Workshop TWEET

Aula Beltrami, Politecnico di Milano, 5 June 2023

Ferroelectric switching of spin-to-charge conversion for ultralow power spintronics

Federico Fagiani, Luca Nessi, Giovanni Gandini, Riccardo Bertacco, Matteo Cantoni

& Christian Rinaldi

Department of Physics, Politecnico di Milano, Milan, Italy

POLITECNICO MILANO 1863

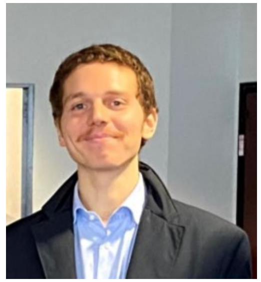
polifab POLITECNICO DI MILANO

Spin-based electronics in Polifab

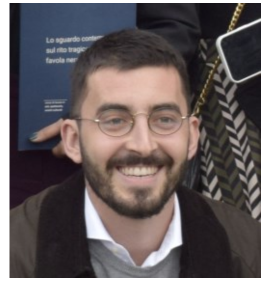
nabis.fisi.polimi.it

polifab
POLITECNICO DI MILANO

C. Rinaldi
Associate Professor



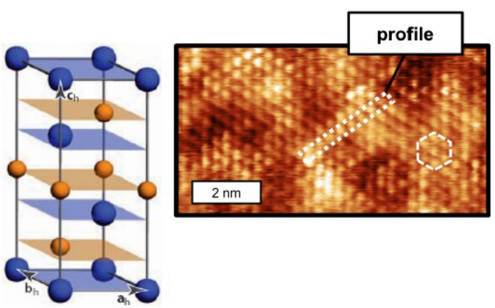
F. Fagiani
Ph.D. student



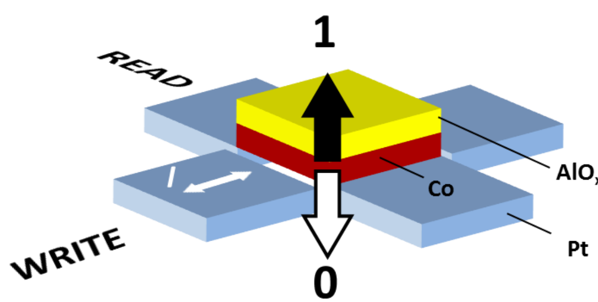
G. Gandini
Ph.D. student

M. Cantoni
Associate Professor

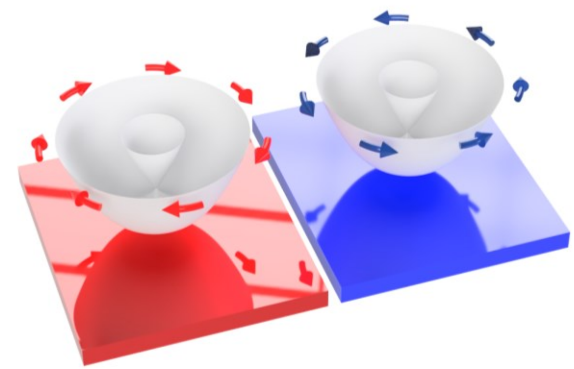
R. Bertacco
Full professor



Growth of magnetic and ferroelectric materials



Magnetization switching for magnetic memories



Rashba semiconductors for spin-based computing

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Some credits

POLITECNICO DI MILANO (MILAN)


C. Rinaldi

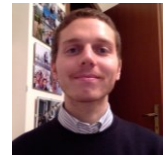

R. Bertacco


M. Cantoni


L. Nessi


D. Petti


E. Albisetti

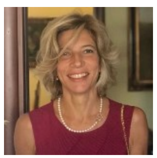

F. Fagiani

Project **ECOS - *E****lectric* ***C****ontrol* ***O****f* ***S****pin transport*

fondazione cariplo

PRIN **TWEET** (2019-2022)
2017YCTB59

CNR (CHIETI & ROMA)

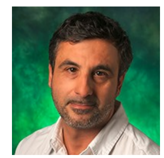

S. Picozzi


R. Calarco

PAUL DRUDE INSTITUTE (BERLIN)


S. Cecchi

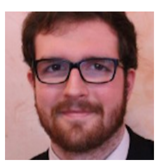
UNIVERSITY OF NORTH TEXAS (DENTON)


M. Buongiorno Nardelli

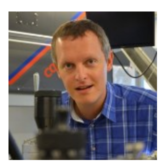
CEA, CNRS (GRENOBLE)

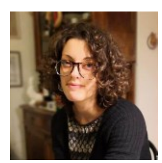

L. Vila


J.-P. Attane


P. Noel

UNITE MIXTE DE PHYSIQUE, CNRS (THALES)


M. Bibes


S. Varotto

UNIVERSITY OF GRONINGEN


J. Sławińska

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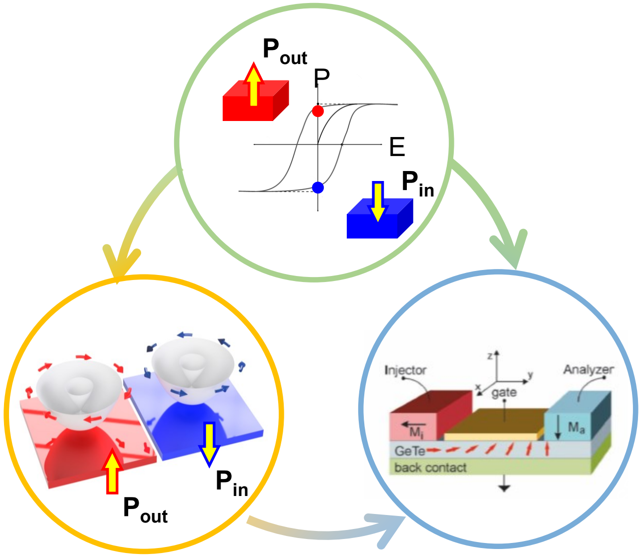
Outline

- General aim
- Ferroelectric Rashba semiconductors
  - I. Rashba effect in GeTe
  - II. Gating of ferroelectricity in the semiconductor GeTe
  - III. Spin-charge interconversion in GeTe
- Materials engineering
- Conclusions and perspectives



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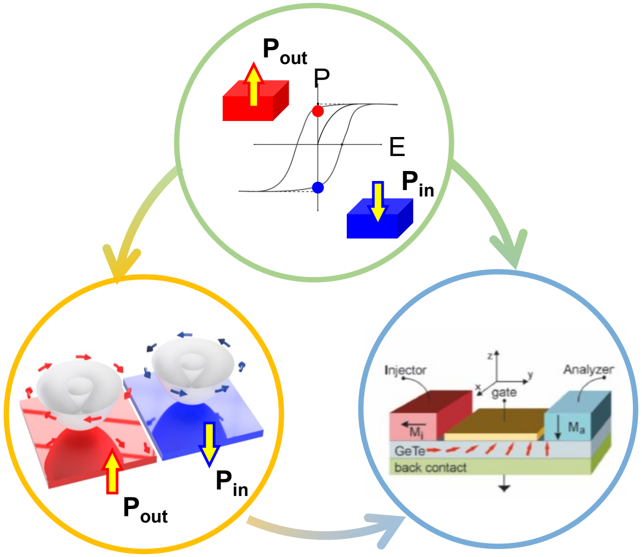
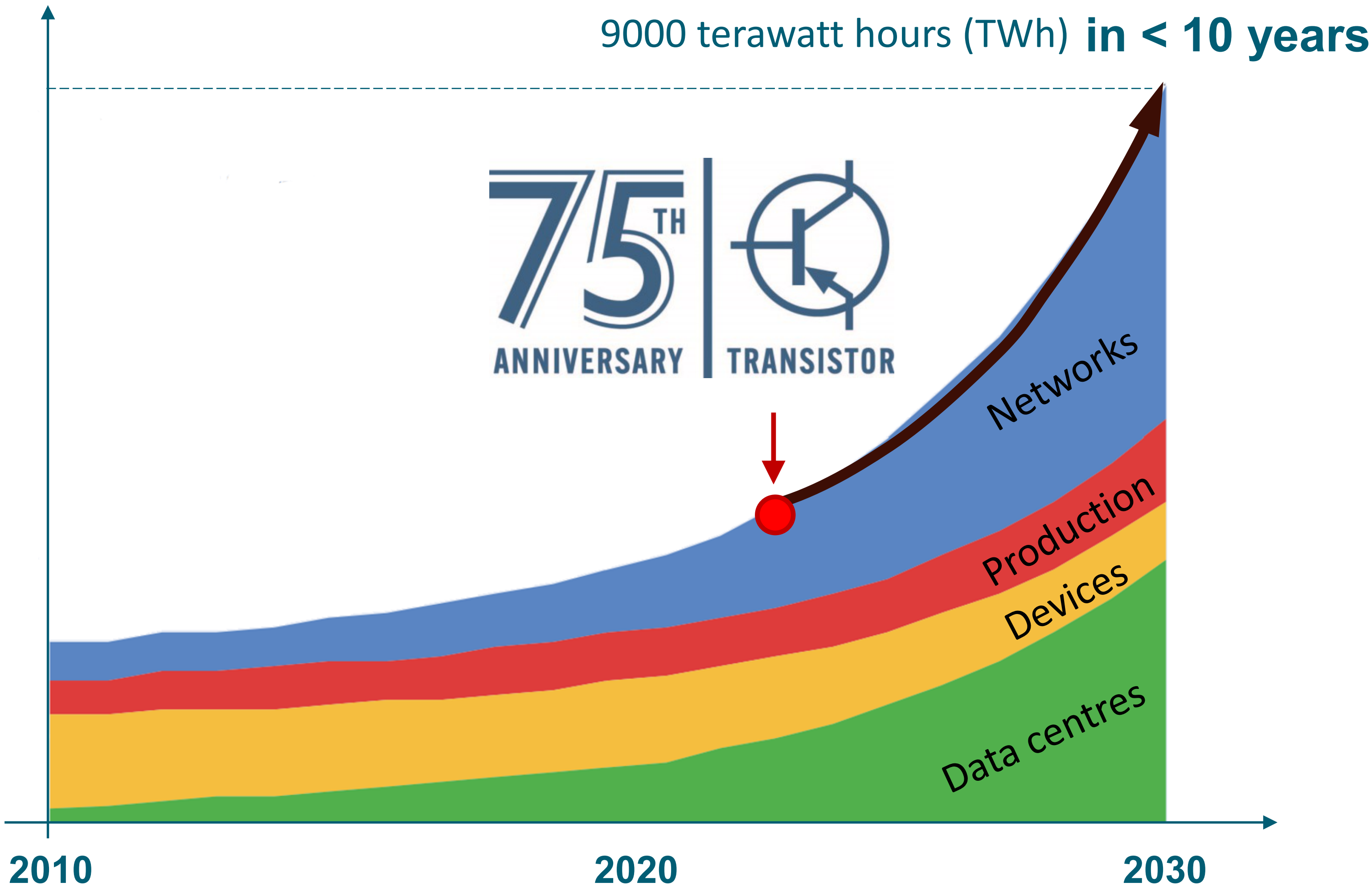


Beyond the transistor: why and when?



N. Jones, The information factories, Nature 561, 163 (2018)

https://eds.ieee.org/about-eds/75th-anniversary-of-the-transistor

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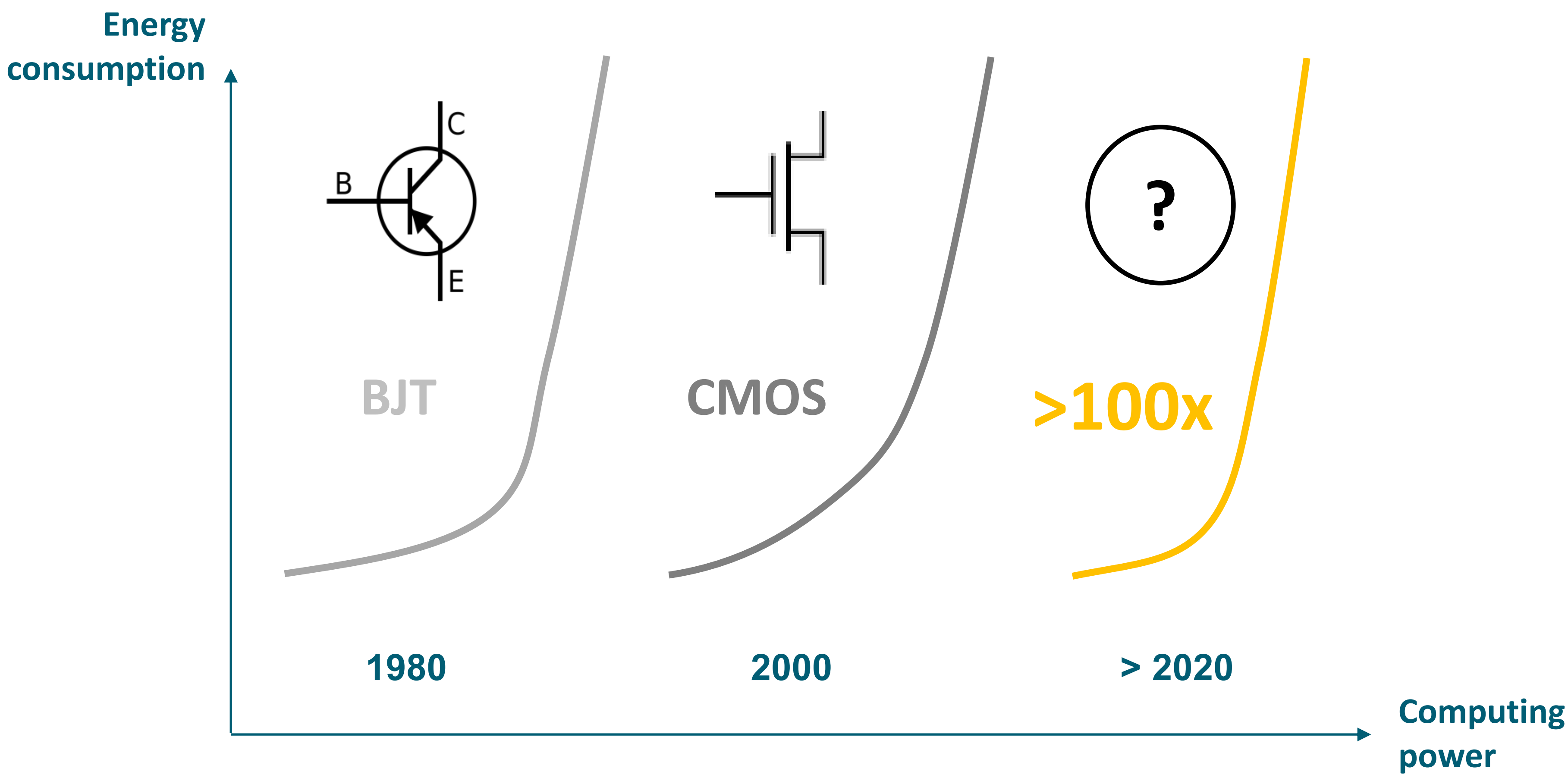
A new physical substrate is needed



