Electric field control of magnetism

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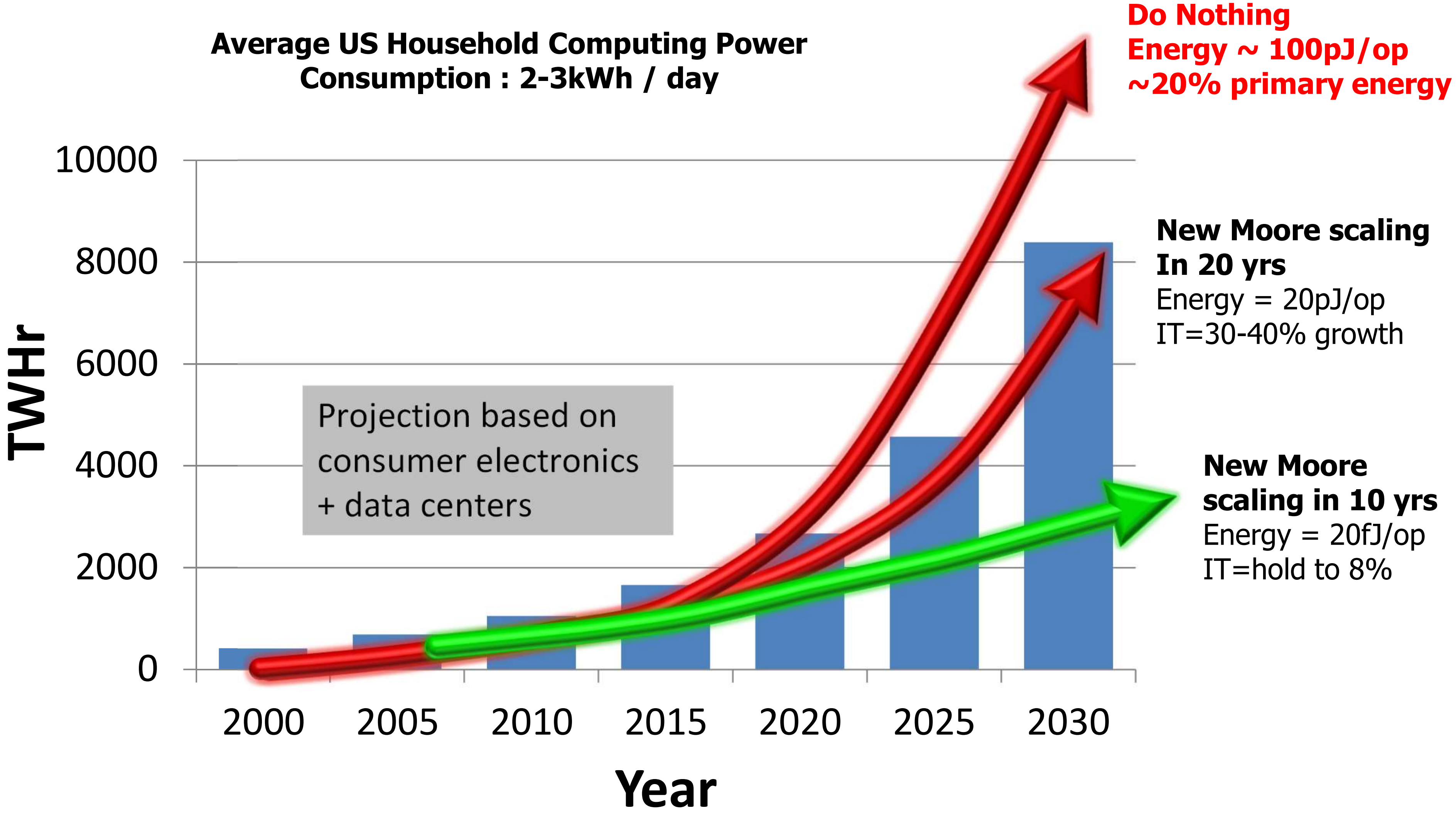
"Electrical control of magnetism by electric field and current-induced torques"
A. Fert, F. Casanova, V. Garcia, R. Ramesh and M. Bibes
Rev. Mod. Phys. 95, 015005 (2024) ; ArXiv 2311.11724

Power consumption of ICT systems

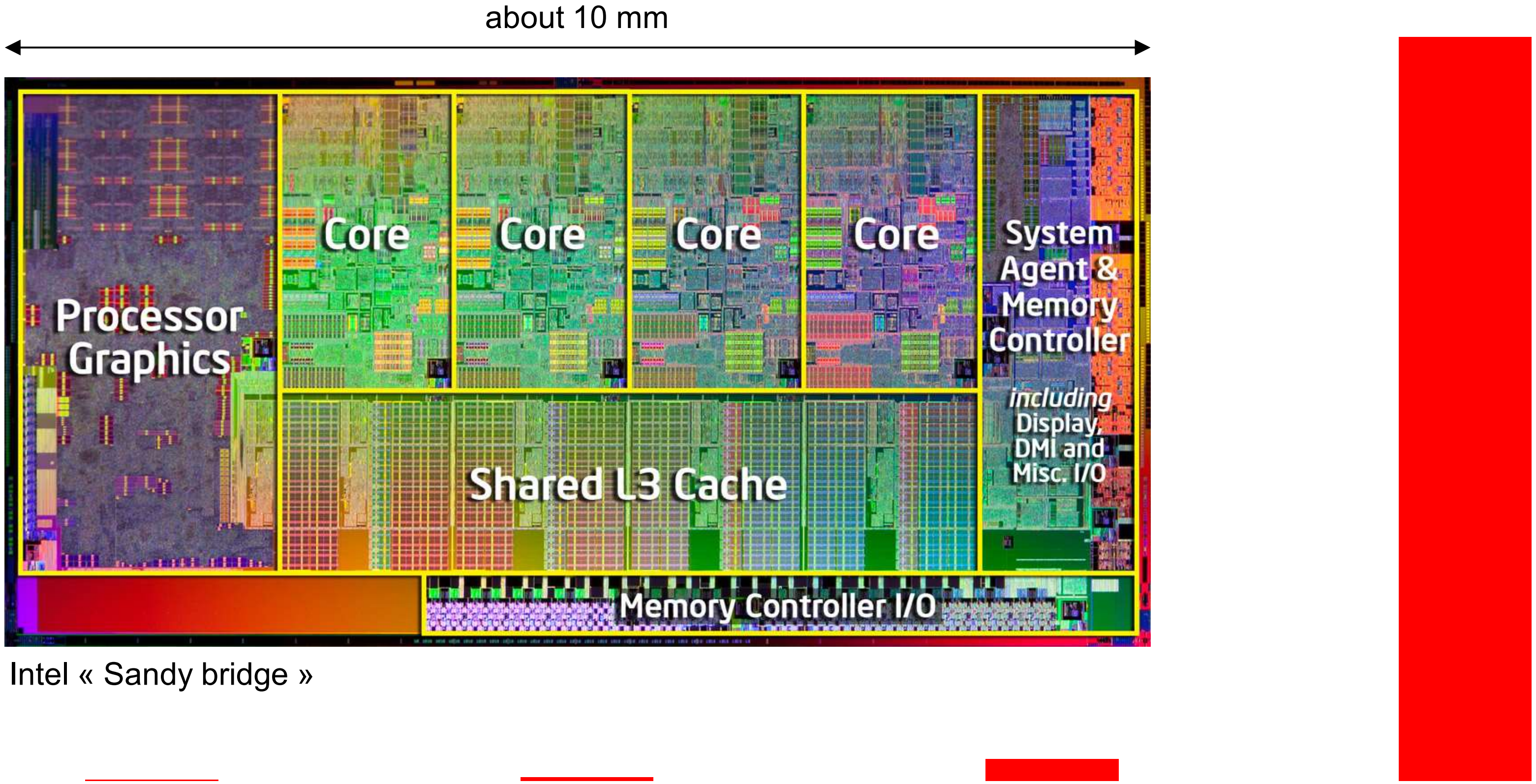
Global Semiconductor market size ~ $2 trillion by 2030



www.alliancetrustinvestments.com/sri-hub/posts/Energy-efficient-data-centres

Courtesy R. Ramesh

Power needs in microprocessors

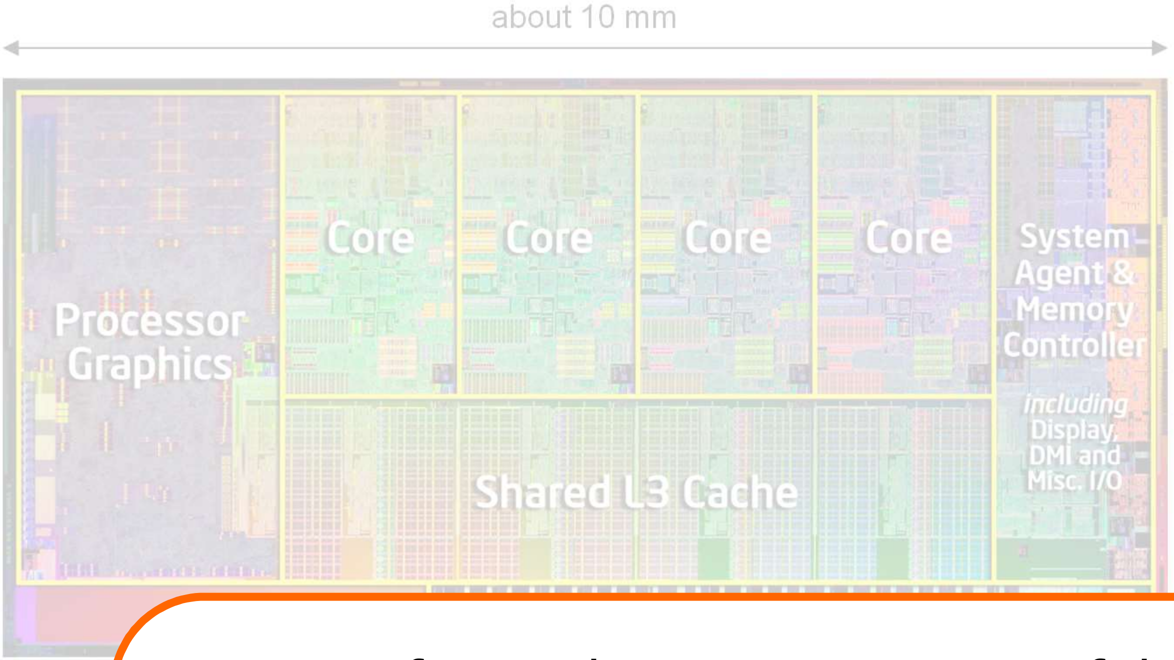


Intel « Sandy bridge »

Read one 64-bit number in SRAM	Multiply two 64-bit numbers	Move one 64-bit number 10 mm away	Move one 64-bit number from external RAM
14 pJ	**50 pJ**	**300 pJ**	**10000 pJ**

GPUs and the future of parallel computing, W.J. Dally et al, IEEE Micro (2011)

Power needs in microprocessors



Intel « S

Read
numb

mber
AM

Data transfer on-chip consumes most of the power !

➔ « **Bring memory into logic** »
➔ Embed memory elements in the logic units

➔ **Ferroic materials** can bring solutions for **beyond CMOS electronics**

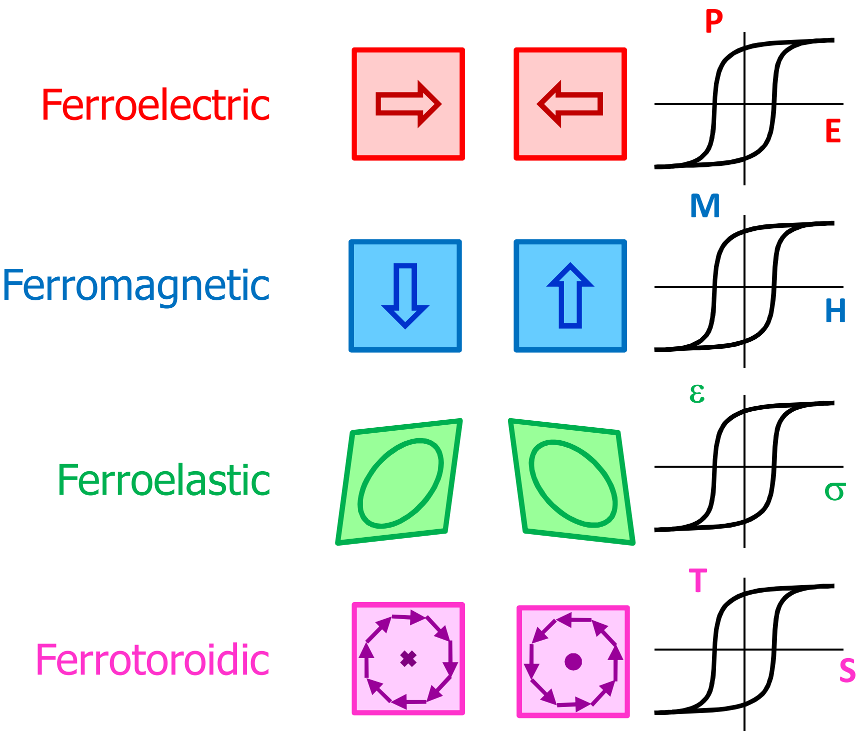
GPUs and the future of parallel computing, W.J. Dally et al, IEEE Micro (2011)

Outline

- ➔ ⦿ Ferroic orders, multiferroics and magnetoelectric coupling
- ⦿ Approaches for the electric-field control of magnetism
- ⦿ Electric-field control of spin-charge interconversion
- ⦿ Low-power spin-based devices for logic-in-memory

Introduction to ferroic orders

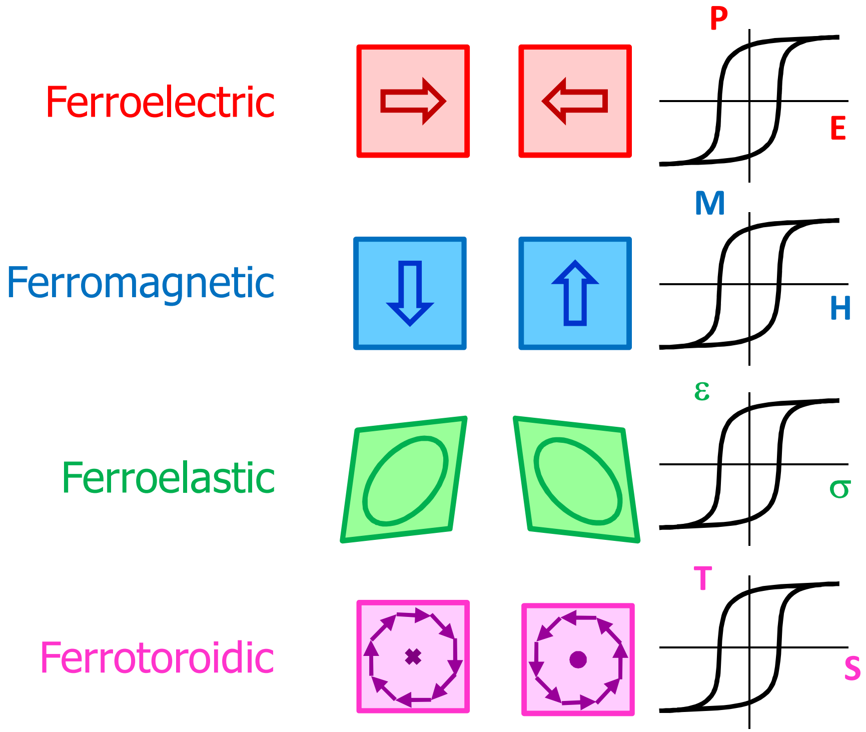
Ferroic orders



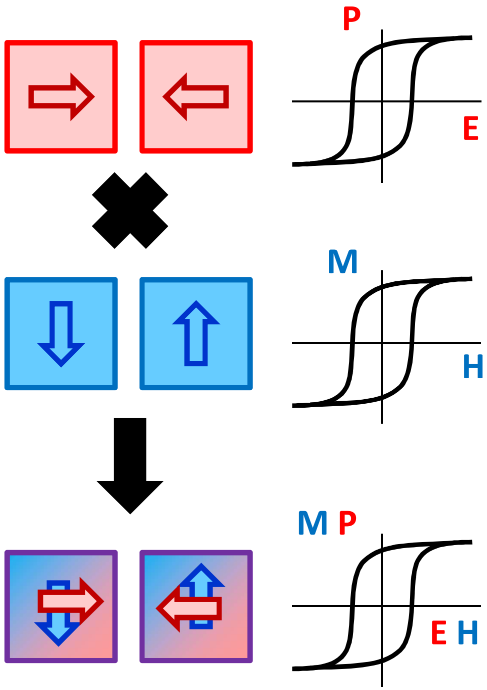
- Hysteretic dependence of order parameter : good for data storage

Introduction to ferroic orders

Ferroic orders



Multiferroic / Magnetoelectric

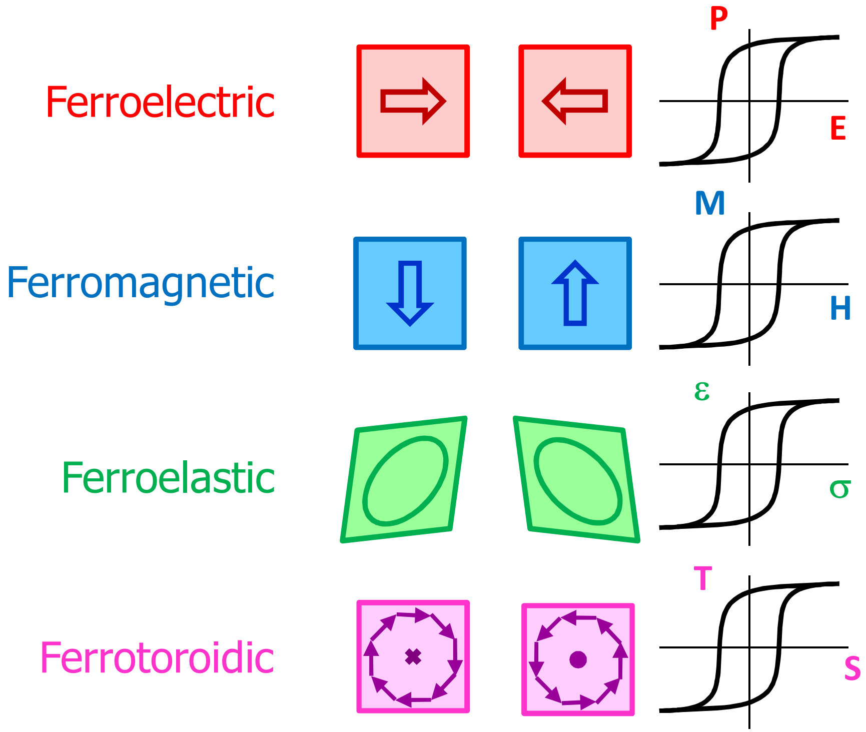


« Intrinsic »

- Hysteretic dependence of order parameter : good for data storage

Introduction to ferroic orders

Ferroic orders



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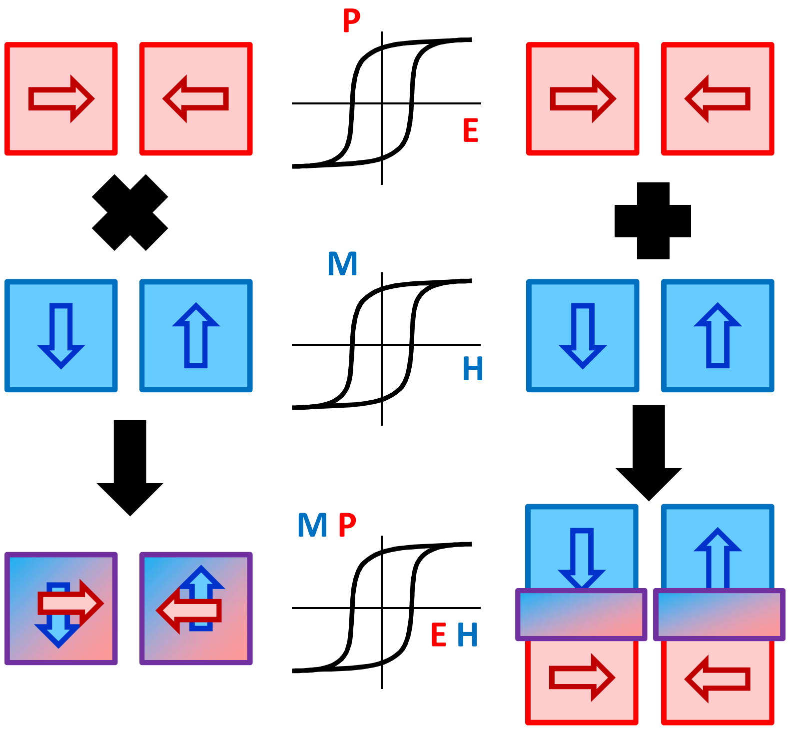
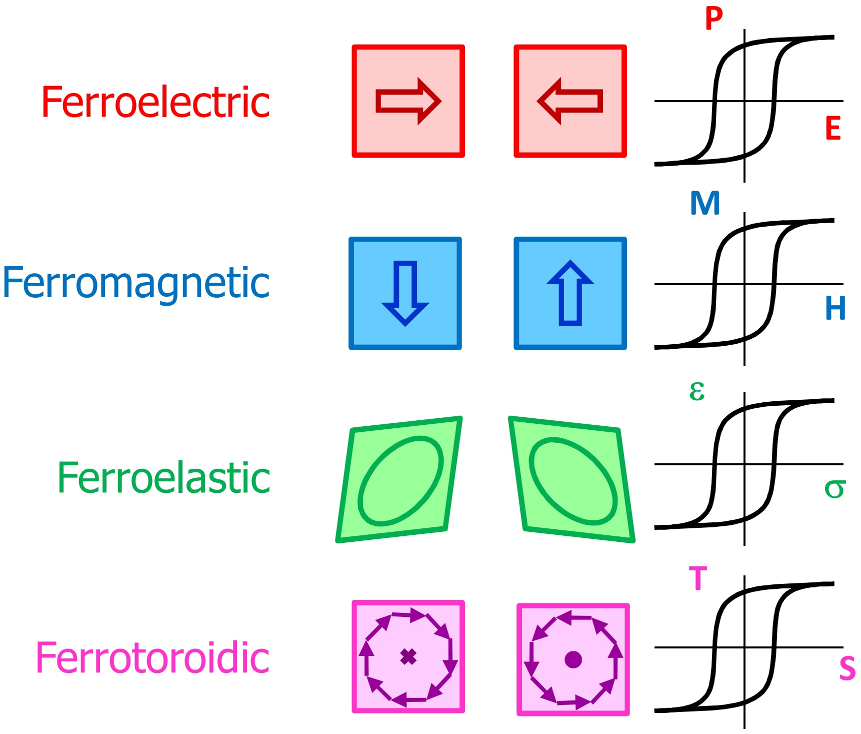


« Intrinsic » « Artificial »

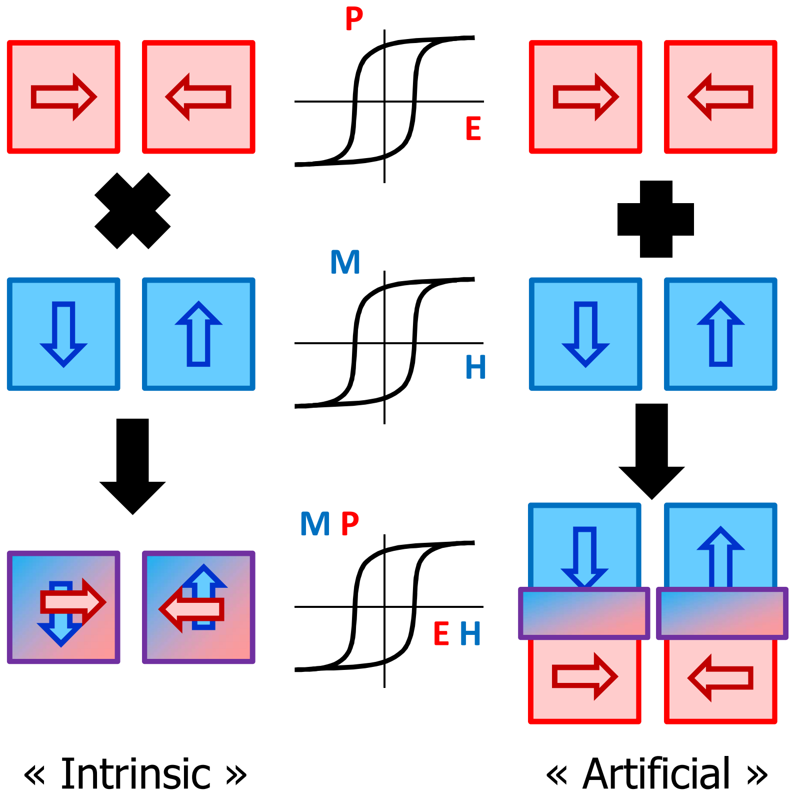
- Hysteretic dependence of order parameter : good for data storage

Introduction to ferroic orders

Ferroic orders



Multiferroic / Magnetoelectric

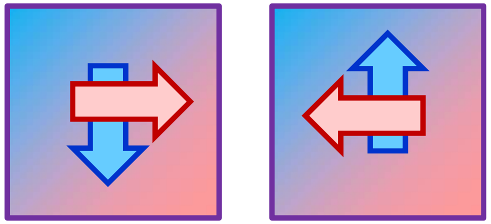


- Hysteretic dependence of order parameter : good for data storage
- Multiple order parameters : increased storage density
- Coupled orders : enhanced flexibility for data writing

MB, Nature Mater. 11, 354 (2012)

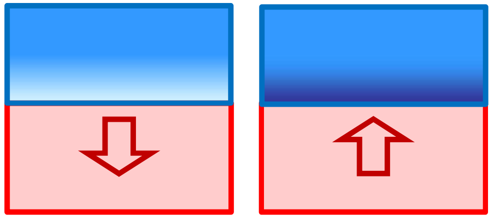
Different approaches for E-field control of magnetism

Intrinsic magnetoelectric



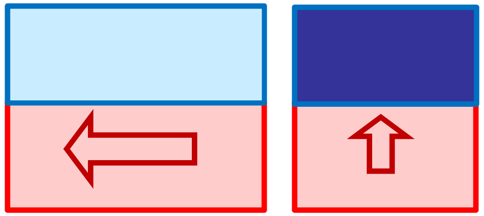
Use single-phase multiferroic material

Field-effect



Combine strong ferroelectric with carrier-mediated ferromagnet

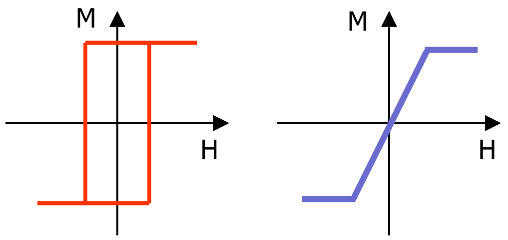
Strain-driven



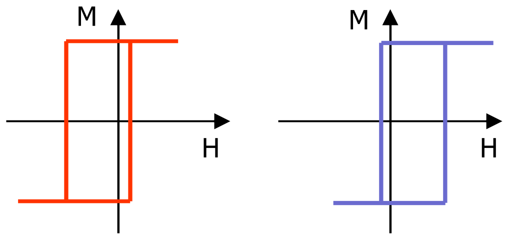
Combine piezoelectric or ferroelectric/ferroelastic with magnetostrictive ferromagnet

Controlling magnetism with electric fields

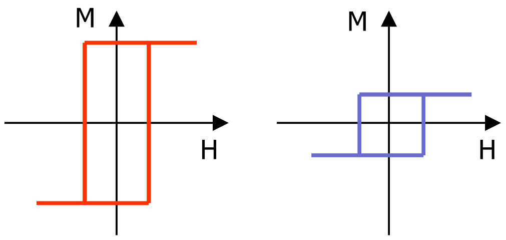
Magnetic anisotropy



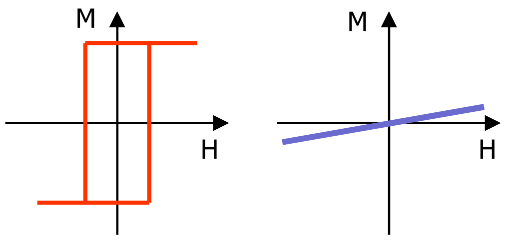
Exchange bias



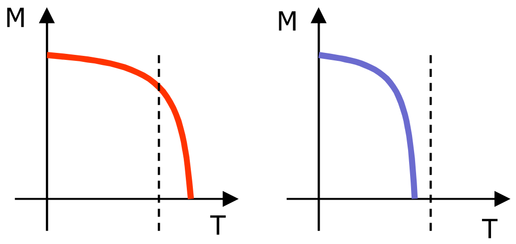
Magnetic moment



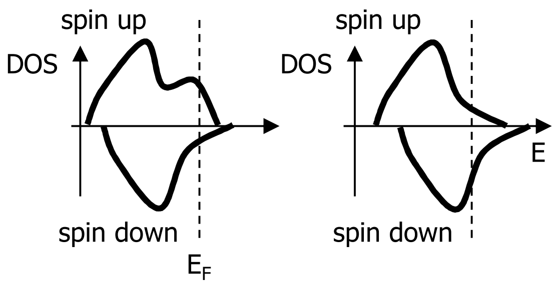
Magnetic order



Curie temperature



Spin polarization



$P_{spin} > 0$ $P_{spin} < 0$

MB, Nature Mater 11, 354 (2012) & MB et al, Annu. Rev. Mater. Res. 44, 91 (2014)

