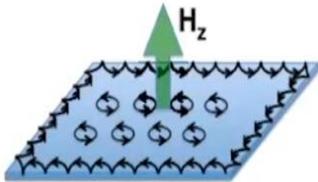
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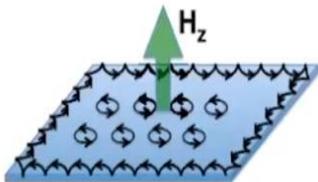
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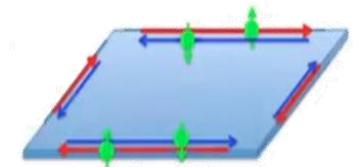


$$\sigma_{xy} = n \frac{e^2}{h}, n = 0, 1, 2$$

2005

Quantum spin hall  
effect**First Description of a TI**

Charles Kane and Eugene Mele



in H. Weng, X. Dai, Z. Fang, Adv. Phys. 64, 227 (2015)

in «Nobel Prize in Physics 2016», [APS News](#) (2016)

● 2007  
First 2d ti  
**Proof of concept**  
HgTe Quantum Well Structure with evidence  
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○ ○ ○  
● 2008-now

Evolution of 3d tis

- 1st Gen.:  $\text{Bi}_x\text{Sb}_{1-x}$
- 2nd Gen.:  $\text{Bi}_2\text{Se}_3$  /  $\text{Bi}_2\text{Te}_3$  /  $\text{Sb}_2\text{Te}_3$
- 3rd Gen.: Topological Crystalline Insulators (TCIs)



● 2007

First 2d ti

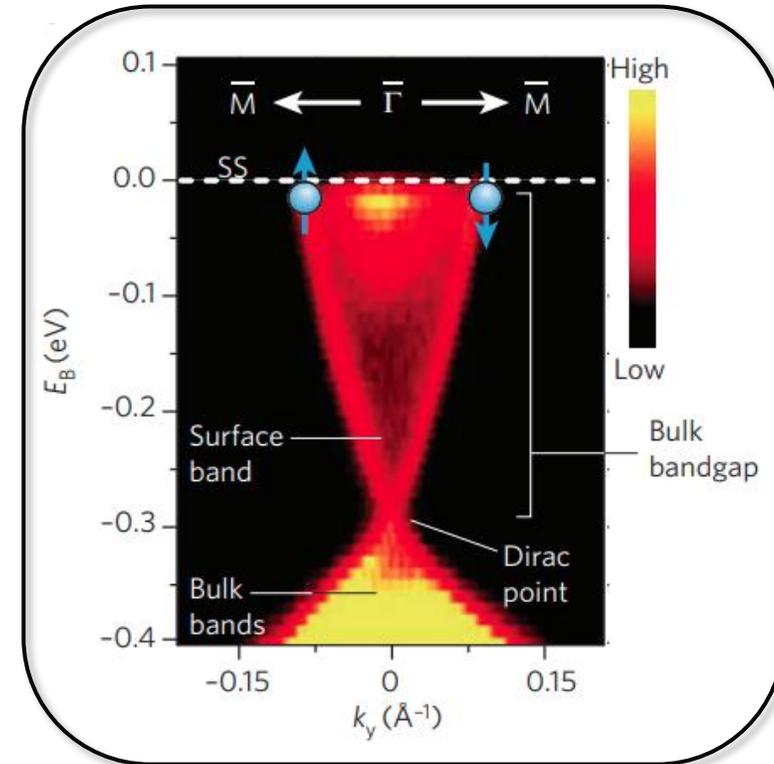
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HgTe Quantum Well Structure with evidence of Quantum Spin Hall States (Konig et.al.)

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**Band structure of Bi-Se, measured by Angle-Resolved Photo-Emission Spectroscopy**

*in H. Zhang et. al., Nature Physics 5, pp. 438–442 (2009)*

**INSULATING BULK**

Bandgaps of 0.2 – 0.3 eV

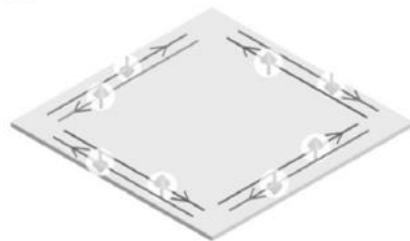
+

**SURFACE STATES**

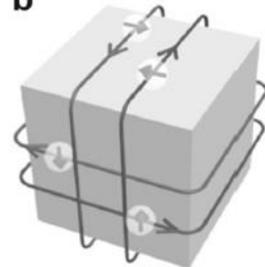
Described by a Dirac Hamiltonian

$$\mathcal{H}(\vec{k}) = \hbar v_F \vec{k} \cdot (\vec{\sigma} \times \hat{z})$$

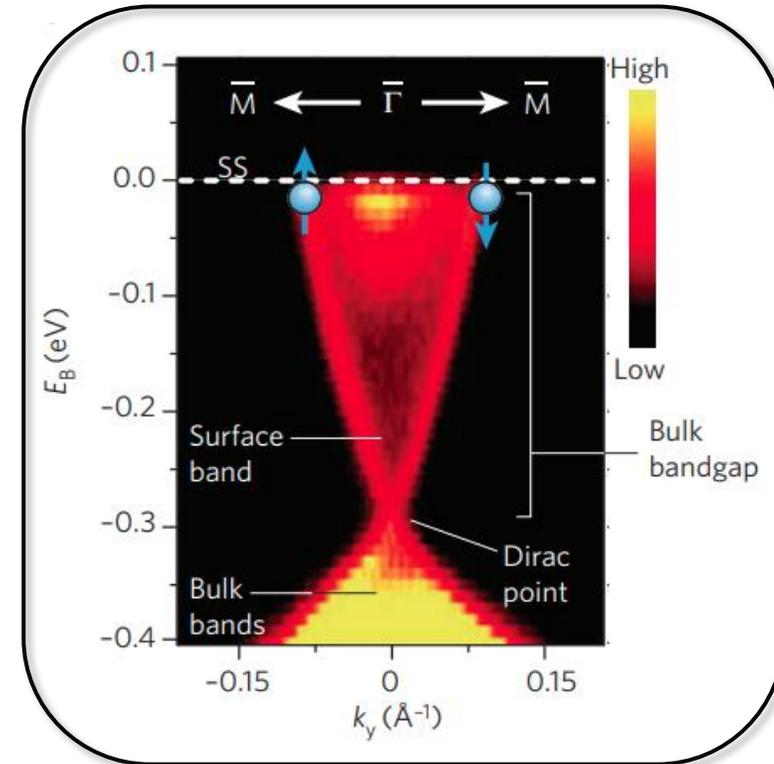
a



b



in Ning Xu, Young Xu and Jia Zhu, *Quantum Materials*, Vol. 2,  
Article number: 51 (2017)



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in H. Zhang et. al., *Nature Physics* 5, pp. 438–442 (2009)

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### Theoretical model

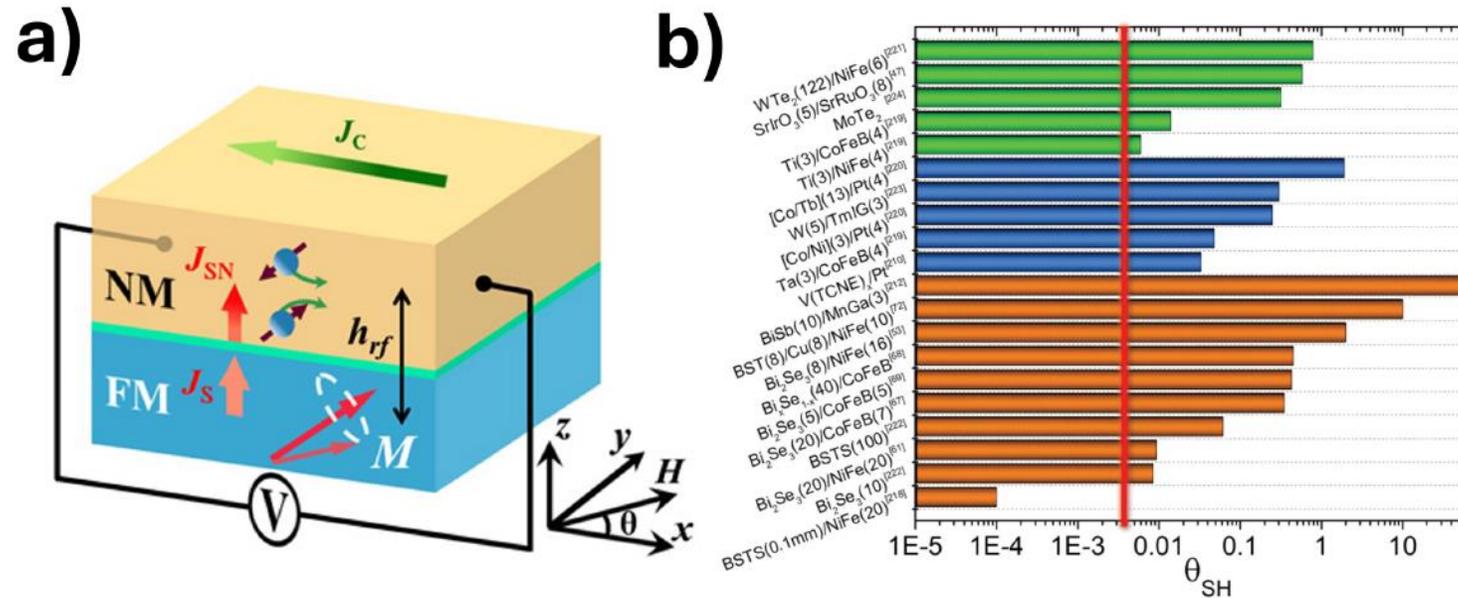
+ Massless Dirac fermions protected by time-reversal symmetry and supported by **high spin-orbit coupling**

### Unique Transport Properties

+ Spin-polarized “metallic” surface channels supporting **high spin-to-charge conversion coefficients** and **spin-coherence lengths**.

### Application in Spintronics

+ Platform for **spin-to-charge conversion** and the development of novel spintronic devices for magnetic memory applications.

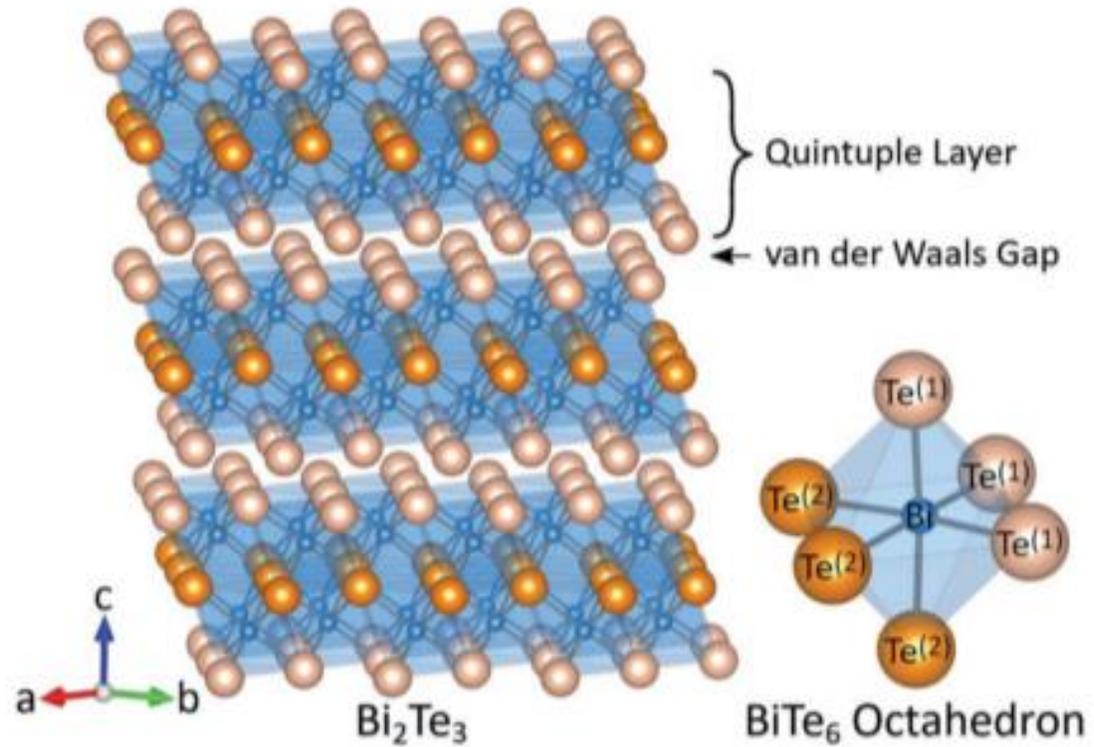


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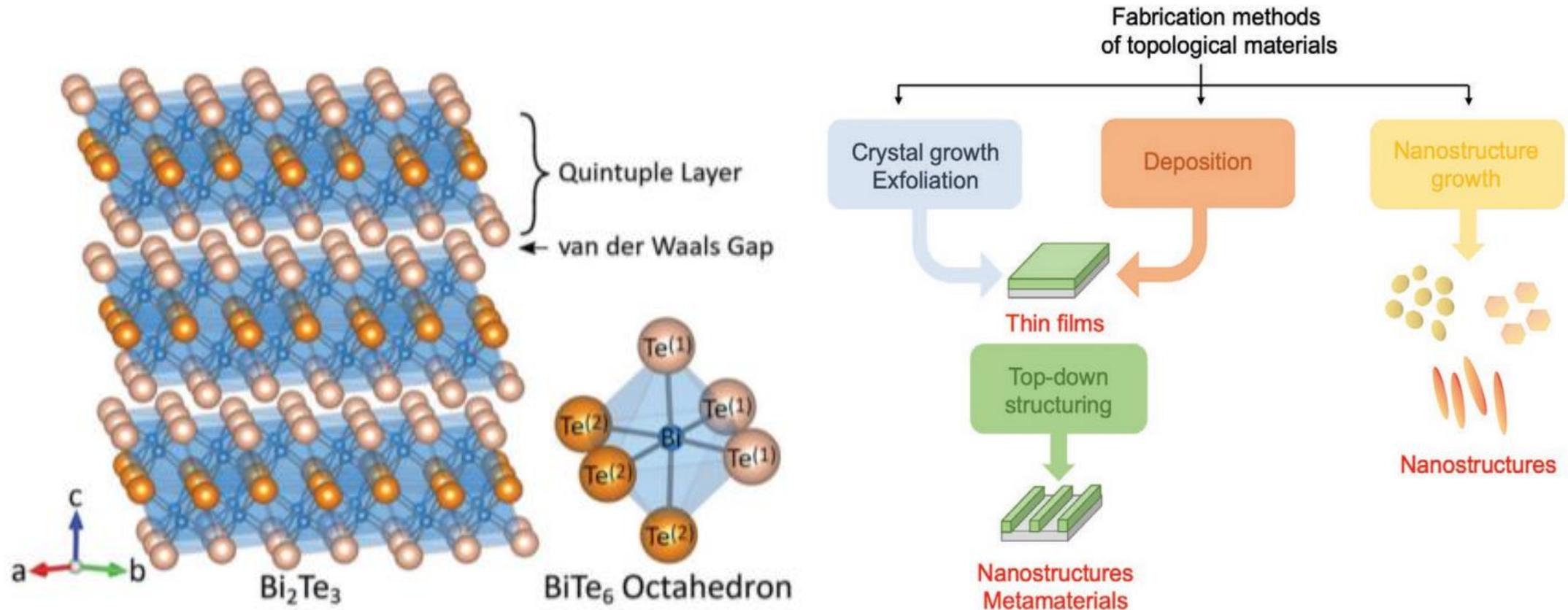
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# 1. Properties and Fabrication of TI Materials