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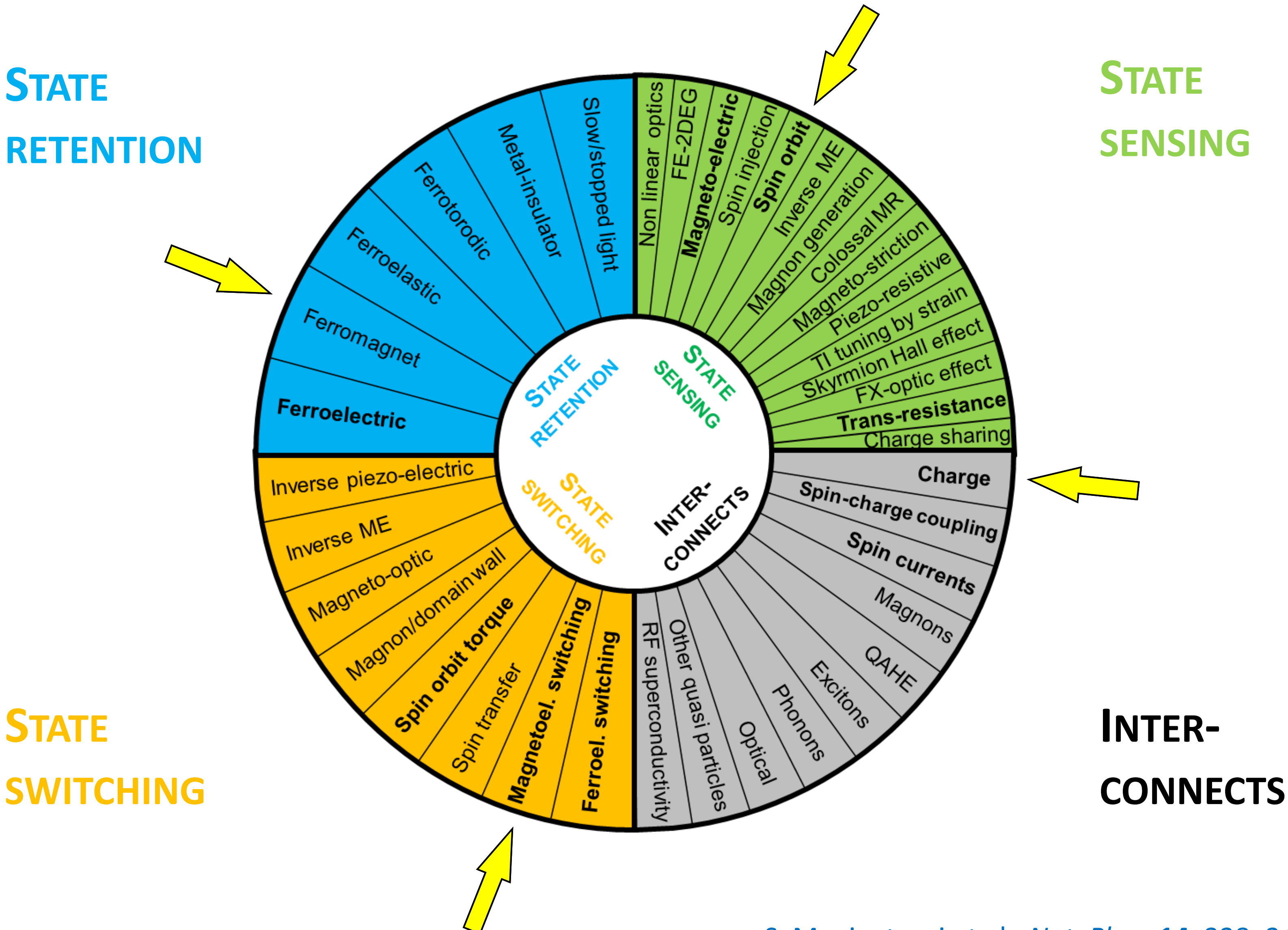
Pathways to quantum materials storage and computing devices



S. Manipatruni et al., *Nat. Phys.* **14**, 338–343 (2018)

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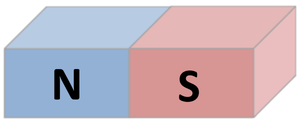
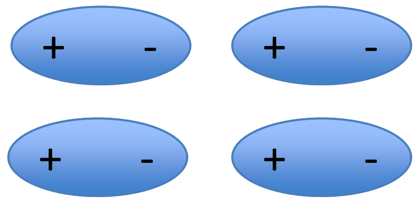
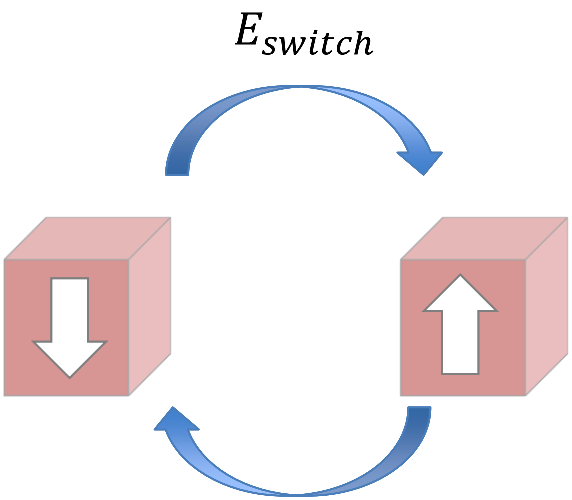
State retention and state switching with collective order parameters

Ferromagnetism



Ferroelectricity





Order parameter:

Magnetic moment

Dipole moment

$$E = I_{STT} V_d t_{STT} = 10\ fJ$$

$$E = 2PV_C = 1\ aJ$$

$$\lambda = \frac{E_{switch}}{E(\Theta)} = 2\ (FE); > 1000\ (STT)$$

The ratio of the switching energy to the barrier height is optimal for ferro-electrics

S. Manipatruni *et al.*, Beyond CMOS computing with spin and polarization, Nature Physics **14**, 338 (2018)

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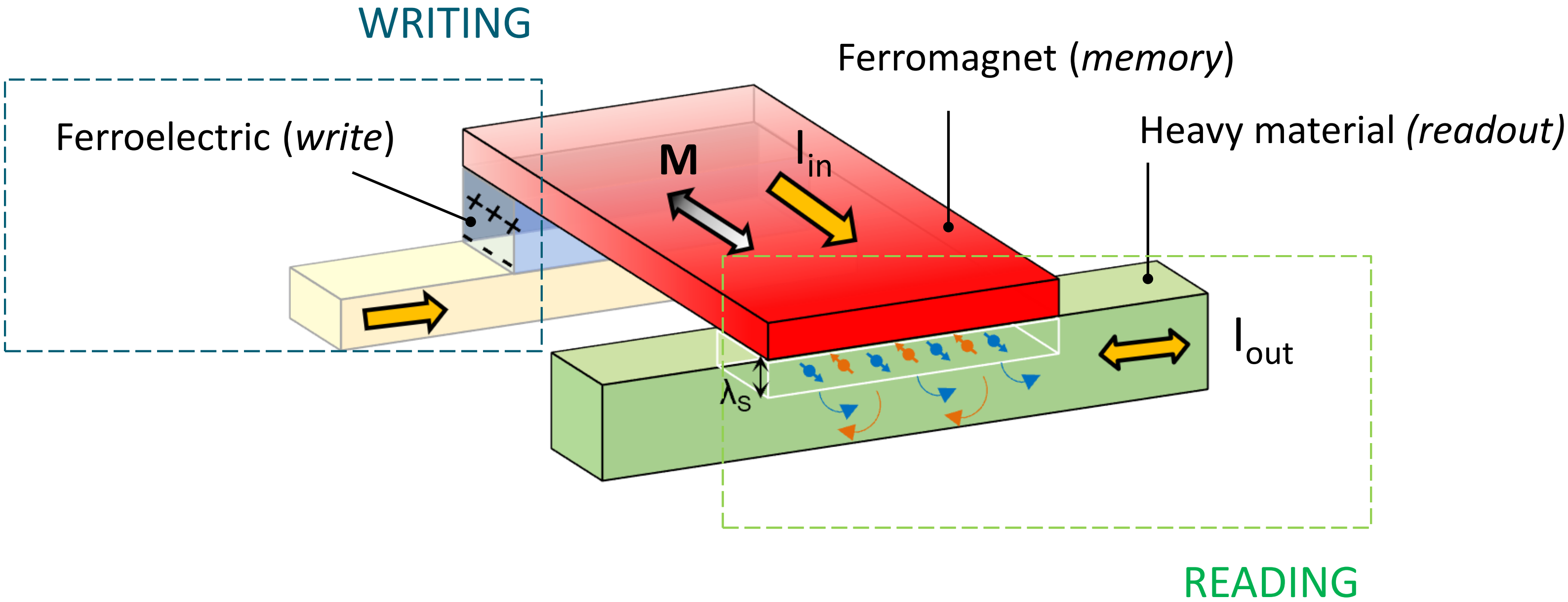
Magneto-electric spin-orbit device (MESO)



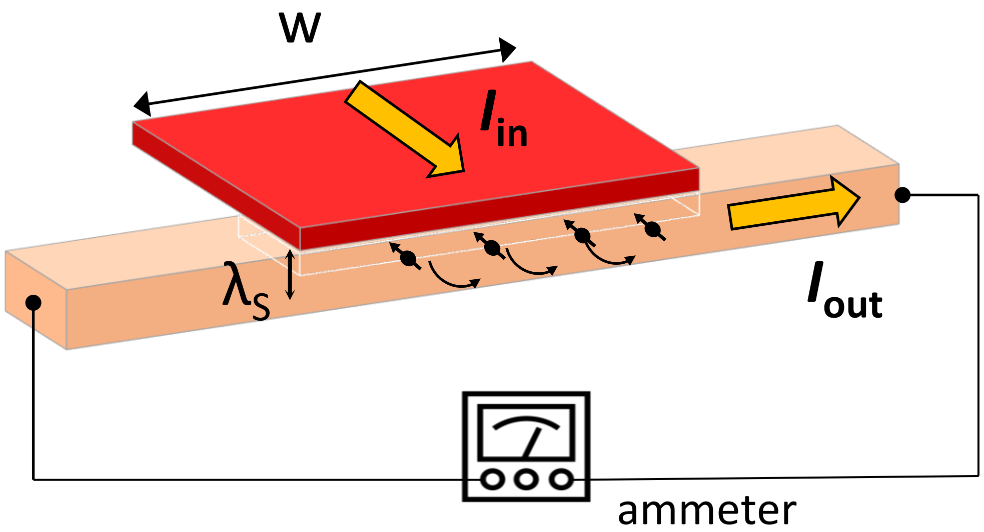
>30x

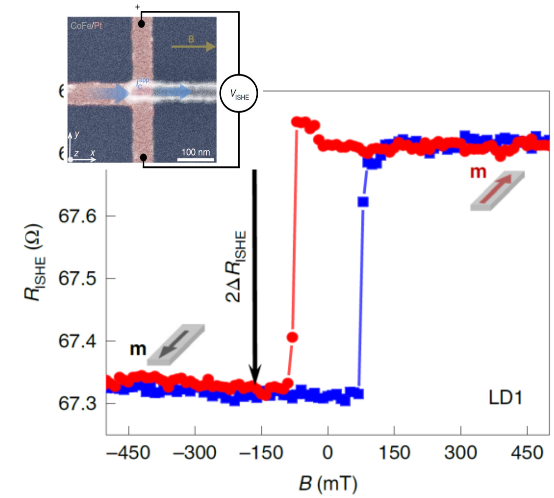
vs CMOS

- ✓ **Non-volatile**
- ✓ **Atto-joule regime**
- ✓ **The smaller the better**

S. Manipatruni *et al.*, Nature, 565, 35-42 (2019)

Read-out efficiency





V.T. Pham *et al.*
Nature Electronics 3.6, 309-315 (2020)

$$\eta = \frac{I_{out}}{I_{in}} = \frac{\lambda_{eff}}{w_{FM}}$$

0.1% in CoFeB/Pt (SHE)

Alternative materials

2DEG, 2D materials, topological materials, etc.