Outline

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- ➔ Approaches for the electric-field control of magnetism
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Different approaches for E-field control of magnetism

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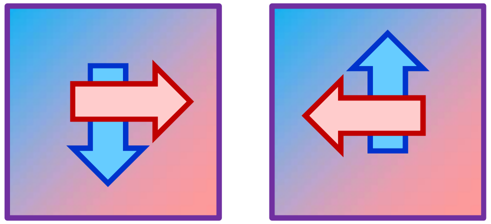
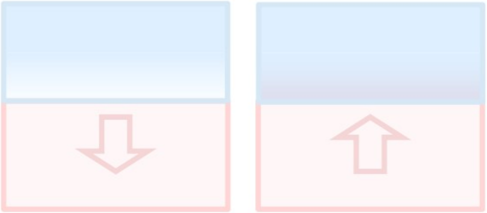


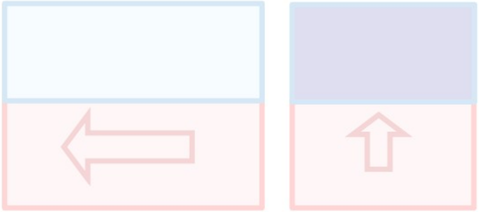
Use single-phase multiferroic material

Field-effect



Combine strong ferroelectric with carrier-mediated ferromagnet

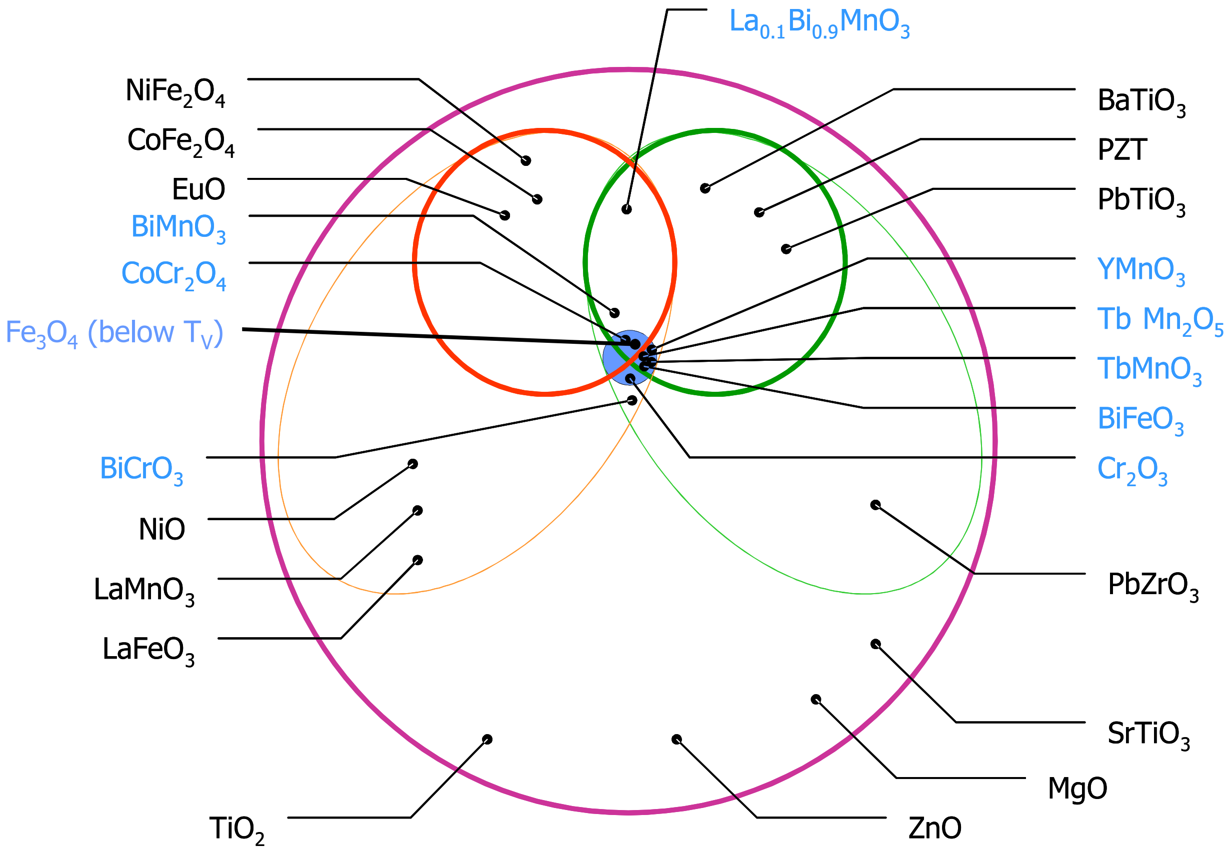
Strain-driven



Combine piezoelectric or ferroelectric/ferroelastic with magnetostrictive ferromagnet

E-field control of magnetism with intrinsic multiferroics

There are very few (room-temperature) multiferroics



$La_{0.1}Bi_{0.9}MnO_3$

$NiFe_2O_4$

$CoFe_2O_4$

EuO

$BiMnO_3$

$CoCr_2O_4$

Fe_3O_4 (below T_V)

$BiCrO_3$

NiO

$LaMnO_3$

$LaFeO_3$

$BaTiO_3$

PZT

$PbTiO_3$

$YMnO_3$

Tb Mn_2O_5

$TbMnO_3$

$BiFeO_3$

Cr_2O_3

$PbZrO_3$

$SrTiO_3$

MgO

ZnO

TiO_2

Magnetically polarizable
Ferro(i)magnetic

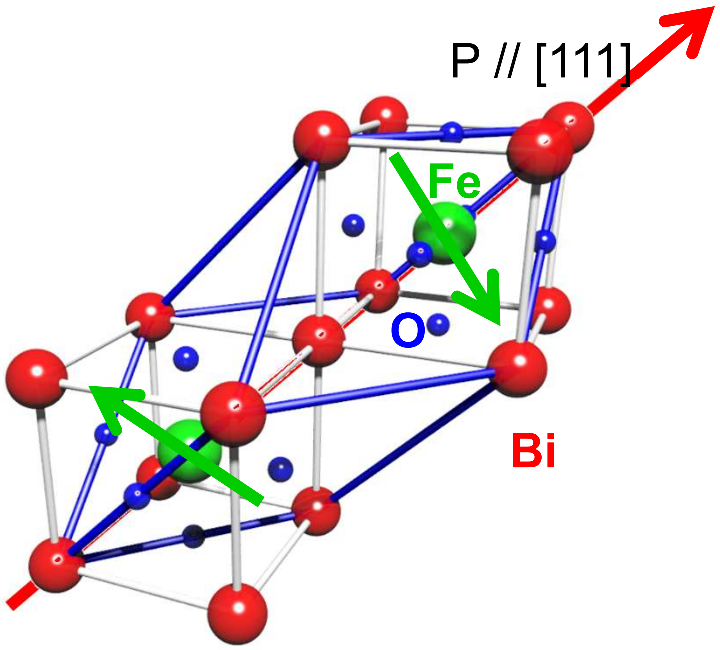
Electrically polarizable
Ferro(i)electric

Magnetoelectric

H. Béa, MB et al, J. Phys.: Condens. Matter 20, 434221 (2008)

Derived from Eerenstein, Mathur and Scott, Nature 442, 759 (2006)

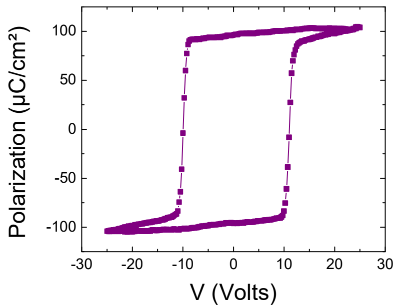
$BiFeO_3$: a room-temperature multiferroic



Ferroelectric properties

- Very high $T_C \approx 1100$ K
- Very large P=100 µC/cm²

Fisher et al., J. Phys. C, 13, 1931 (1980)
Béa, MB et al, APL 93, 072091 (2008)



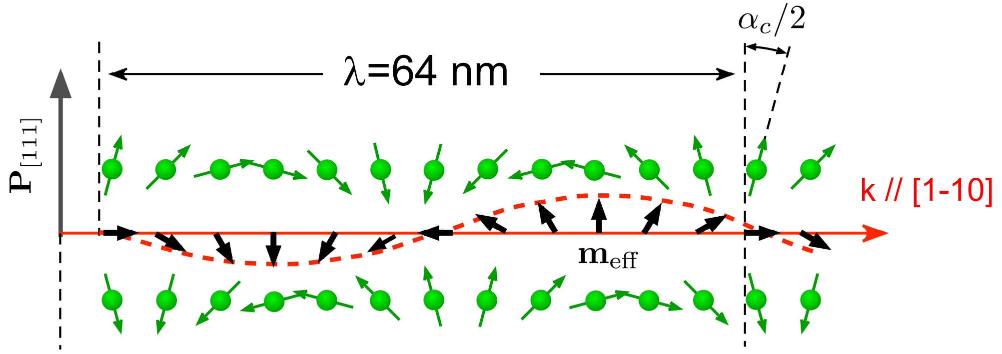
Magnetic properties

- G-type antiferromagnetic

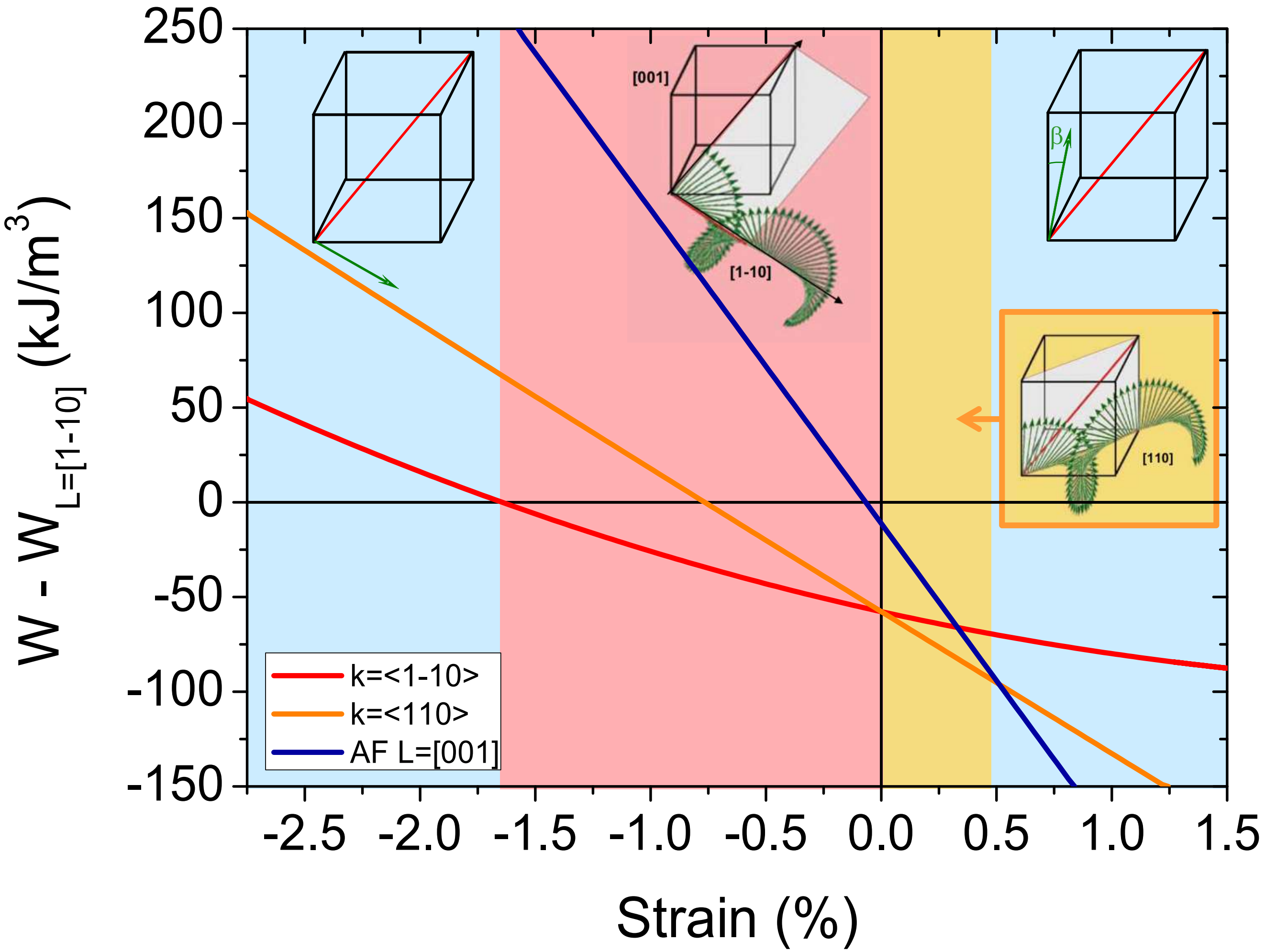
+ cycloidal modulation (λ=62 nm)

- Weak moment with periodic modulation
- $T_N \approx 640$ K

Sosnowska et al., J. Phys. C, 15, 4835 (1982)



Influence of epitaxial strain on the magnetic properties of $BiFeO_3$



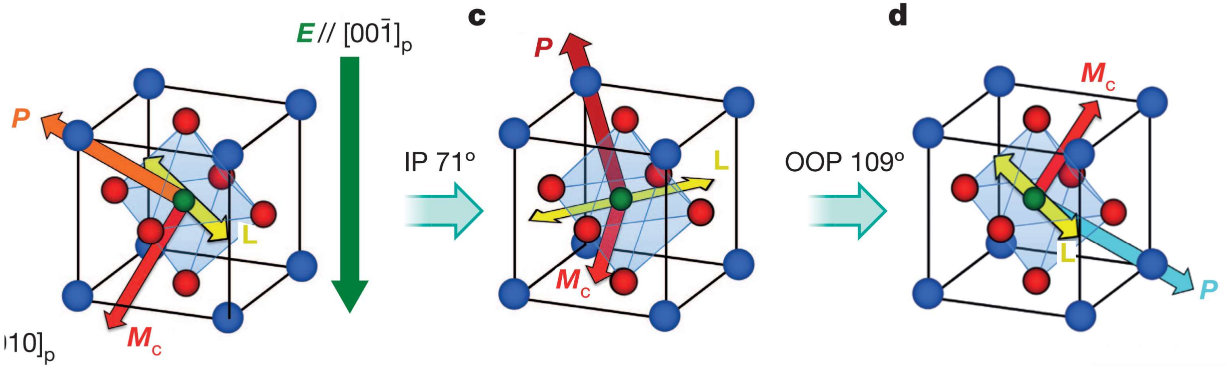
- Cycloidal state is destabilized by strain-induced (magnetoelastic) anisotropy
- Weak-FM state at high tensile or compressive state
- New cycloid stabilized at low tensile strain

} Mössbauer spectroscopy + theory

D. Sando, MB et al, Nature Mater. 12, 641 (2013)

E-field induced magnetization switching with $BiFeO_3$ thin films

Sequential switching of P promotes switching of weak M



Heron et al, Nature 370, 516 (2014)

E-field induced magnetization switching with $BiFeO_3$ thin films

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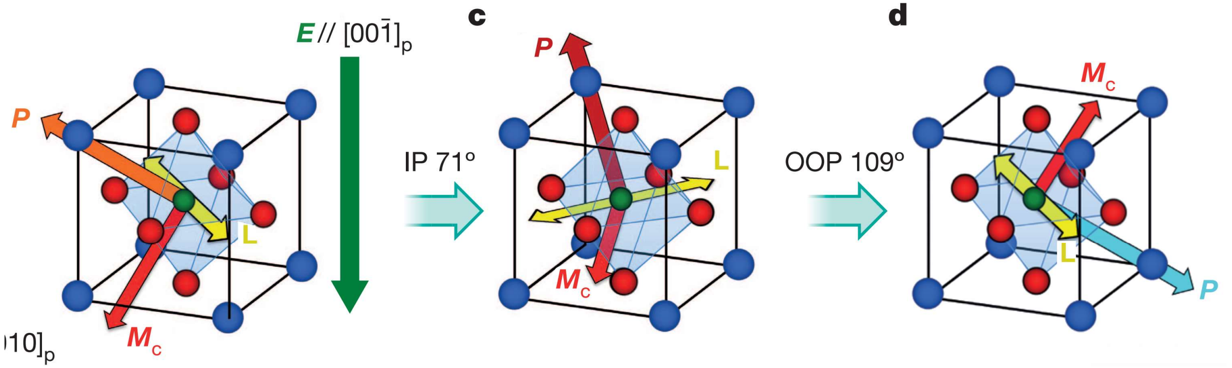
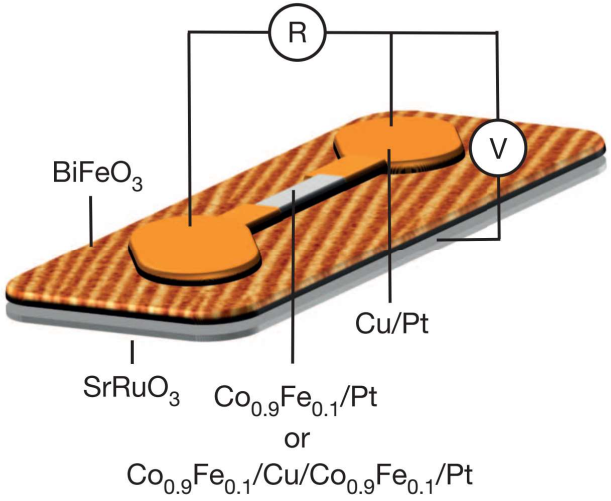
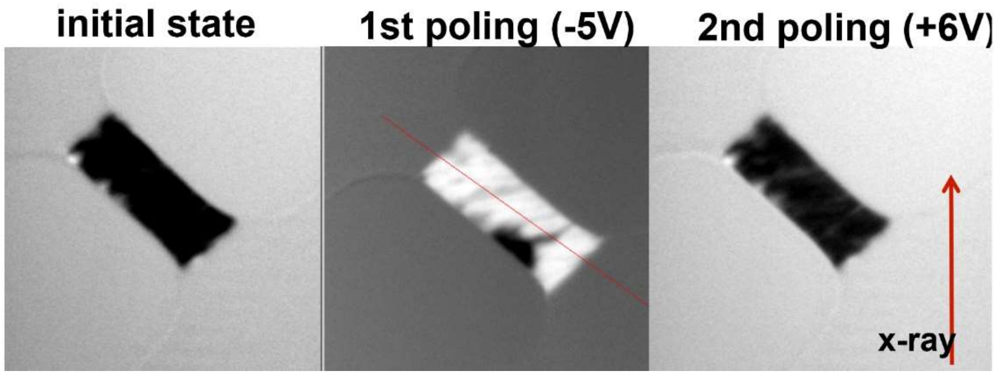


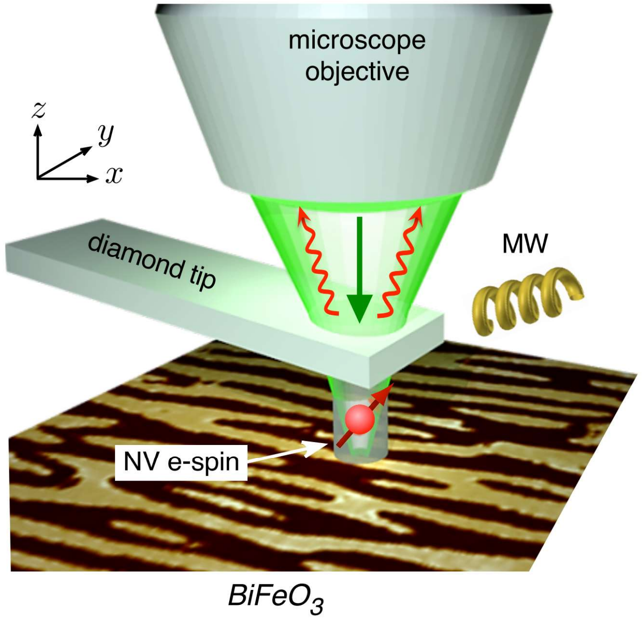
Heron et al, Nature 370, 516 (2014)

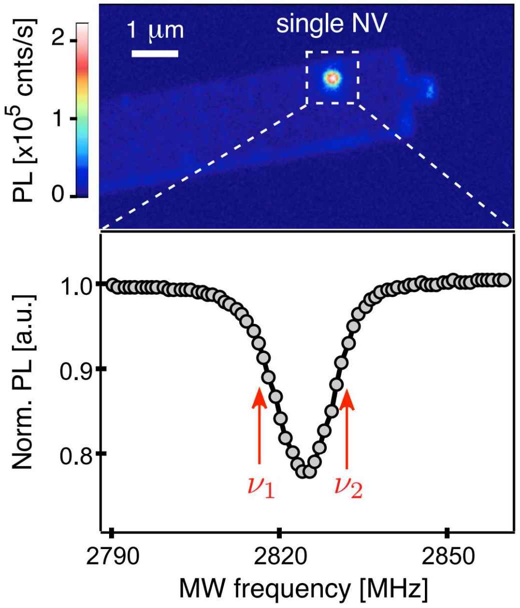




- ⊙ Application of out-of-plane voltage to BFO film promotes local switching of magnetization in Co film grown on top of BFO

Direct magnetic imaging of BFO with NV center microscopy

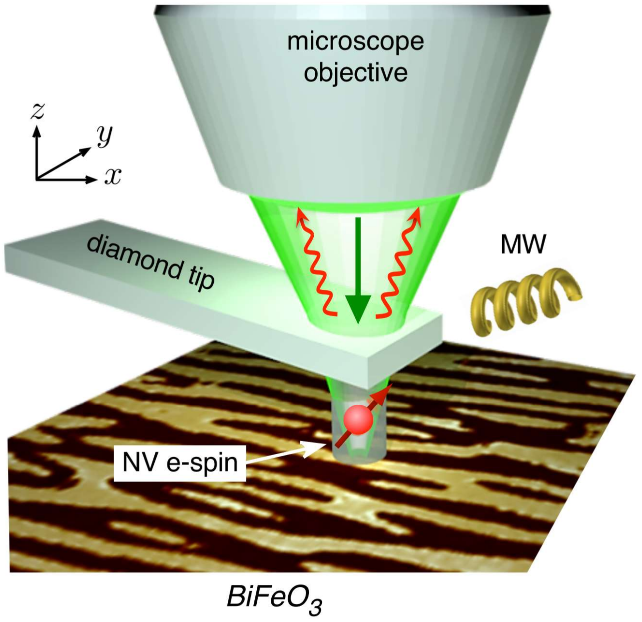


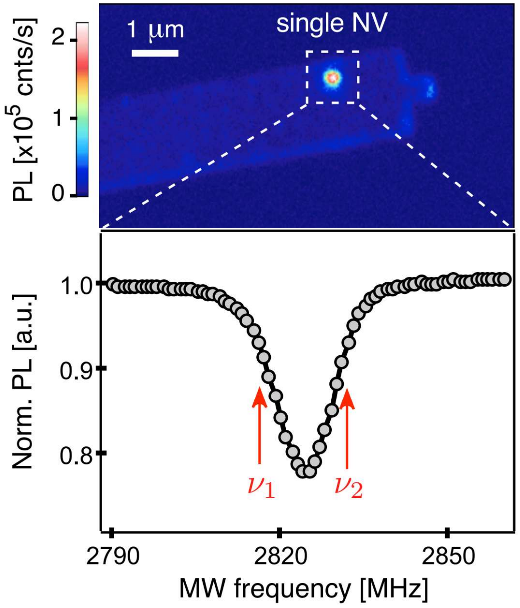


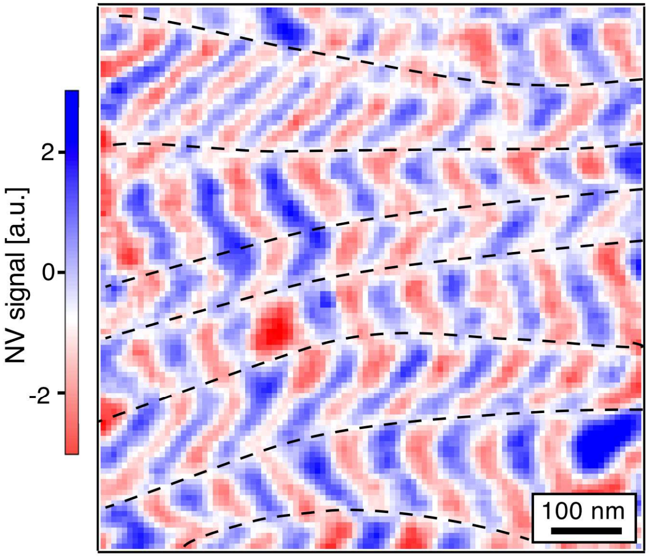
- Atomic-sized detection volume
- Quantitative and vectorial
- No magnetic back-action onto sample

Collab. V. Jacques, U. Montpellier and
P. Maletinsky, Basel

Direct magnetic imaging of BFO with NV center microscopy





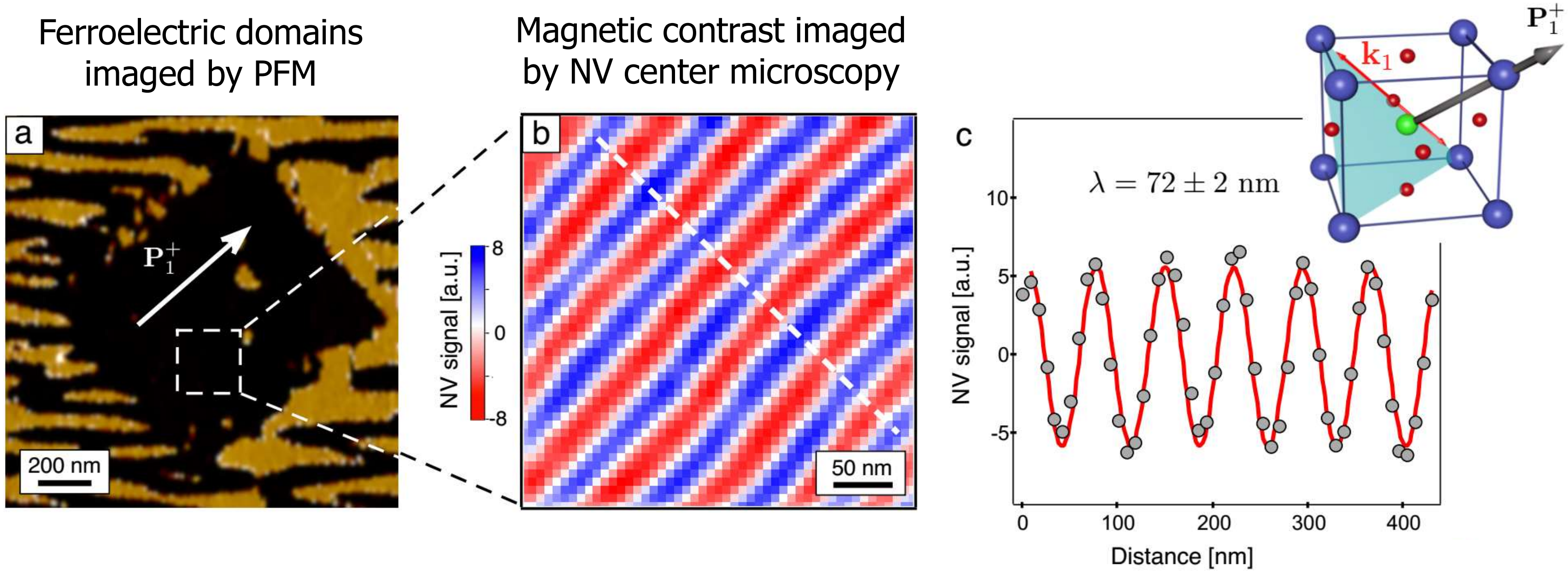


- ⊙ Atomic-sized detection volume
- ⊙ Quantitative and vectorial
- ⊙ No magnetic back-action onto sample