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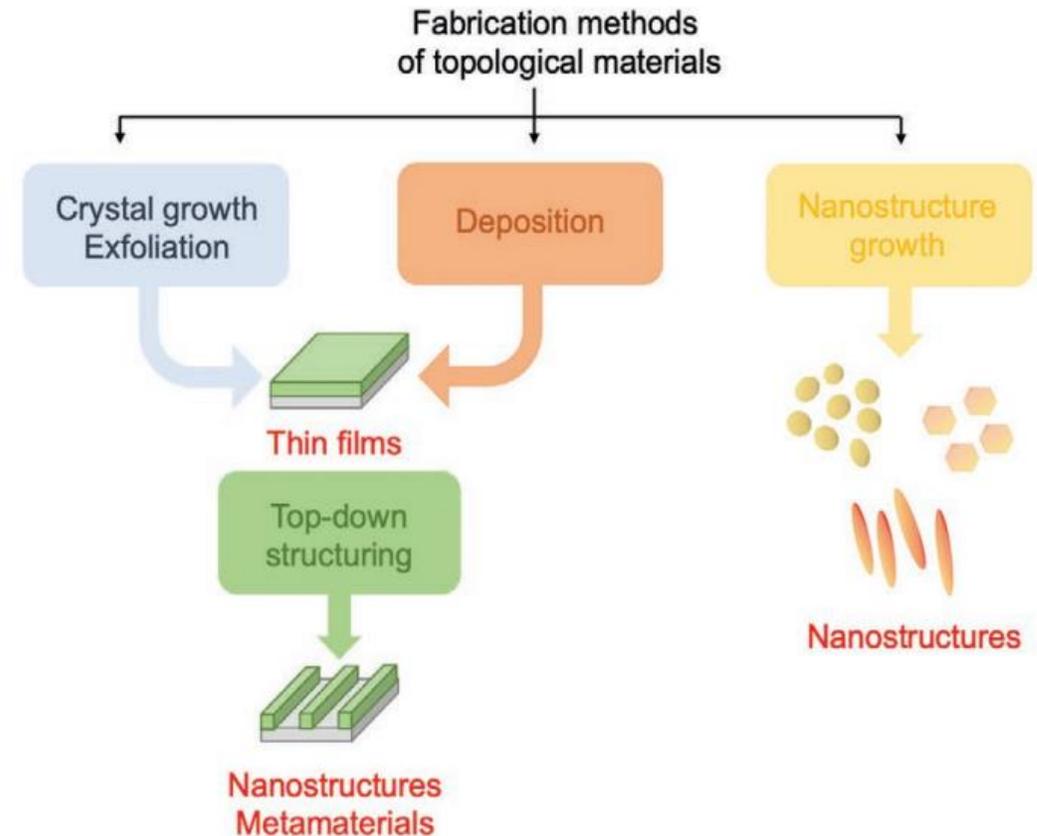
# 1. Properties and Fabrication of TI Materials



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## Critical challenges:

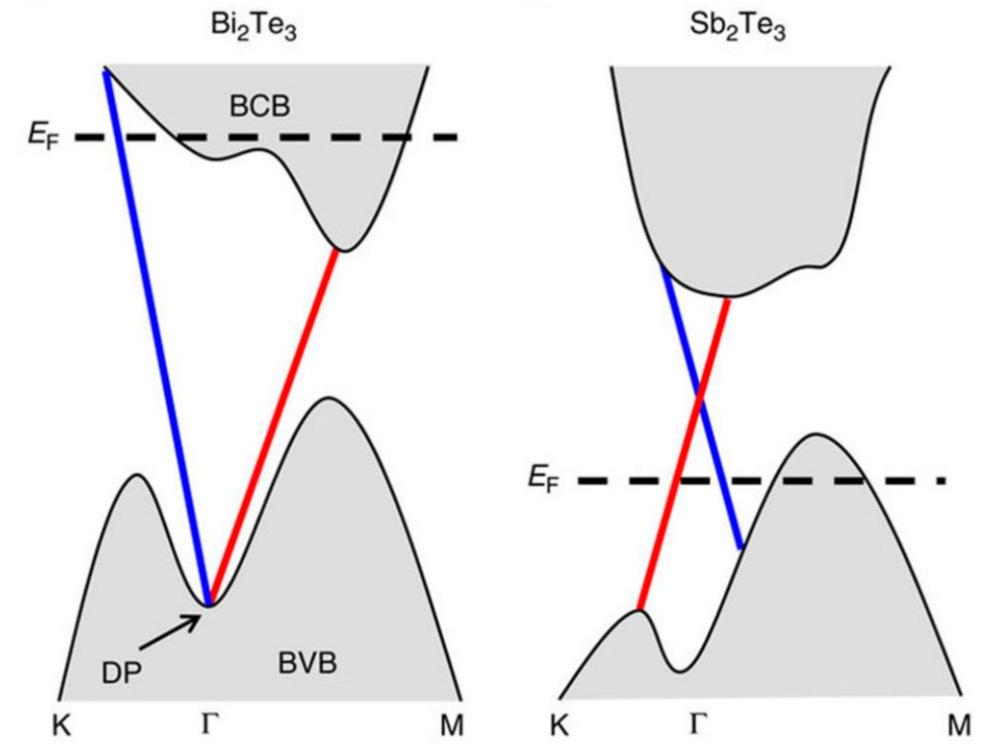
- ∇ Developing scalable and cost-efficient methods to fabricate the materials
- ∇ Control the surface states (TSS), in the face of competing conduction channels and substantial bulk contributions



# 1. Properties and Fabrication of TI Materials

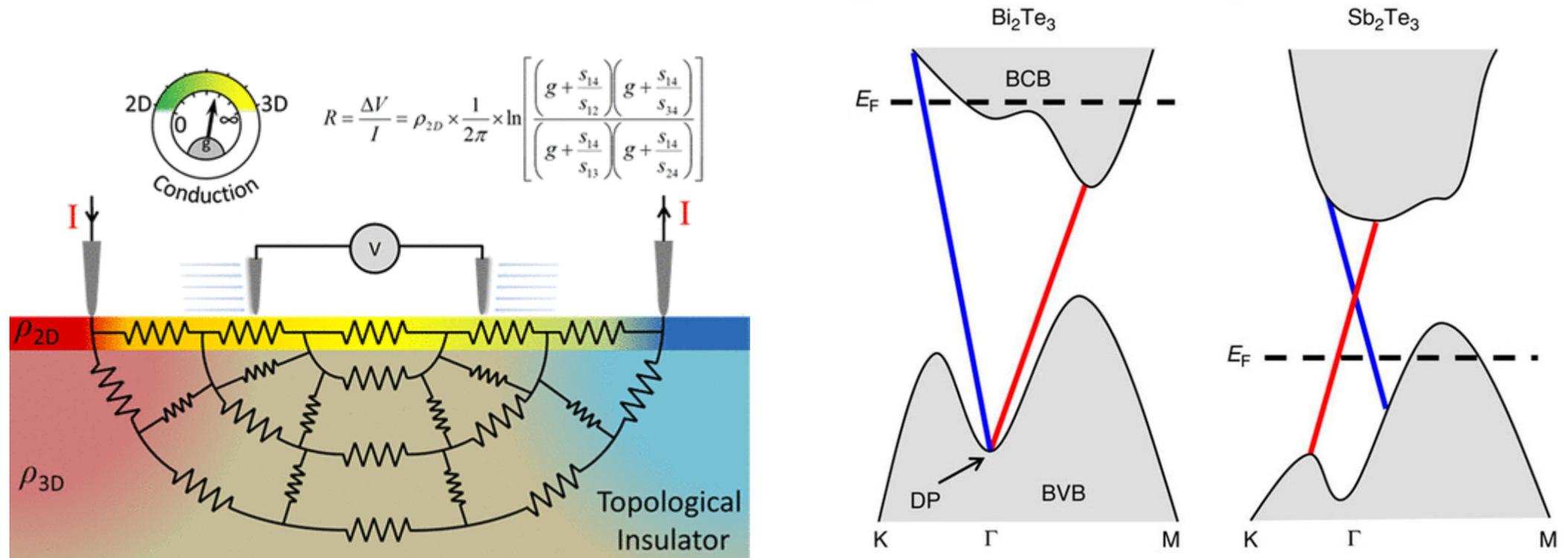
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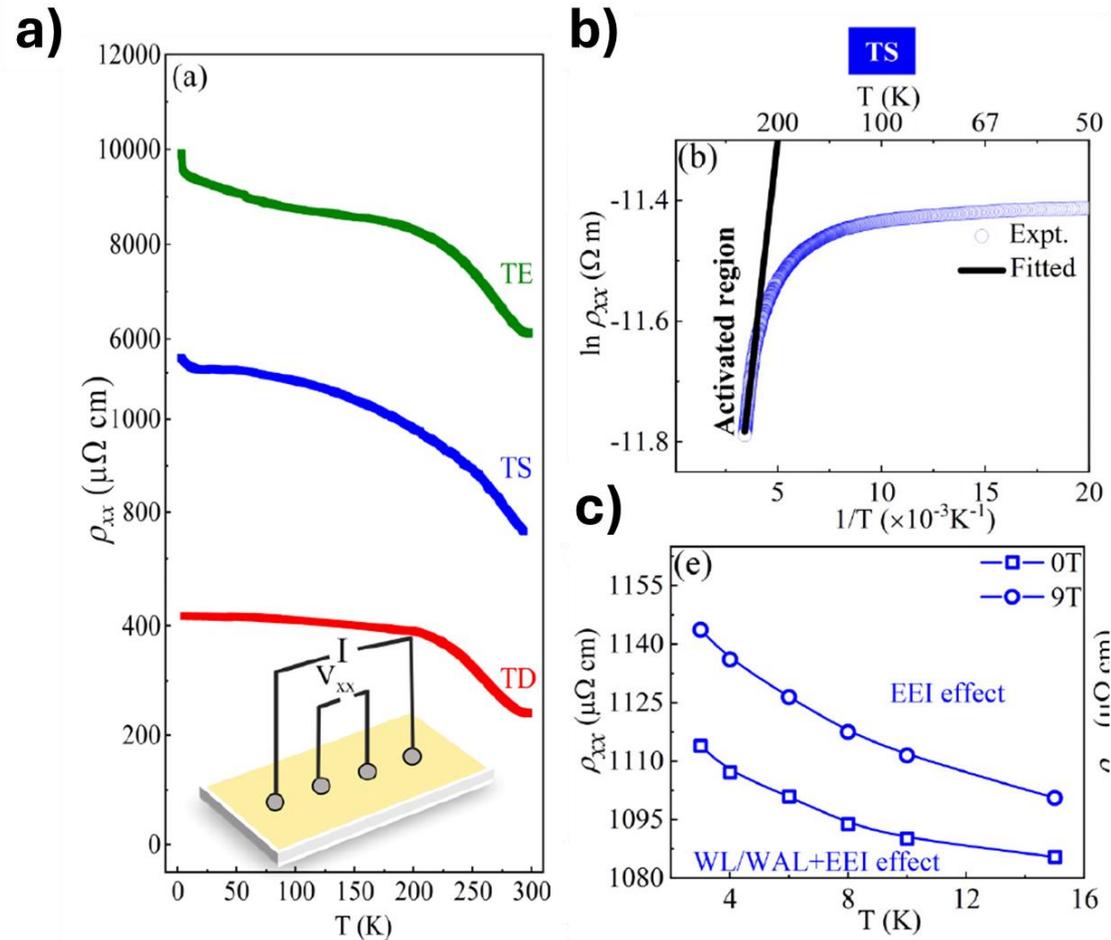
**The Fermi Level position is highly affected by intrinsic defects, entangling bulk and surface contributions to transport.**