$\lambda_{eff} > 10 - 15$ nm

Scaling of the device dimensions

$w_{FM} \approx$ ***tens*** *of nm*

Relevant numbers for MESO logic (*T* > 420 K)

Switching voltage

100-300 mV

<100 mV ($BaTiO_3$, 2022)

Nanomagnet width

w~ 10 nm

7 nm

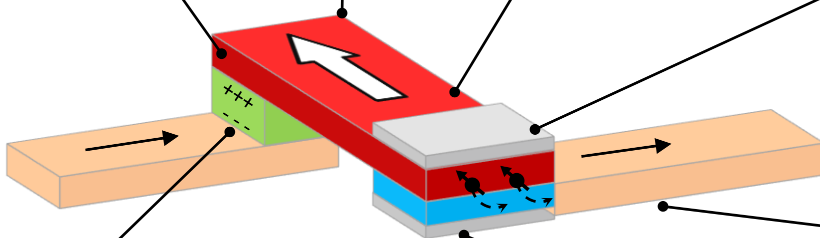
Spin polarization

P_S> 80%

Heusler alloys?

Current pulse

10 ps – 1 fs



Resistivity

ρ_{SOC}> 10 mΩ

Switching energy

1- 10 aJ

10 aJ ($BaTiO_3$, 2022),

20 aJ (optical)

Spin-to-charge conversion

I_C/I_S > 90-100%

0.1% in CoFeB/Pt (SHE)

Target

State-of-the-art

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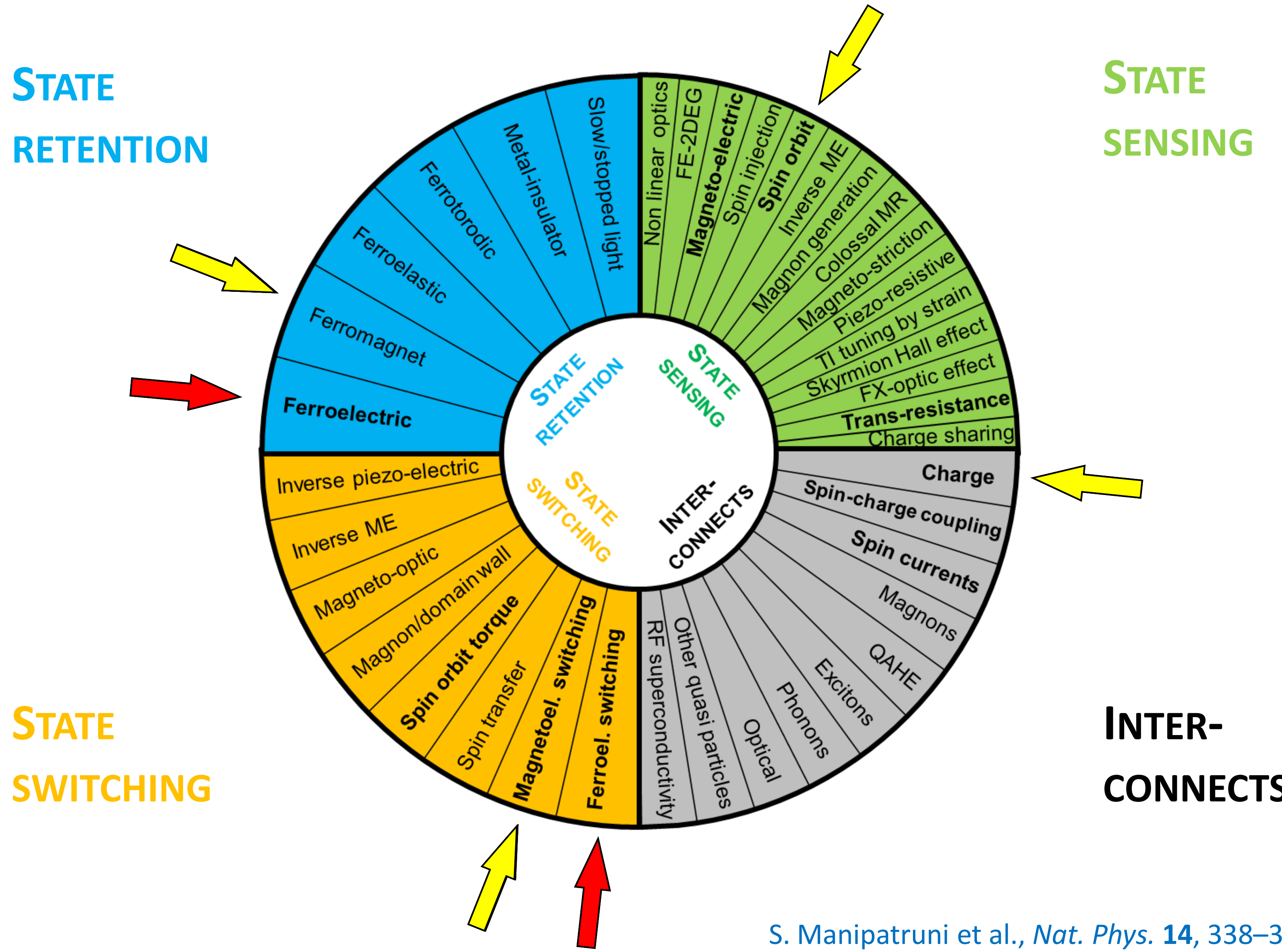
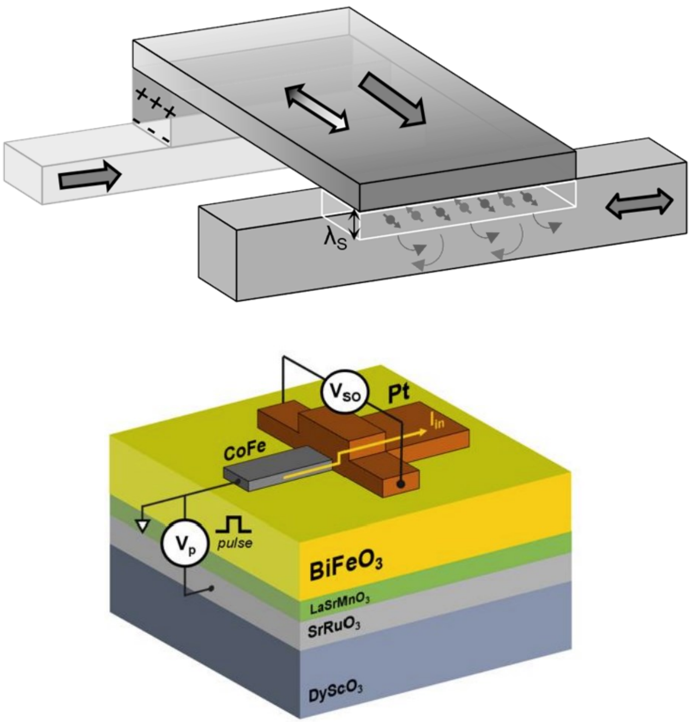
Exploring other solutions



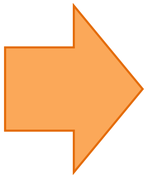
S. Manipatruni et al., *Nat. Phys.* **14**, 338–343 (2018)

State-of-art

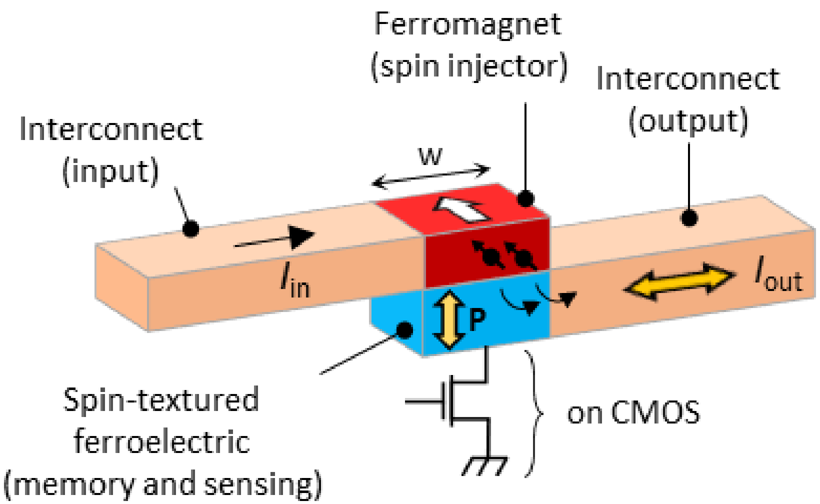
Magneto-electric spin-orbit logic



D. C. Vaz, F. Casanova *et al.*,
arXiv:2302.12162 (2023)



Ferro-electric spin-orbit logic



S. Varotto, C. Rinaldi *et al.*,
Nature Electronics **4**, 740–747
(2021)

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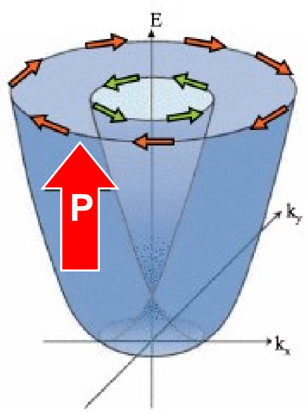
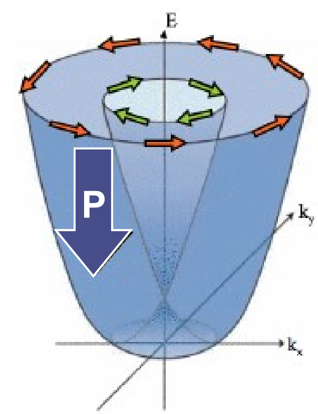
Roberto Carlos, French – Brazil 1997





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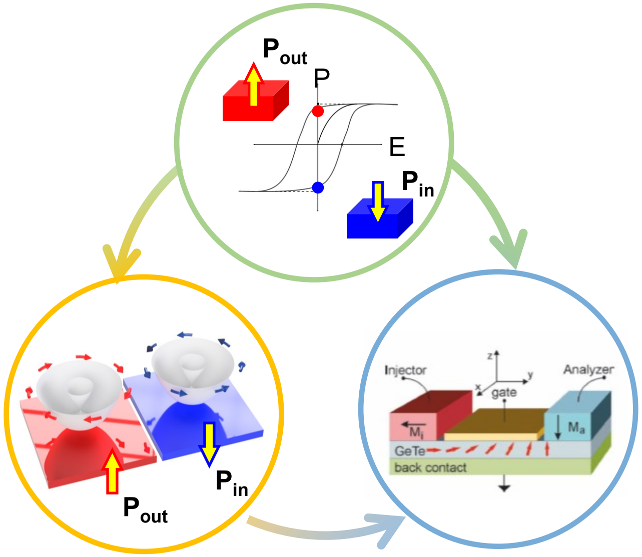
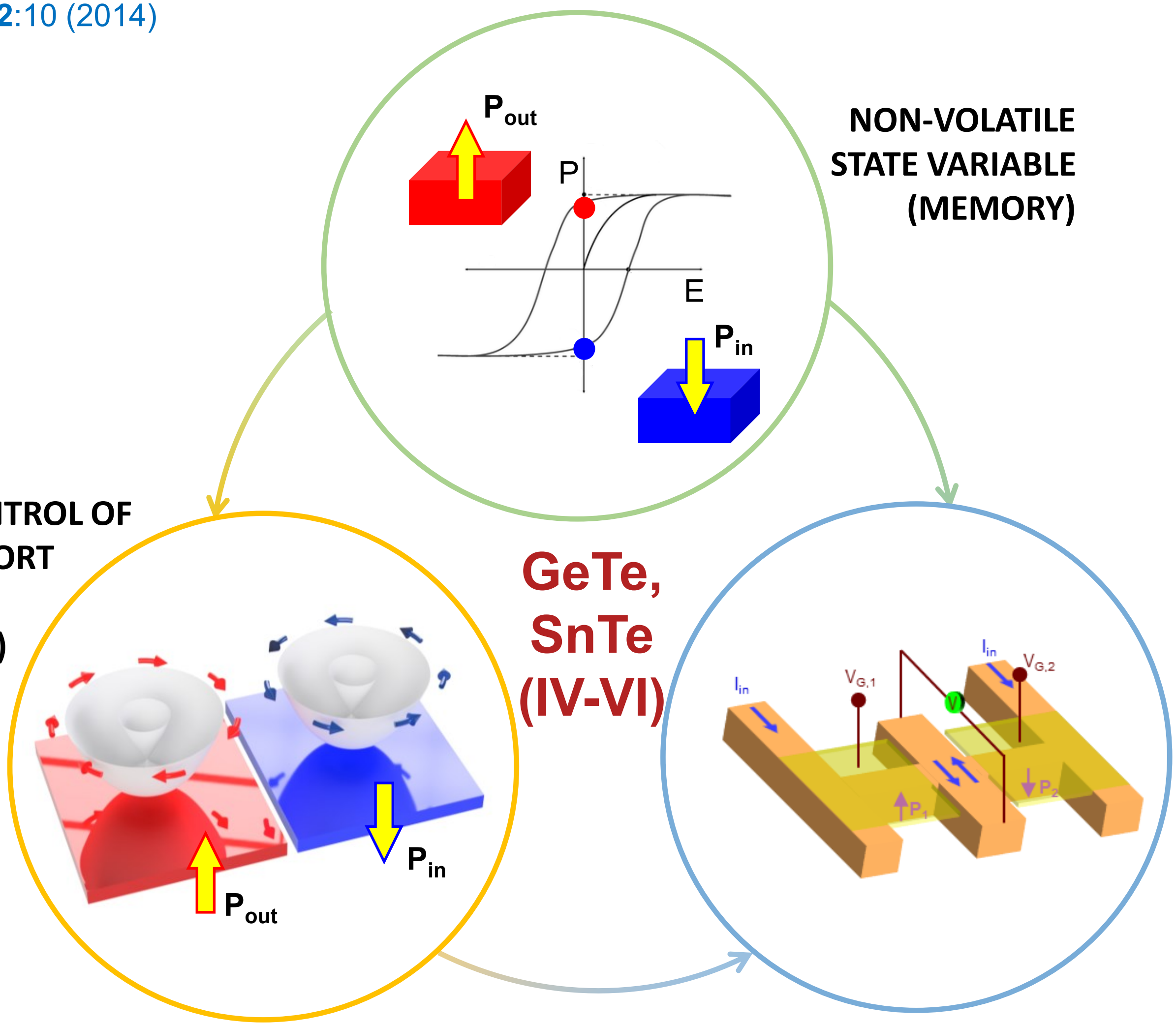