- ⊙ Clear periodic contrast of magnetic origin

Collab. V. Jacques, U. Montpellier and P. Maletinsky, Basel

Magnetic imaging of single ferroelectric domains


Ferroelectric domains imaged by PFM

Magnetic contrast imaged by NV center microscopy

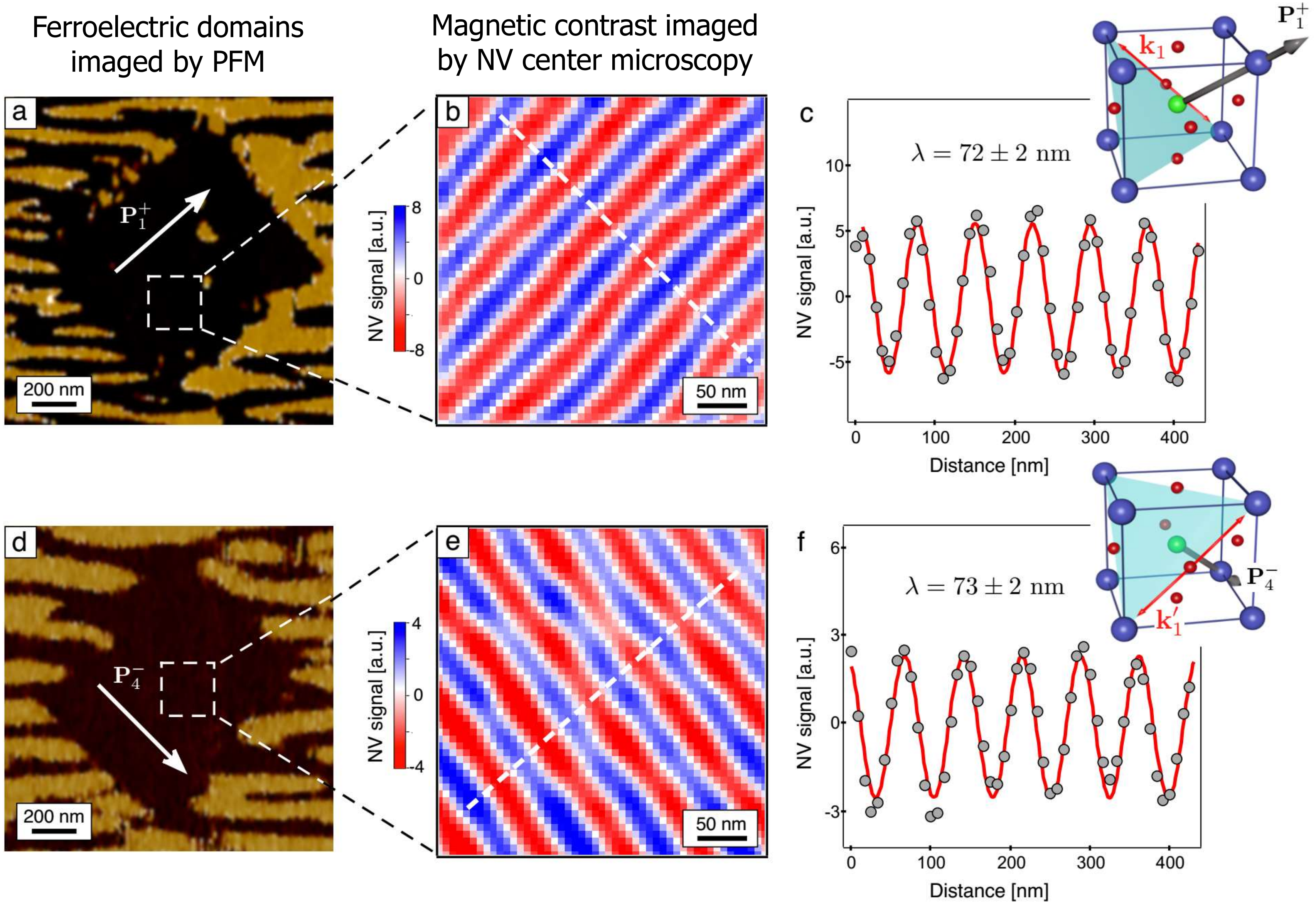
- Electric poling of BFO film : single ferroelectric and magnetic domain
- Periodic contrast with well-defined propagation direction and period
- Period is **72 nm**, slightly longer than in bulk (64 nm), likely due to epitaxial strain

I. Gross, MB et al, Nature 549, 252 (2017)

Magnetic imaging of single ferroelectric domains

Ferroelectric domains imaged by PFM

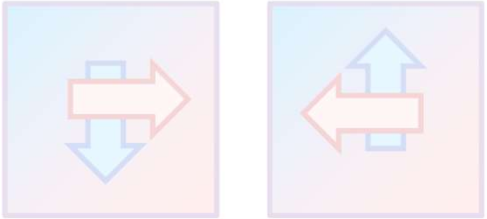
Magnetic contrast imaged by NV center microscopy



- **Electric-field control** of magnetic texture / cycloidal propagation direction

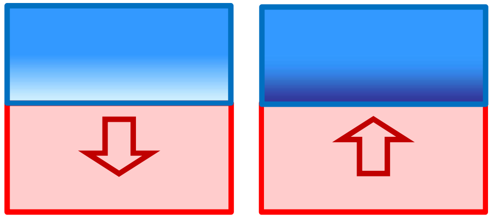
Different approaches for E-field control of magnetism

Intrinsic magnetoelectric



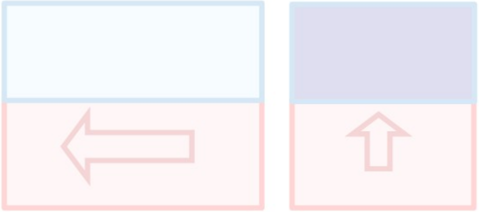
Use single-phase multiferroic material

Field-effect



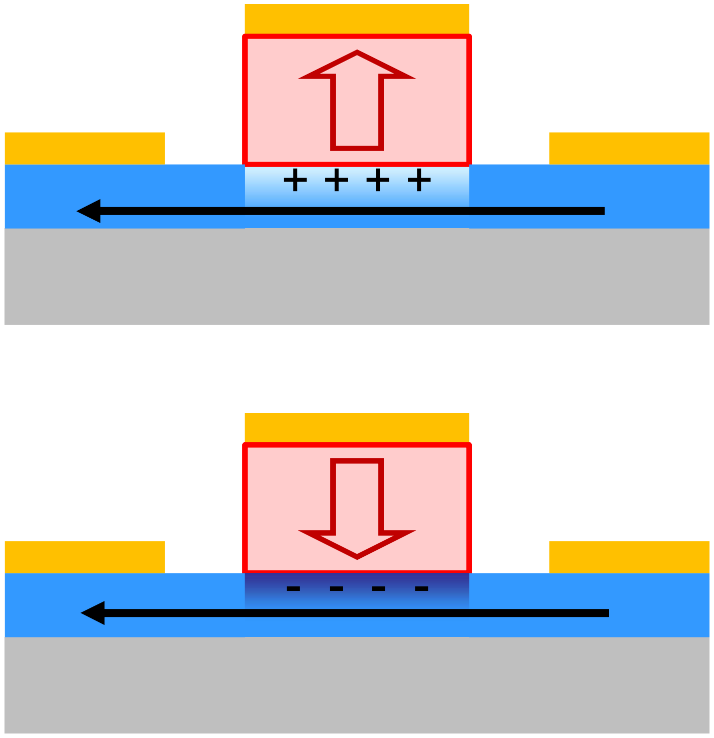
Combine strong ferroelectric with carrier-mediated ferromagnet

Strain-driven



Combine piezoelectric or ferroelectric/ferroelastic with magnetostrictive ferromagnet

Field-effect control of magnetism

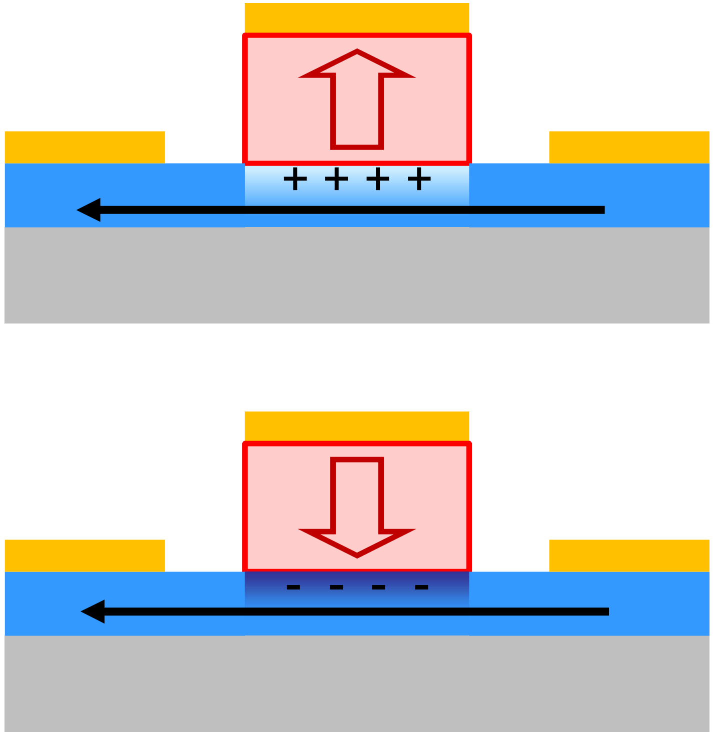


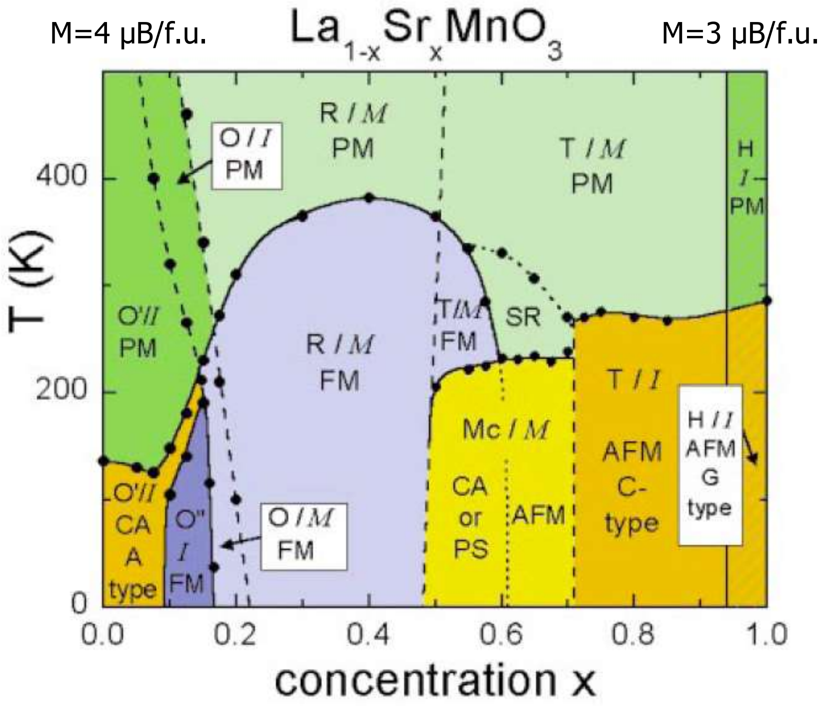
- Charge accumulation / depletion thanks to a dielectric or ferroelectric (non-volatile)
- If magnetism in channel material is (highly) sensitive to carrier density

➔ **Change of magnetic properties by electric field**

- Effect occurs over small distance, typically **Thomas Fermi screening length** (Å for metals, nm for oxides)

Field-effect control of magnetism





Hemberger et al., PRB, 66, 094410 (2002)

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➔ **Change of magnetic properties by electric field**

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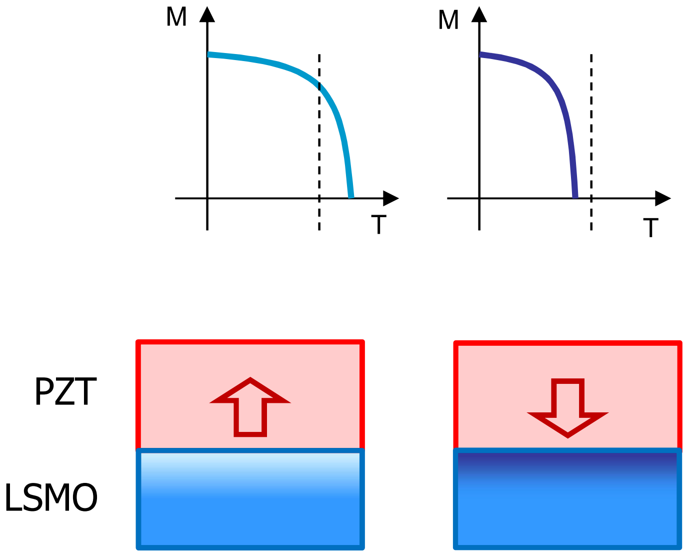
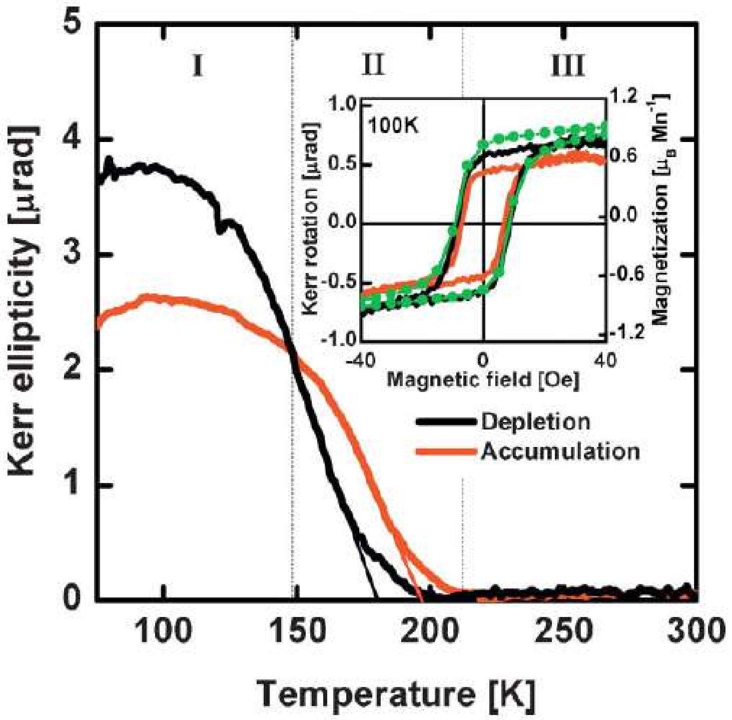
Field-effect control of Curie temperature



deplete electrons
accumulate holes
T_C increases

accumulate electrons
deplete holes
T_C decreases



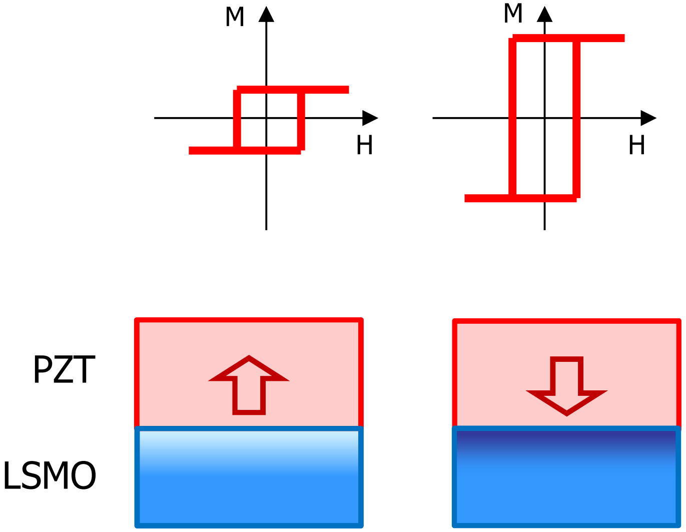
Vaz et al, PRL 104, 127202 (2010) & Molegraaf et al, Adv. Mater. 21, 3470 (2009)

- Combination of a **ferroelectric** and a **carrier-mediated ferromagnet**
- Switching P in ferroelectric PZT produces charge accumulation/depletion in manganite

➔ Change T_C of manganite

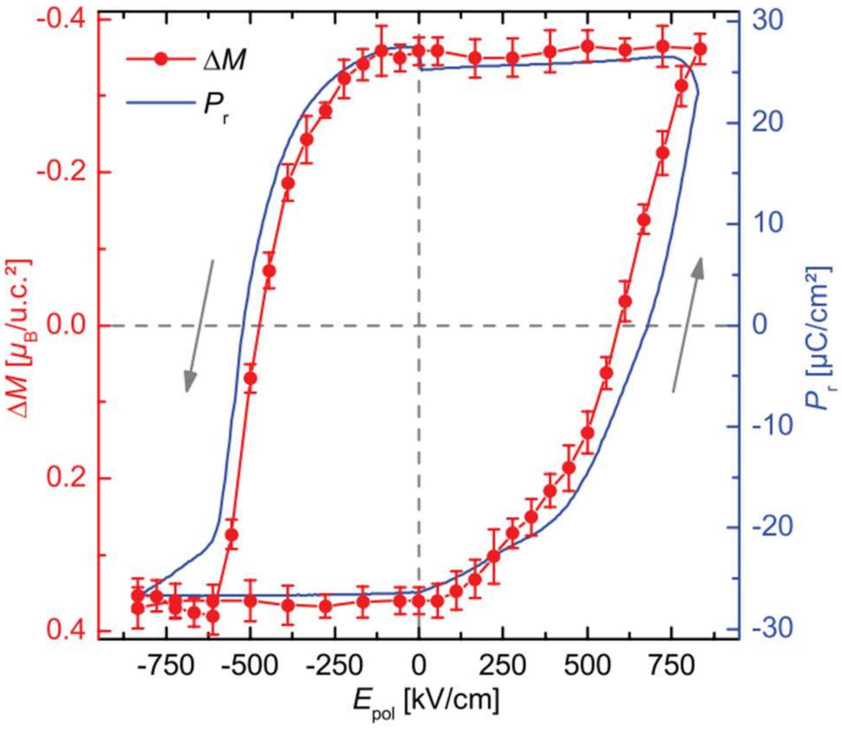
- Limited to low-temperature (also with GaMnAs)

Field-effect control of magnetic moment



deplete electrons
accumulate holes
M decreases

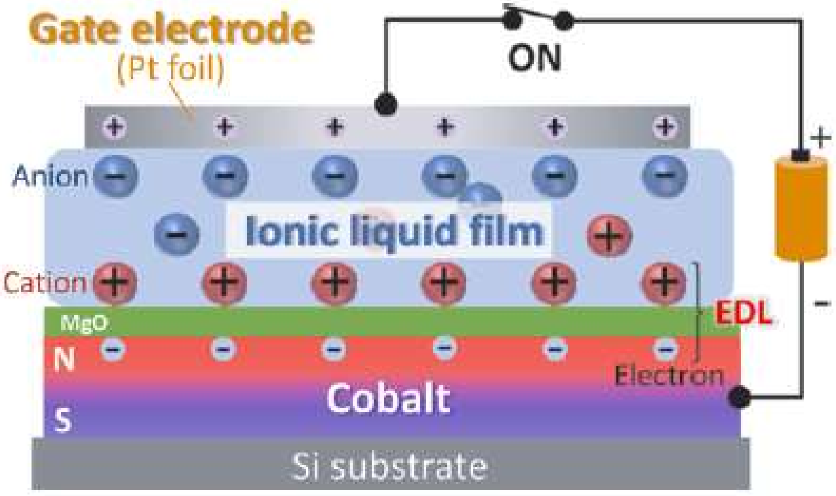
accumulate electrons
deplete holes
M increases



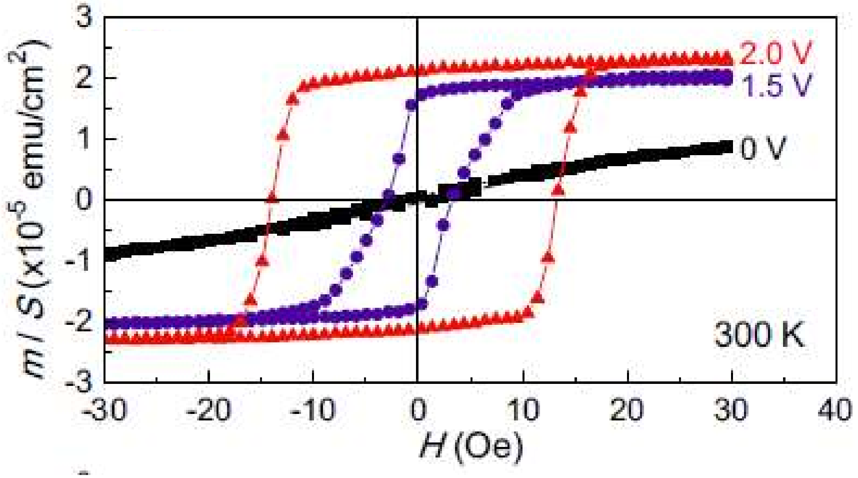
Leufke et al, Phys. Rev. B 87, 094416 (2013)

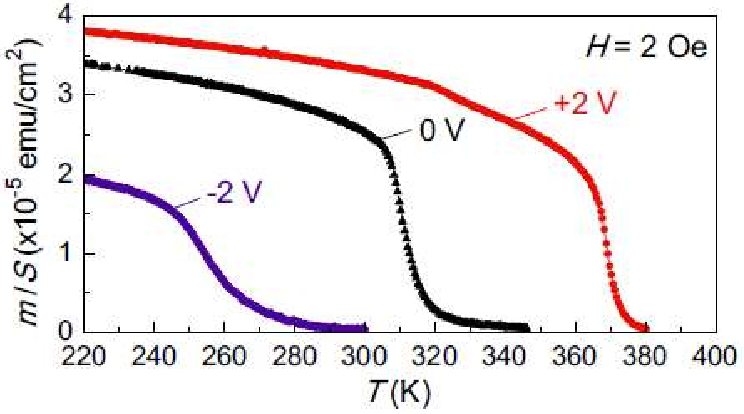
Field-effect control of Curie temperature

Increase accumulated charge density : ionic liquids



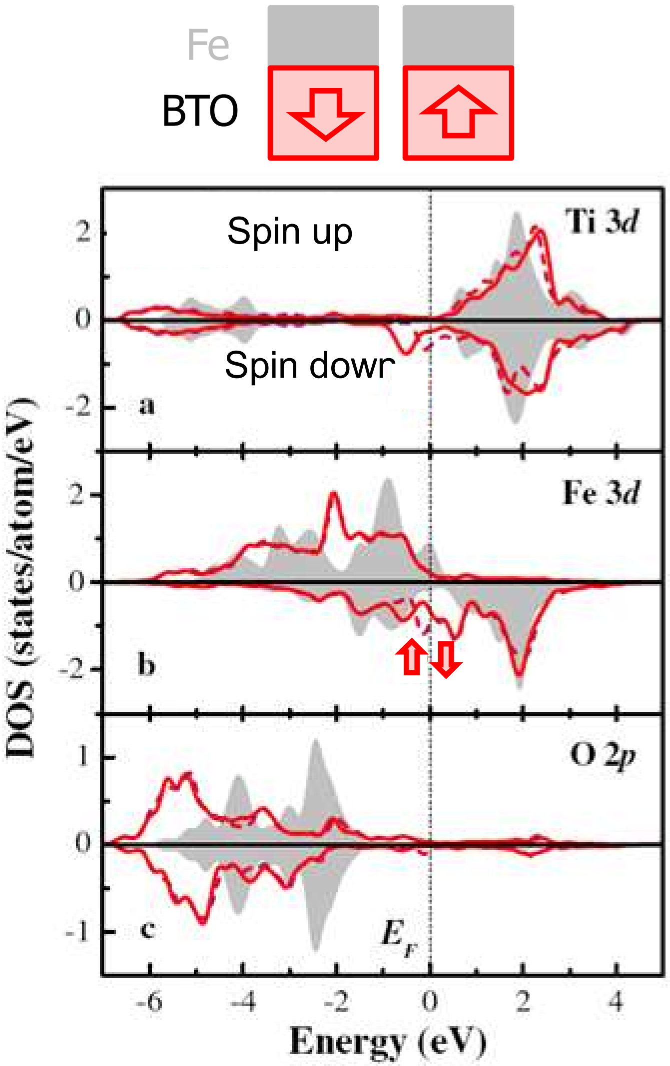
Chiba and Ono, J. Phys. D 46, 213001 (2013)





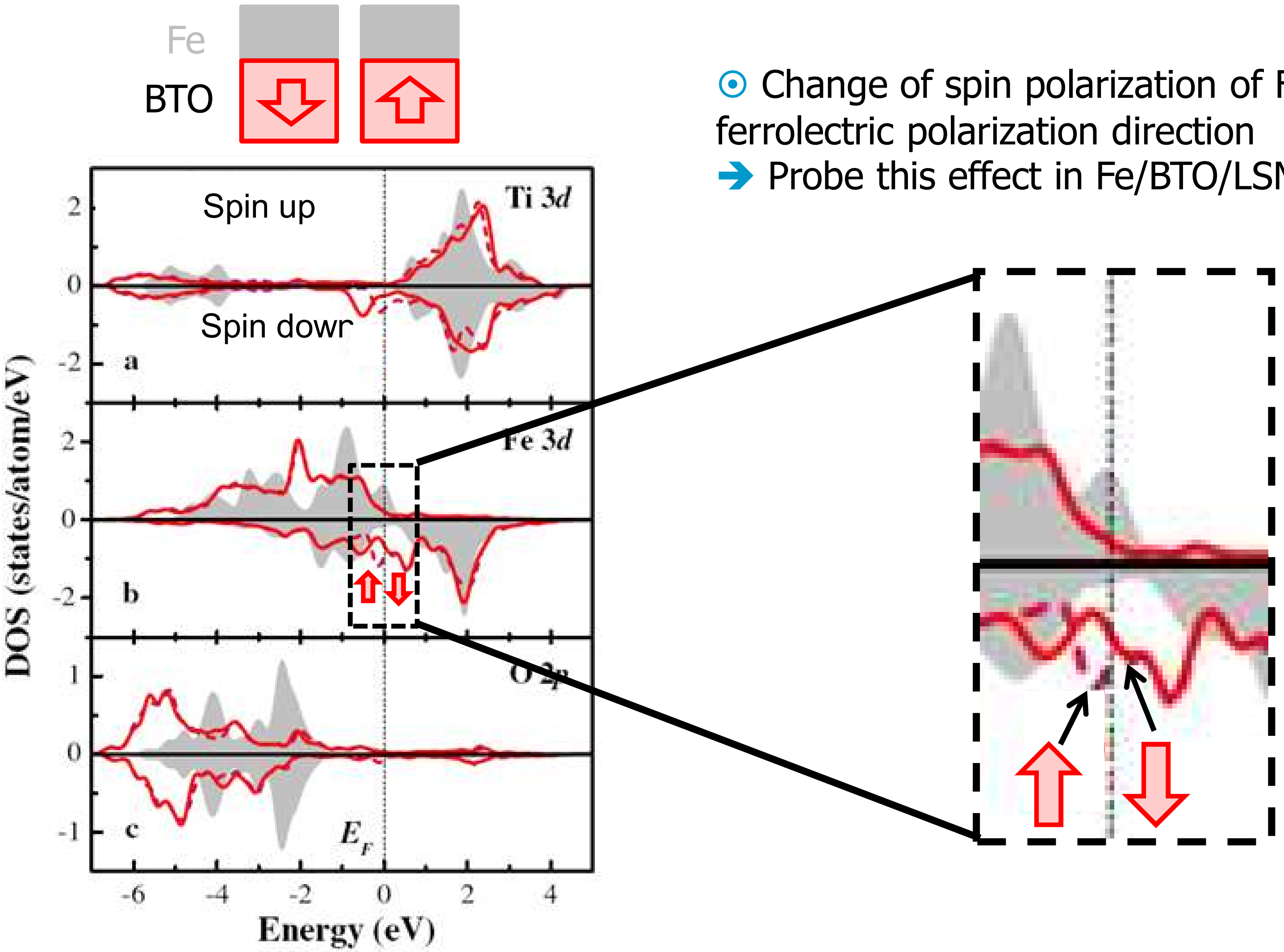
- Large field effect in 0.6 nm Co film using ionic liquid gating
- Possible with ferroelectrics (i.e. PZT/ultrathin Co) ?