## 2. Transport Signatures of Topological Surface States

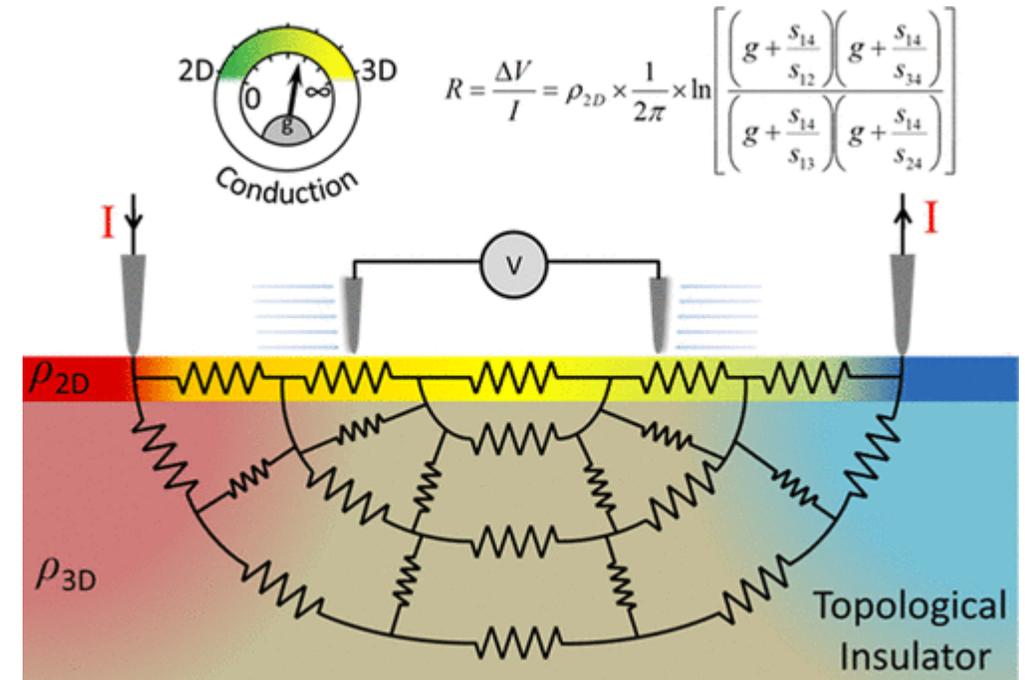


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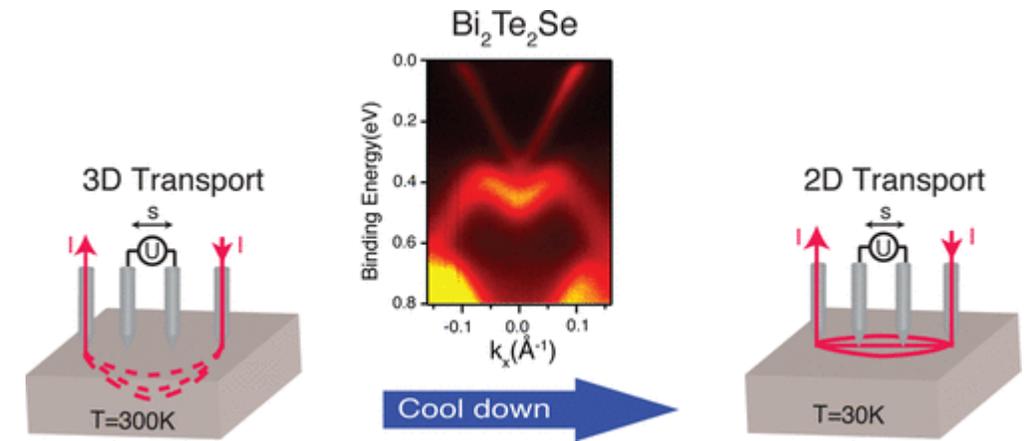
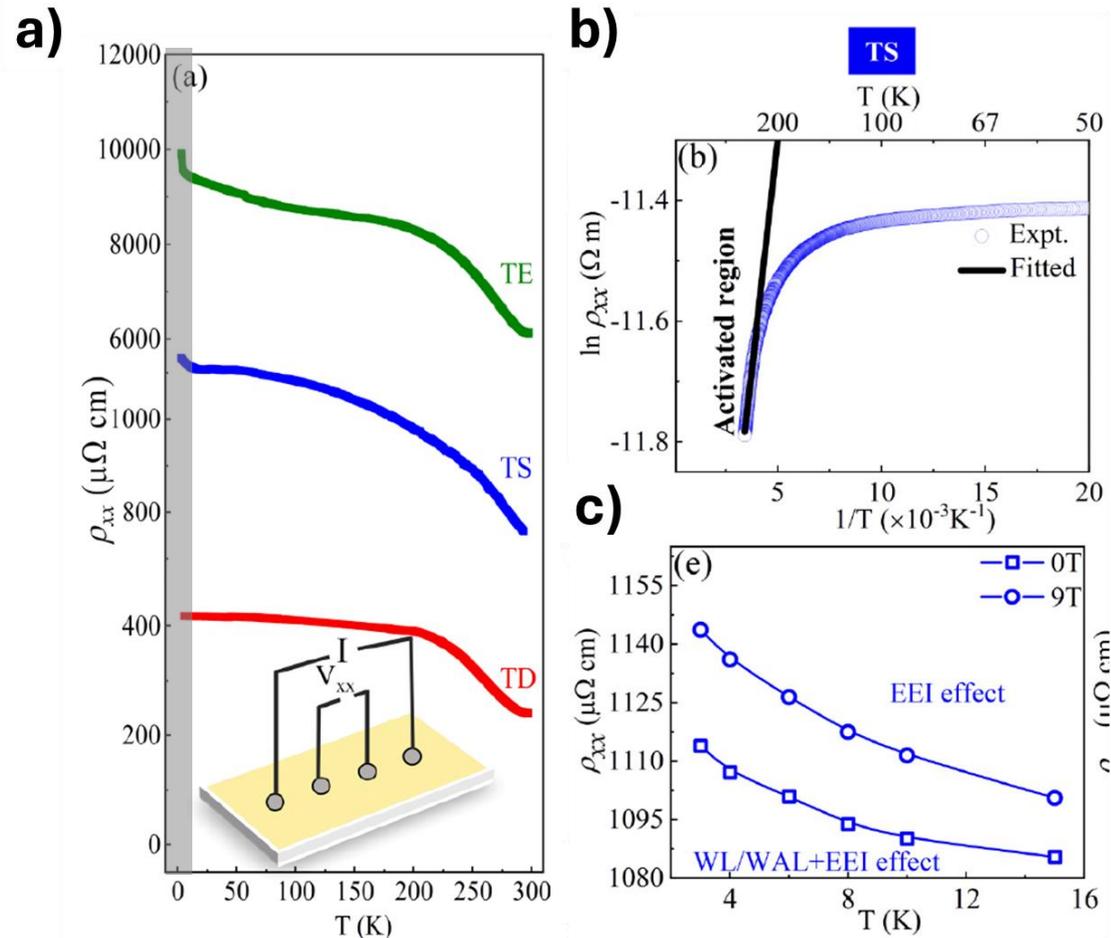
## 2. Transport Signatures of Topological Surface States



Pandey et al.,  
*Physical Review Materials* **6** (2022).



## 2. Transport Signatures of Topological Surface States



At low temperatures (~ 20 K) transport properties of TSS to become more prominent

## 2. Transport Signatures of Topological Surface States

A stronger signature of TSS conduction is observed in the magnetoresistance as a *Weak Anti-localization (WAL) Effect*, modeled by a [Hikami-Larkin-Nagaoka](#) description:

$$HLN = \frac{\alpha e^2}{h} \left( \log \left( \frac{B_\phi}{B} \right) - \Psi \left( \frac{1}{2} + \frac{B_\phi}{B} \right) \right)$$

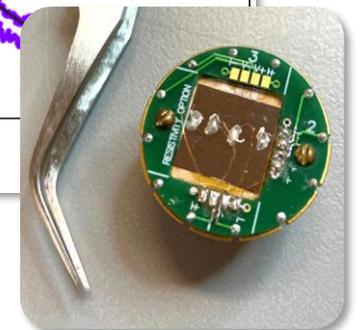
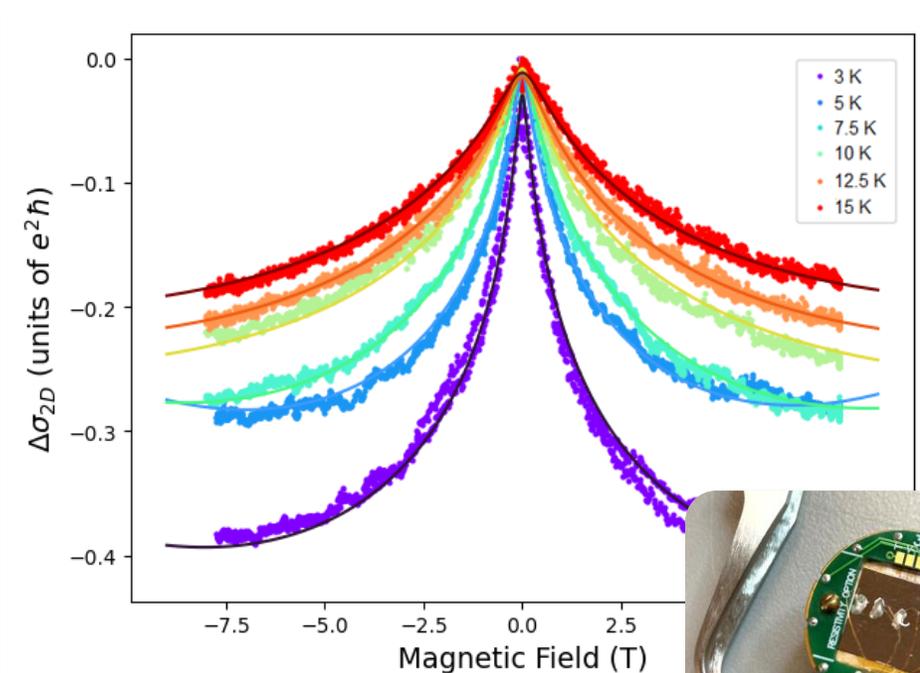
$\alpha \sim 0.5$  per spin-channel

$$B_\phi \propto \frac{1}{L_\phi^2} \leftrightarrow L_\phi: \text{Phase Coherence Length}$$

$H$  is the applied magnetic field,

$\Psi$  is the digamma function

$$\mathbf{BACKGROUND} = \beta B^2 + aB + c$$



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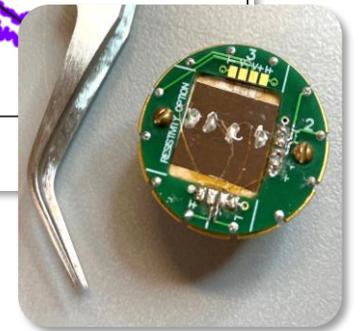
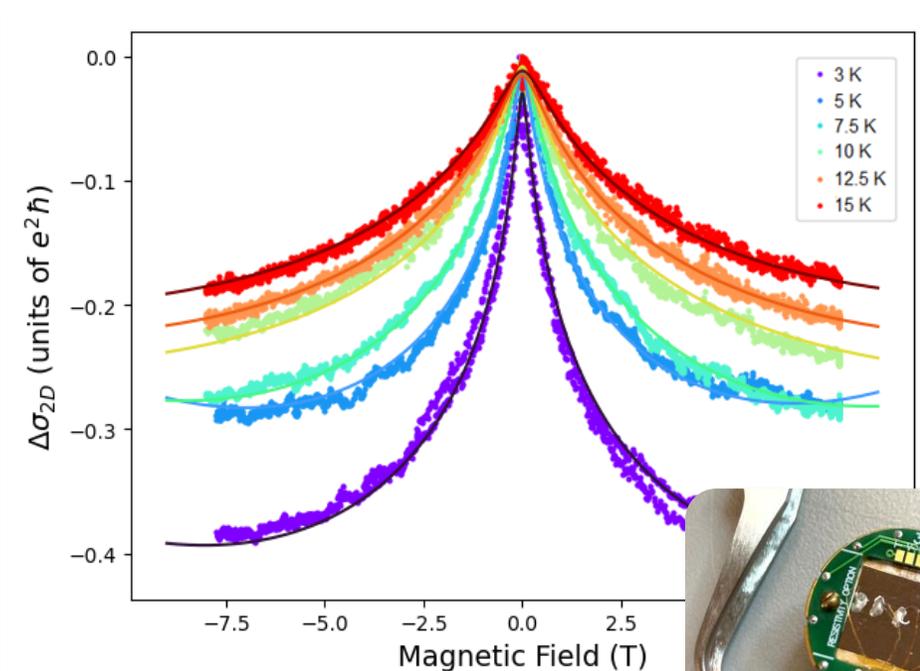
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Motivation

State-of-the-art

**Experimental results**

Research Proposal

Future studies



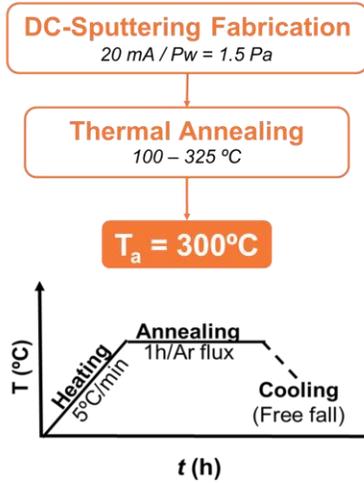
### Hot Topics

**Fabrication Method** DC Magnetron-Sputtering  
Deposition of 13, 25, 51, 97 and 191 nm thin  
films onto flexible Kapton® substrates,  
optimized by *ex-situ* thermal annealing