FErroelectric Rashba SemiConductors (FERSC)

D. Di Sante *et al.*, Adv. Mater. **25**, 509 (2013)
S. Picozzi, Front. Phys., **2**:10 (2014)

NON-VOLATILE
STATE VARIABLE
(MEMORY)

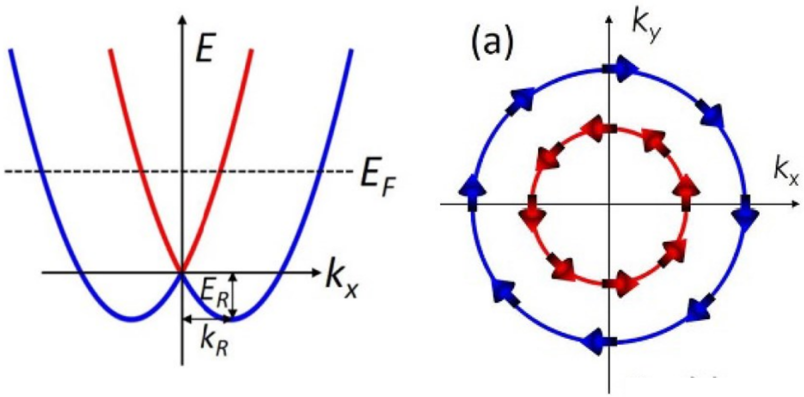
ELECTRIC CONTROL OF
SPIN TRANSPORT
PROPERTIES
(COMPUTING)



COMPUTING
AND MEMORY
IN ONE DEVICE

Rashba physics in ferroelectrics

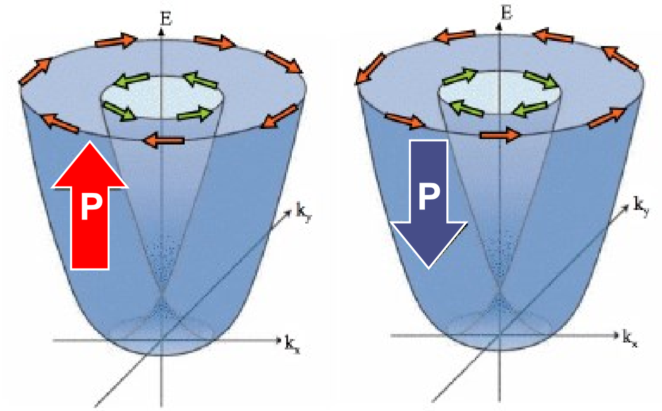
Rashba splitting and spin-momentum locking

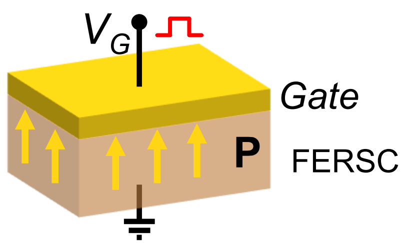


$$H_{SO} = \frac{\hbar}{4m^2c^2}(\nabla V \times \mathbf{p}) \cdot \boldsymbol{\sigma}$$

L. L. Tao and E. Y. Tsymbal, J. Phys. D 54, 113001 (2021)
A. Manchon et al., Nature Materials 14, 871 (2015)

Non-volatile Rashba SOC in FERSC





D. Di Sante *et al.*, **Adv. Mater. 25**, 509 (2013)

Ferroelectric control of the spin transport in ferroelectric Rashba semiconductors

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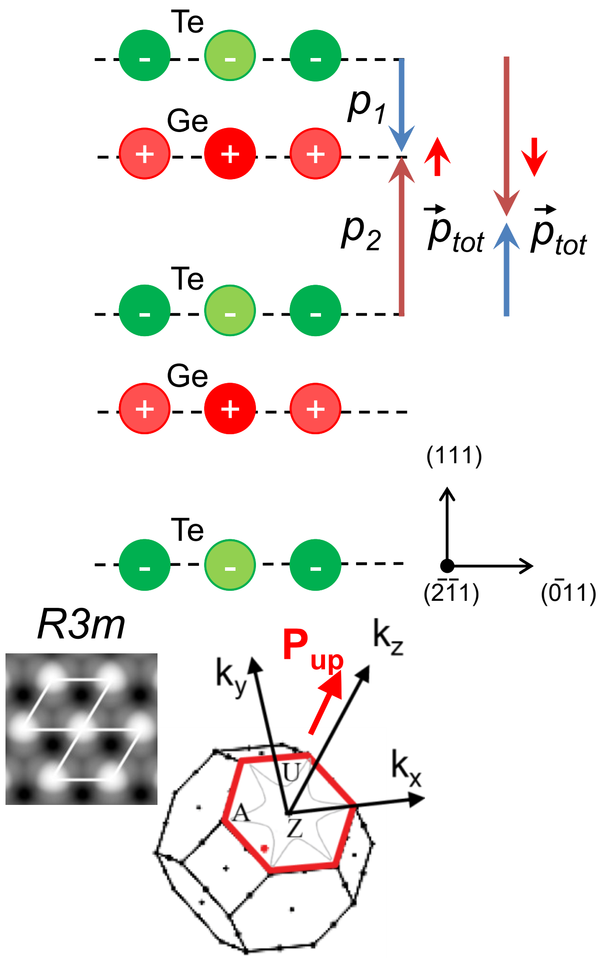
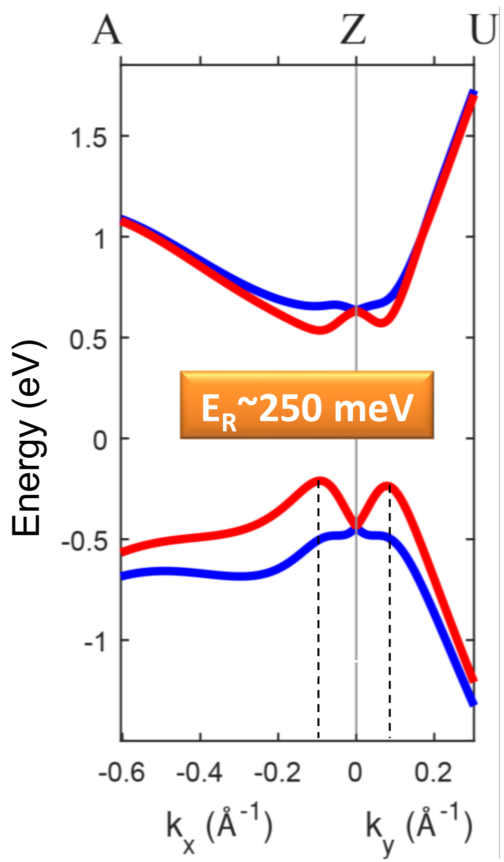
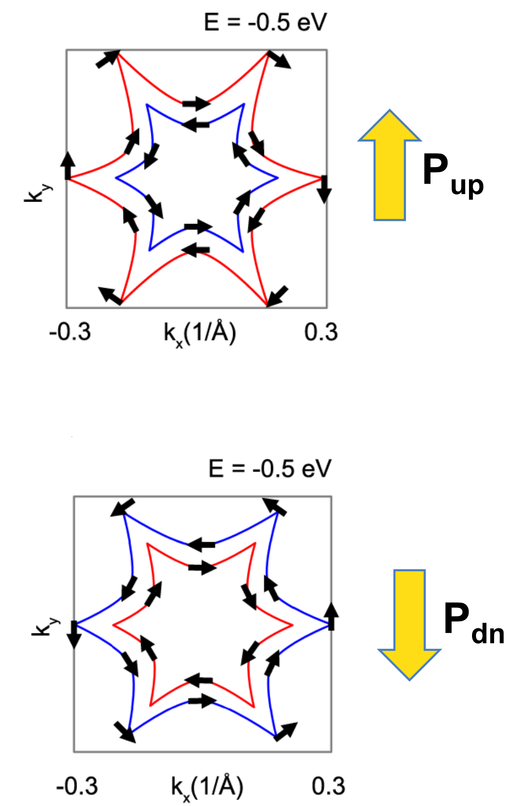
Germanium Telluride as FERSC

FERROELECTRICITY | GIANT RASHBA | SPIN TEXTURE





Polarization dependent spin texture



Kobolov *et al.*, APL Materials 2, 066101 (2014).

D. Di Sante, *et al.*, Adv. Mat. 25, 509-513 (2013).

S. Varotto *et al.*, Nano Letters 18, 2751 (2018).

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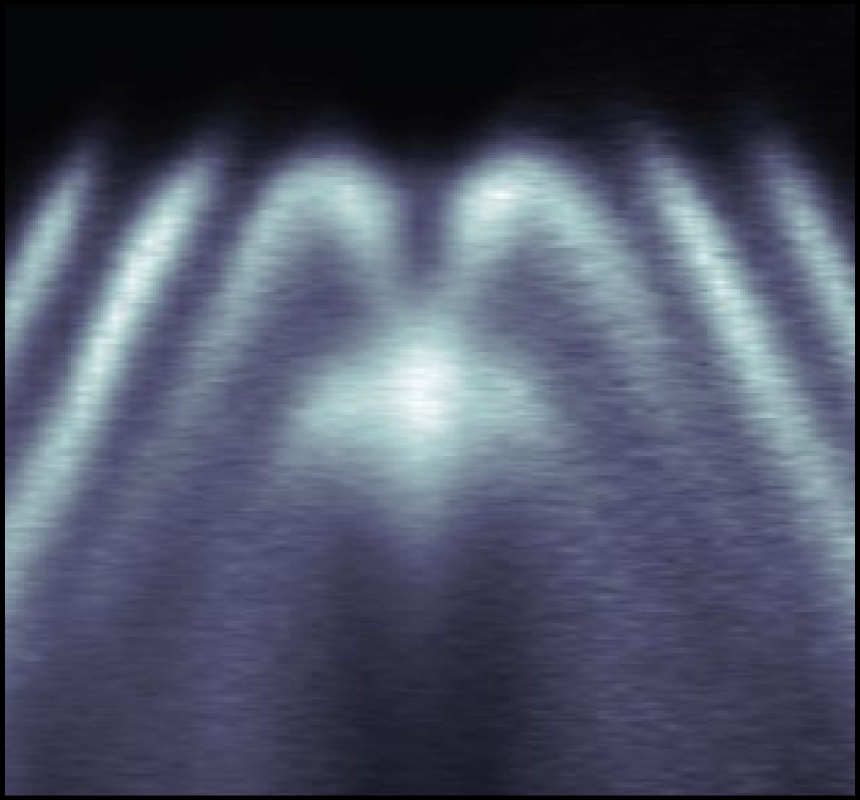
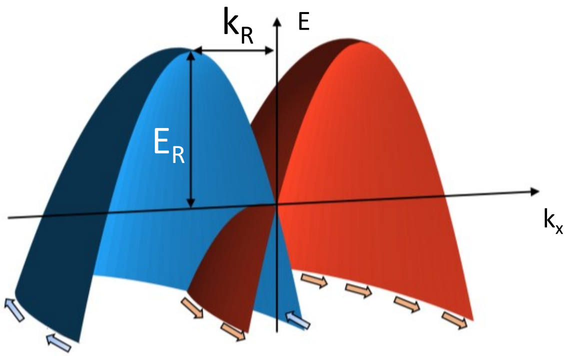
How to look at the band structure for two opposite ferroelectric polarizations?