Electric-field control of spin polarization



Duan et al., PRL 97, 047201 (2006)
Fechner et al, PRB 78, 212406 (2008)

Electric-field control of spin polarization



- Change of spin polarization of Fe depending on ferrolectric polarization direction

➔ Probe this effect in Fe/BTO/LSMO tunnel junctions

Duan et al., PRL 97, 047201 (2006)
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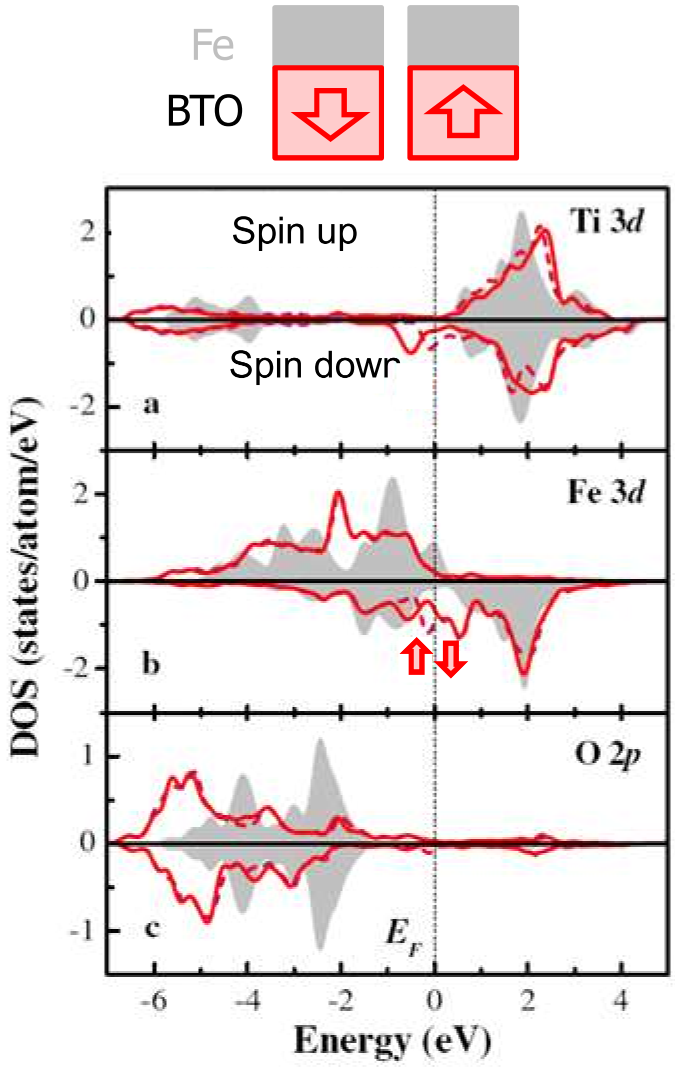

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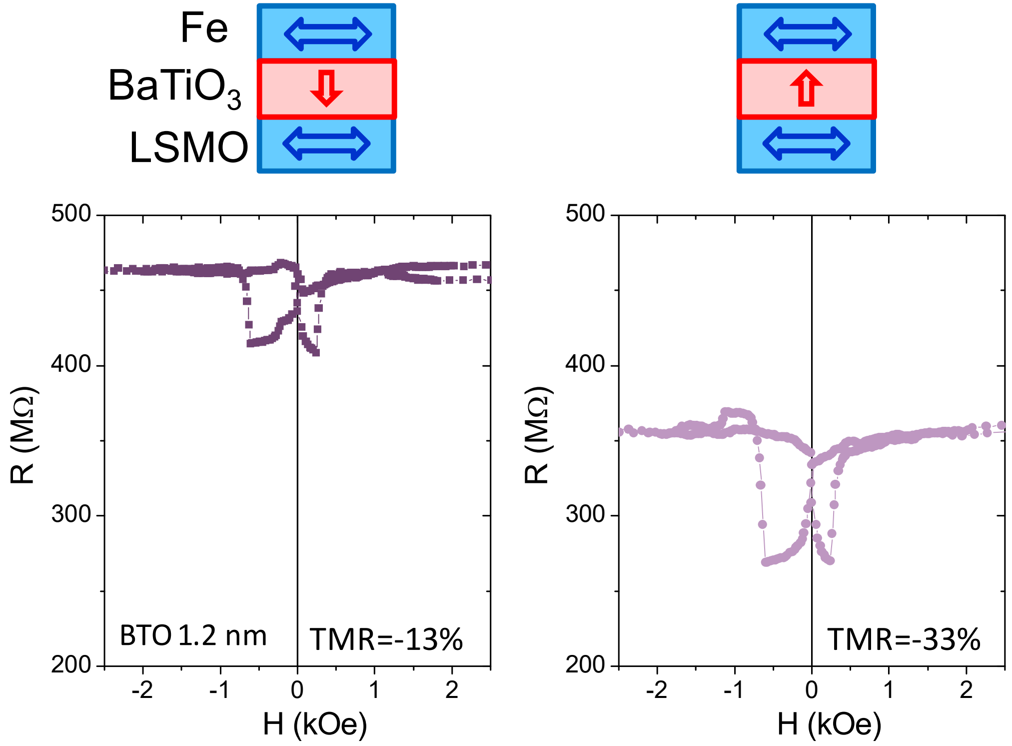
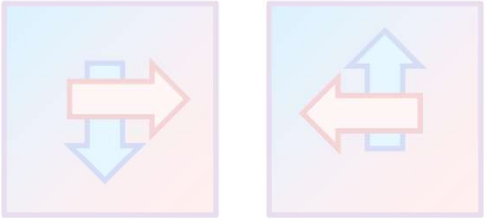


- ⦿ TMR amplitude depends on direction of P
- ➔ **Ferroelectric control of spin polarization**
- ⦿ Combination of field-effect and hybridization changes

V. Garcia, MB et al, Science 327, 1106 (2010)
S. Valencia, MB et al, Nature Mater. 10, 753 (2011)

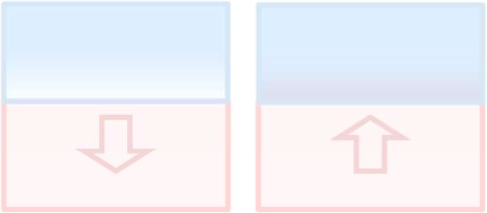
Different approaches for E-field control of magnetism

Intrinsic magnetoelectric



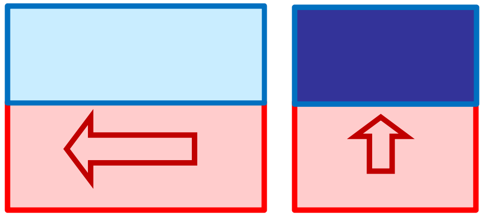
Use single-phase multiferroic material

Field-effect



Combine strong ferroelectric with carrier-mediated ferromagnet

Strain-driven



Combine piezoelectric or ferroelectric/ferroelastic with magnetostrictive ferromagnet

Strain-induced control of magnetic anisotropy

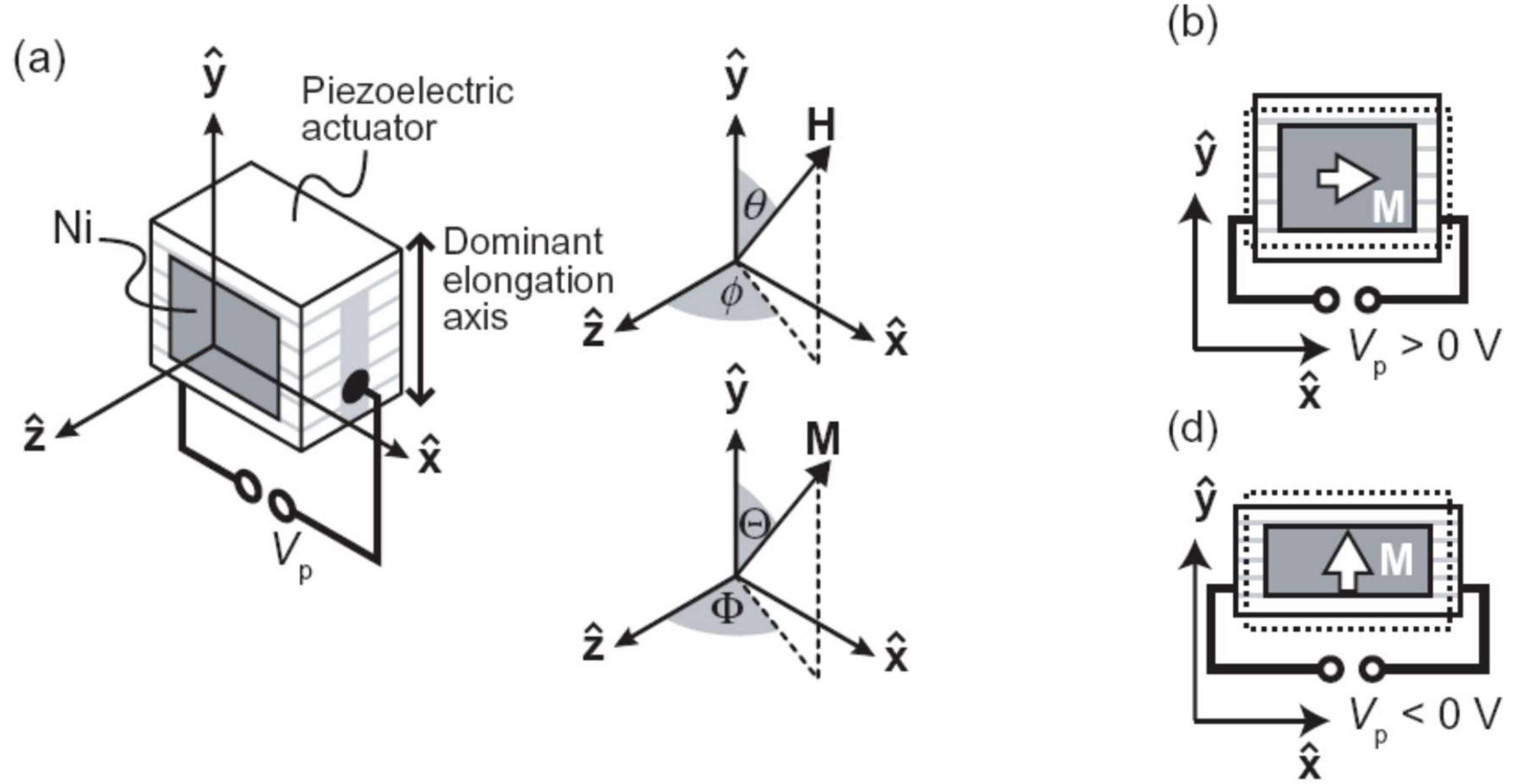
Example : experiments on PZT/Ni Weiler et al, New J. Phys 2009

Principle :

E-field applied to PZT : change in PZT dimensions due to **converse piezoelectric effect**

➔ Change in dimensions induced in Ni : strain effect

➔ Due to **magnetostriction** in Ni, strain modifies the magnetic properties



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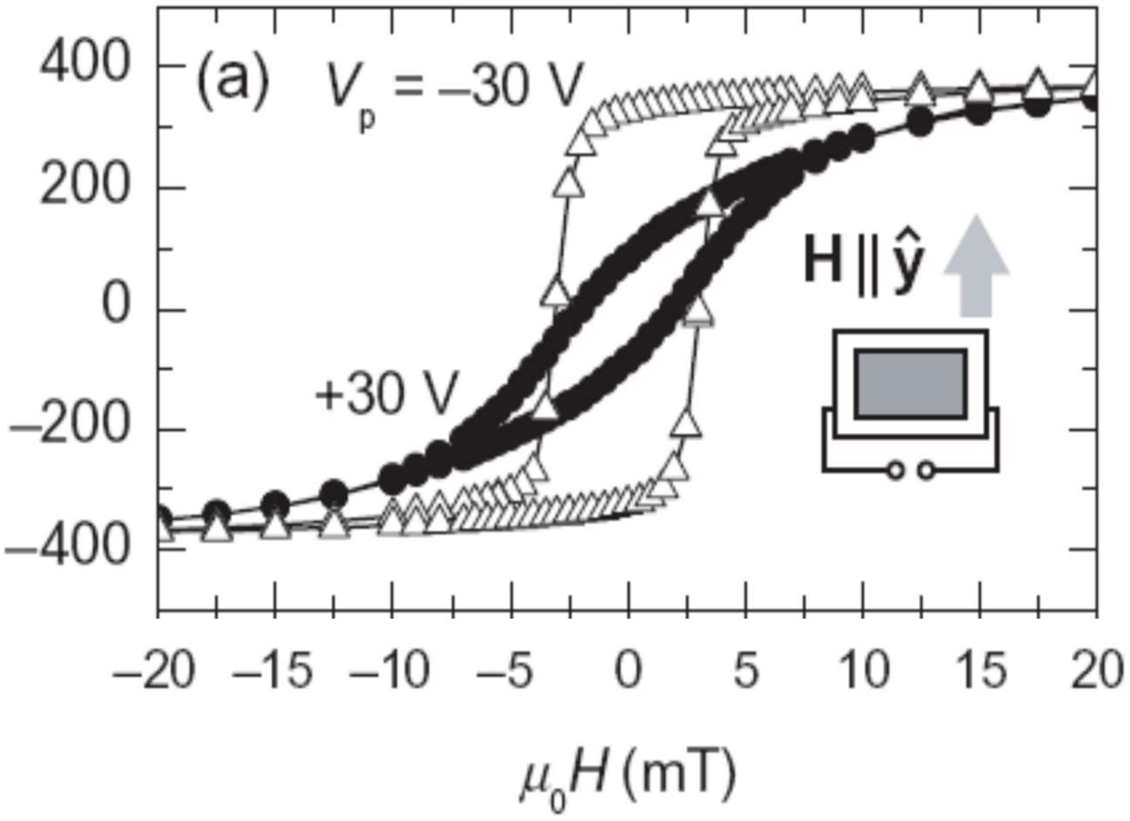
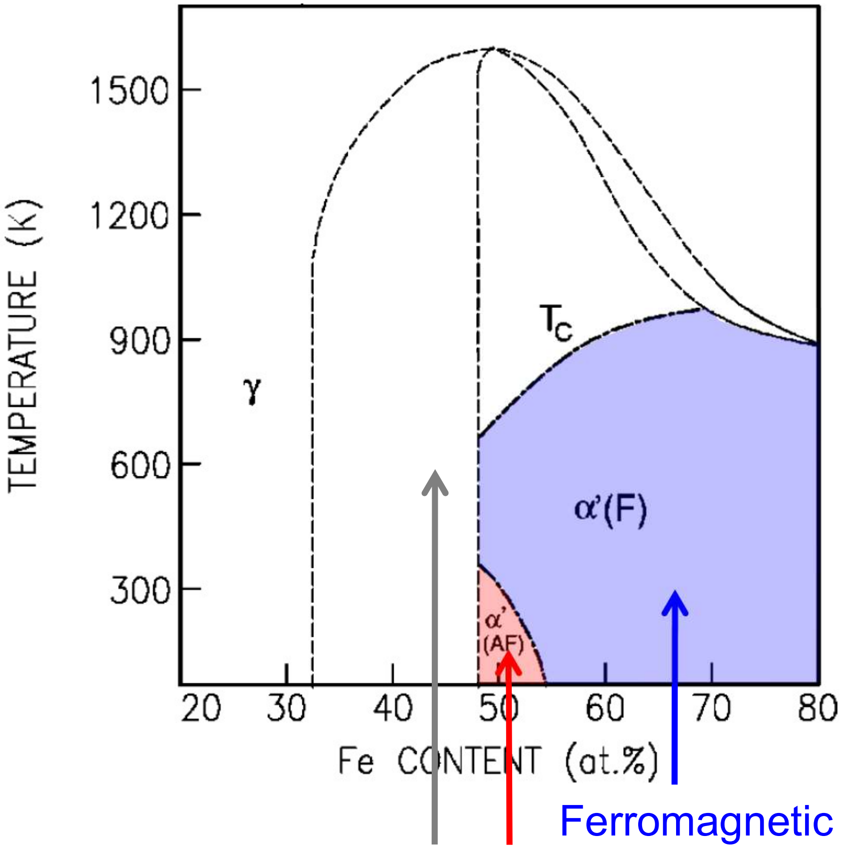


Weiler et al, New J. Phys 2009

Electric-field induced control of magnetization easy axis

Strain-induced control of magnetic order



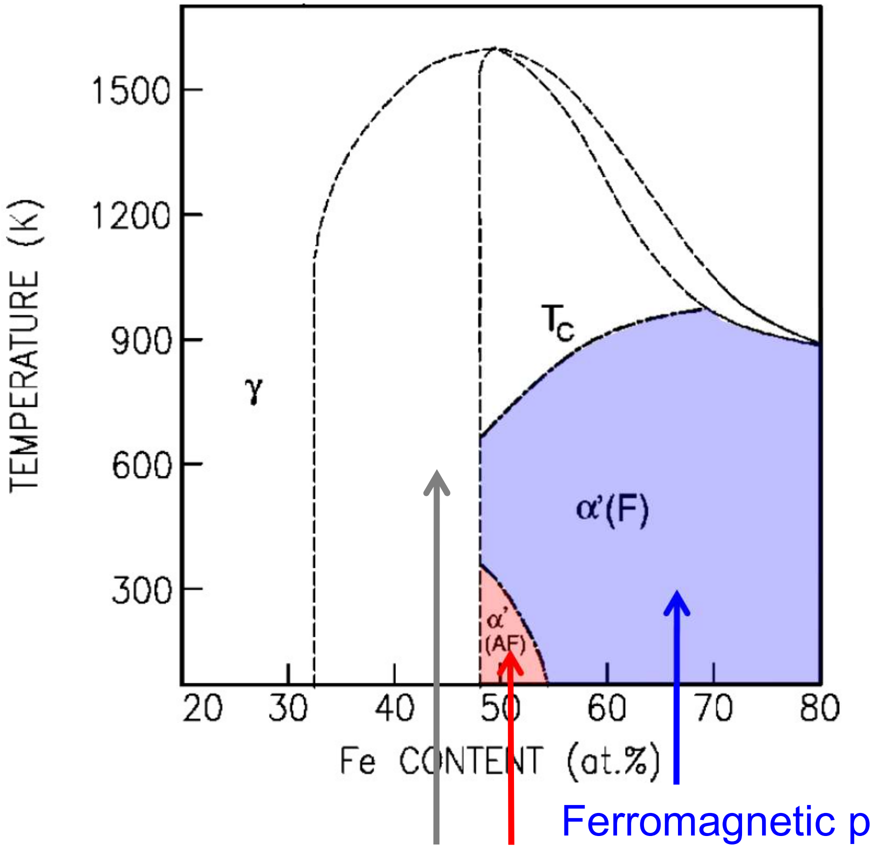
Ferromagnetic phase

Paramagnetic phase Antiferromagnetic phase

γ phase : fcc ; α phase : disordered bcc
α' phase : Fe/rh ordered bcc

van Driel et al, JAP 85, 1026 (1999)

Strain-induced control of magnetic order



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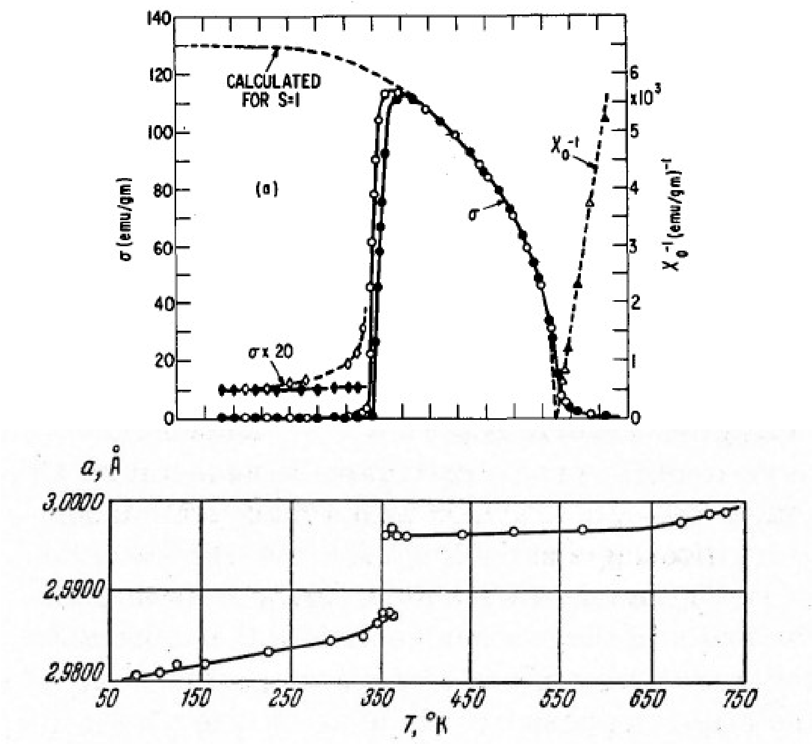
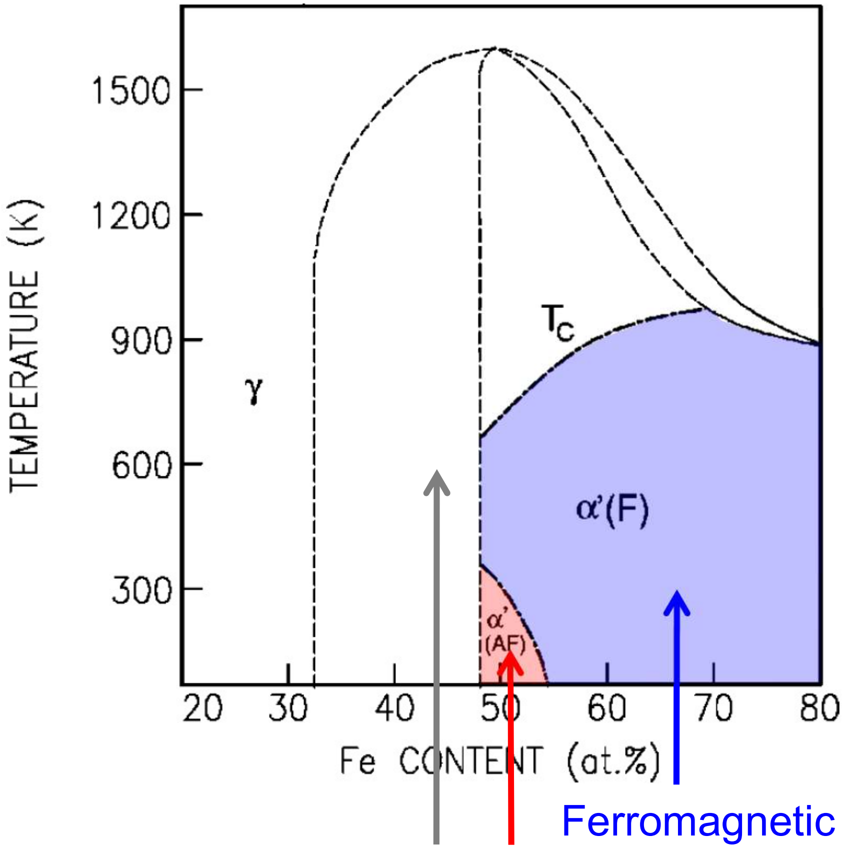


- Near $Fe_{50}Rh_{50}$, transition from AFM to FM at about 370K
- Transition is first order
- Associated large resistivity drop
- Jump of cell volume by ~1% at T*

Zakharov et al, Sov. Phys. JETP 19, 1348 (1964)

Strain-induced control of magnetic order



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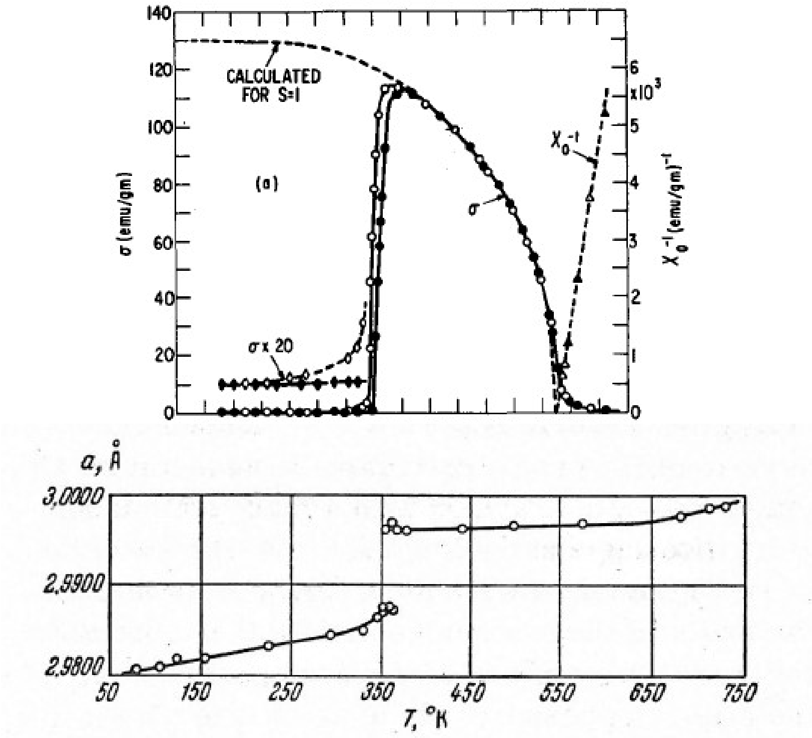

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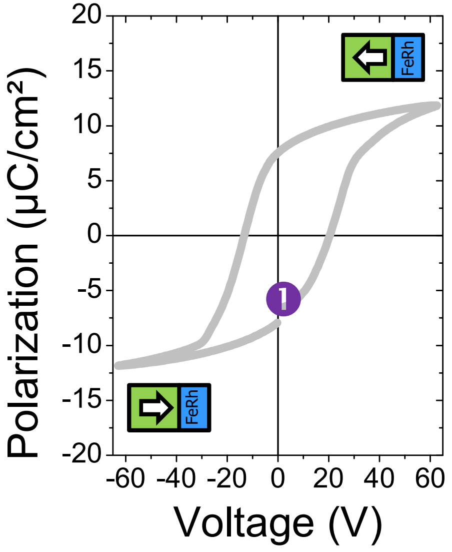
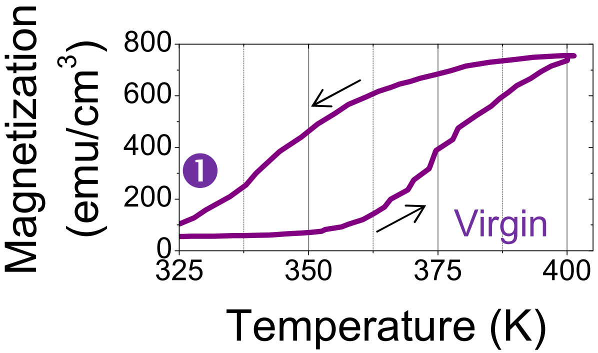
- ⊙ Magnetic state of FeRh is sensitive to pressure

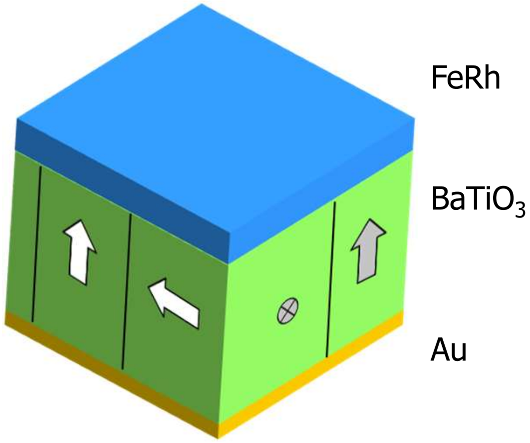
➔ Grow on **ferroelectric/ferroelastic $BaTiO_3$** substrate to achieve E-field control