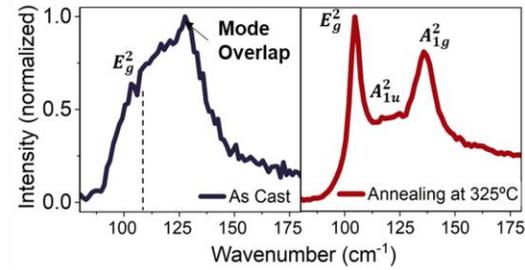
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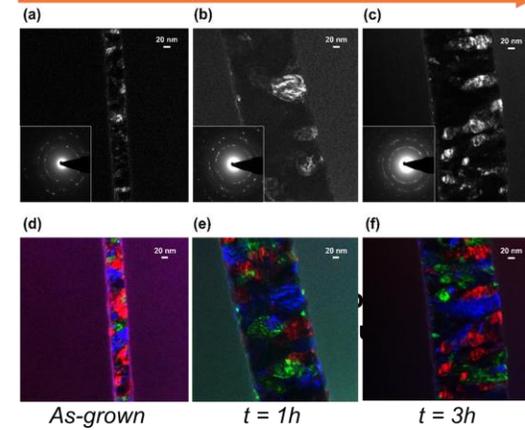


Above  $T_a = 275^\circ\text{C}$ , samples exhibit:

- Polycrystalline organization
- Crystallite size
- Local defects (self-doping)



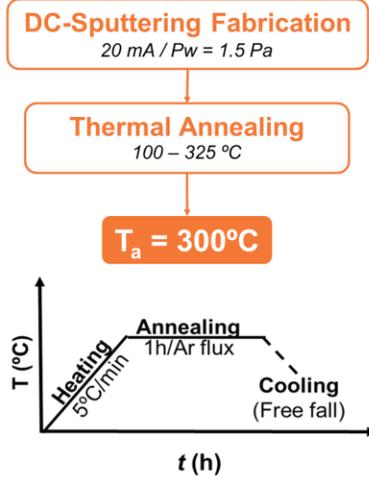
**Future study: Annealing time**





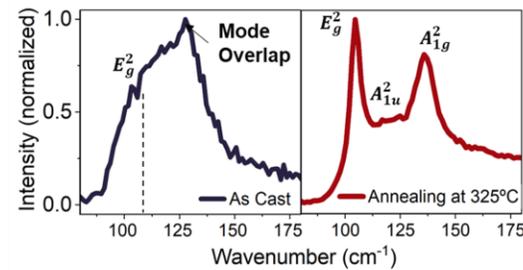
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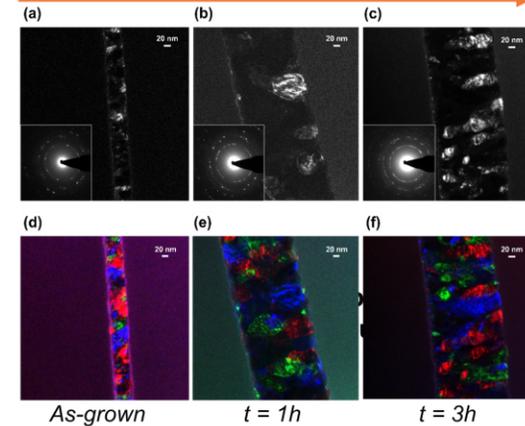


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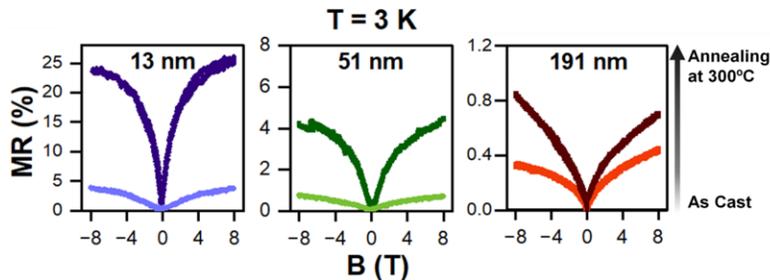
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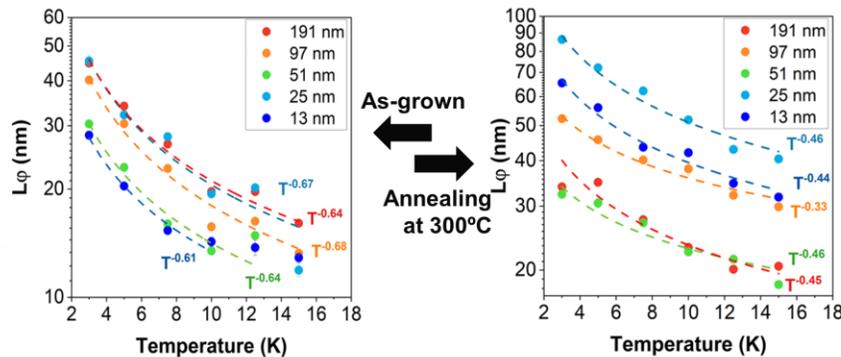
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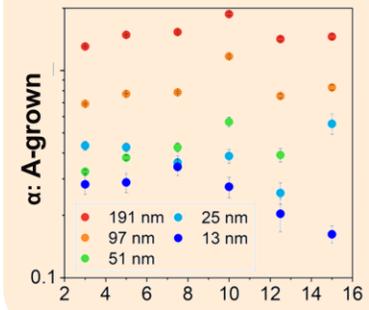
**Change In Magnetic Signatures Of The Surface States:**



Low  $L_\phi$  / Decay rate  $\sim 0.7$   
 = 3D EEI (bulk carriers)

High  $L_\phi$  / Decay rate  $\sim 0.5$   
 = 2D EEI (surface carriers)

**What doesn't change?**  
 Thickness-dependent  $\alpha$   
 = Bulk-mediated coupling of spin-channels<sup>6</sup>



Motivation

State-of-the-art

Experimental results

**Research Proposal**

Future studies



### Thin film fabrication

DC Magnetron  
Sputtering on Polyimide  
(Kapton®), Glass and  
PET substrates

### Standard characterization

- XRD/XRR
- SEM/EDX
- Raman Spectroscopy
- Resistivity...

### Advanced characterization

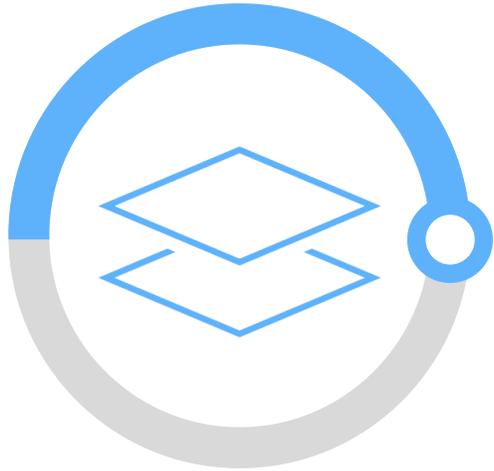
- ARPES
- TEM

### High-frequency measurements

- FMR
- Spin-Hall Angle

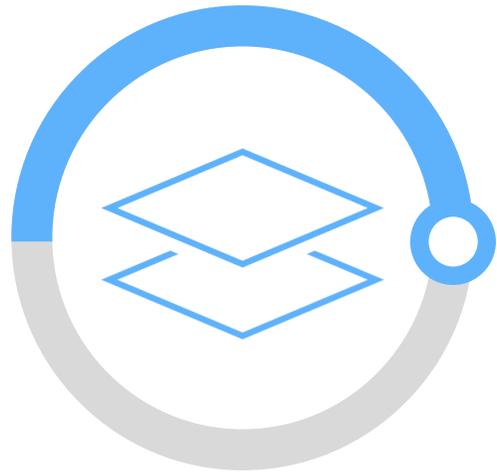
### Theoretical modelling

## 1. Fabrication of Thin Film Samples

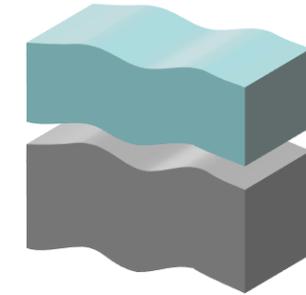
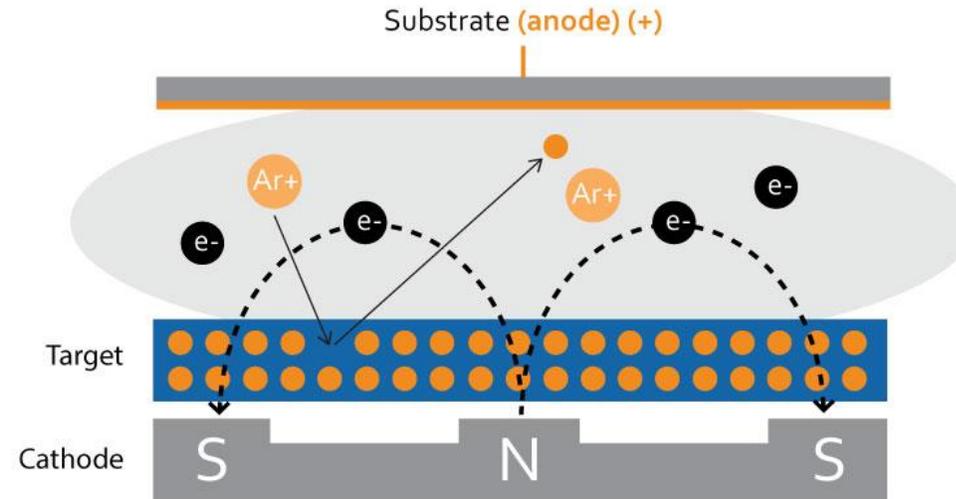


**Magnetron-Sputtering  
Fabrication**

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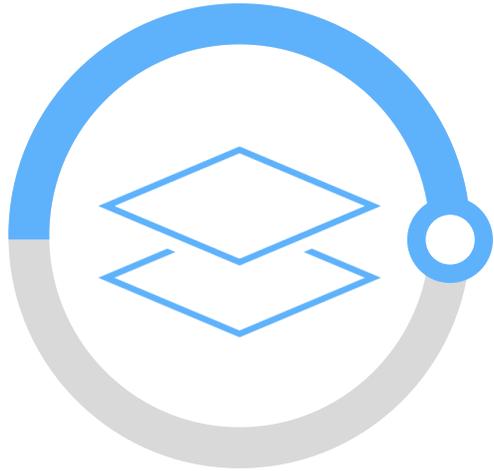


Amorphous substrate  
(Glass / Kapton / PET)

Optimize deposition parameters

- Applied current / Power
- Gas flow

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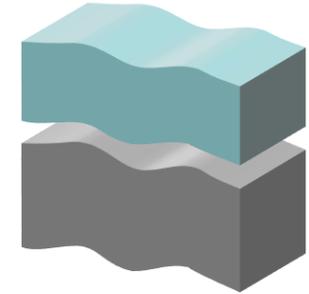
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Fabrication**

### 3D TI Materials:

- $\text{Bi}_2\text{Te}_3$
- $\text{Sb}_2\text{Te}_3$

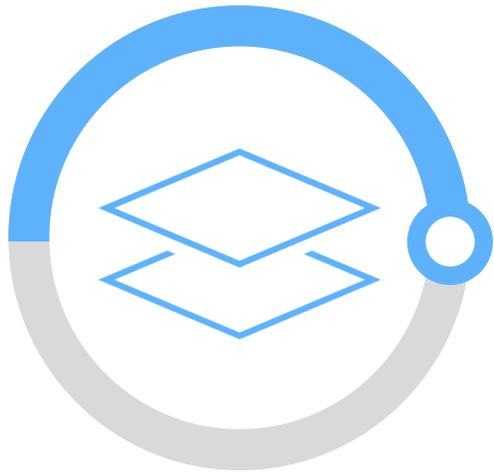
### Phase Change Materials:

- $\text{Ge}_2\text{Sb}_2\text{Te}_5$
- $\text{In}_3\text{SbTe}_2$



Amorphous substrate  
(Glass / Kapton / PET)

## 1. Fabrication of Thin Film Samples



**Magnetron-Sputtering  
Fabrication**

### 3D TI Materials:

- $\text{Bi}_2\text{Te}_3$
- $\text{Sb}_2\text{Te}_3$

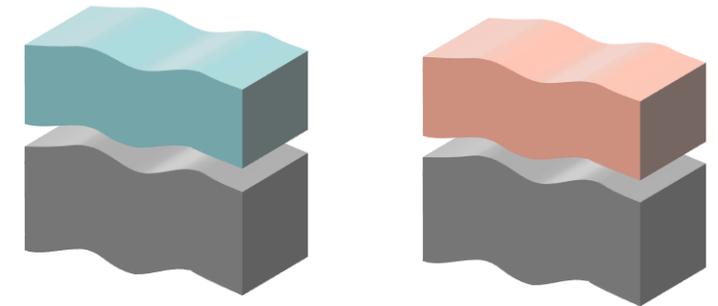
### Phase Change Materials:

- $\text{Ge}_2\text{Sb}_2\text{Te}_5$
- $\text{In}_3\text{SbTe}_2$

### Ferromagnetic Materials:

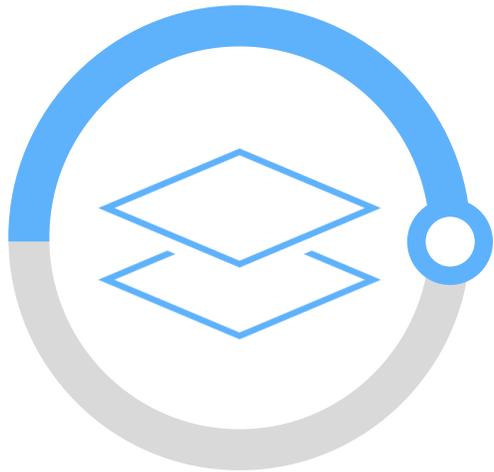
- NiFe
- CoFe

\*Buffer Layers: Ta / Te



Amorphous substrate  
(Glass / Kapton / PET)