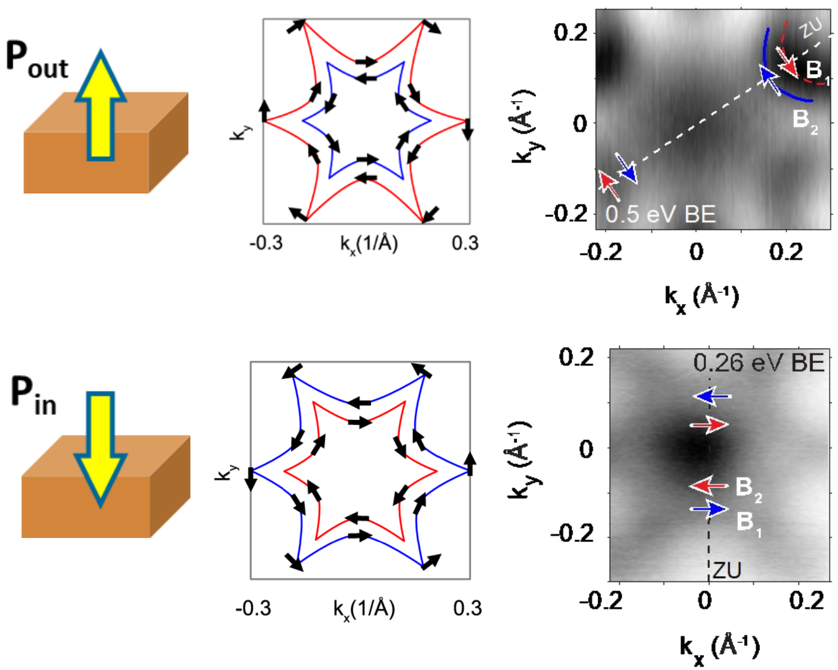
Spin and Angular Resolved Photoemission Spectroscopy (SARPES)

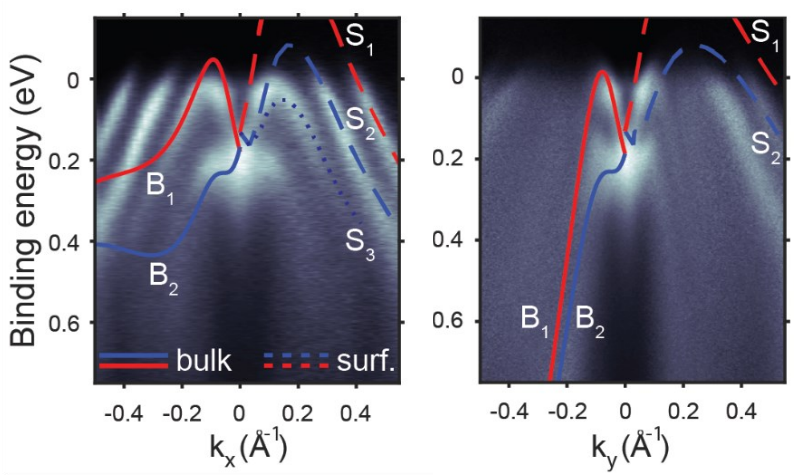


Interplay between ferroelectricty and Rashba spin texture



M. Liebmann, C. Rinaldi, *et al.*, **Adv. Mater.** 28, 560 (2016)
C. Rinaldi *et al.*, **Nano Letters** 18, 2751 (2018)





Opposite ferroelectric polarizations corresponds to opposite spin circulation

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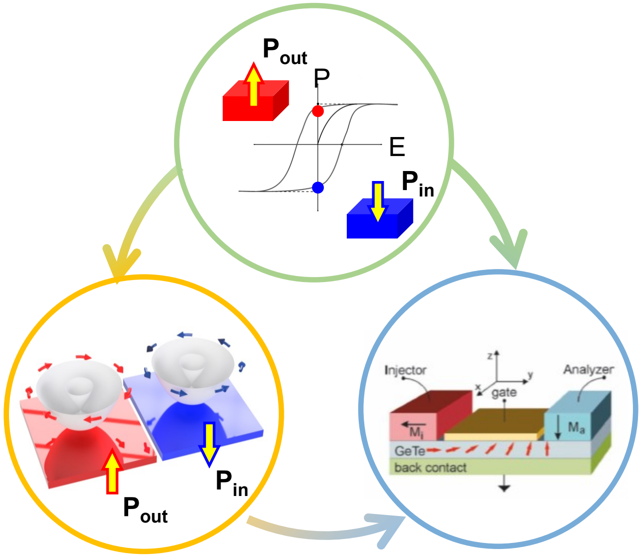
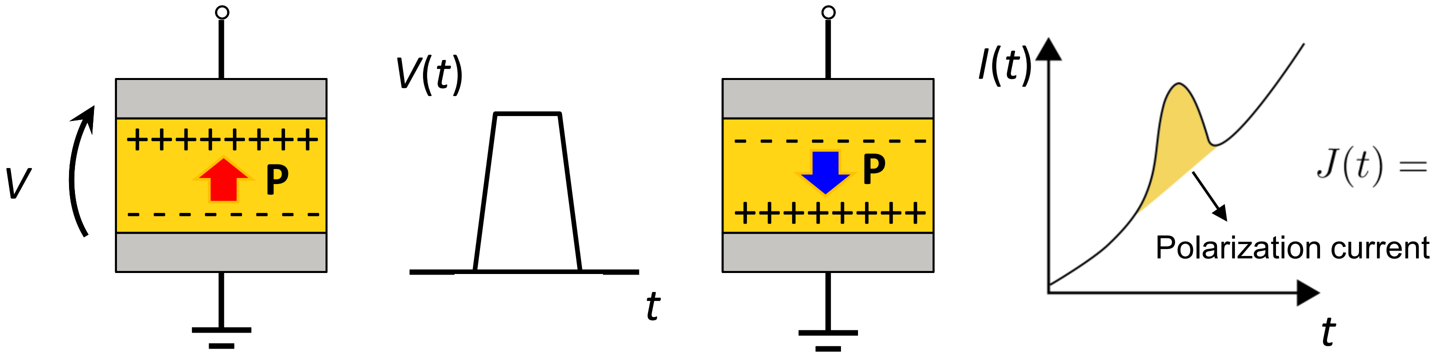


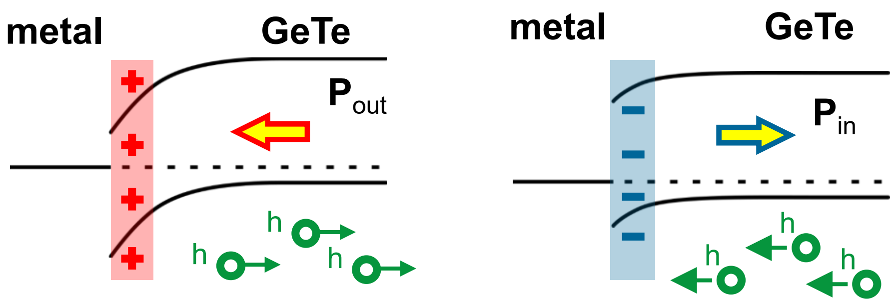
Gating of ferroelectric semiconductors



$$J(t) = \frac{\partial D(t)}{\partial t} = \epsilon_0 \frac{\partial E}{\partial t} + \frac{\partial P}{\partial t}$$

Scott, J. F. *et al.*, J. Appl. Phys. 64, 787–792 (1988)

Ferroelectric control of charge transport



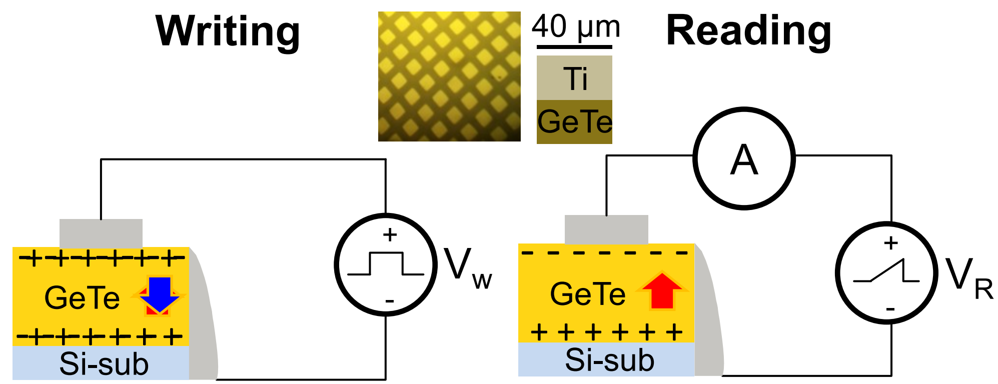
Lower conductance ($\mathbf{P}_{out}$)

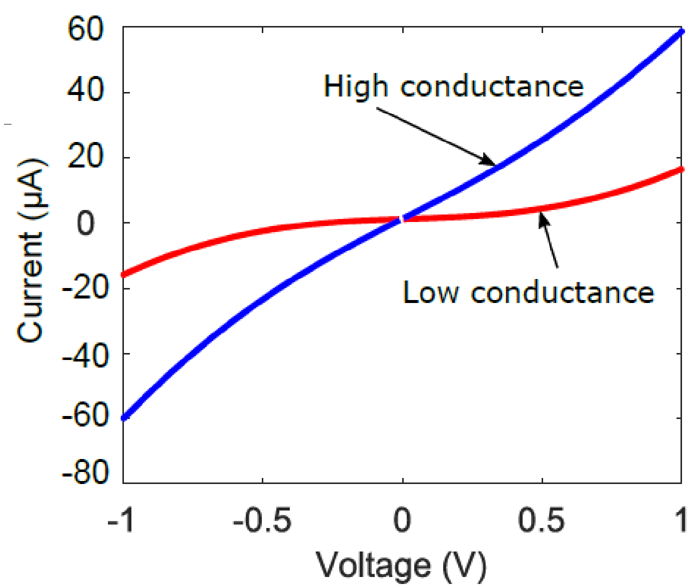
Higher conductance ($\mathbf{P}_{in}$)

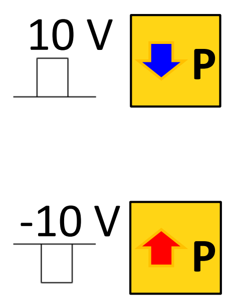
P-dependent conductivity through metal/semiconductor interface

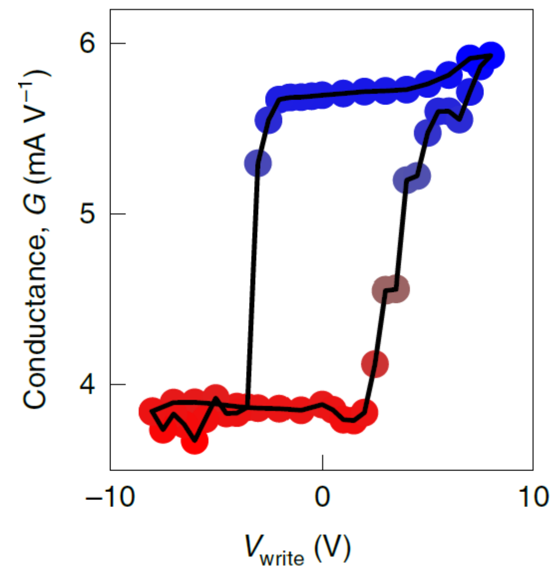
P. W. M. Blom *et al.*, Phys. Rev. Lett. 73, 2107 (1994)