Strain-induced control of magnetic order

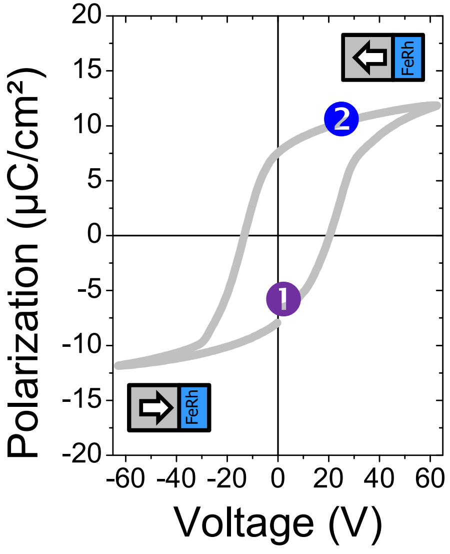


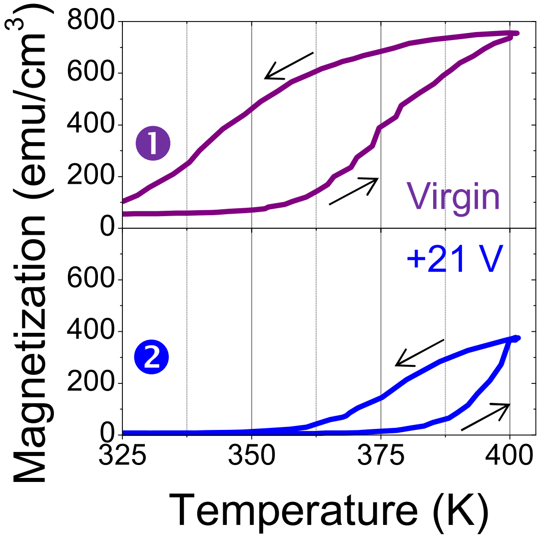


- At 0V at 20 kOe, T*≈360 K

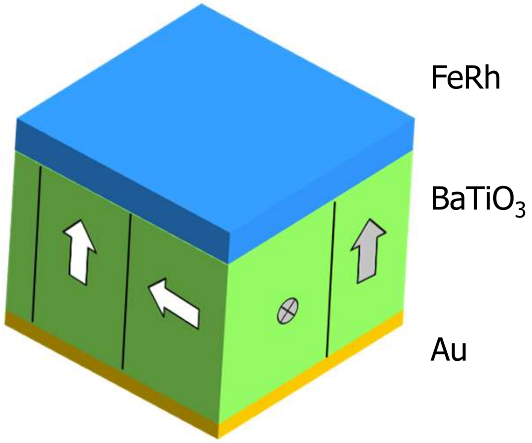


Strain-induced control of magnetic order

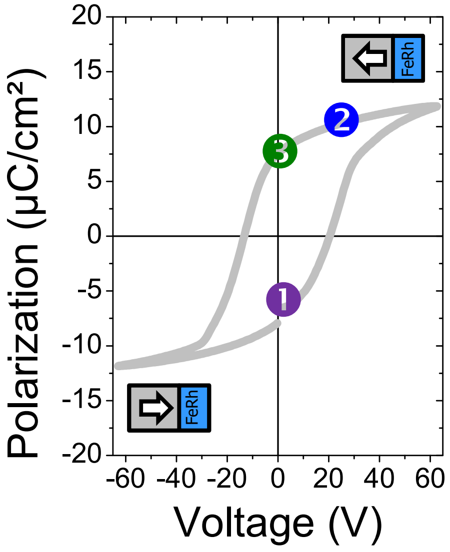


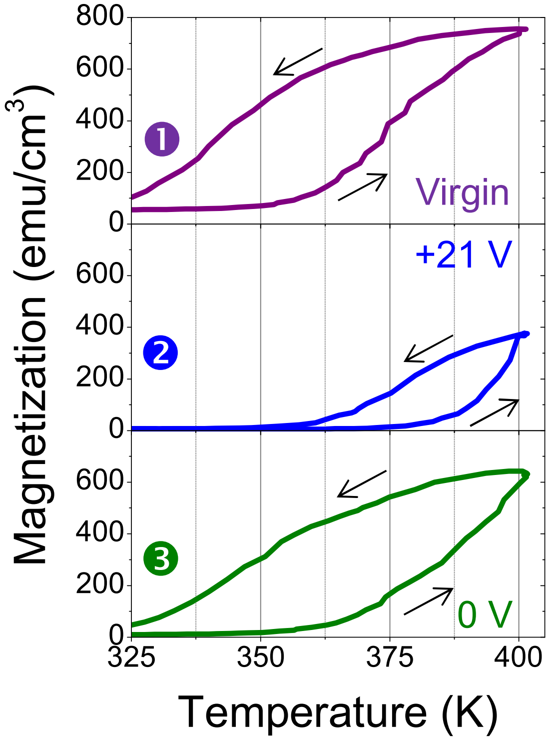


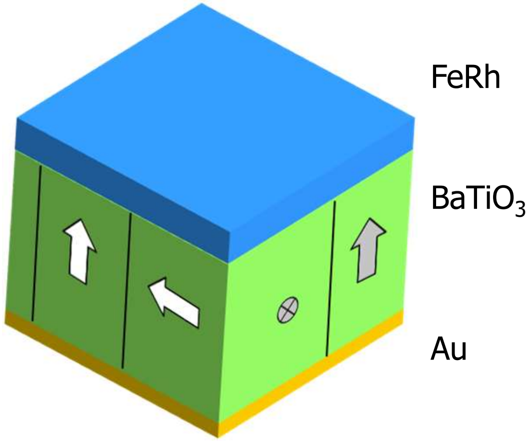
- ⊙ At 0V at 20 kOe, T*≈360 K
- ⊙ Voltage shifts T* by ~20K



Strain-induced control of magnetic order

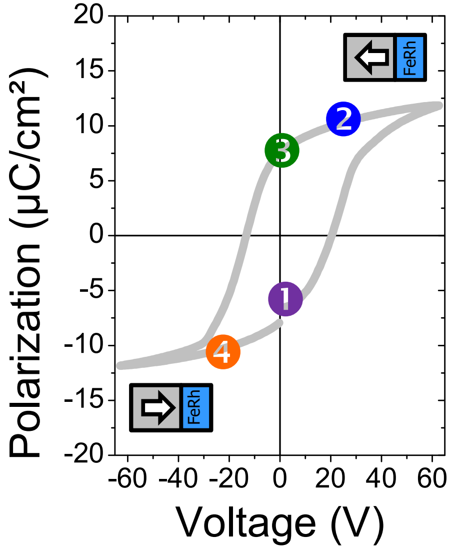


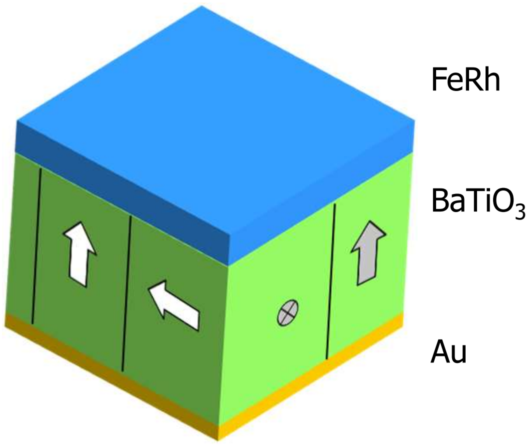


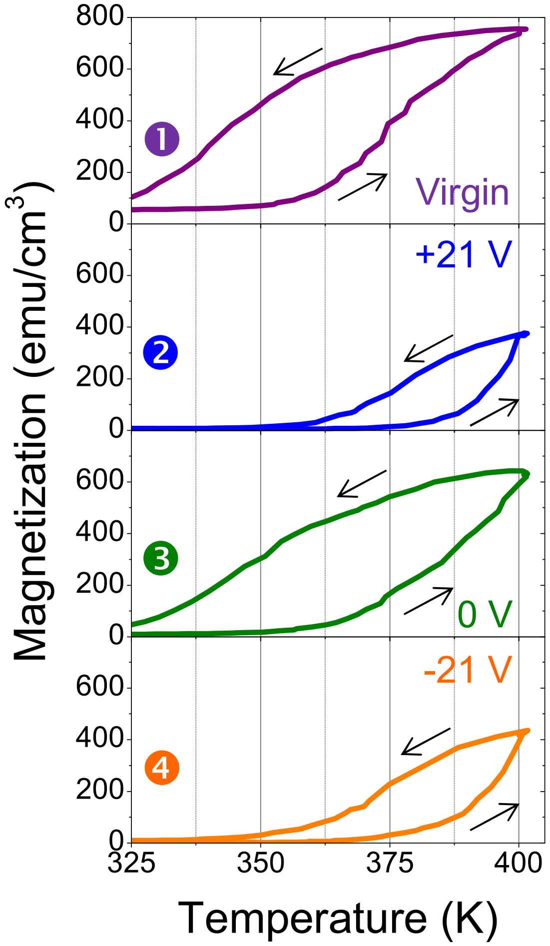


- At 0V at 20 kOe, $T^* \approx 360$ K
- Voltage shifts T* by ~20K
- Effect is reversible

Strain-induced control of magnetic order







- At 0V at 20 kOe, T*≈360 K
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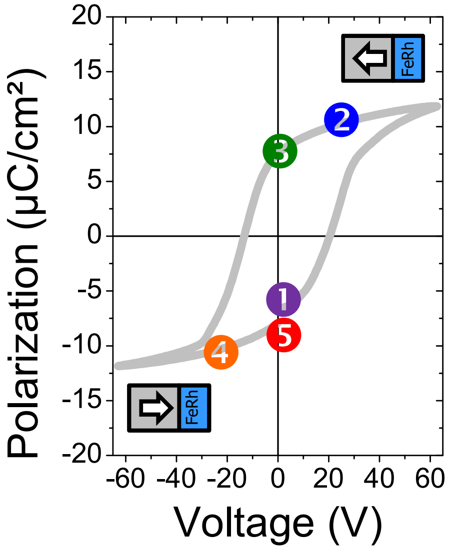
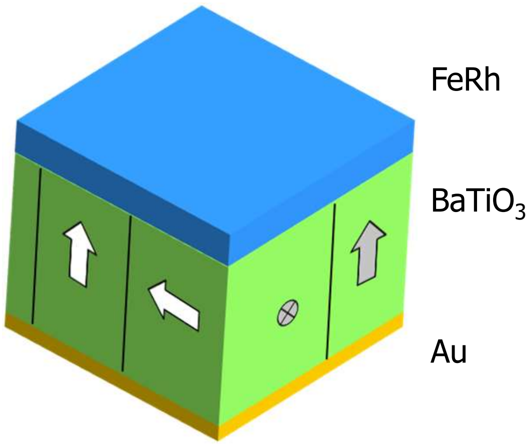
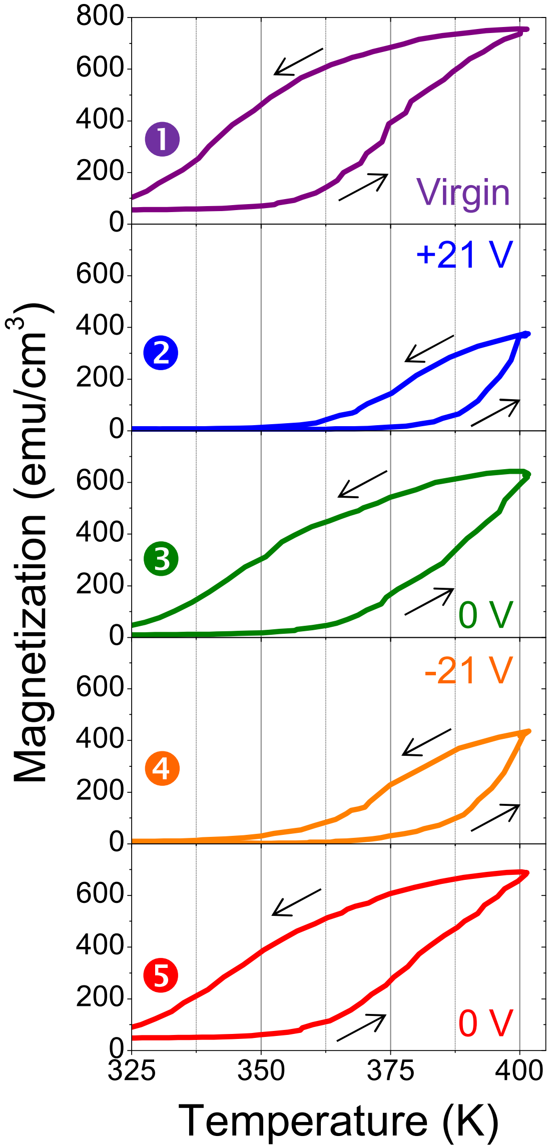
- Positive or negative voltages give roughly similar effect

Strain-induced control of magnetic order







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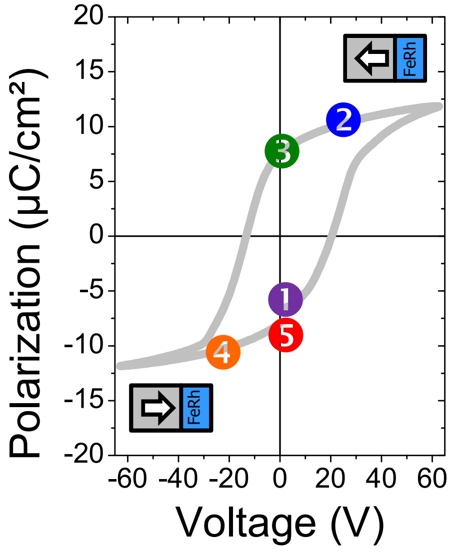

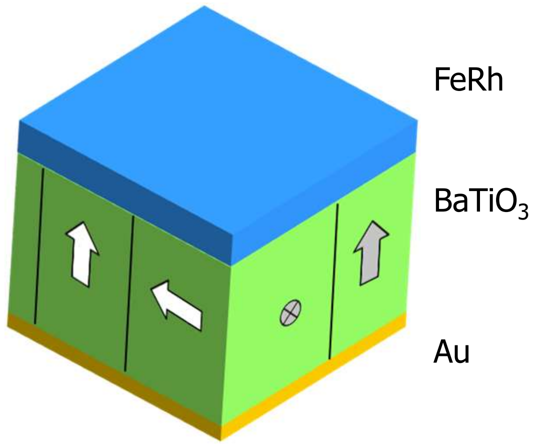

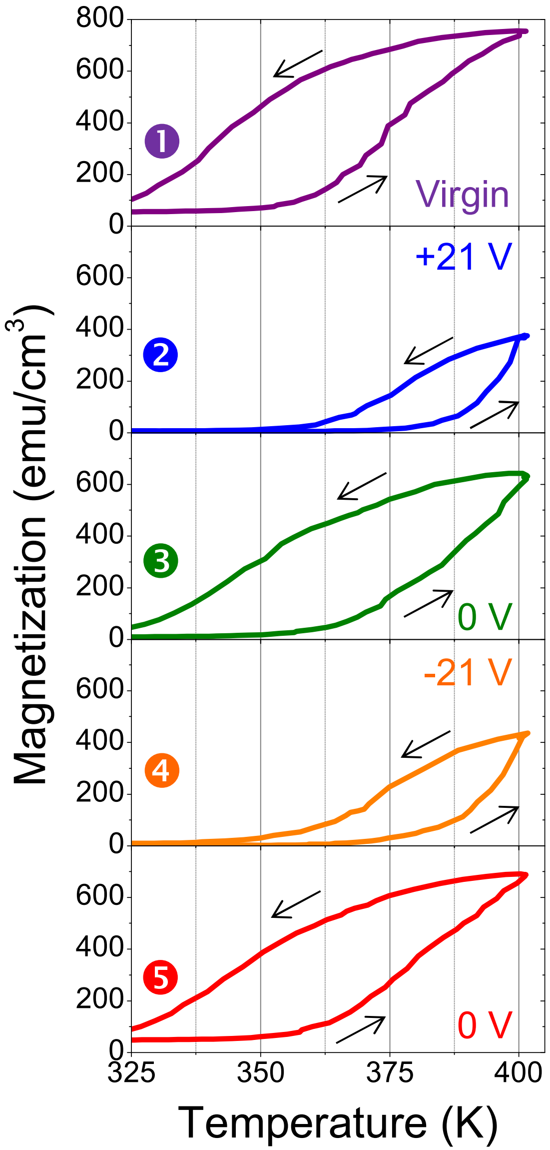

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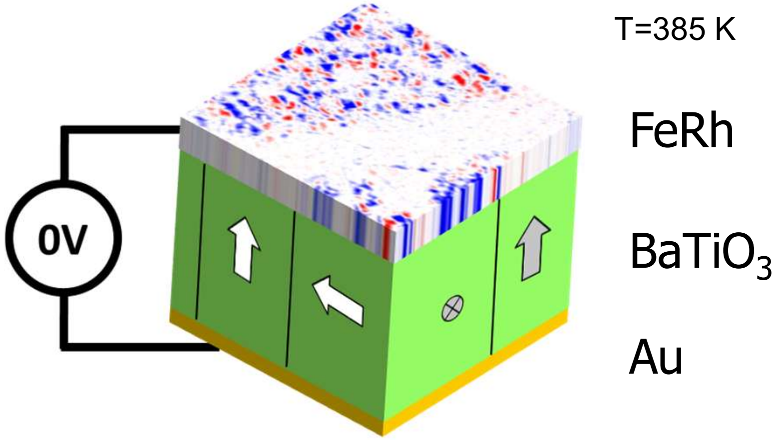
- Max magnetization change ~600 emu/cm^3
- ME coupling α=1.6.10^{-5} s/m
- Larger than in any single phase material by 5 orders
- Larger than in any artificial multiferroic by factor >10

Cherifi, MB et al, Nature Mater. 13, 345 (2014)

Strain-induced control of magnetic order

Direct imaging of magnetic state using XCMD-PEEM



Mixed ferro/
antiferromagnetic state

Strain-induced control of magnetic order

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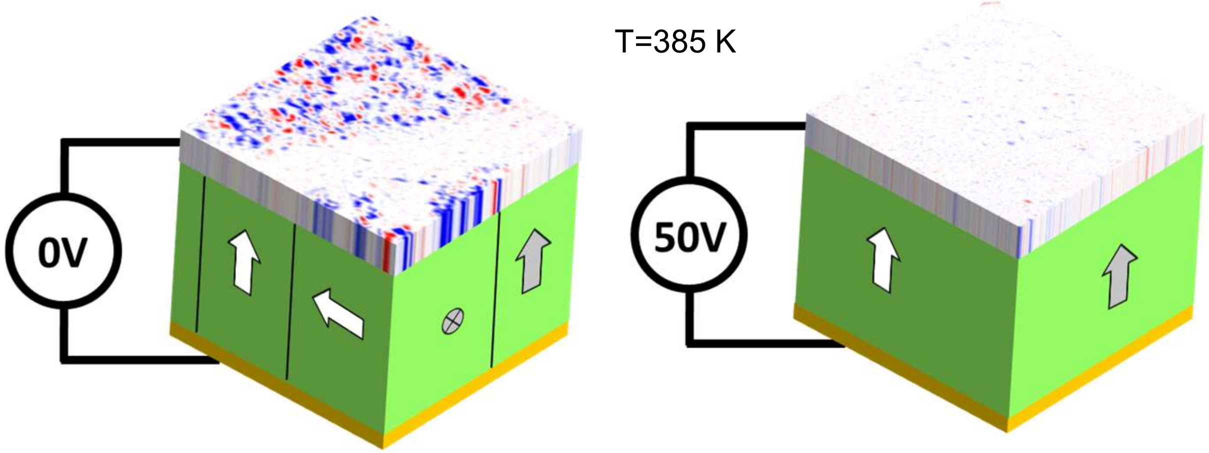

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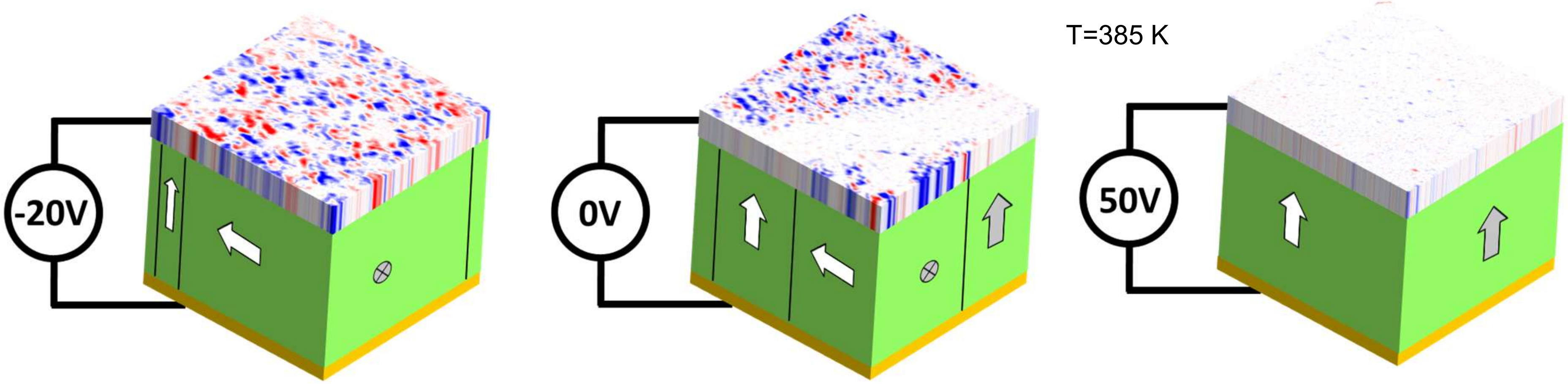

Ferromagnetic state

Mixed ferro/
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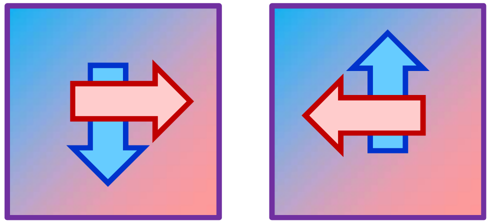
Antiferromagnetic state

- Switch ferromagnetism **OFF and ON** by electric field, just above room temperature

Phillips, MB et al, Sci. Rep. 5, 10026 (2014)

Different approaches for E-field control of magnetism

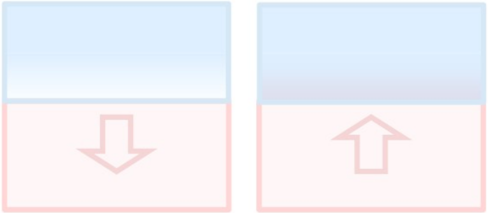
Intrinsic magnetoelectric



Use single-phase multiferroic material

- ✓ Simple approach, just one material
- ✓ Beautiful physics, potential for new science
- × BFO only RT multiferroic
- × Can be leaky, hard to switch

Field-effect



Combine strong ferroelectric with carrier-mediated ferromagnet

- ✓ Broader choice of materials
- ✓ Well-suited for perpendicular transport
- × Few ferromagnetic oxides with high T_C ; need simple metals
- × Effect occurs over very small thickness (few nm max)
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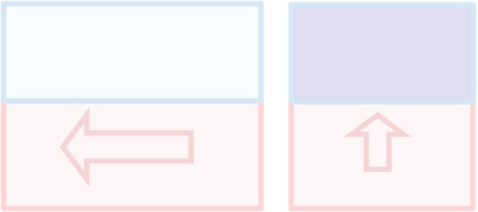
Strain-driven



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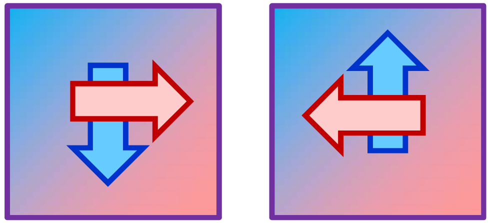

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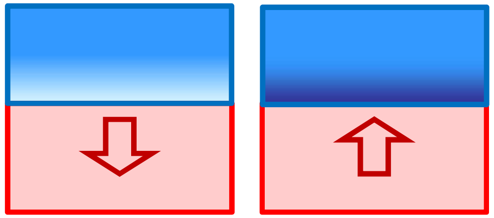

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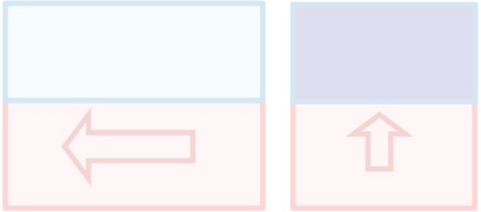

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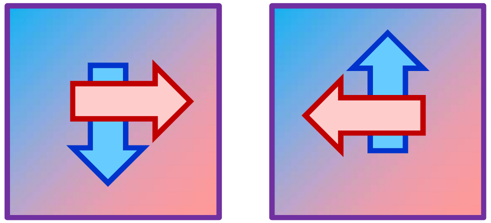

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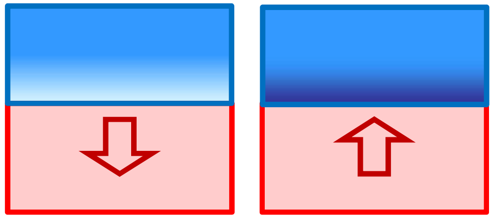

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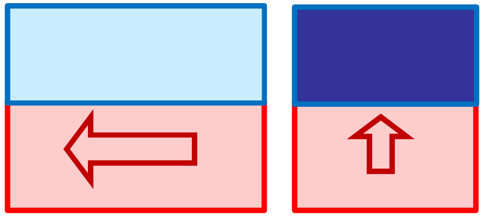

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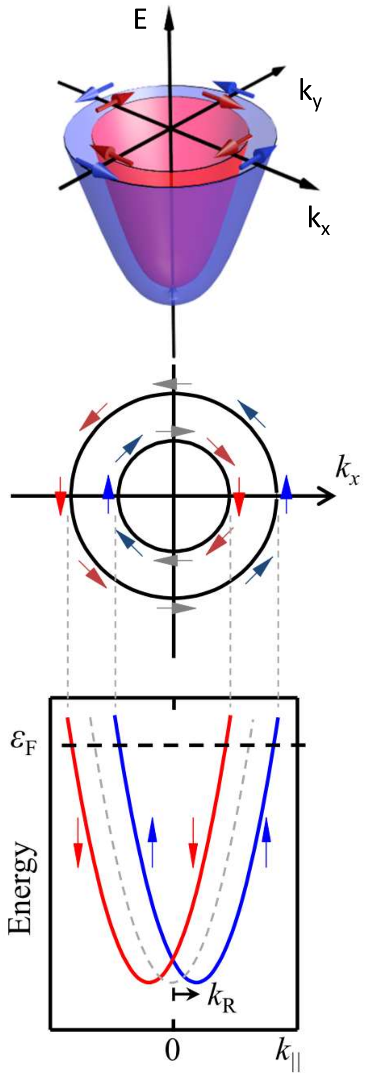
Outline

- ⊙ Ferroic orders, multiferroics and magnetoelectric coupling
- ⊙ Approaches for the electric-field control of magnetism
- ➔ ⊙ Electric-field control of spin-charge interconversion
- ⊙ Low-power spin-based devices for logic-in-memory

Rashba and Edelstein effects



$$\varepsilon_k = \frac{\hbar^2 k^2}{2m^*} \pm \alpha_R k$$

The **Rashba effect** – manifestation of spin-orbit interaction (SOI) in solids, more particularly in two-dimensional electron systems, where spin degeneracy is lifted due to a symmetry-breaking electric field normal to an heterointerface.

$$H_R = \frac{\alpha_R}{\hbar}(\vec{\sigma} \wedge \vec{p}) \bullet \vec{z}$$

Bychkov & Rashba, Sov. Phys. JETP Lett. 39, 78 (1984)
Manchon et al., Nature Mater. 14, 871 (2015)

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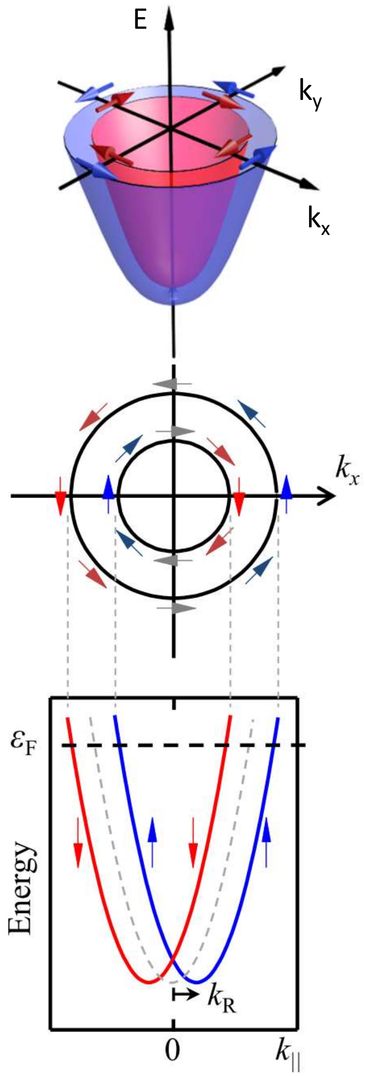