## 1. Fabrication of Thin Film Samples



Magnetron-Sputtering  
Fabrication

### 3D TI Materials:

- $\text{Bi}_2\text{Te}_3$
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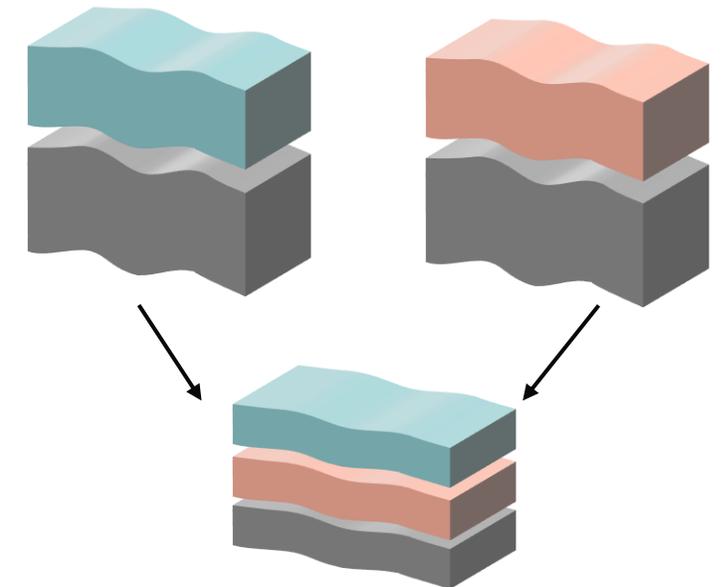
### Phase Change Materials:

- $\text{Ge}_2\text{Sb}_2\text{Te}_5$
- $\text{In}_3\text{SbTe}_2$

### Ferromagnetic Materials:

- NiFe
- CoFe

\*Buffer Layers: Ta / Te



**Goal:**  
Bilayer/trilayer 3D-SOT  
structures

## 2. Standard Characterization

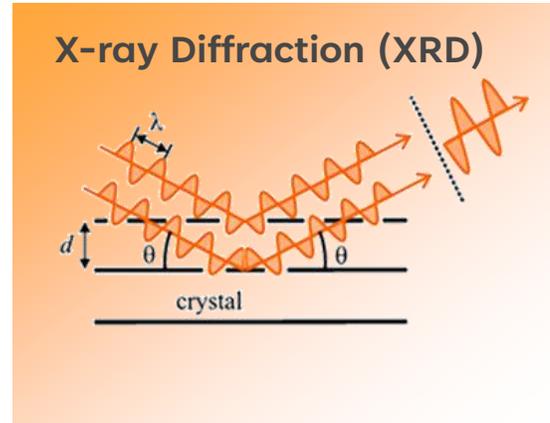


**Structural and  
morphological properties**

## 2. Standard Characterization



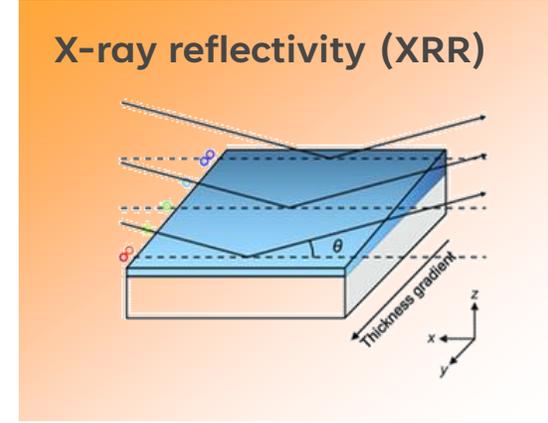
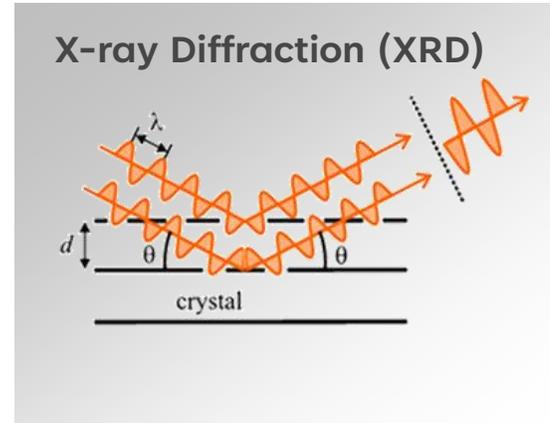
**Structural and  
morphological properties**



## 2. Standard Characterization



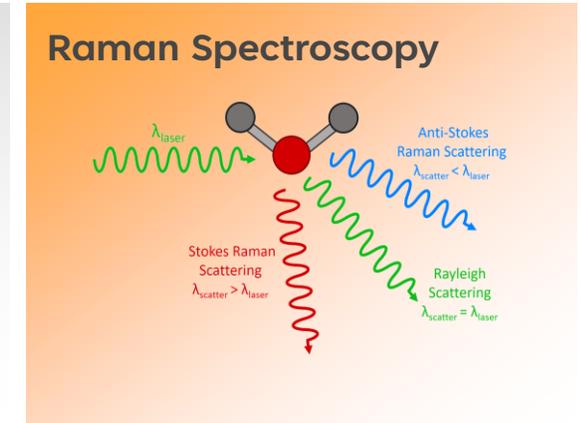
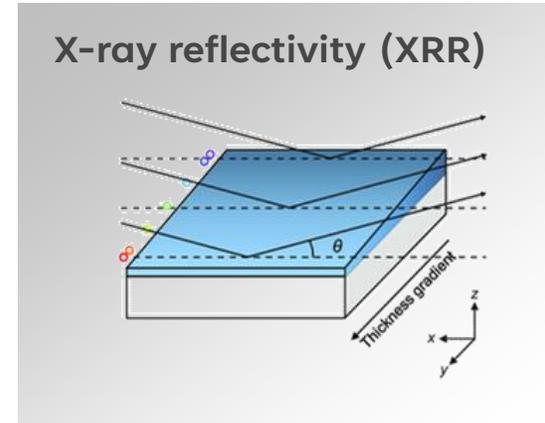
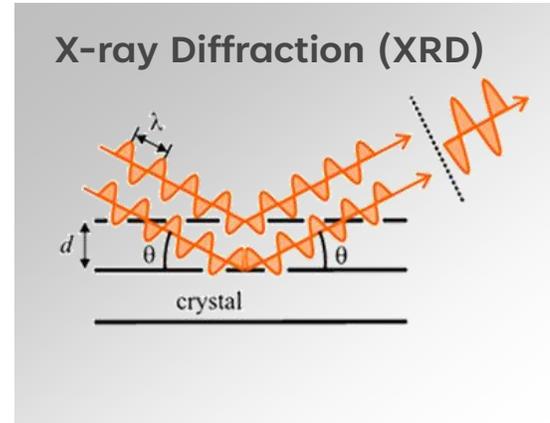
**Structural and morphological properties**



## 2. Standard Characterization



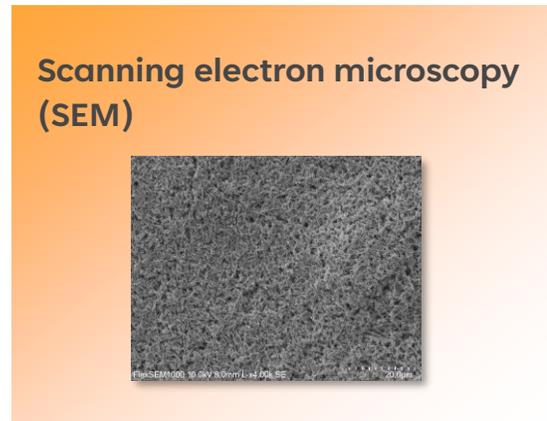
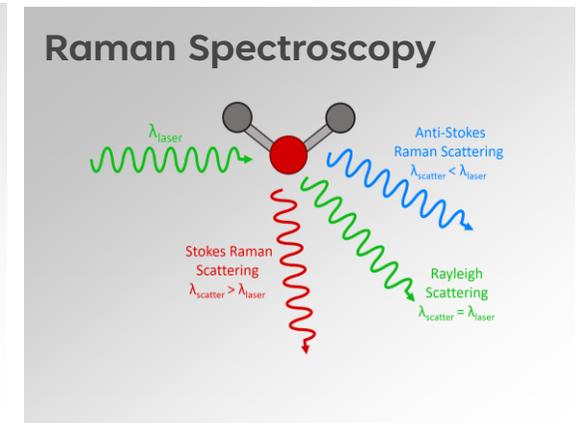
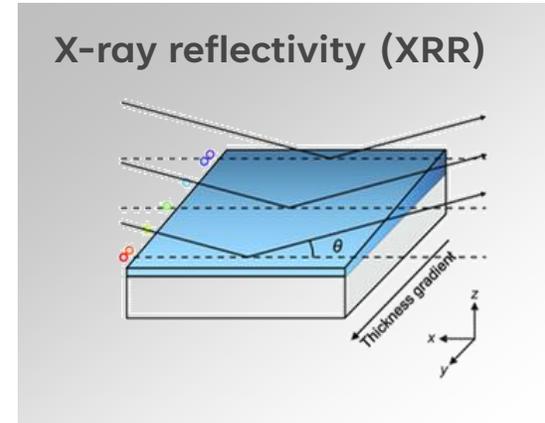
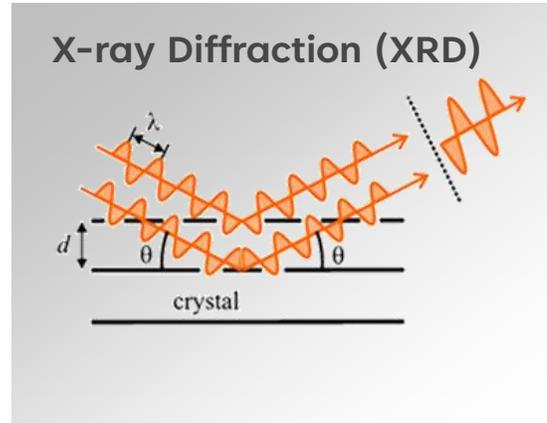
Structural and morphological properties



## 2. Standard Characterization



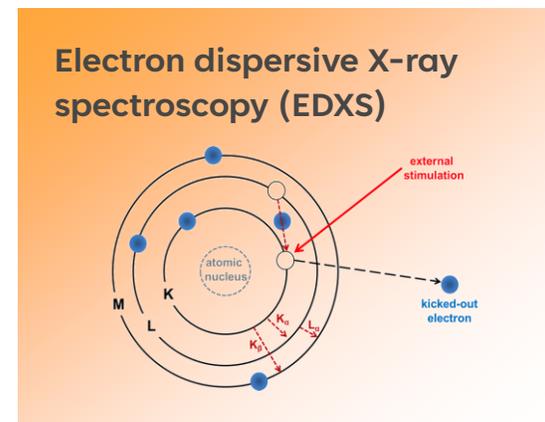
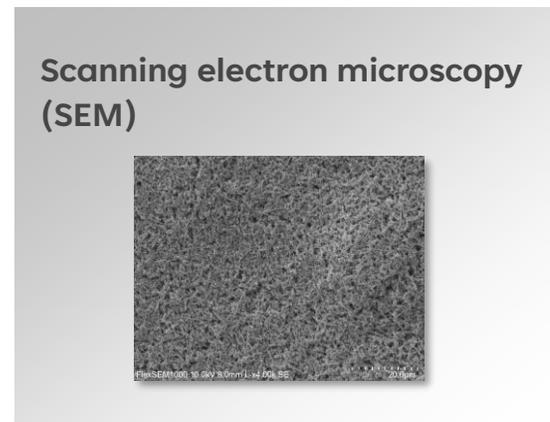
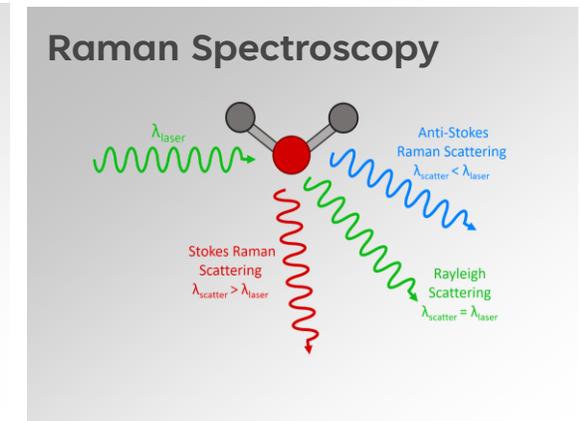
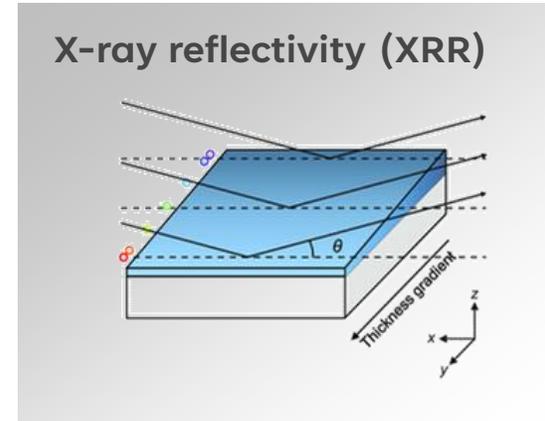
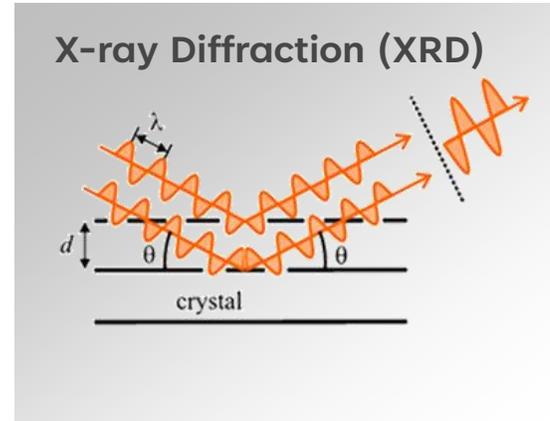
Structural and  
morphological properties