Polarization-dependent resistance of metal/GeTe junctions



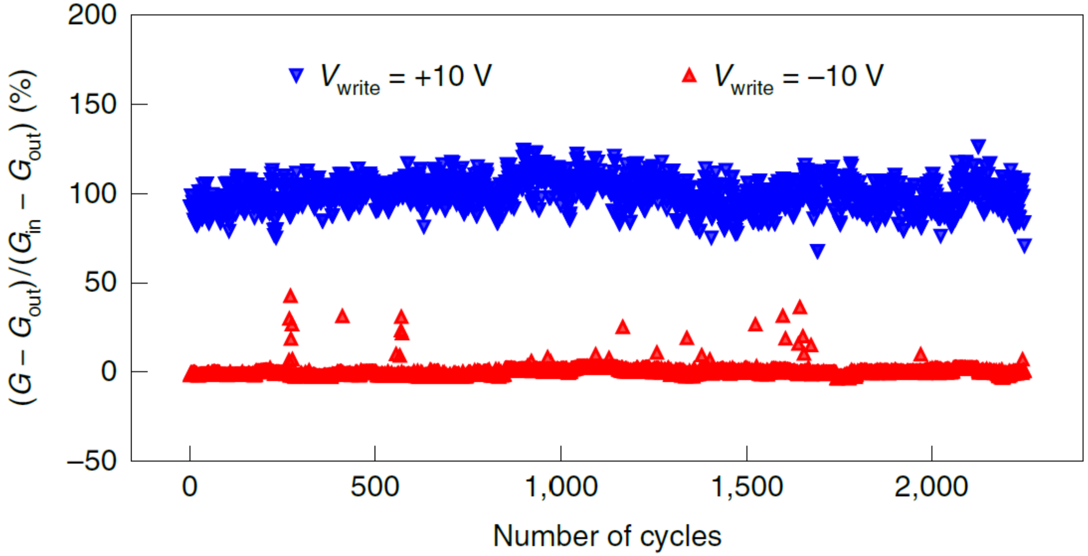


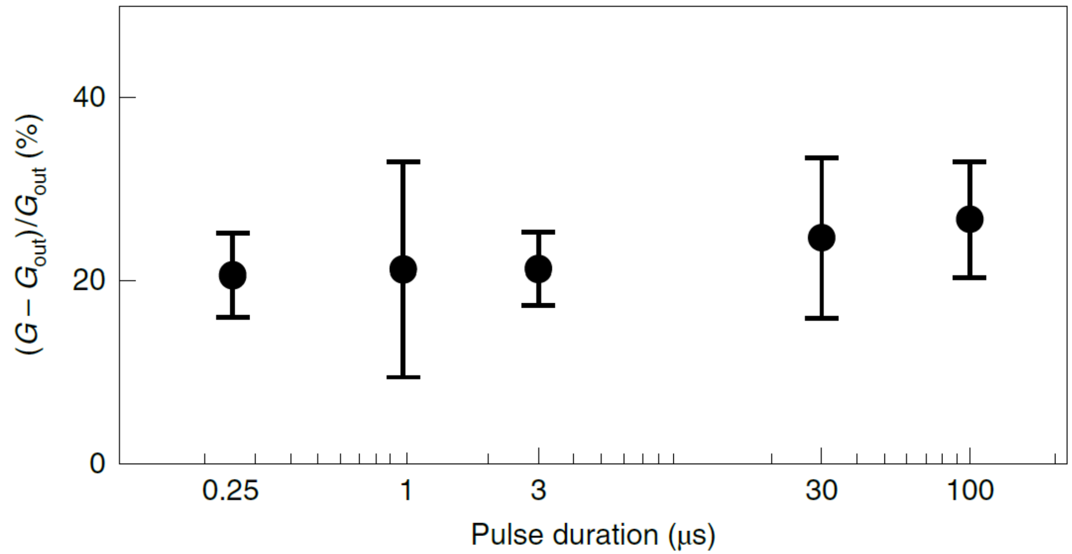




S. Varotto, CR *et al.*, Nature Electronics **4**, 740–747 (2021)

Electrical gating: endurance and switching time





ENDURANCE
up to 10^5 cycles

FAST SWITCHING
definitively < 250 ns

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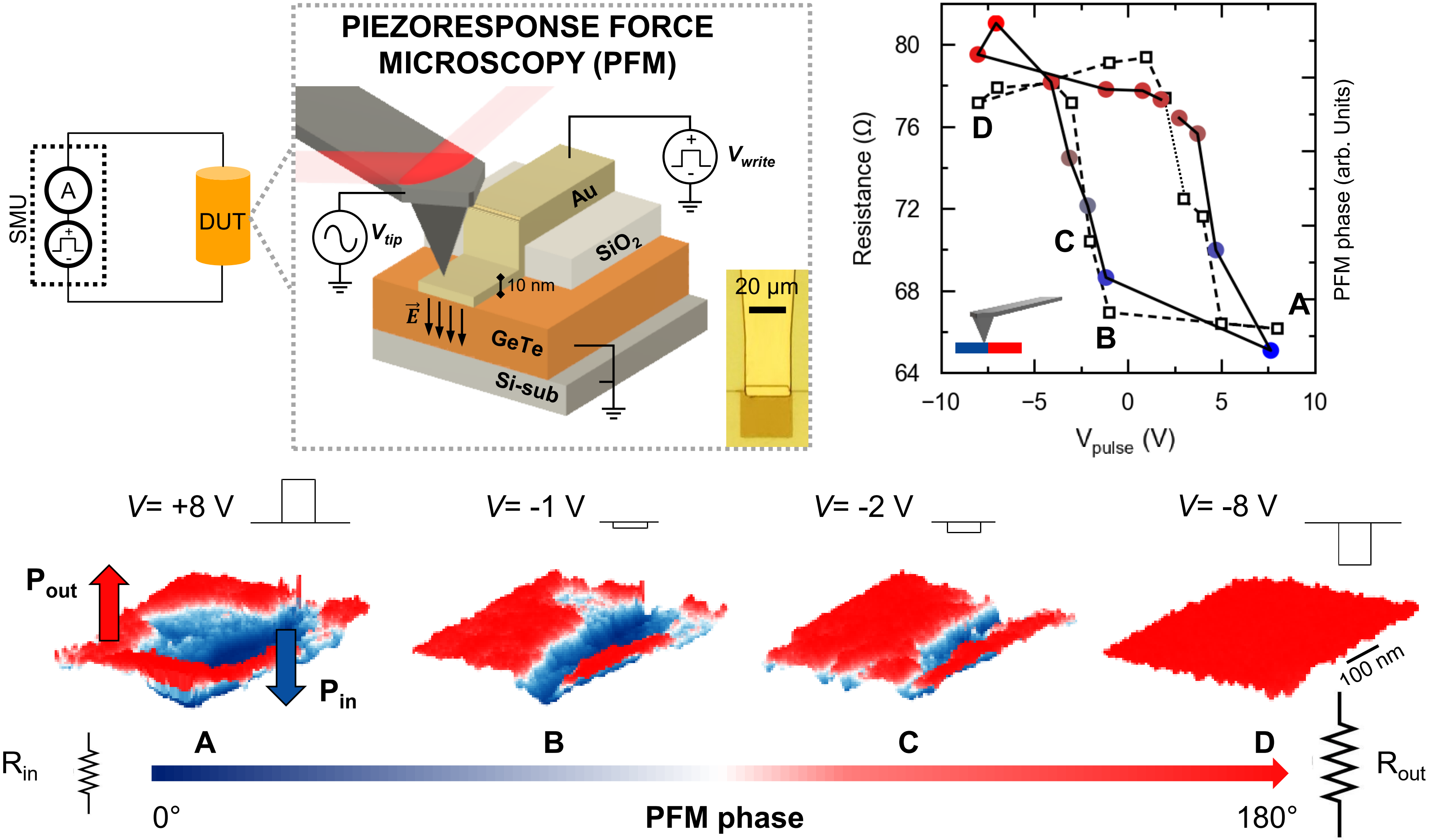
Correlation of resistivity and ferroelectric state



The polarization of epitaxial GeTe films can be reversed by electrical gating

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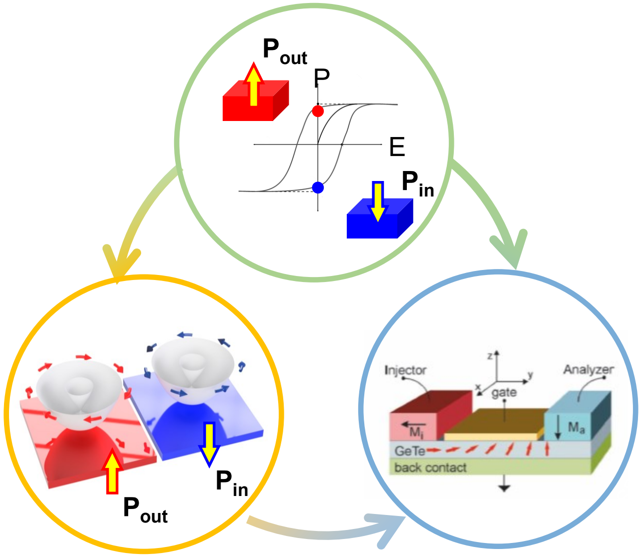

- Materials engineering
- Conclusions and perspectives

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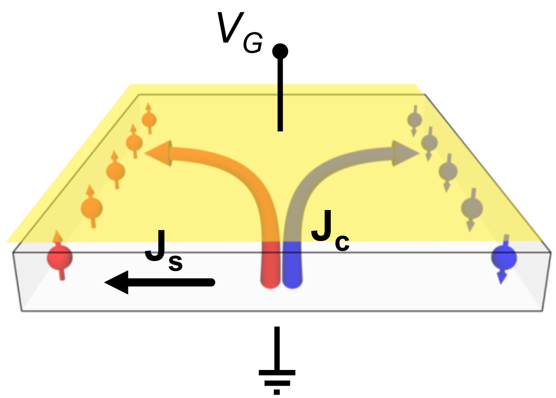
Ferroelectric control of spin-to-charge

Spin Hall effect (bulk effect)

S. Murakami *et al.*, Science 301, 1348 (2003)
A. Manchon *et al.*, Nature Mater. 14, 871 (2015)



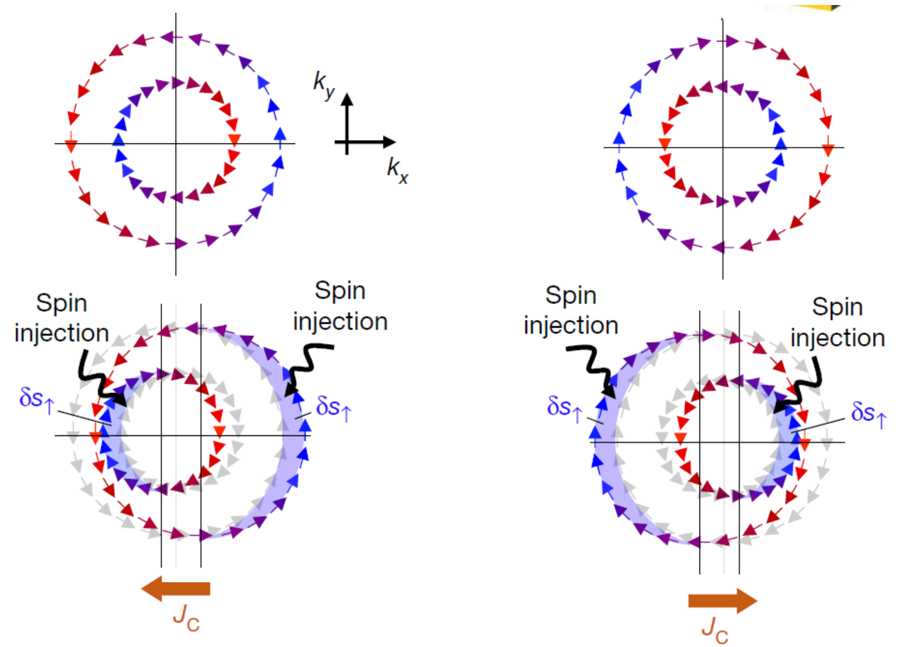
P acts on the bulk band structure

$$\mathbf{J}_s = \vartheta_{SHE}(\mathbf{P})\frac{2e}{\hbar}(\boldsymbol{\sigma}\times\mathbf{J}_c)$$

Spin-Hall angle

Rashba-Edelstein effect (*usually* interfacial)