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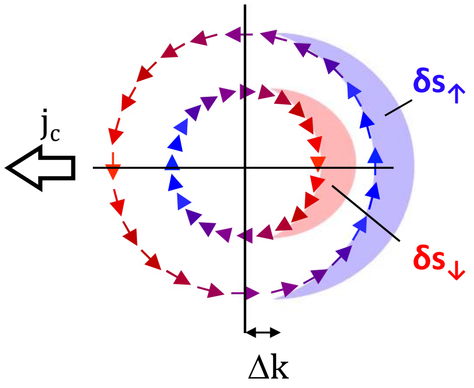
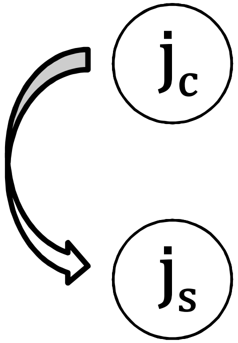
Direct Edelstein effect (EE)



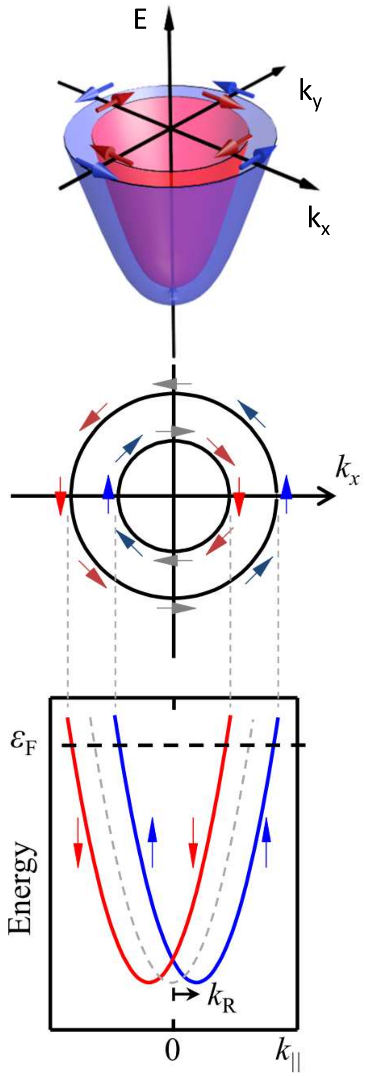


Injection of a charge current

Generation of spin accumulation

Edelstein, Solid State Commun. 73, 233 (1990)
Aronov et al , JETP Lett. 50, 431 (1989)

Rashba and Edelstein effects



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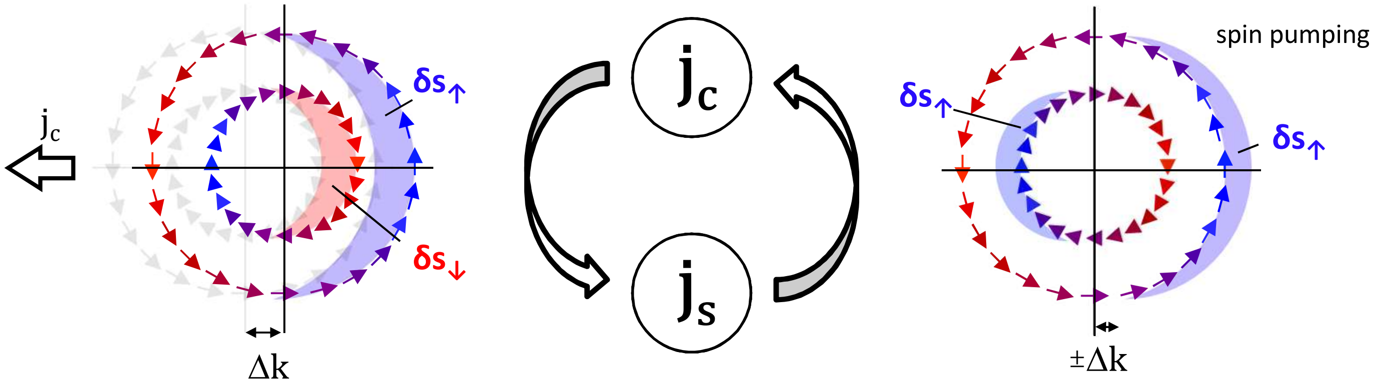
Direct Edelstein effect (EE)

Inverse Edelstein effect (IEE)



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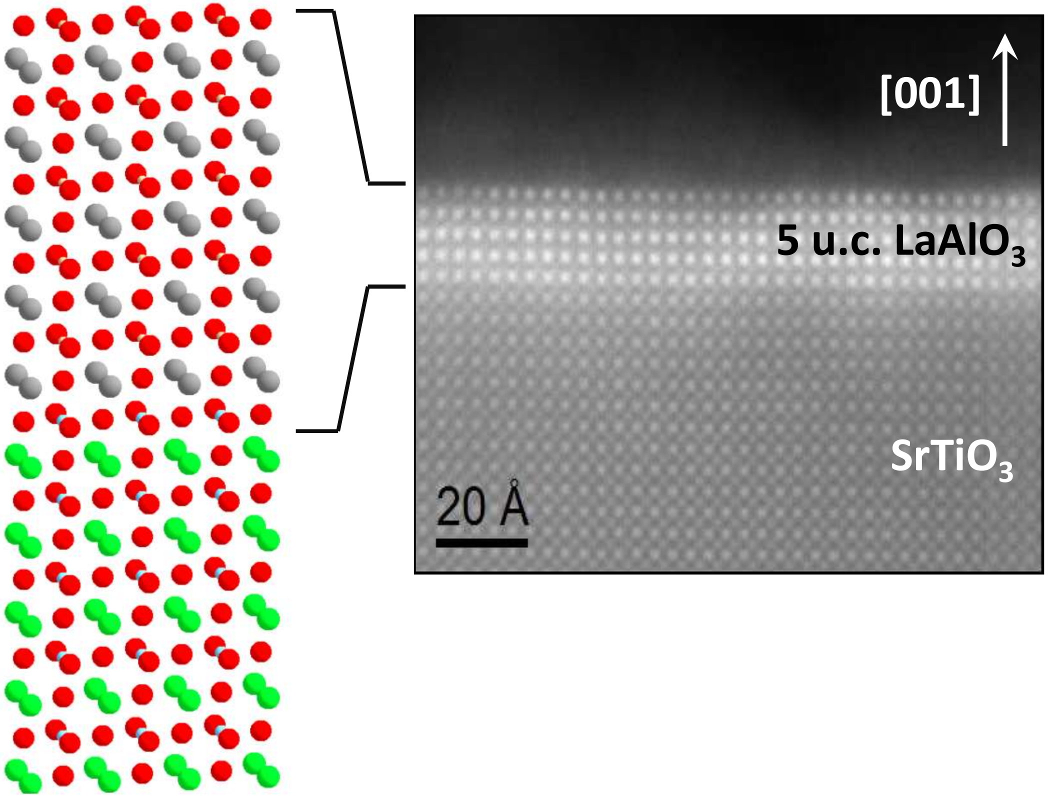
Rojas-Sánchez et al., Nat. Commun. 4, 2944 (2013)
Shen et al., Phys. Rev. Lett. 112, 096601 (2014)

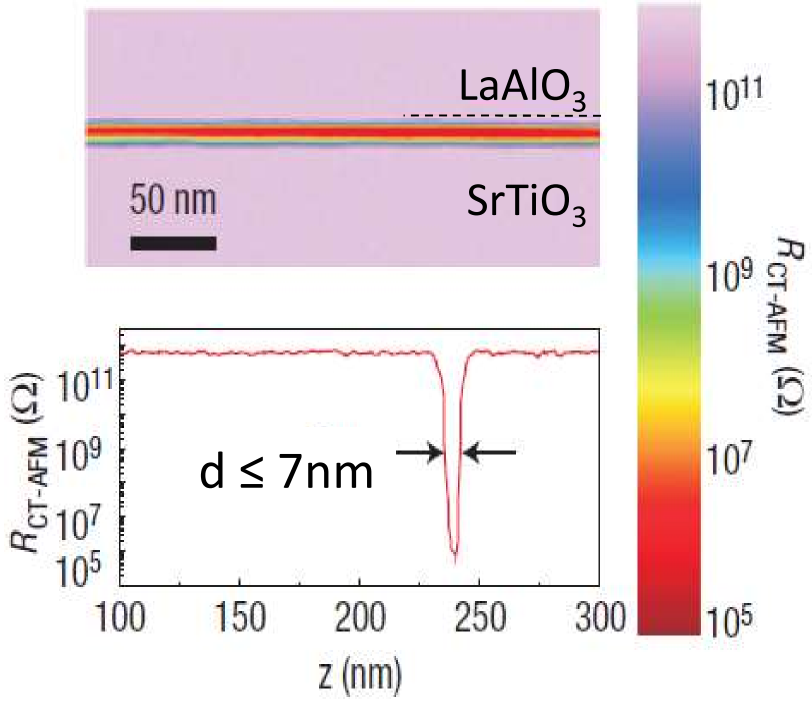
Figure of merit : $\lambda_{IEE} = \frac{j_c^{2D}}{j_S^{3D}} = \frac{\alpha_R \tau}{\hbar}$

The $LaAlO_3/SrTiO_3$ system



TEM image by f L. Fitting-Kourkoutis

Resistance map in cross-section (CT-AFM)

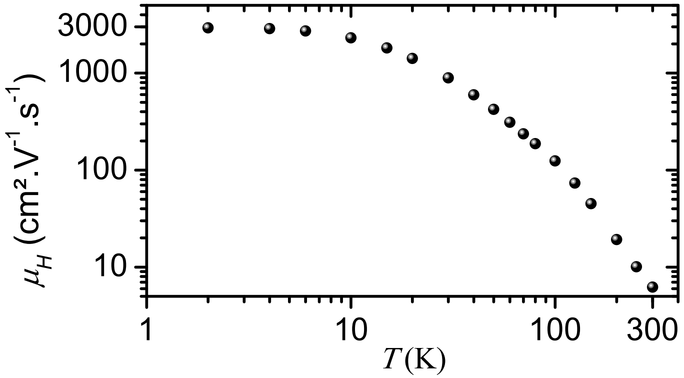


➔ Quasi-**two-dimensional** conduction

M. Basletic, MB et al., Nat. Mater. 7, 621 (2008)
O. Copie, MB et al., Phys. Rev. Lett. 102, 216804 (2009)

The $LaAlO_3/SrTiO_3$ system

- High Electron Mobility



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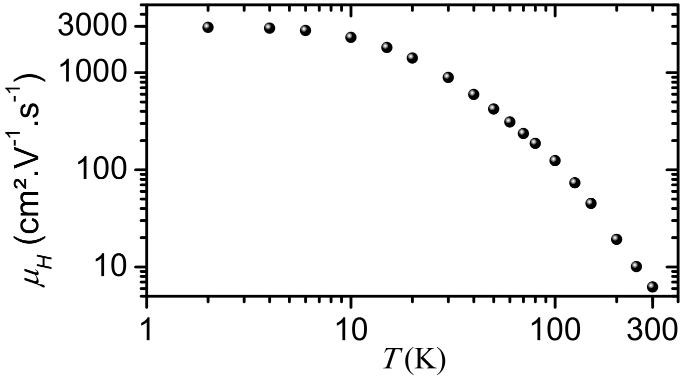
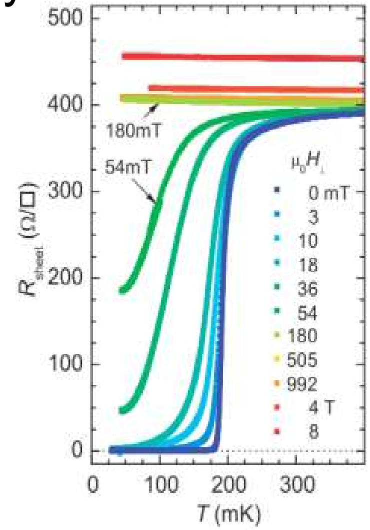
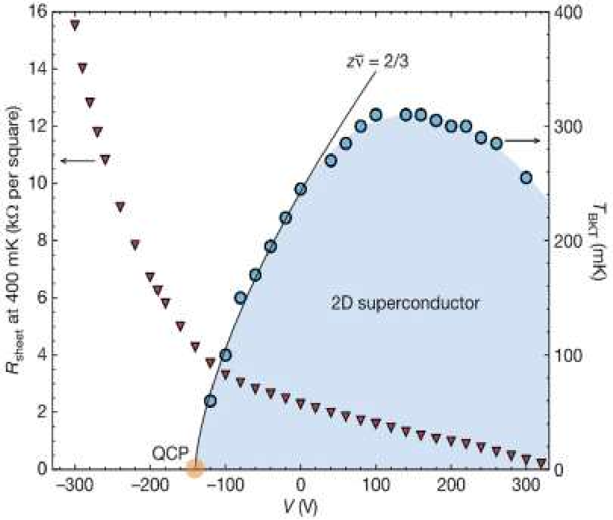


- Two-dimensional Superconductivity + gateable system





N. Reyren et al., Science 317, 1196 (2007) ; A. D. Caviglia et al., Nature 456, 624 (2008)

The $LaAlO_3/SrTiO_3$ system

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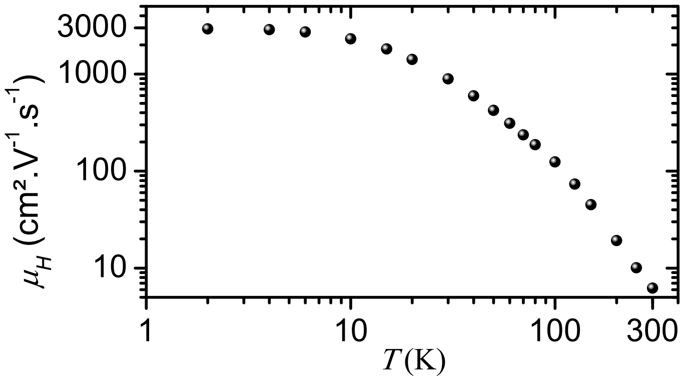

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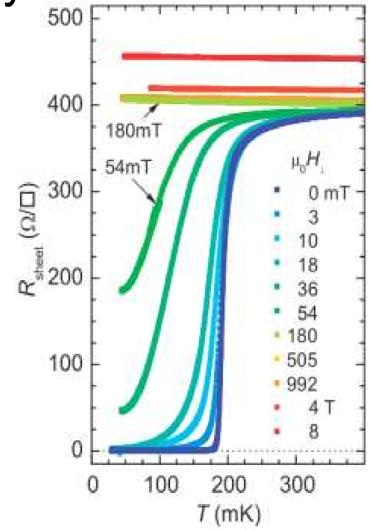
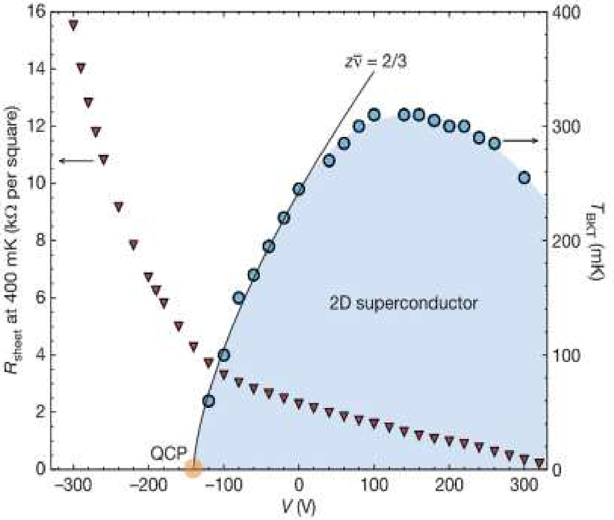
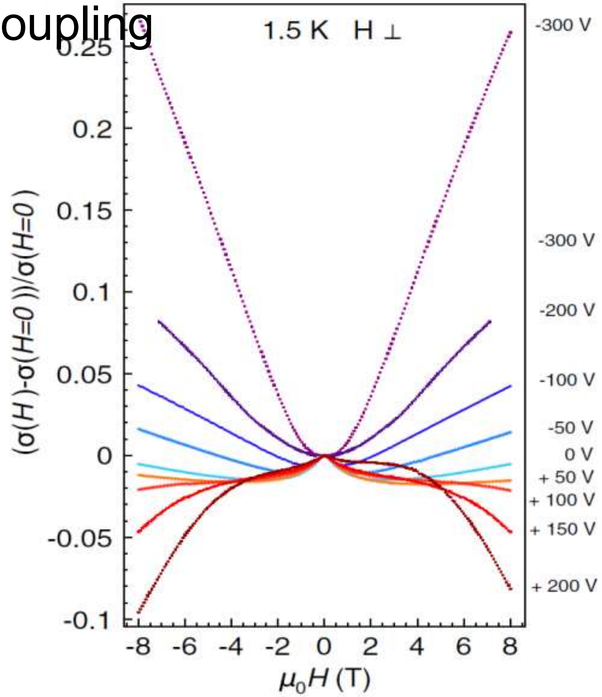
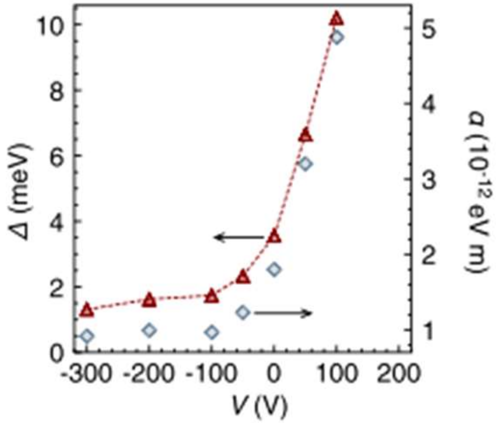




N. Reyren et al., Science 317, 1196 (2007) ; A. D. Caviglia et al., Nature 456, 624 (2008)

- Sizeable Rashba spin-orbit coupling



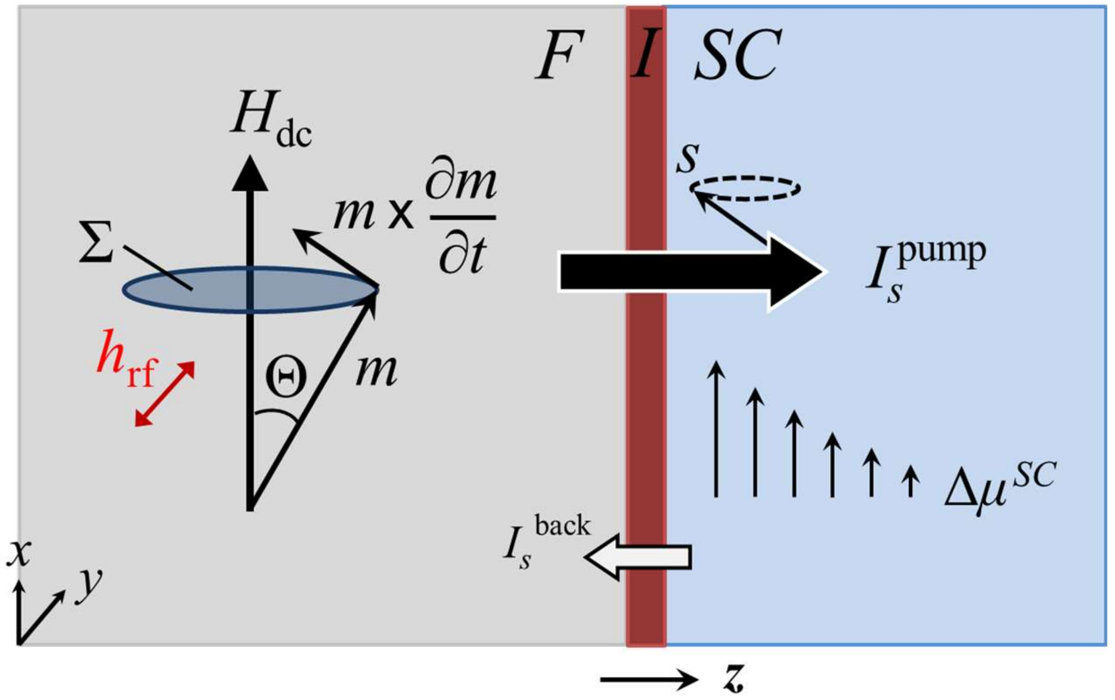


A.D. Caviglia et al., PRL. 104, 126803 (2010)

Spin pumping

- An microwave excitation field drives magnetization dynamics
- Ejects transverse spin angular momentum
- Creates an imbalance of spin up and spin down populations

➔ Generation of a pure spin current I_s.



$$\frac{\partial \boldsymbol{m}}{\partial t} = -\gamma\left(\boldsymbol{m} \times \boldsymbol{H}_{\text{eff}}\right) + \alpha_G\left(\boldsymbol{m} \times \frac{\partial \boldsymbol{m}}{\partial t}\right) + \frac{\gamma}{M_s\mathcal{V}}\left(\boldsymbol{m} \times \boldsymbol{I}_s\right) \times \boldsymbol{m}$$

A. Brataas et al., Phys. Rev. B 66, 060404(R) (2002)
Y. Tserkovnyak, et al., Rev. Mod. Phys. 77, 1375 (2005)

Spin pumping

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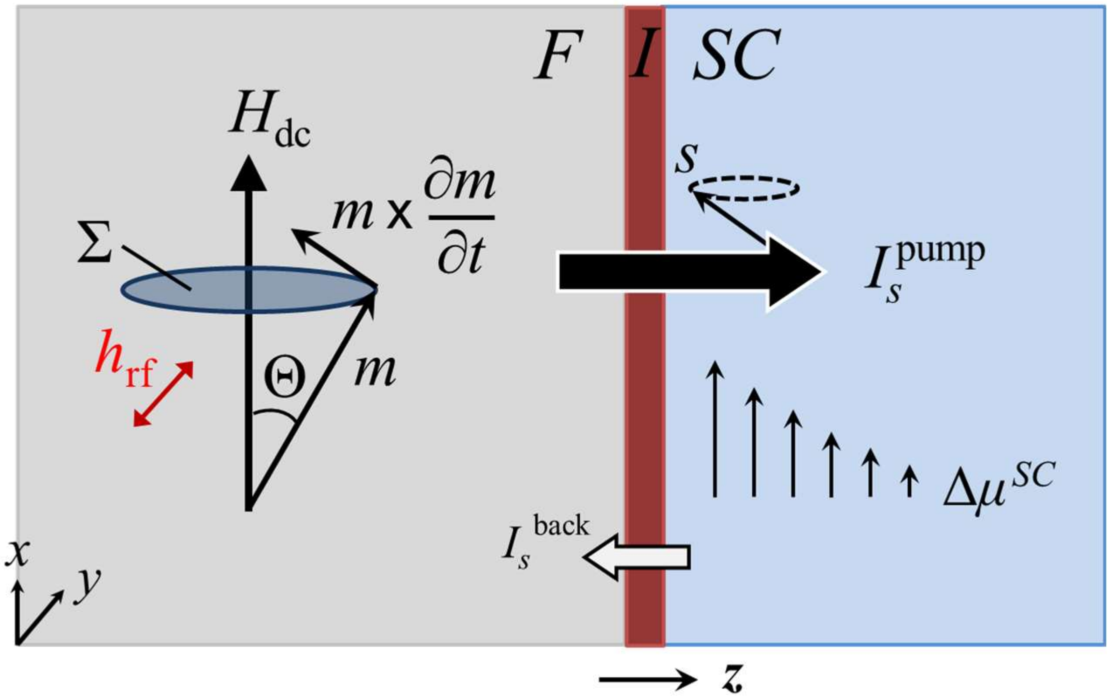

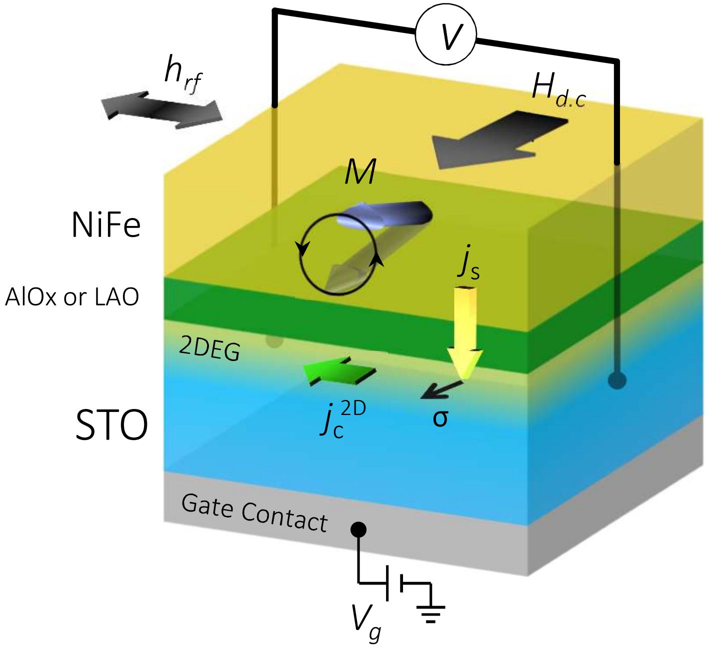

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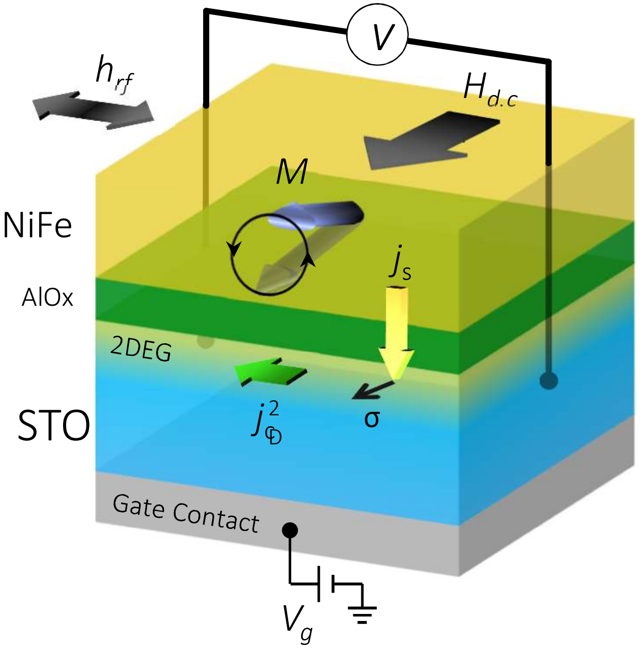
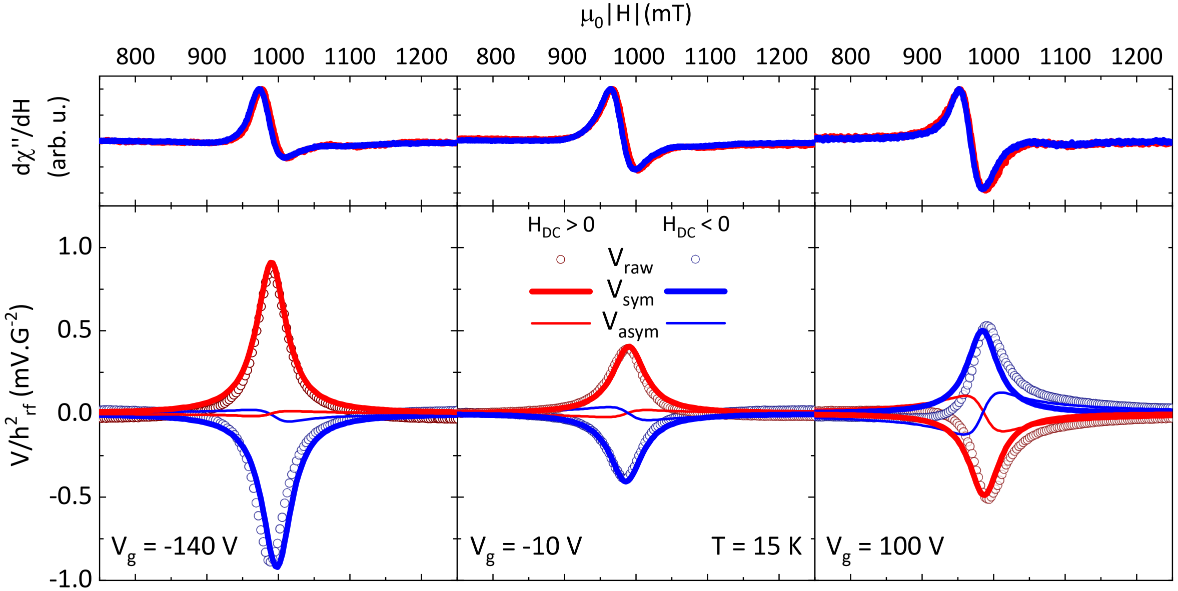
Spin-charge conversion in Al/STO 2DEGs