## 2. Standard Characterization



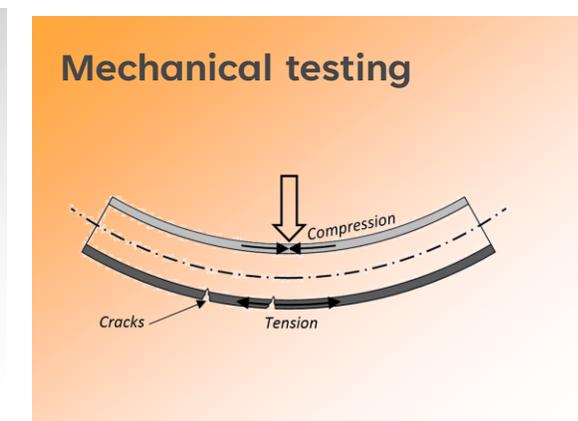
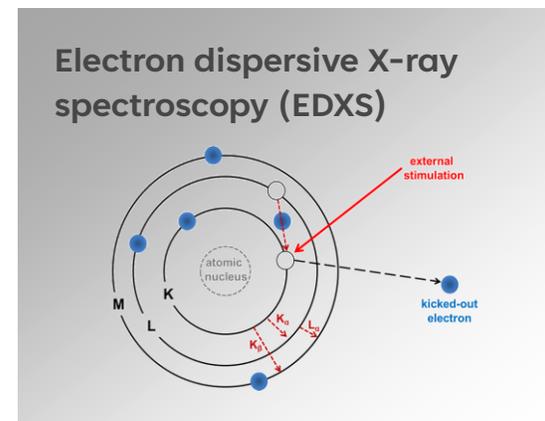
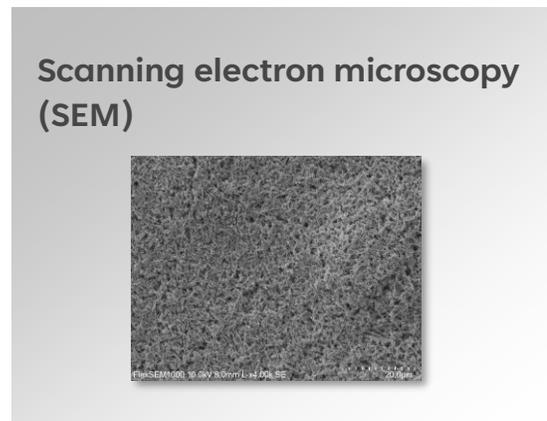
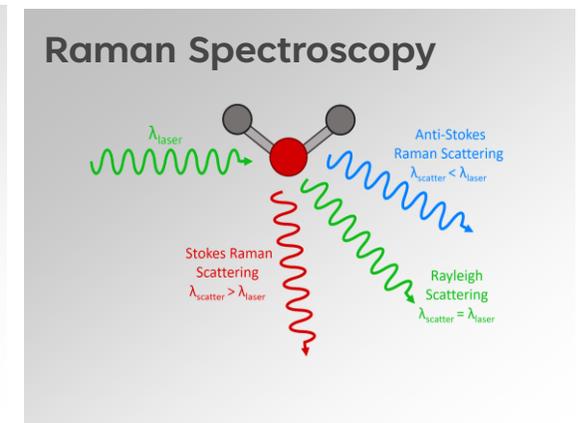
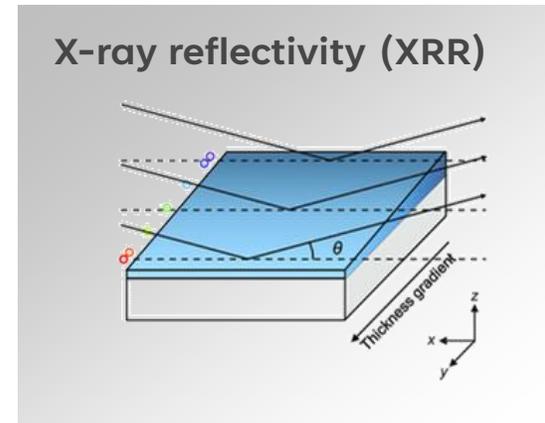
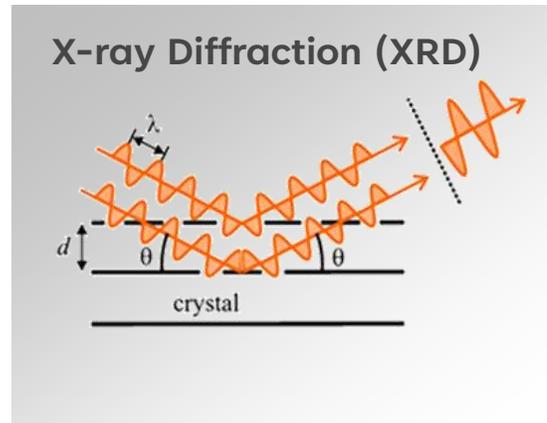
**Structural and morphological properties**



## 2. Standard Characterization



Structural and morphological properties

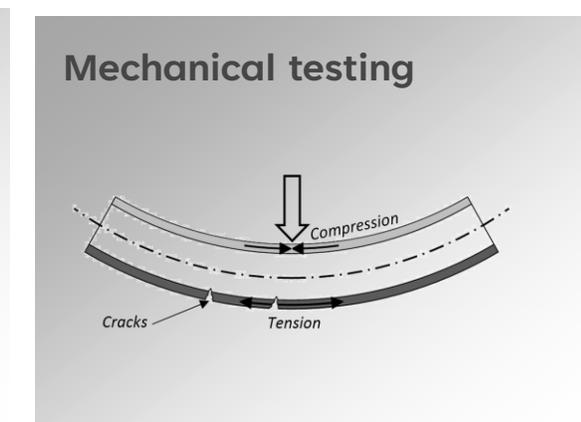
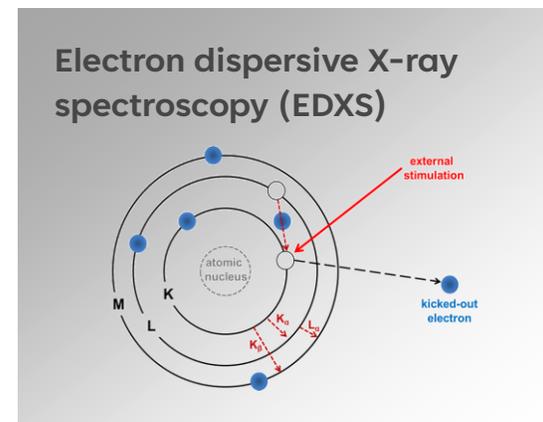
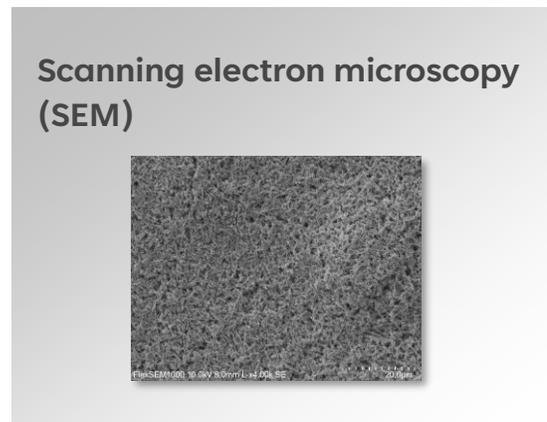
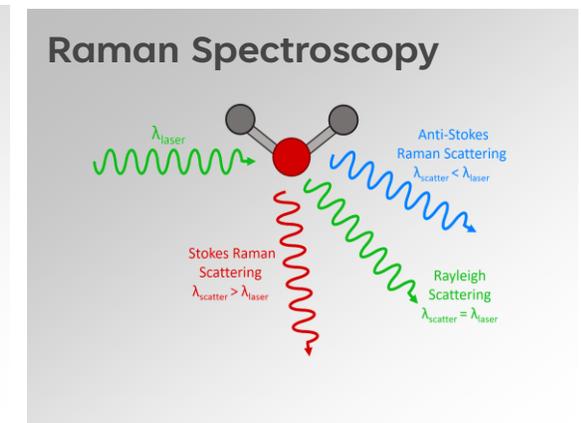
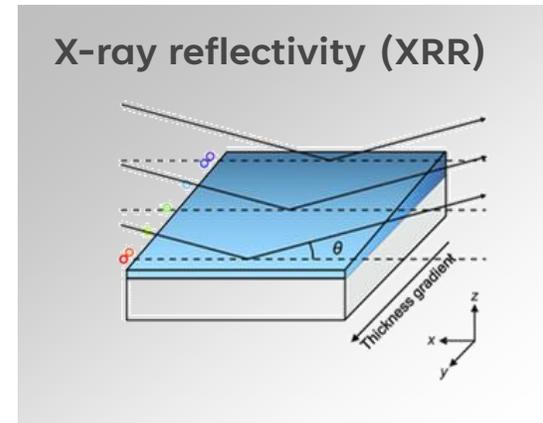
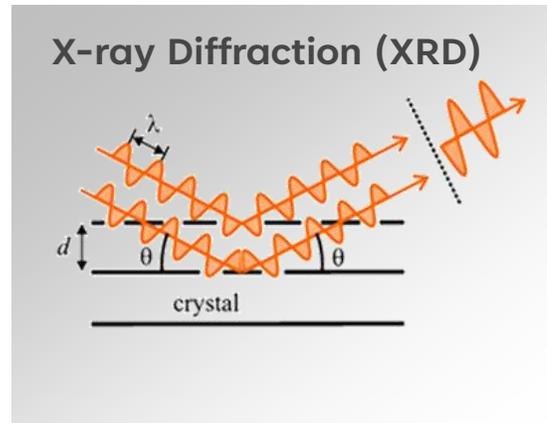


## 2. Standard Characterization



**Structural and morphological properties**

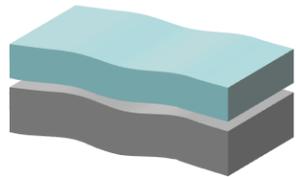
- ✓ Quality control
- ✓ Compatibility with flexible substrates



## 2. Standard Characterization



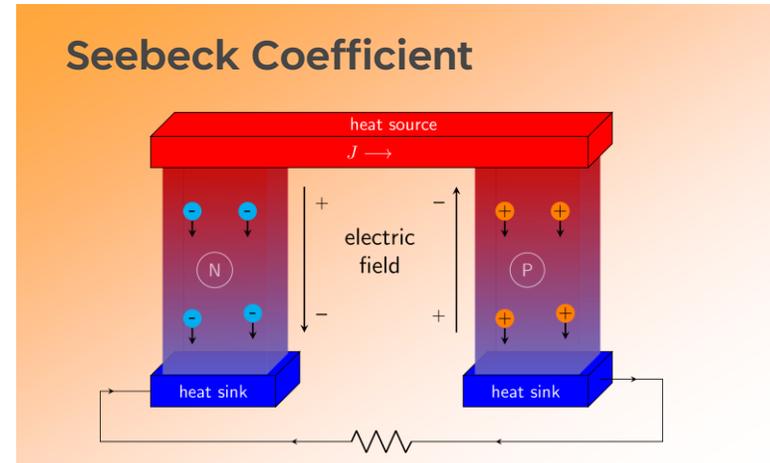
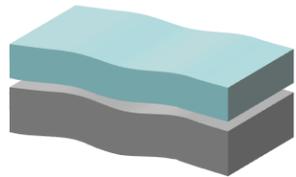
**Transport Properties**



## 2. Standard Characterization



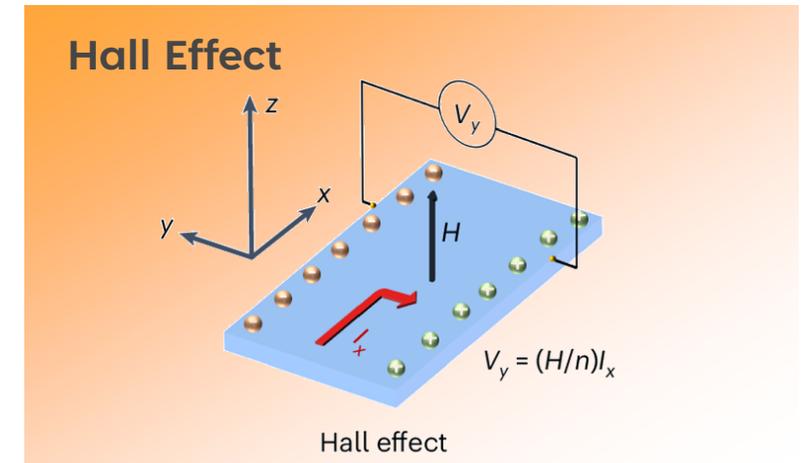
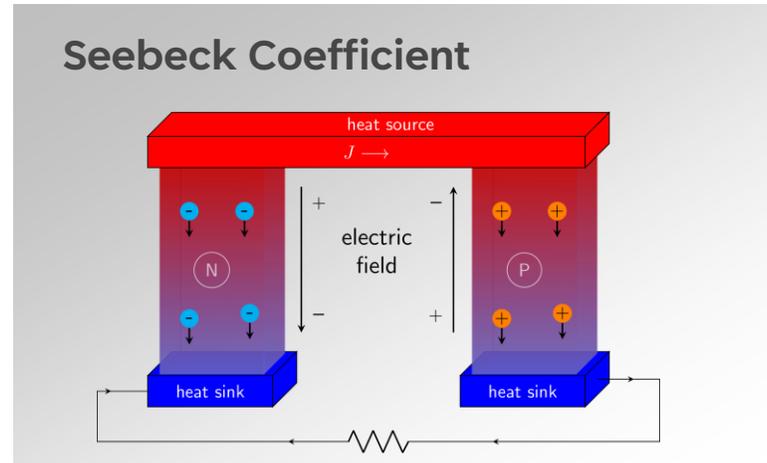
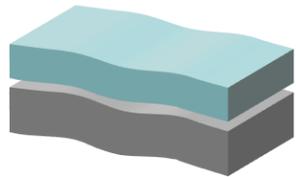
### Transport Properties