P. Noël *et al.*, Nature 580, 483 (2020)



The chirality of Rashba bands naturally reverses with P

$$\lambda_{IREE} = \frac{j_C^{2D}}{j_S^{3D}} = \frac{\alpha_R\tau}{\hbar}$$

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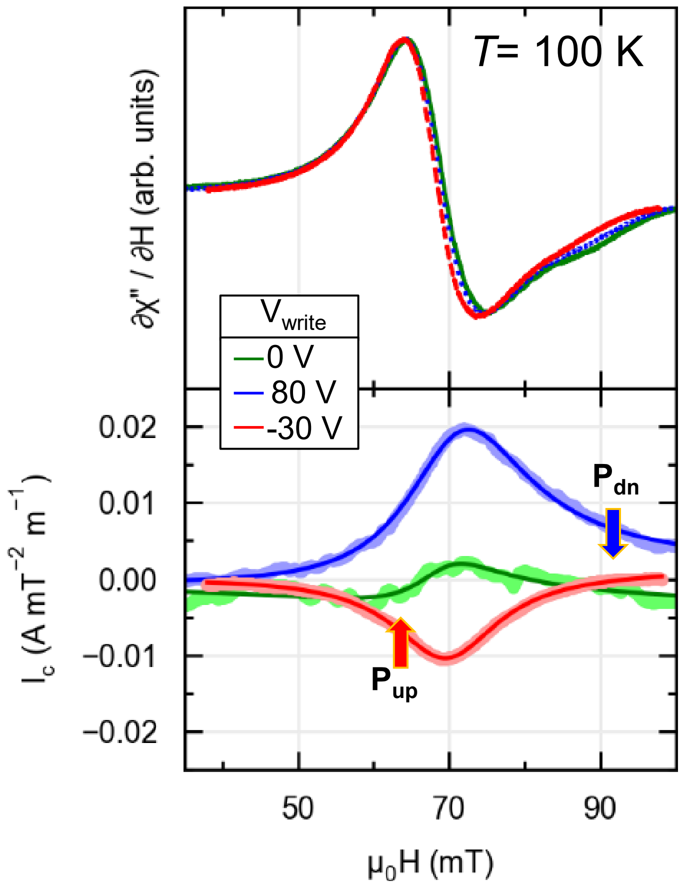
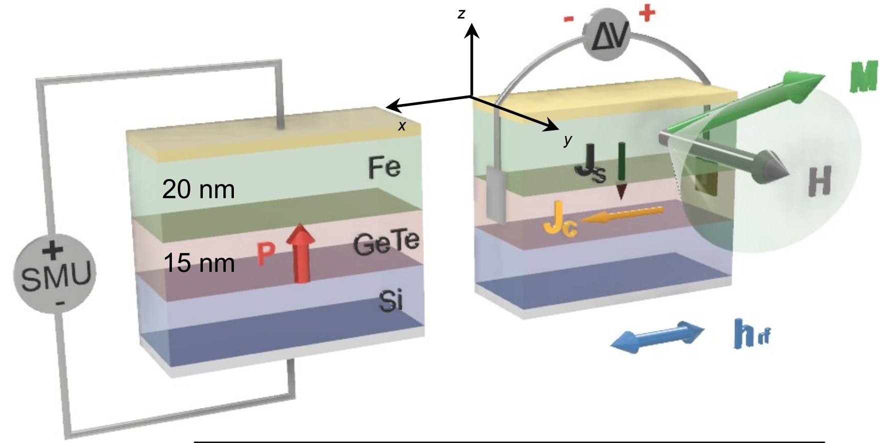
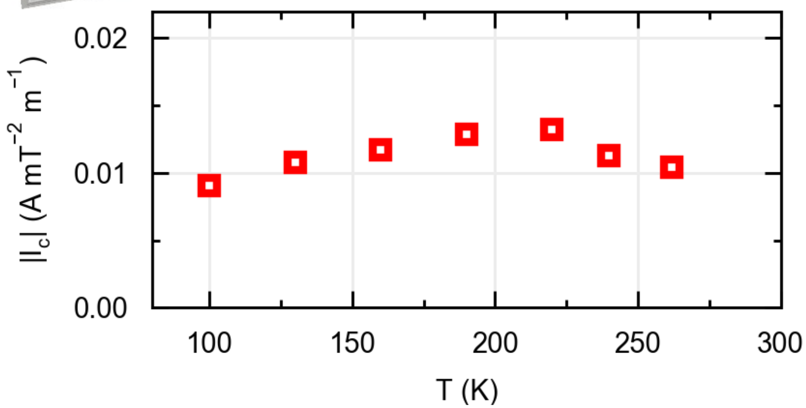
Ferroelectric control of spin-charge conversion







S. Varotto, CR *et al.*, Nature Electronics 4, 740–747 (2021)

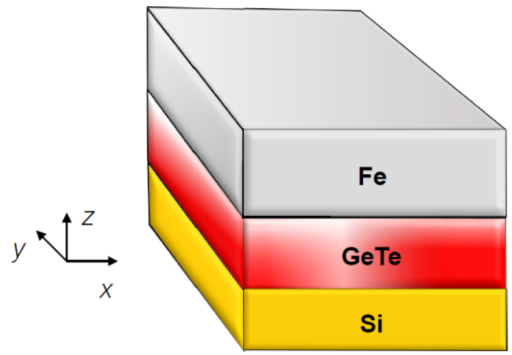
The polarization reversal switches the sign of the spin-to-charge conversion

Charge-to-spin conversion in bulk GeTe

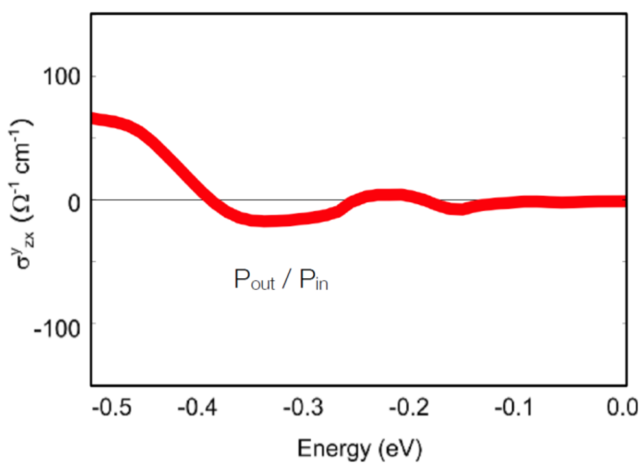
Bulk results are the same for P_{out} and P_{in}

Using a slab is more realistic but we cannot have currents flowing through the vacuum.

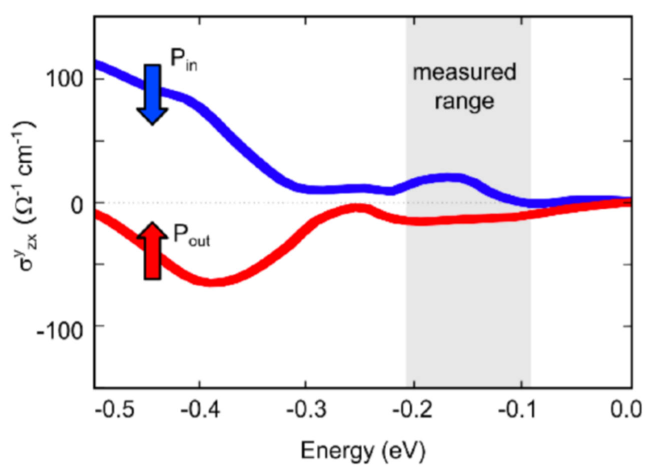
In experiments σ^{y}_{zx} is measured.



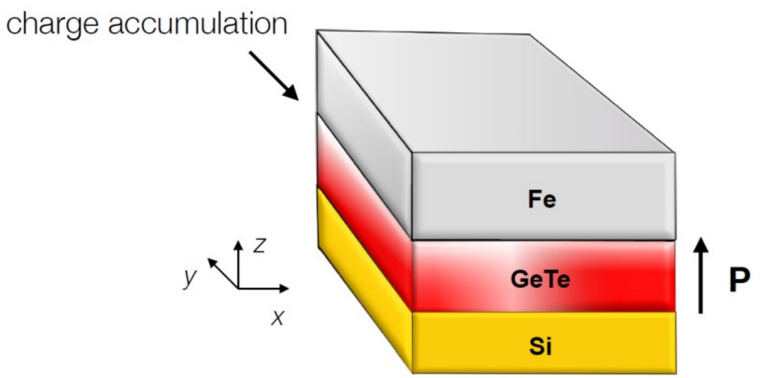
Calculated for bulk GeTe

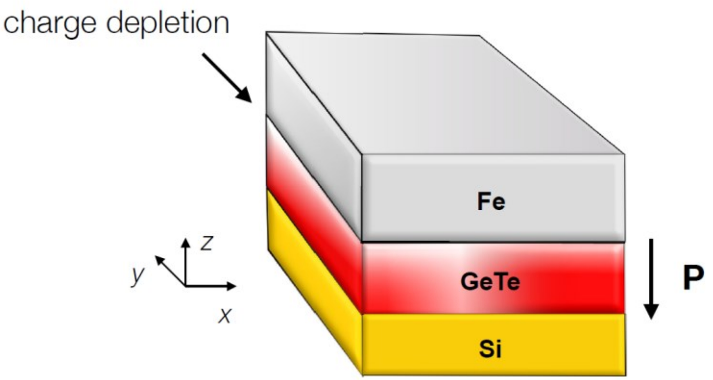


Calculated for GeTe slab

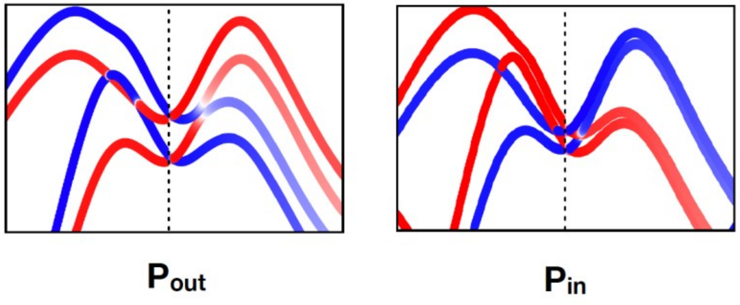


Ferroelectric switching of spin-to-charge currents in GeTe

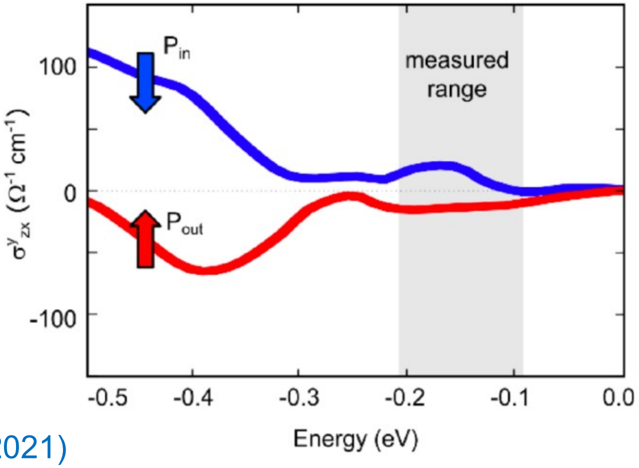




We extract matrix elements from PAO Hamiltonians of the slabs and create an artificial bulk



Calculated for GeTe slab



S. Varotto, JS, CR *et al.*, Nature Electronics **4**, 740–747 (2021)

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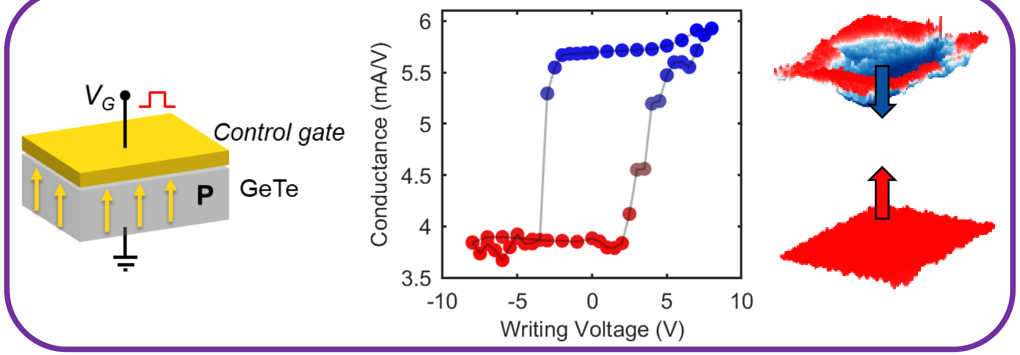
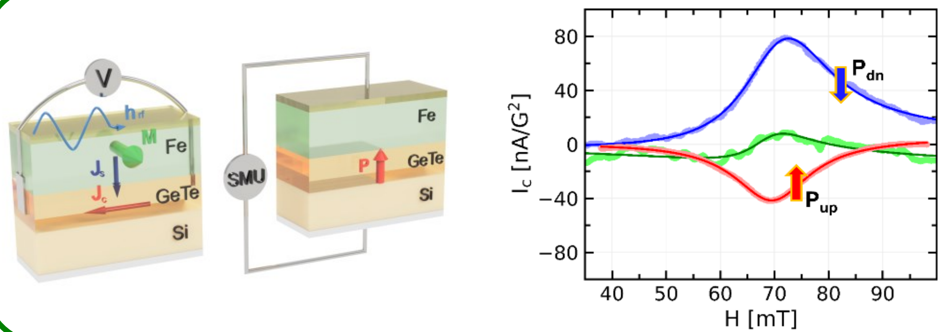
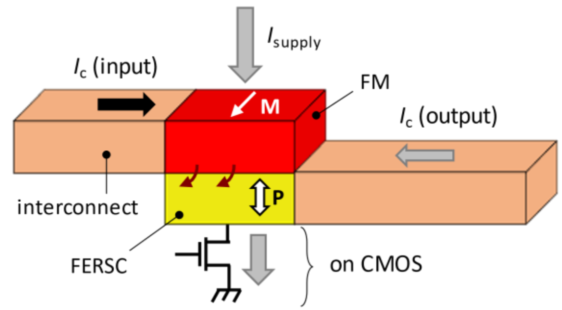
Summary about GeTe

Ferroelectric switching of the semiconductor GeTe with gate





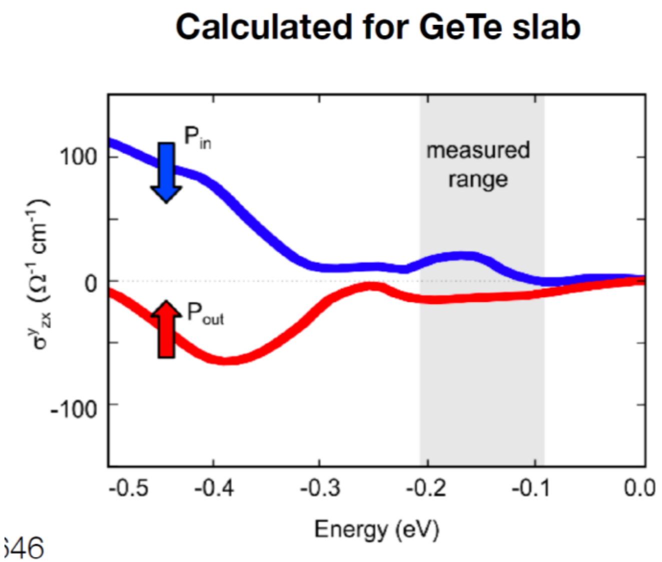
Ferroelectric control of room-temperature spin-charge conversion in GeTe

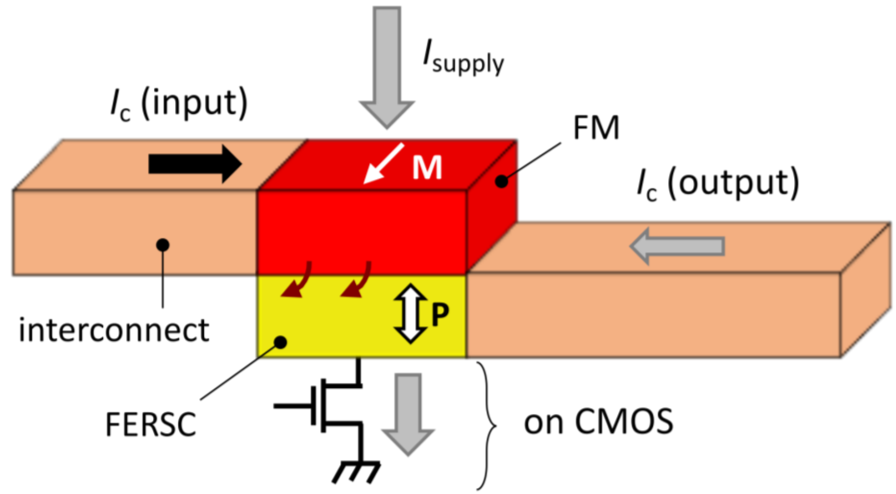


Ferroelectric spin-orbit logic with Ferroelectric Rashba semiconductors

S. Varotto, JS, CR *et al.*, Nature Electronics **4**, 740–747 (2021)

What is the gap to fill in terms of materials?