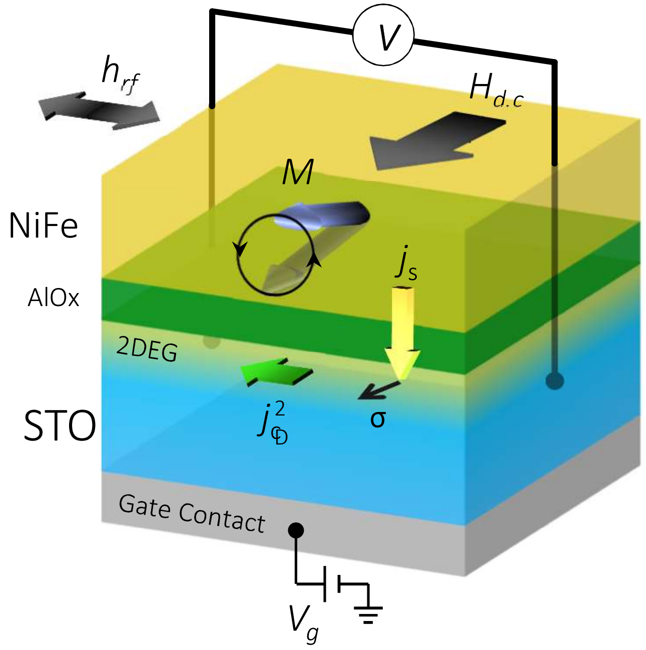


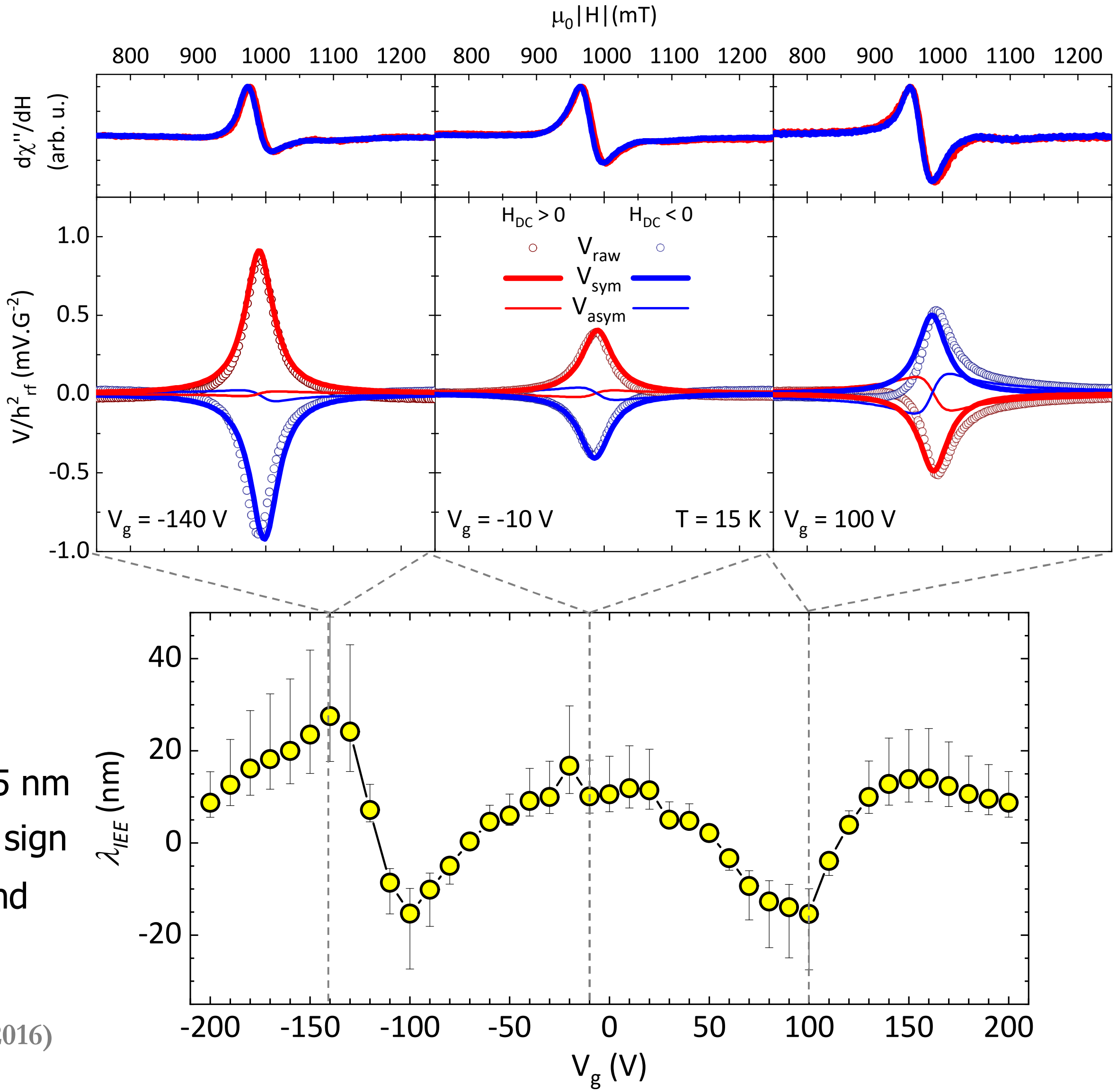


- Voltage peak almost entirely symmetric

➔ **Inverse Edelstein effect**

Spin-charge conversion in Al/STO 2DEGs

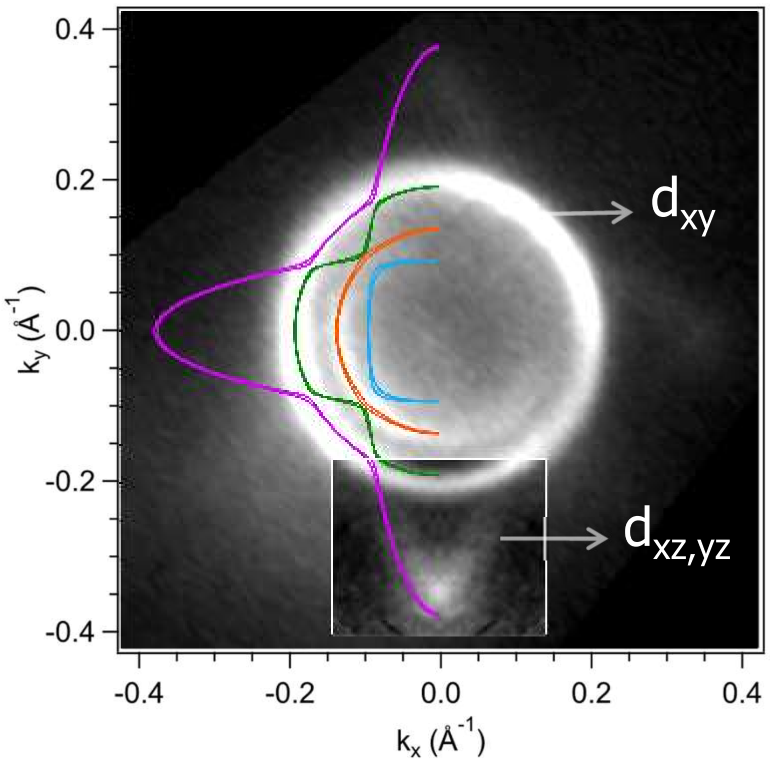




- ⊙ Voltage peak almost entirely symmetric
- ➔ **Inverse Edelstein effect**
- ⊙ Very large conversion effect with λ_{IEE}>25 nm
- ⊙ Strong gate dependence of amplitude & sign
- ⊙ Efficiency larger topological insulators and LAO/STO

Rojas-Sánchez et al., Nature Comm. 4, 2944 (2013)
Rojas-Sánchez et al., Phys. Rev. Lett. 116, 096602 (2016)
E. Lesne, MB et al., Nature Mater. 15, 1261 (2016)

Electronic structure of STO 2DEGs



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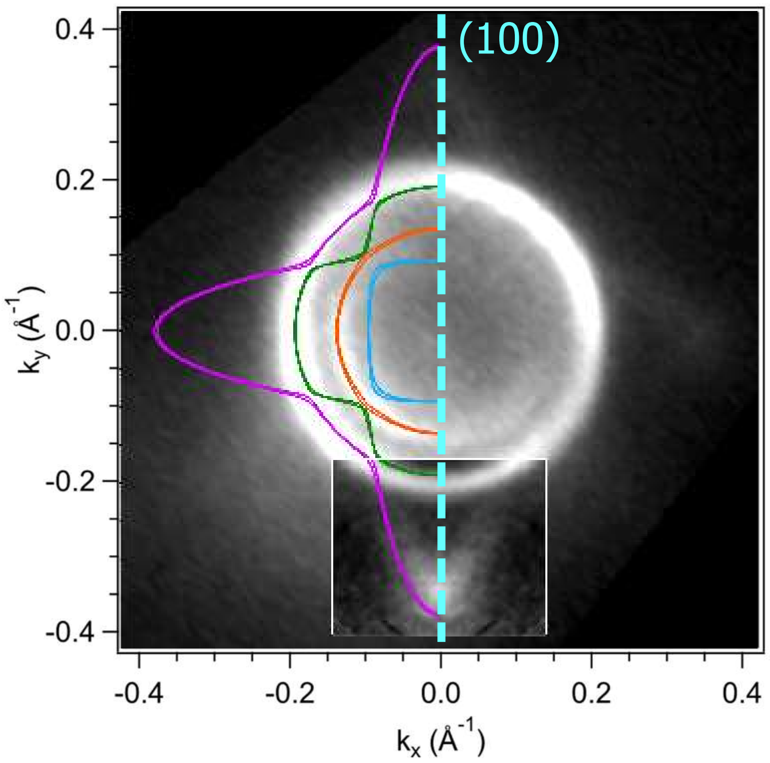

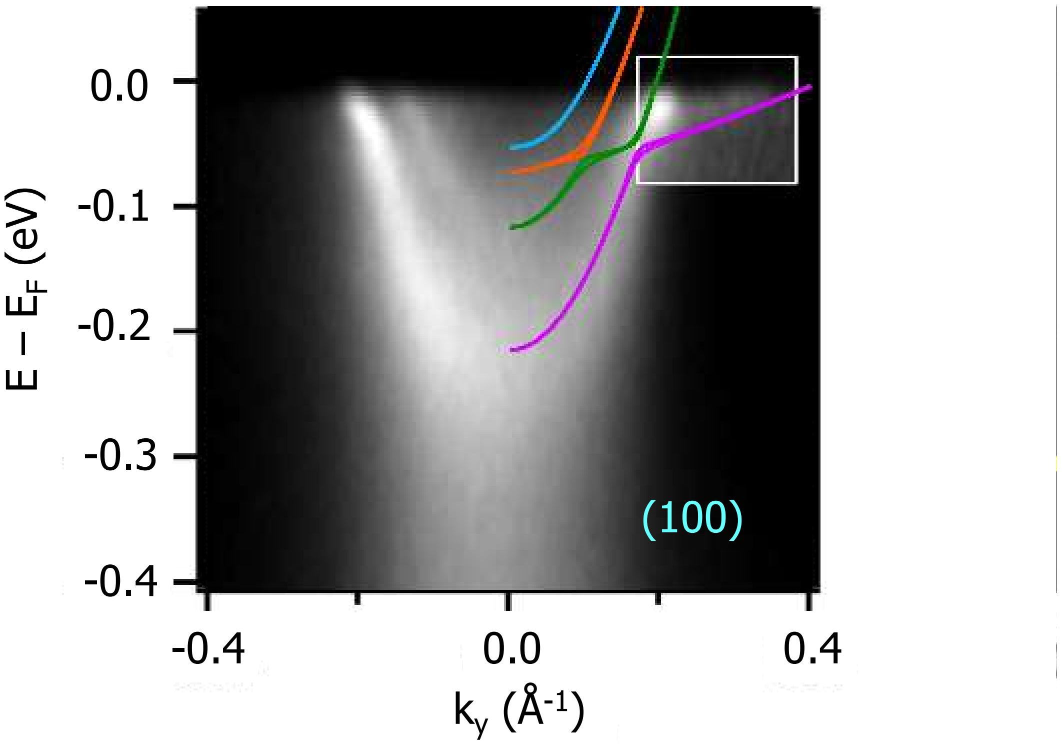

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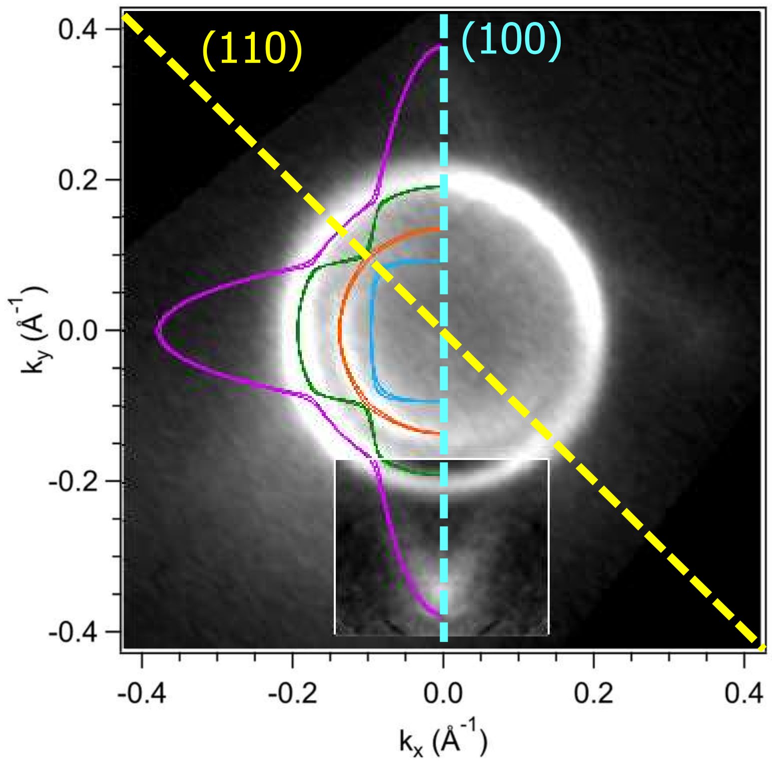

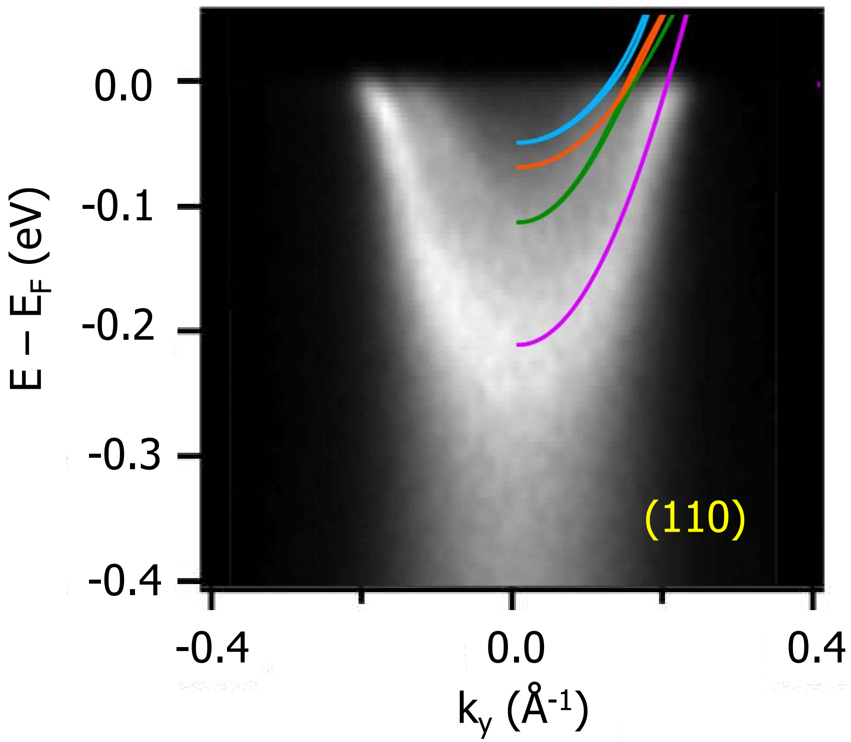

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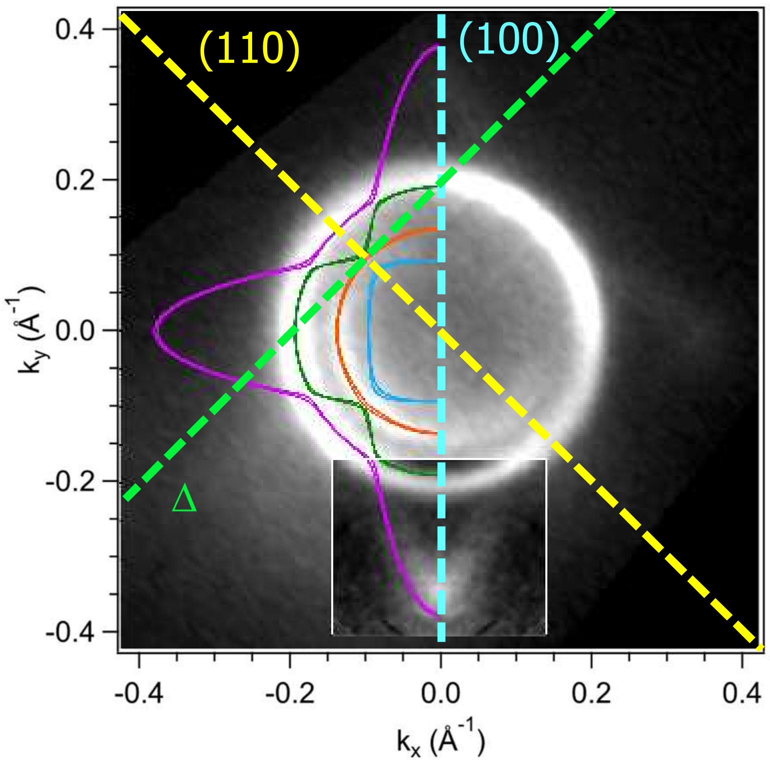

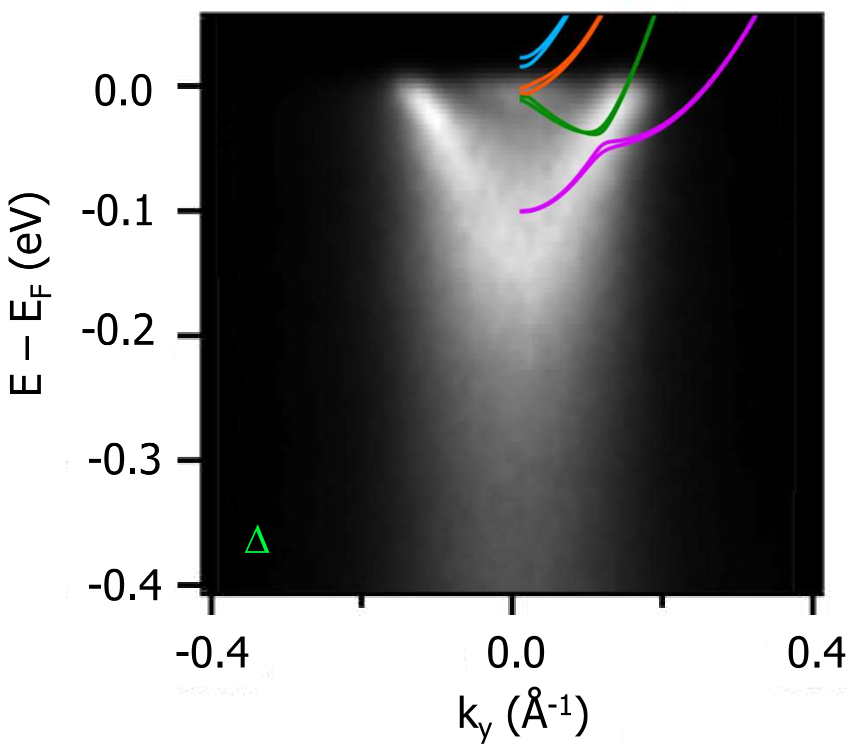

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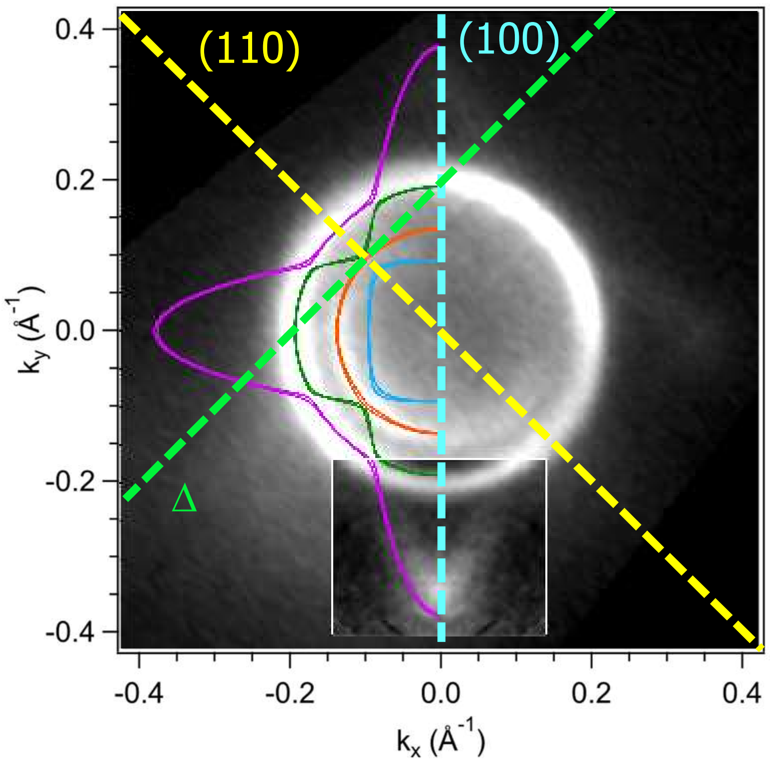
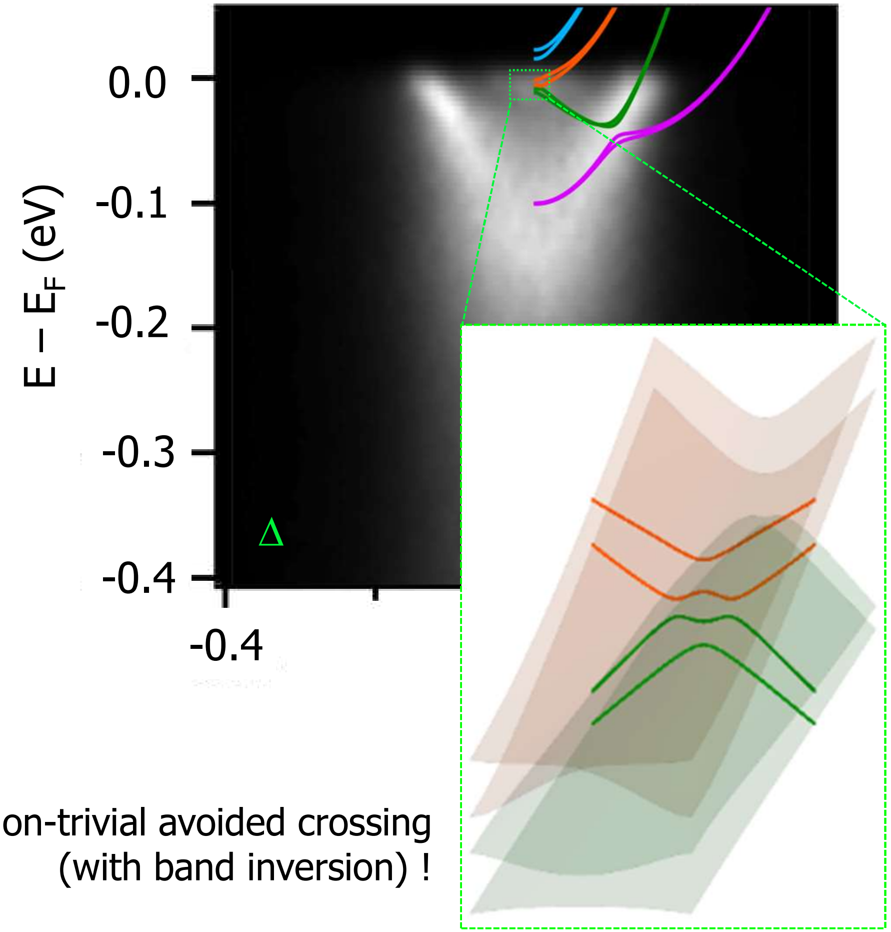
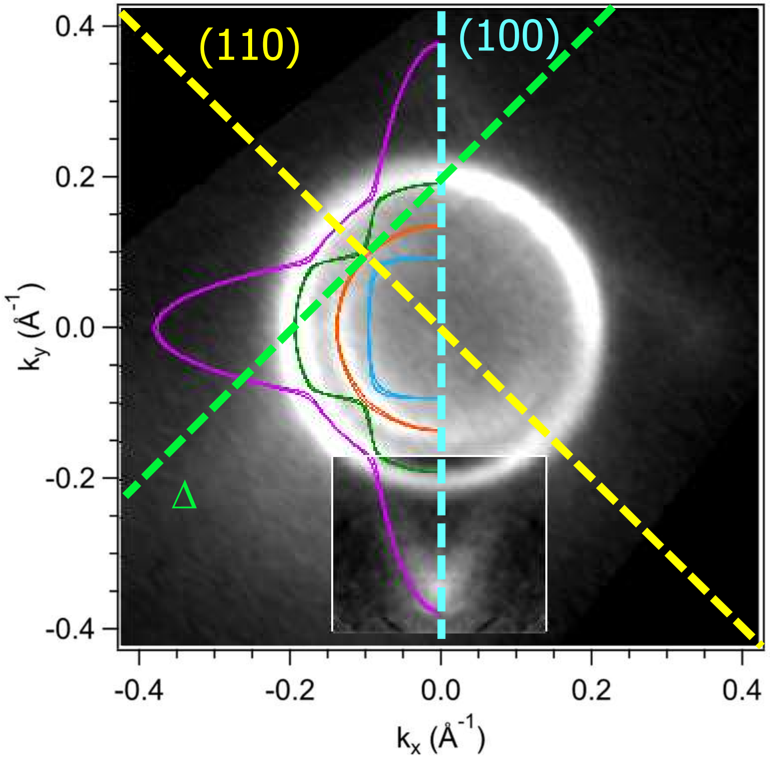


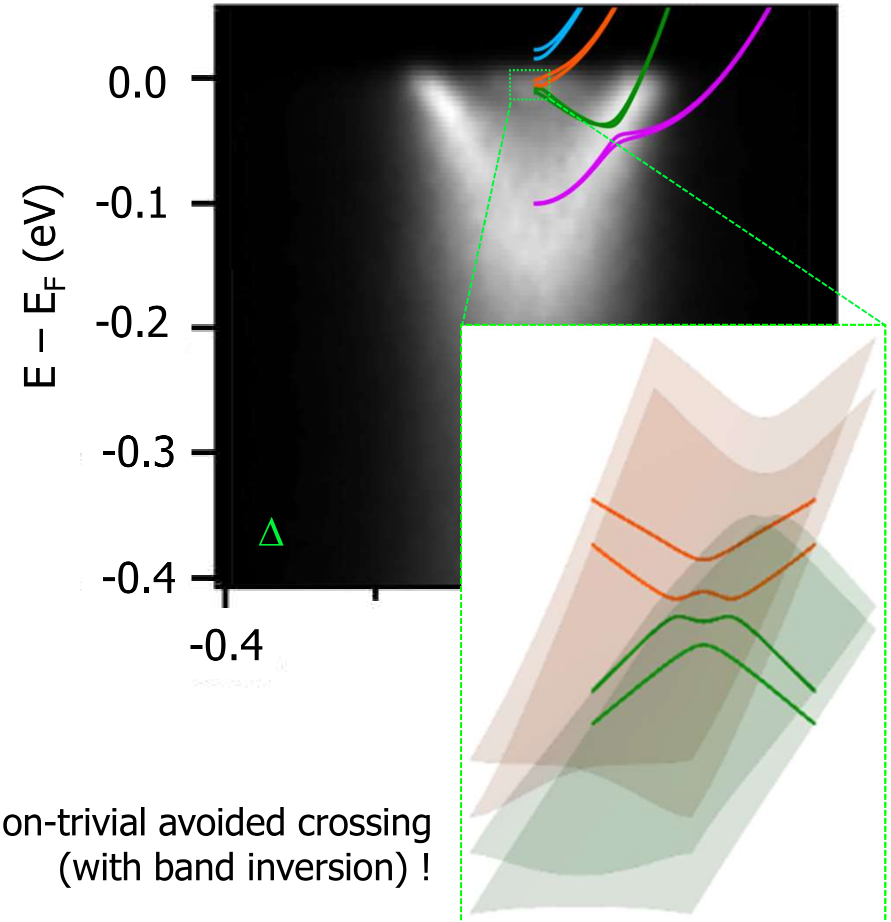


Topologically non-trivial avoided crossing
(with band inversion) !