## 2. Standard Characterization



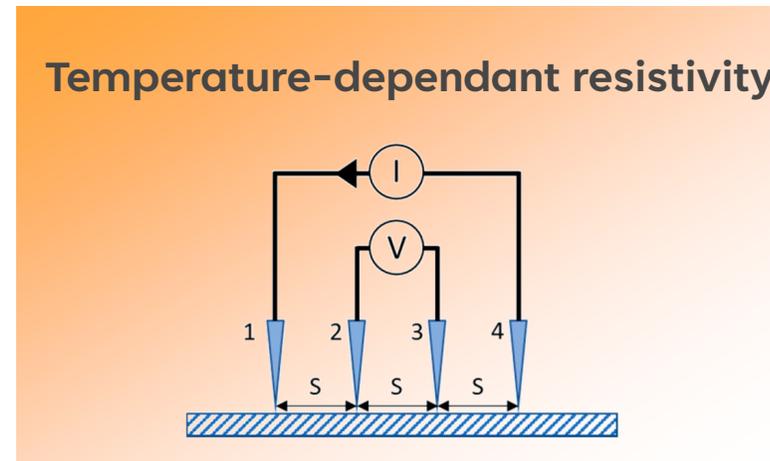
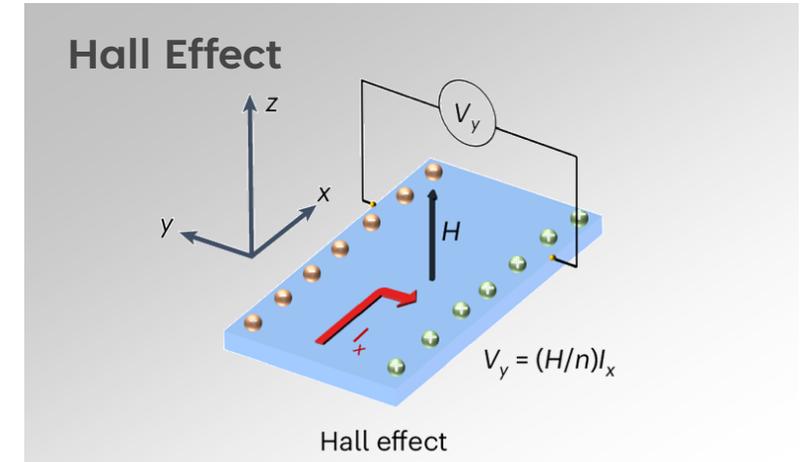
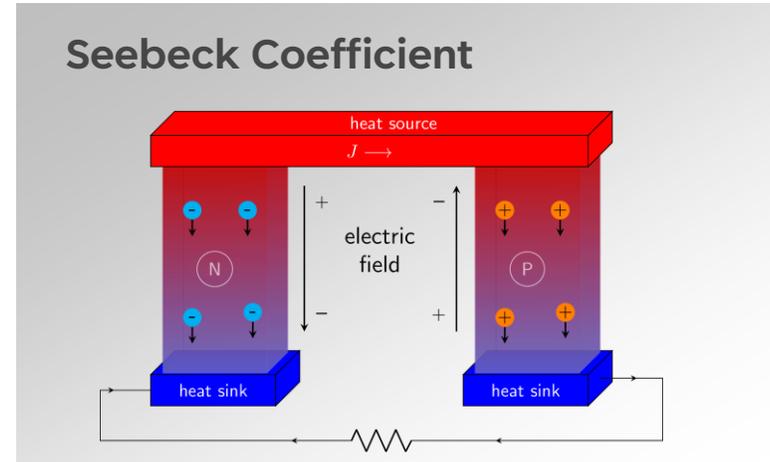
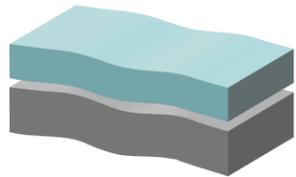
### Transport Properties



## 2. Standard Characterization



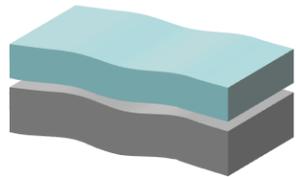
Transport Properties



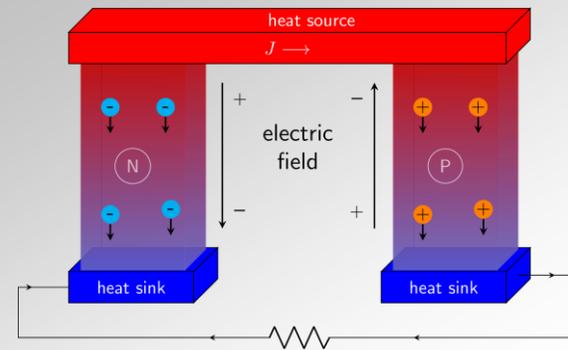
## 2. Standard Characterization



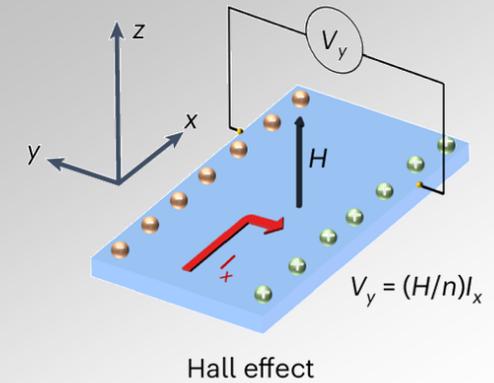
### Transport Properties



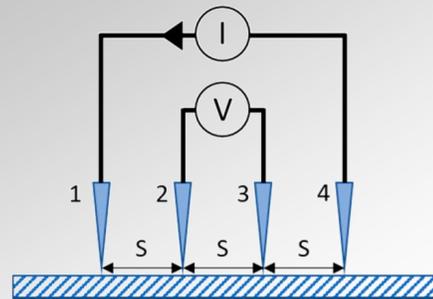
### Seebeck Coefficient



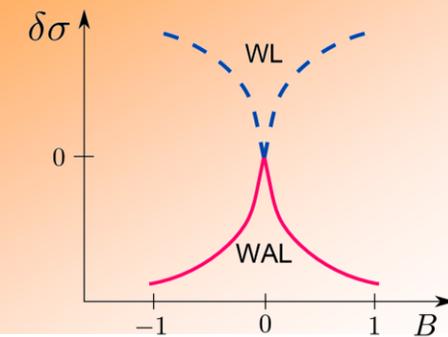
### Hall Effect



### Temperature-dependant resistivity



### Magnetoresistance



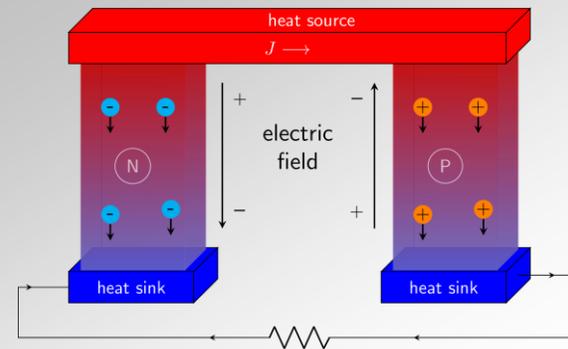
## 2. Standard Characterization



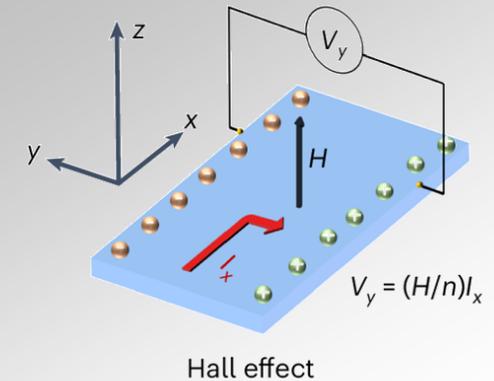
### Transport Properties

- ✓ Differentiate bulk vs surface state conduction
- ✓ Quantify quantum transport

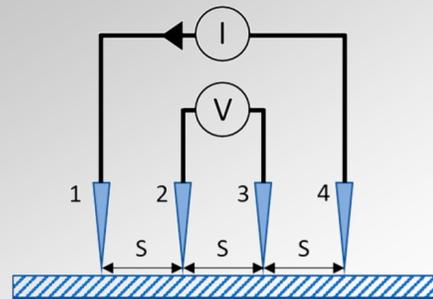
### Seebeck Coefficient



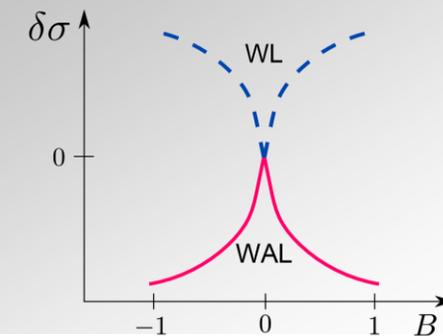
### Hall Effect



### Temperature-dependant resistivity



### Magnetoresistance

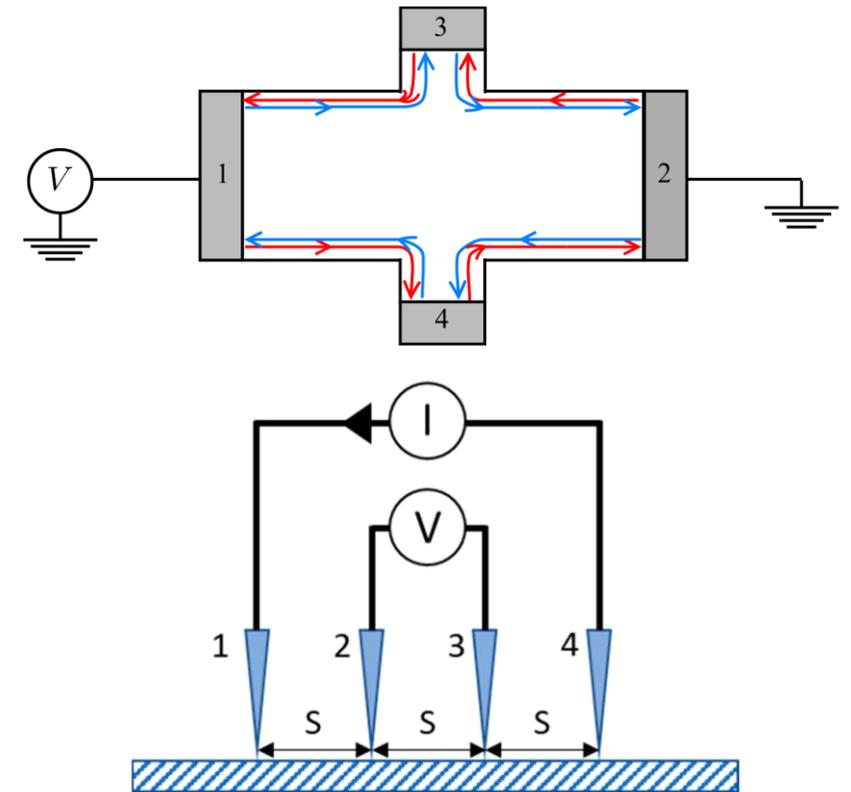


## 2. Standard Characterization



### Transport Properties

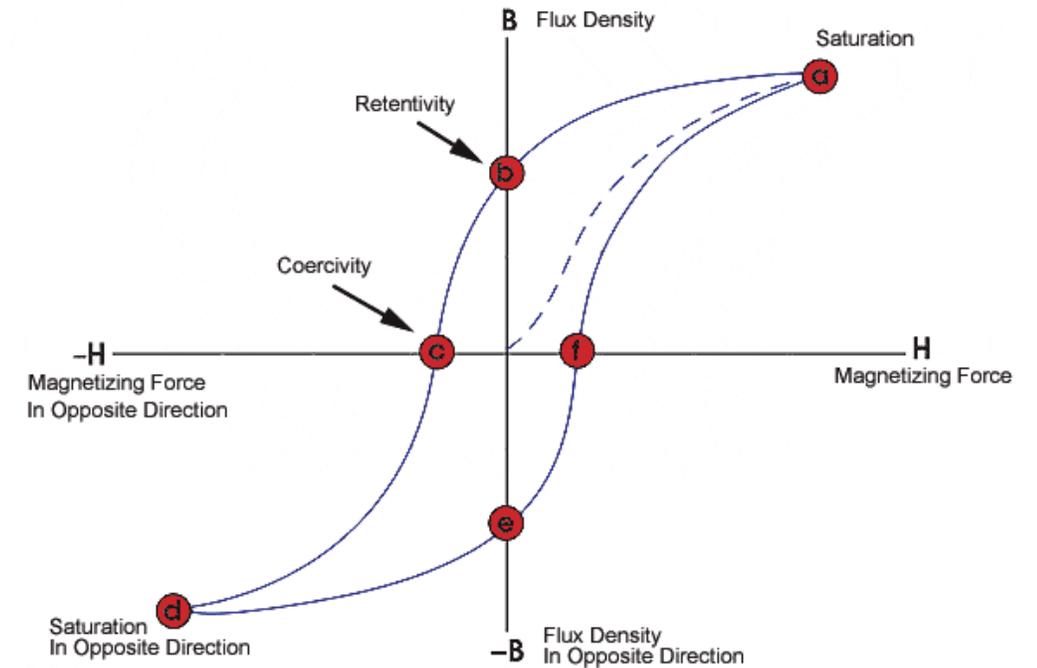
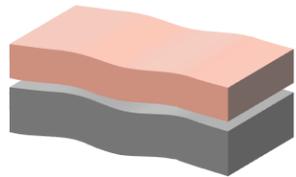
- ✓ Differentiate bulk vs surface state conduction
- ✓ Quantify quantum transport