- Static nanomagnet, all electric
- Switching energy: **< 10 fJ @ 50 nm**
- Switching time: **< 250 ns**
- Potential for monolithic integrability of GeTe on Si

- **Relatively low spin-to-charge conversion efficiency** (a few %) in GeTe
- Conversion from bulk state only, surface states are hindered
- **Relatively large switching voltages**

S. Varotto, CR *et al.*, Nature Electronics 4, 740–747 (2021)

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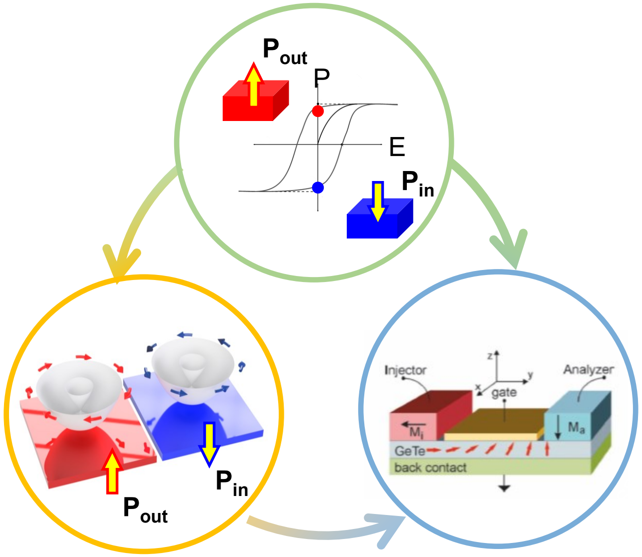
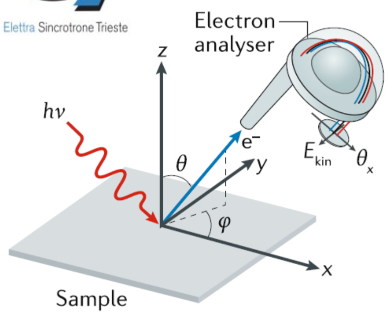
Outline

- General aim
- Ferroelectric Rashba semiconductors
    - I. Rashba effect in GeTe
    - II. Gating of ferroelectricity in the semiconductor GeTe
    - III. Spin-charge interconversion in GeTe
- **Materials engineering**
- Conclusions and perspectives

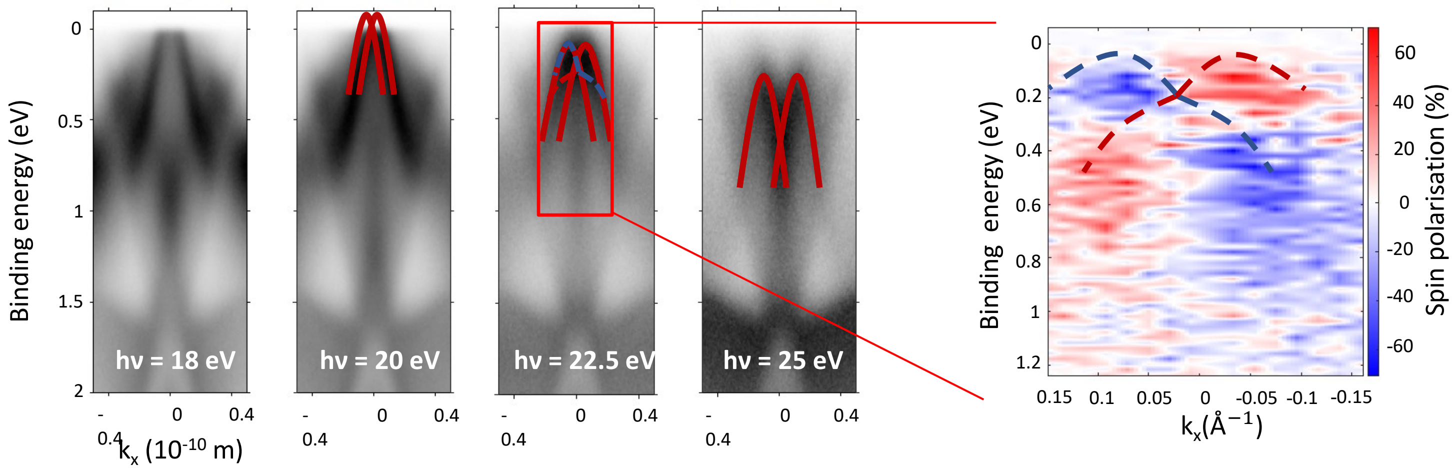


Band dispersion in $Ge_{0.3}Sn_{0.7}Te$



Spin and **A**ngle **R**esolved **P**hotoemission **S**pectroscopy

@ T= 77K



Sn-rich $Ge_{0.3}Sn_{0.7}Te$ shows bulk Rashba features at low temperature (77 K)

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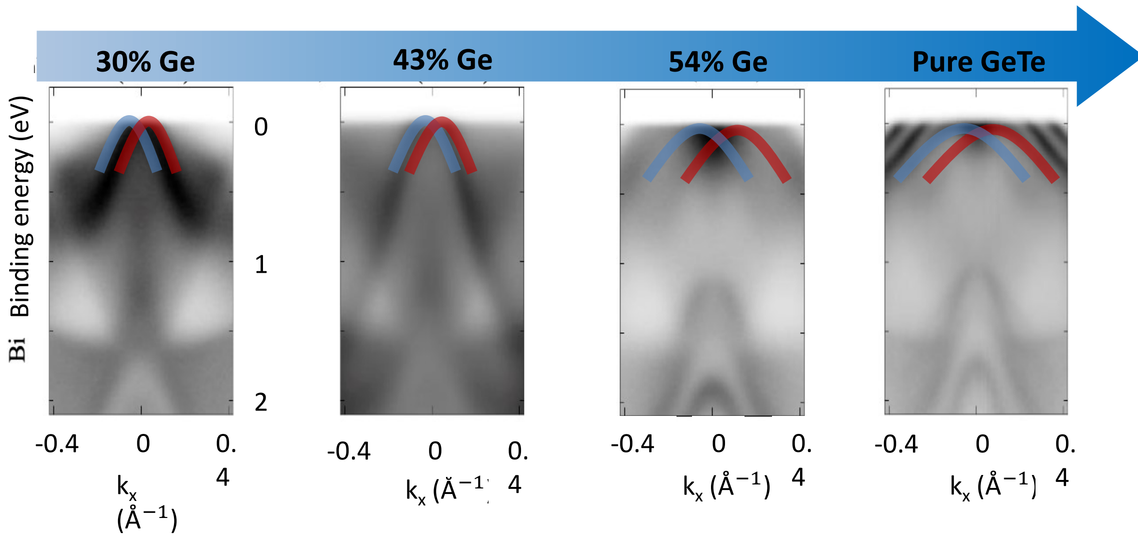
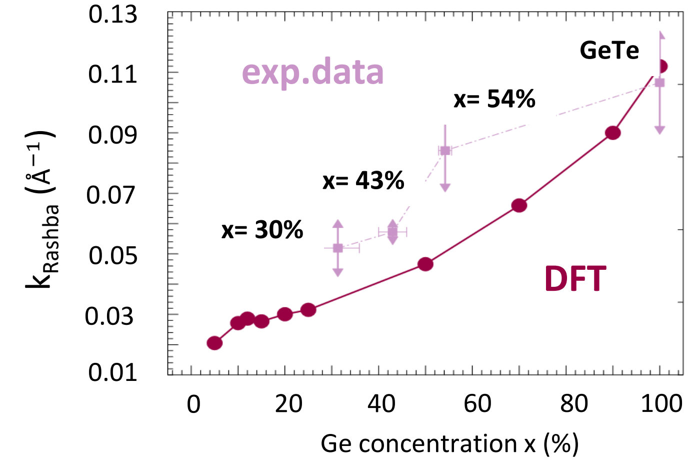
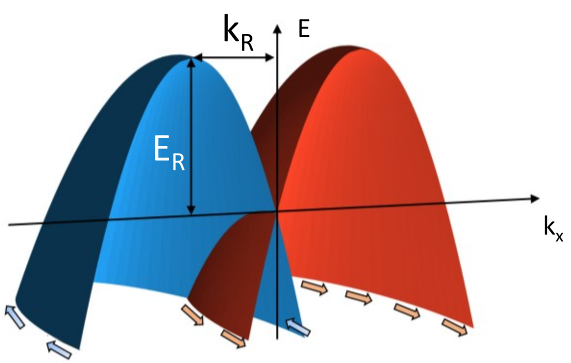
Band dispersion versus composition





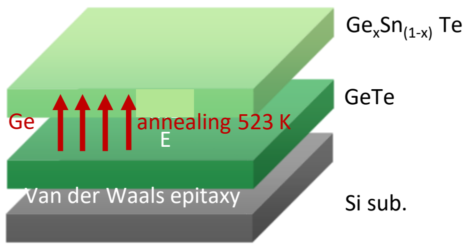


Tailoring Rashba features with concentrations, in good agreement with DFT calculation

Manuscript in preparation

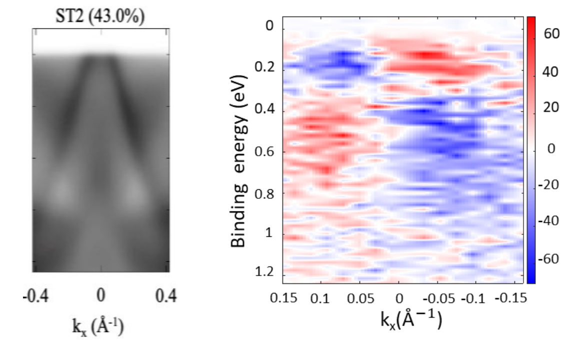
Conclusions and perspectives

✓ Synthesis of epitaxial $Ge_xSn_{(1-x)}Te$

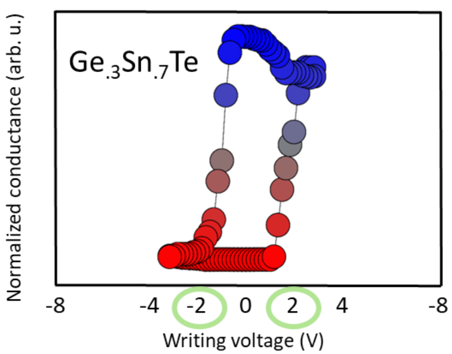


Ge alloying of SnTe films

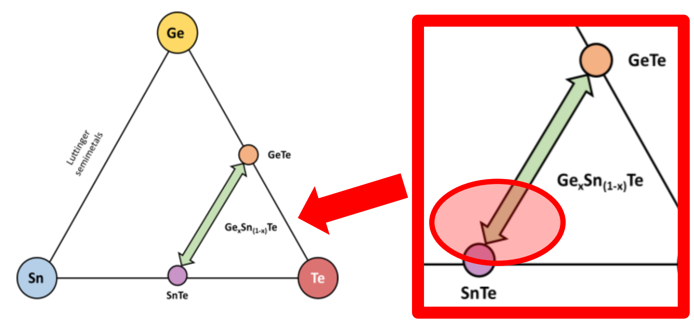
✓ Detection of giant Rashba effect in $Ge_xSn_{(1-x)}Te$



✓ Tailoring of T_C and E_C with the composition



❑ To do: investigation of the coexistence of Rashba and topological features (% Ge < 20%)



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fondazione cariplo

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Thanks for your kind attention

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