## 2. Standard Characterization



Magnetic Properties



### 3. Advanced Characterization

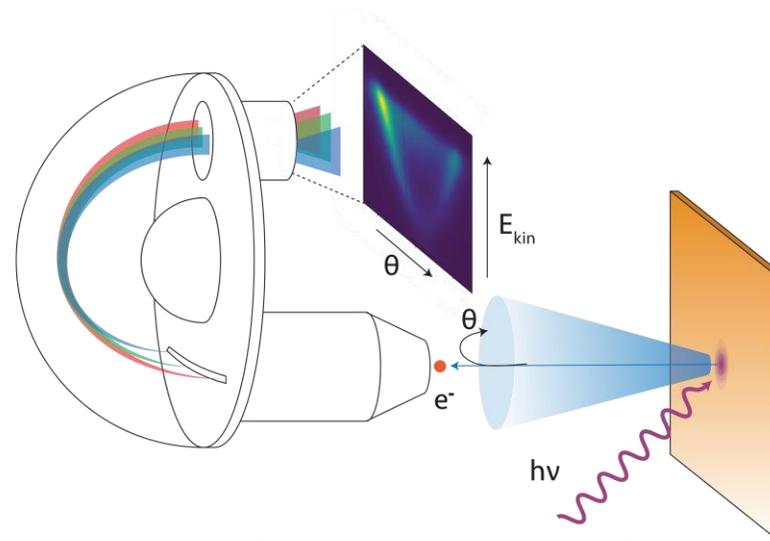
#### ARPES

Angle-resolved Photoemission Spectroscopy

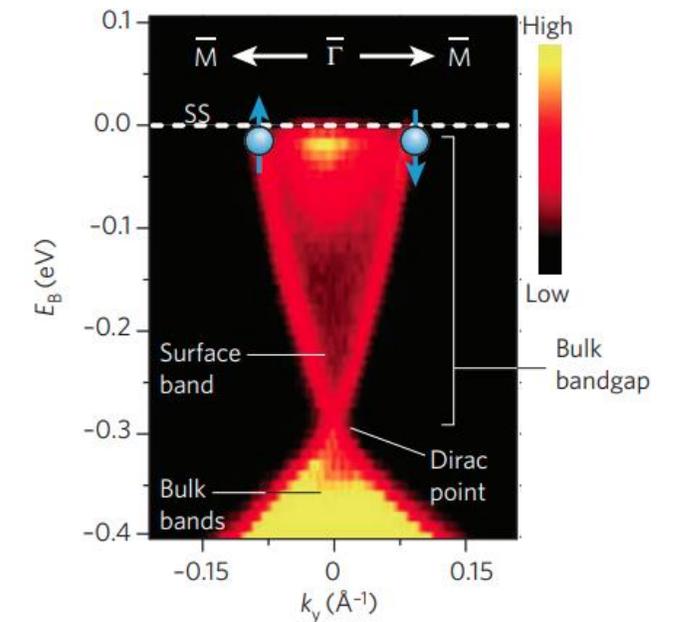


Advanced  
characterization

- ARPES
- TEM

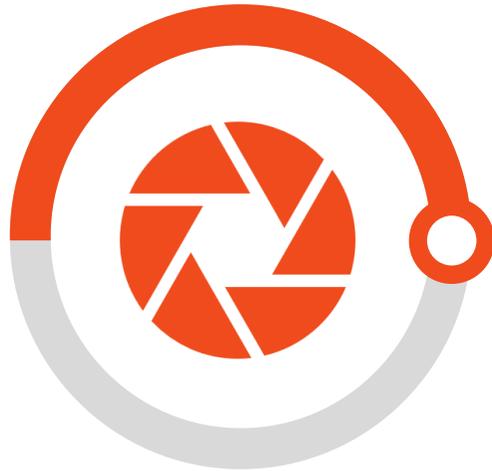


Adapted from Damascelli, Hussain, Shen, *Rev. Mod. Phys.* **75**, 2003



in H. Zhang et al., *Nature Physics* **5**, pp. 438–442 (2009)

### 3. Advanced Characterization

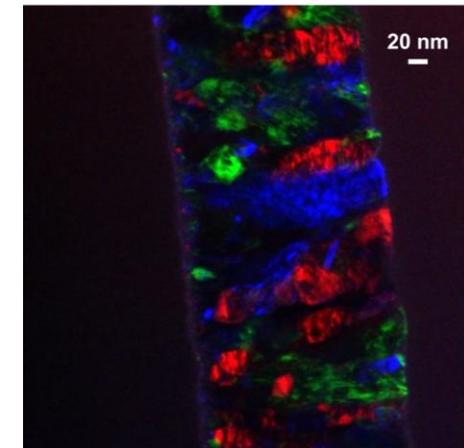
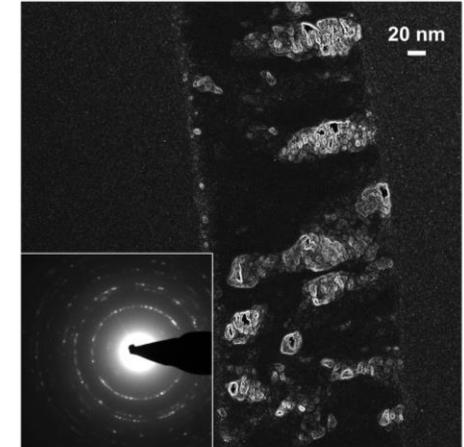
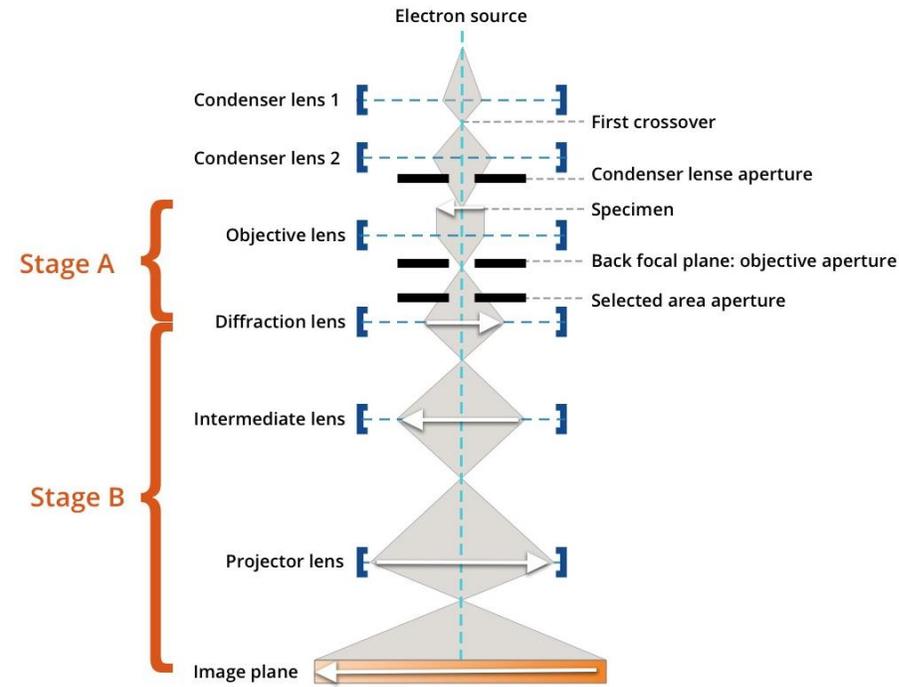


#### Advanced characterization

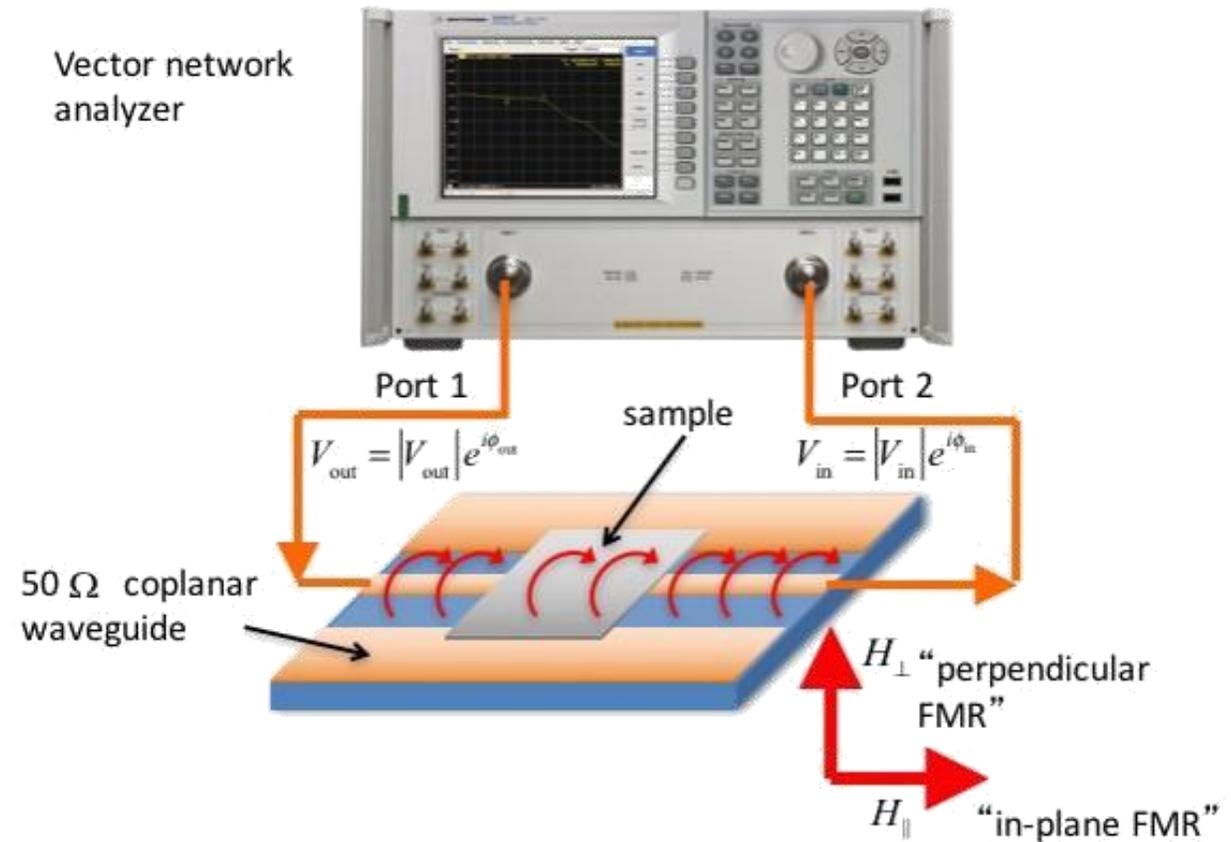
- ARPES
- TEM

#### TEM

#### Transmission Electron Microscopy



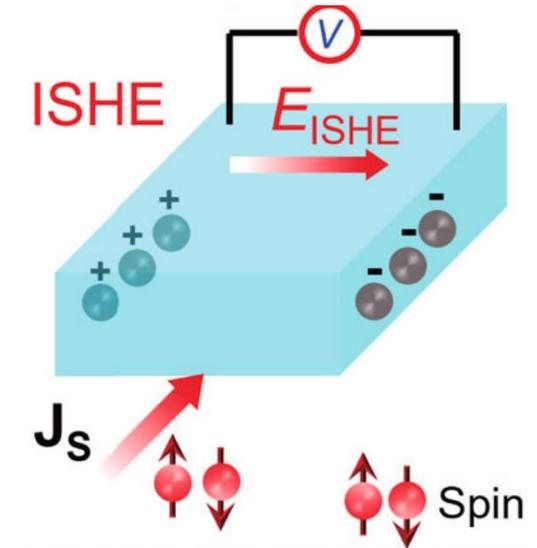
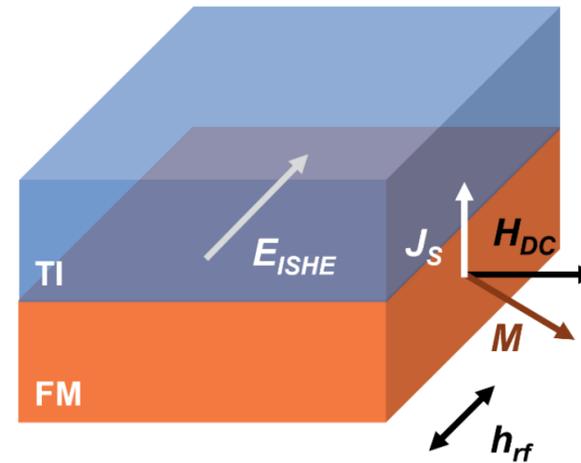
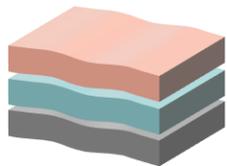
## 4. High-frequency measurements



## 4. High-frequency measurements



$$\mathbf{J}_c = \theta_{SH} \frac{2e}{\hbar} \mathbf{J}_s \times \mathbf{s}$$



- Test SCI efficiency through the **Inverse Spin-Hall Effect** using TI-based heterostructures





# conclusions

- ∇ There remains significant work in developing **scalable, cost-effective fabrication** methods that preserve the **unique properties of TI materials**.
- ∇ This proposal delivers a comprehensive investigation of TI thin films on **flexible substrates** — an area still largely unexplored — with clear relevance to emerging **spintronic and IoT technologies**.
- ∇ By addressing the role of **structural disorder**, this work lays essential groundwork for future studies into more complex heterostructures and the **interplay of topological quantum effects**.



Thank you for your attention.

**ANY QUESTIONS?**



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ORCID ID: 0000-0002-1733-7406