M. Vivek et al, PRB 95, 165117 (2017)

Electronic structure of STO 2DEGs





Topologically non-trivial avoided crossing
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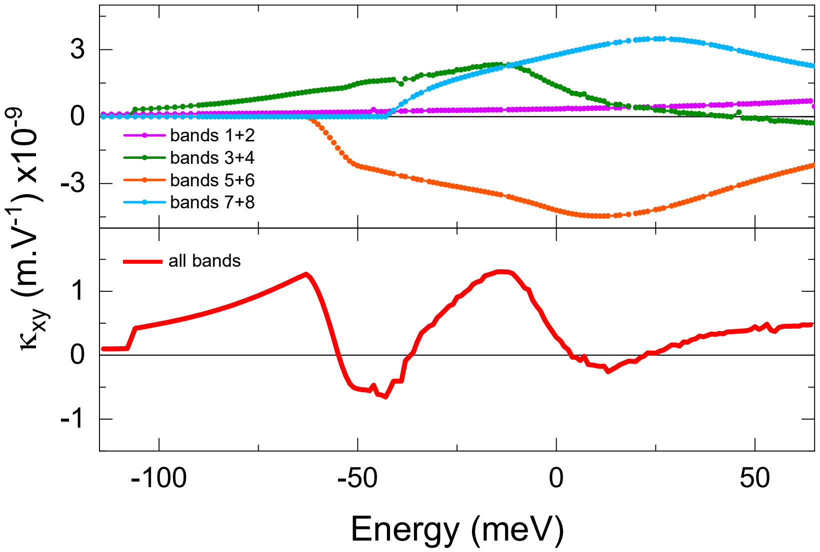
Electronic structure of STO 2DEGs determined by 4 ingredients

1. Splitting of d_{xy} and $d_{xz/yz}$ bands by confinement potential
2. Sub-bands dues to quantum confinement
3. Spin-orbit coupling
4. Orbital mixing

Vaz, MB et al, Nature Mater. 18, 1187 (2019)

Energy dependence of the Edelstein effect



D.C. Vaz, MB et al, Nature Mater. 18, 1187 (2019)

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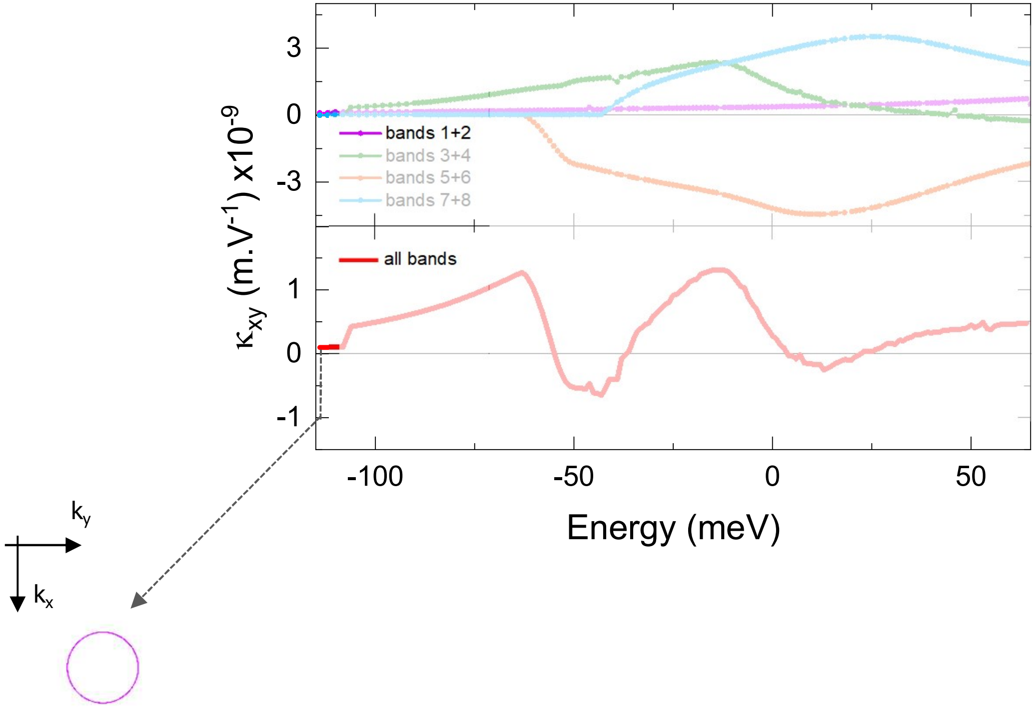
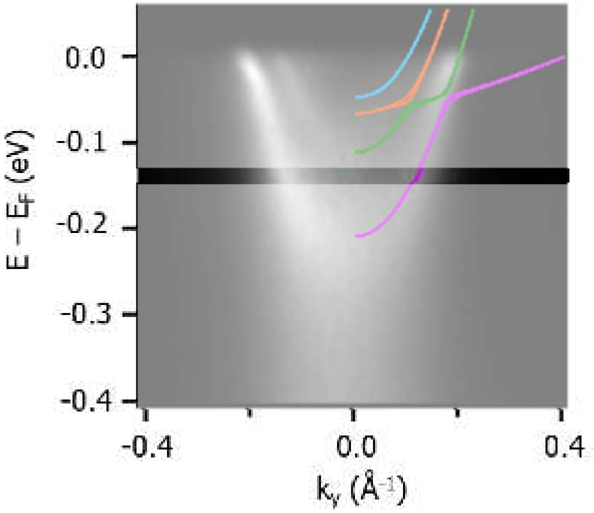


➊

$\lambda_{IEE} \sim 0$



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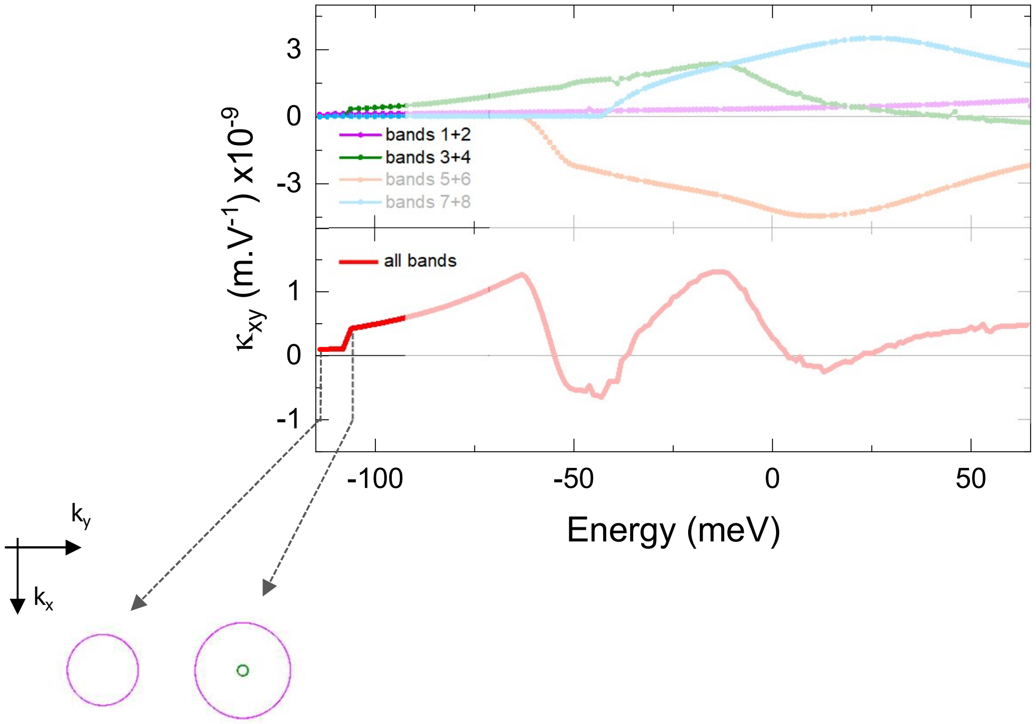
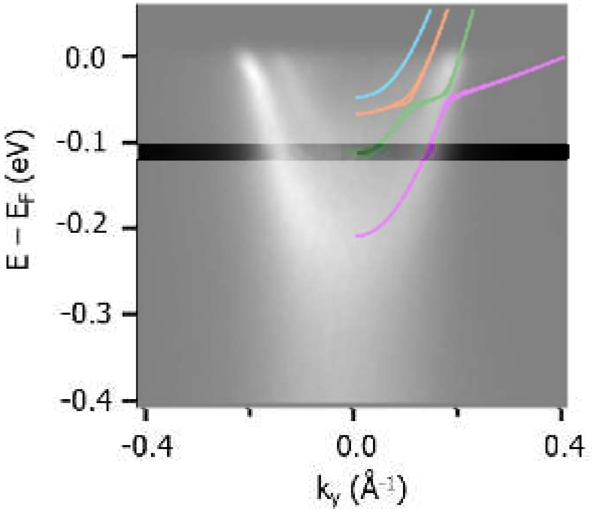


① ②

$\lambda_{IEE} \sim 0$ $\lambda_{IEE} > 0$



D.C. Vaz, MB et al, Nature Mater. 18, 1187 (2019)

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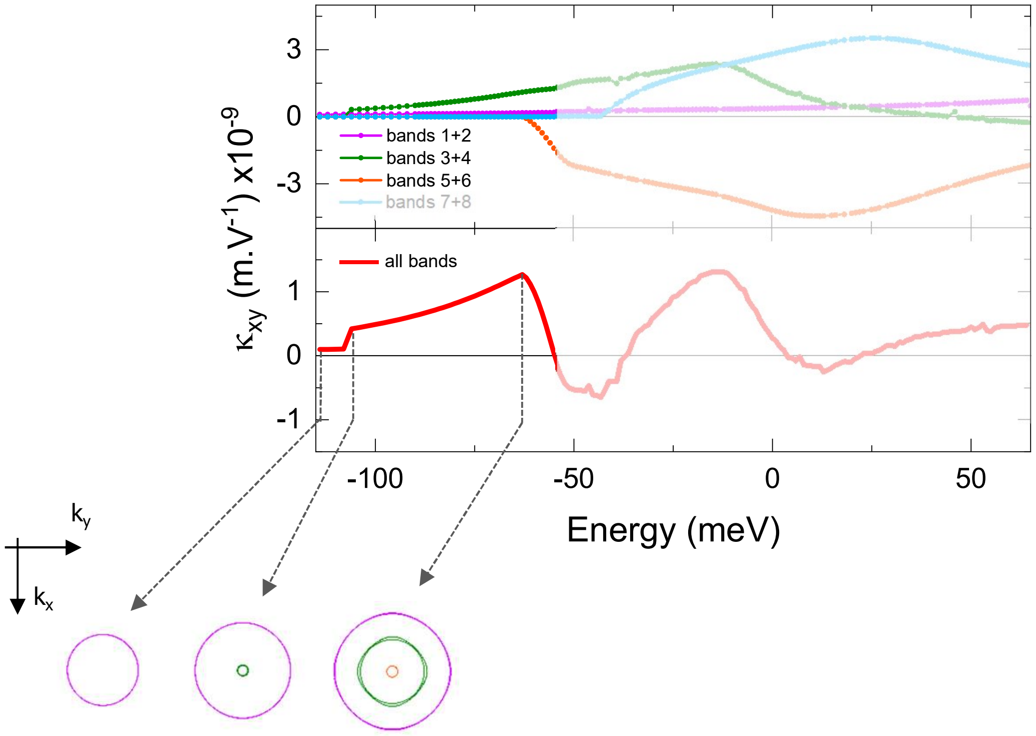
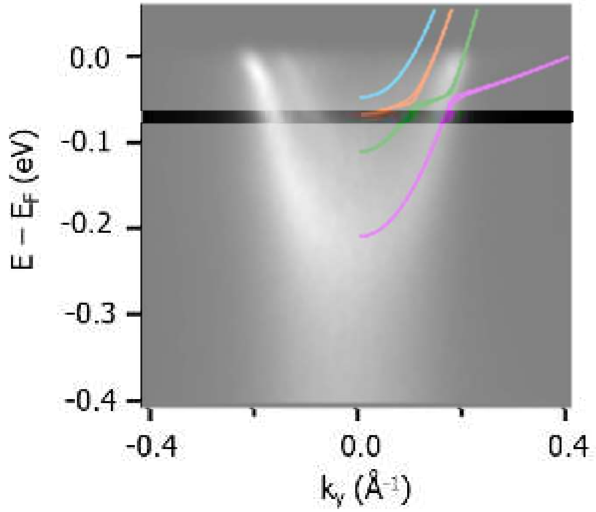


➊ ➋ ➌

$\lambda_{IEE} \sim 0$ **$\lambda_{IEE} > 0$** **$\lambda_{IEE} > 0$**



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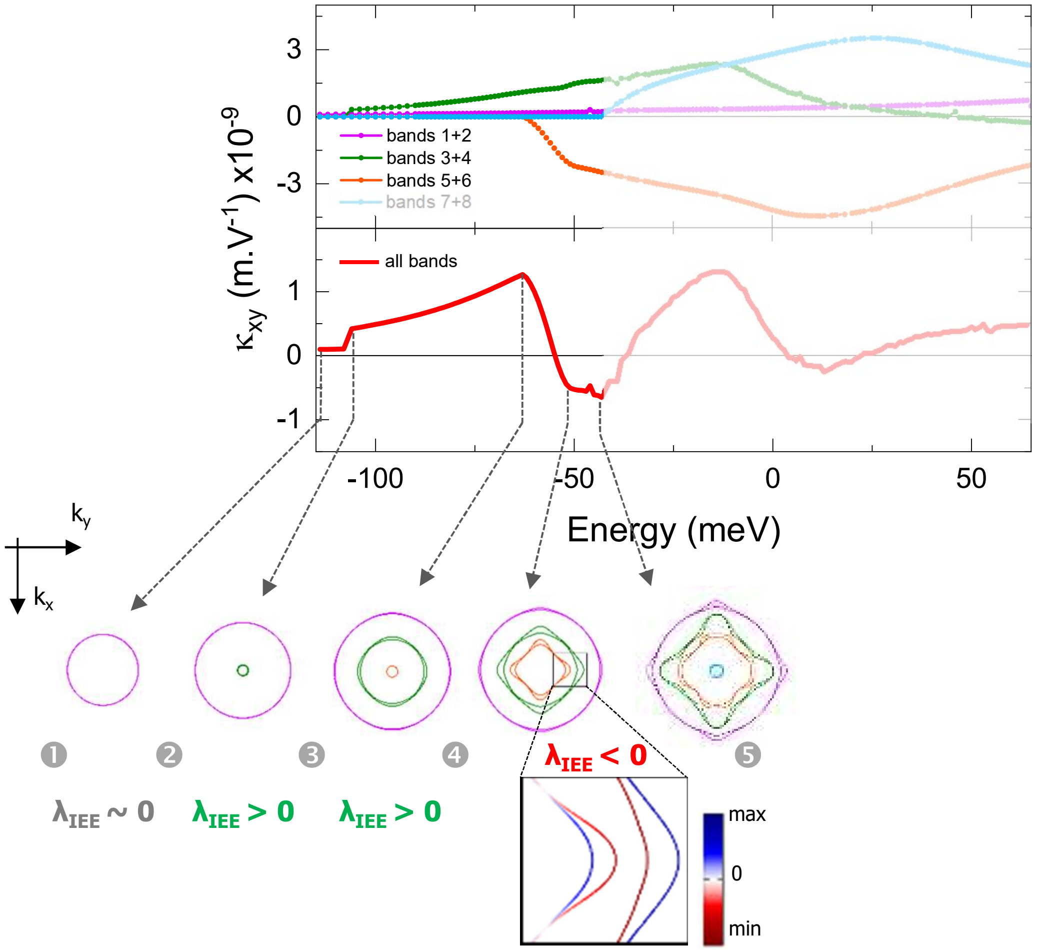

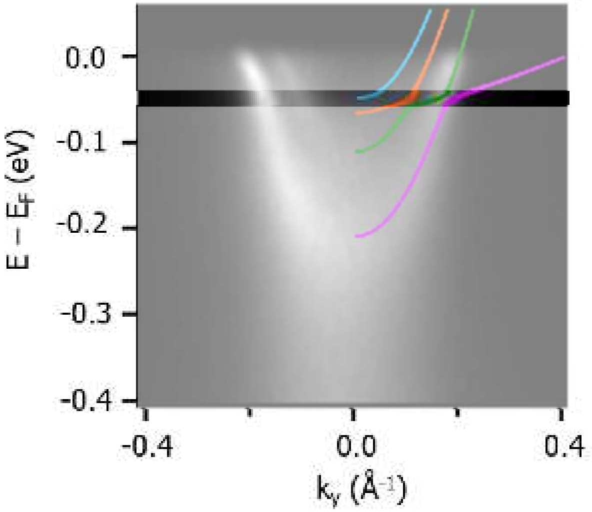

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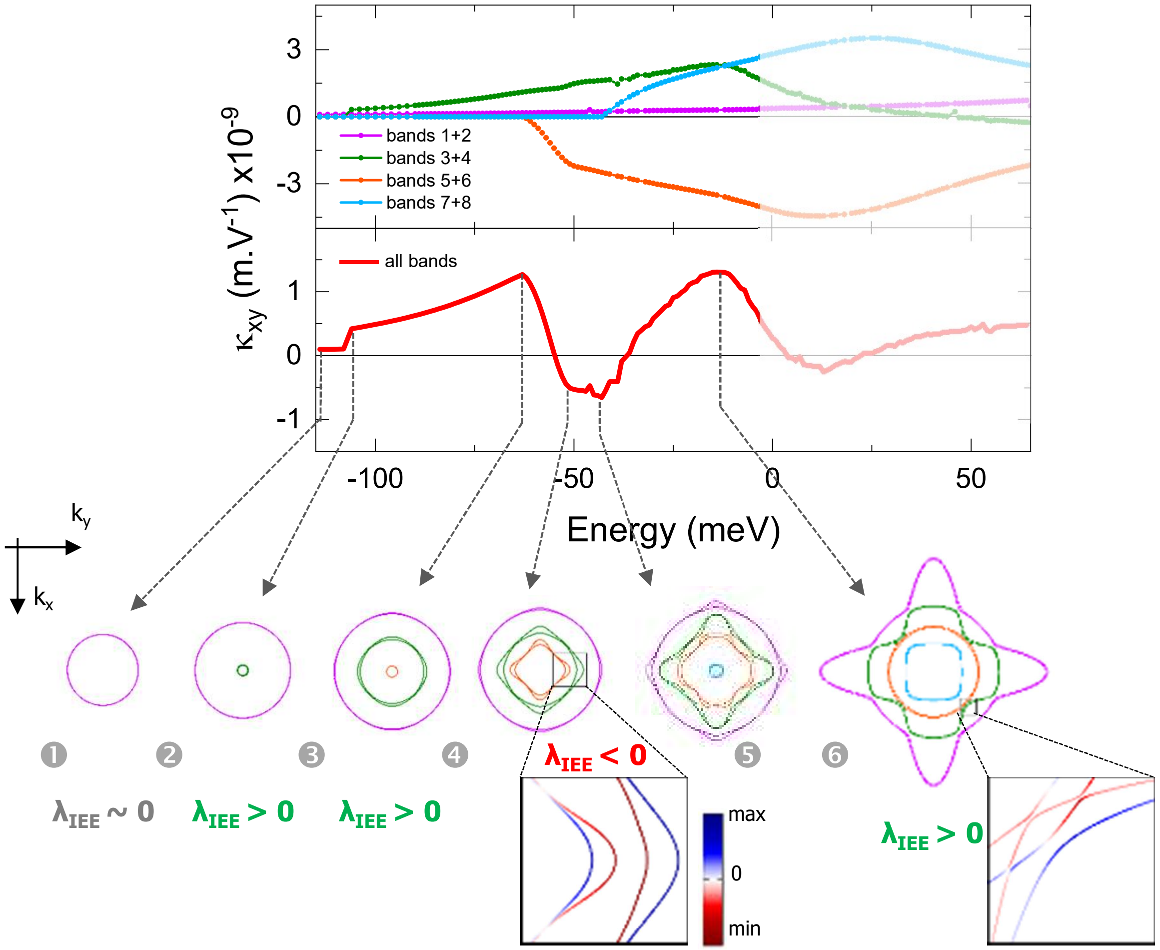

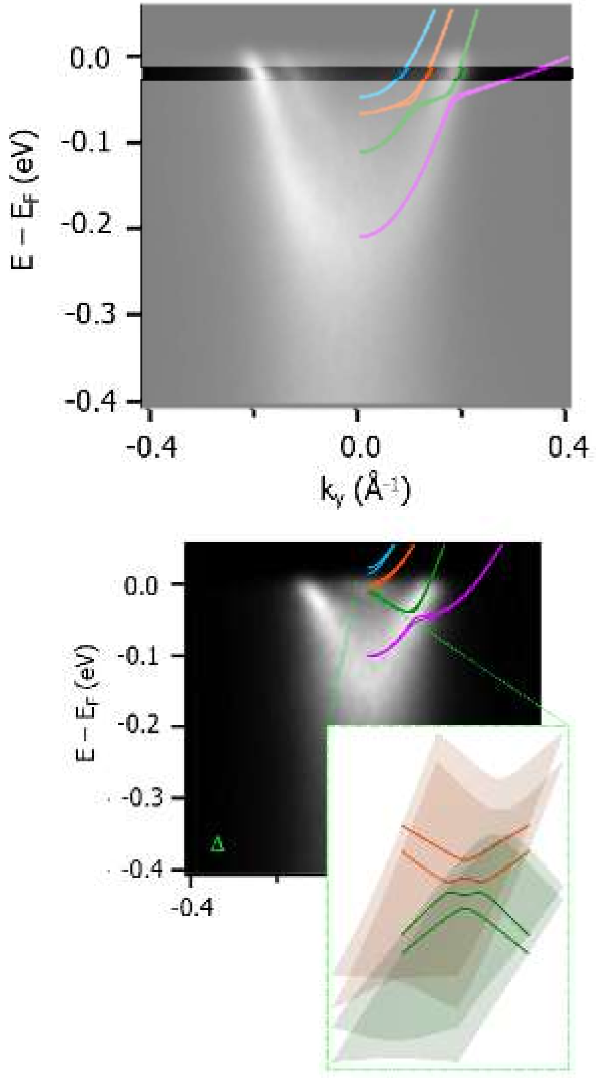

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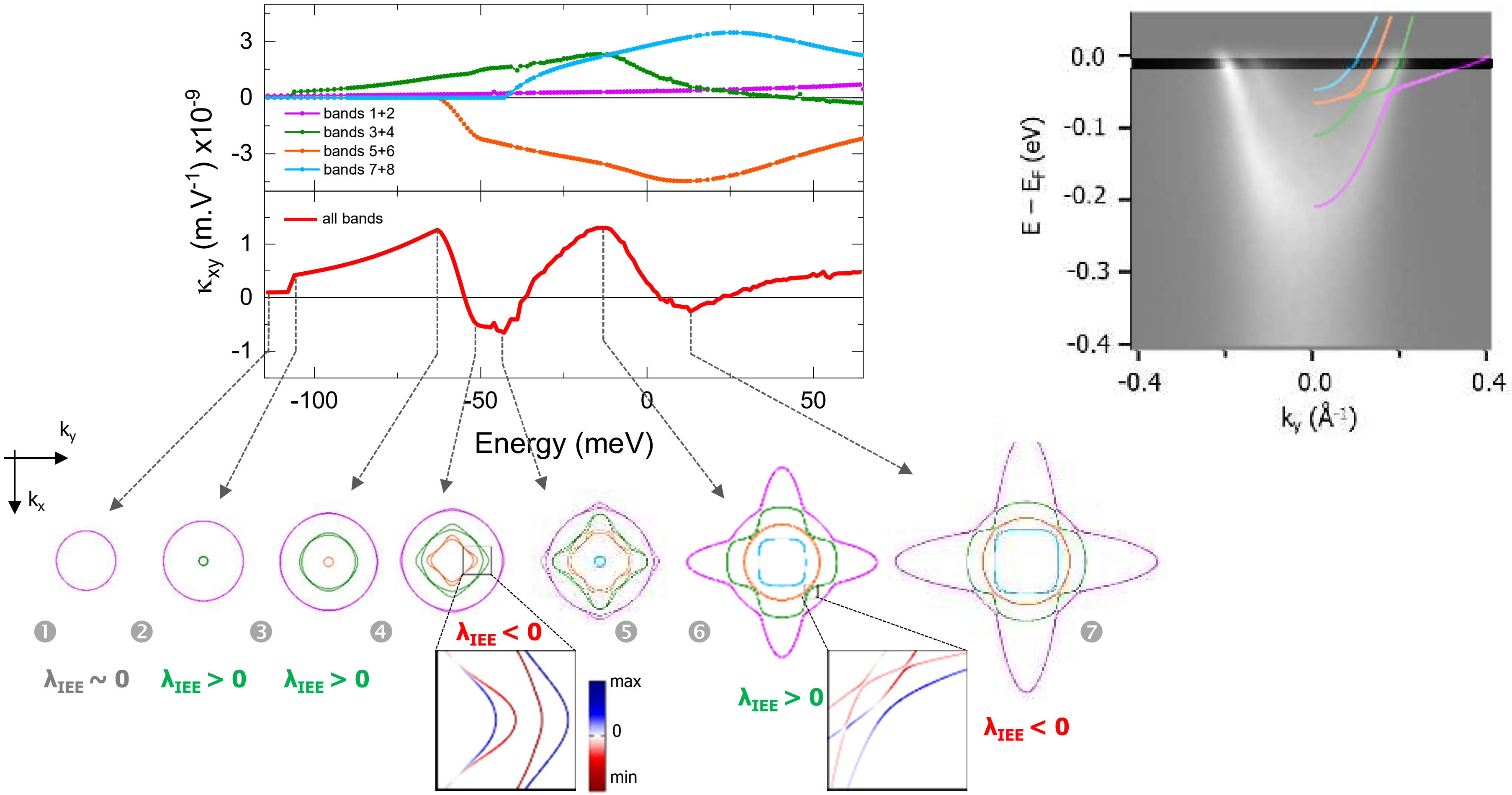
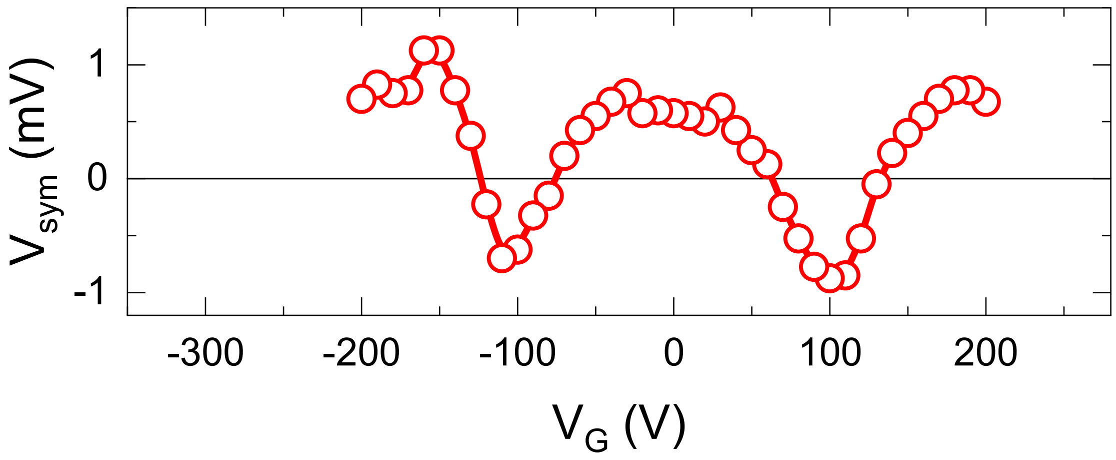
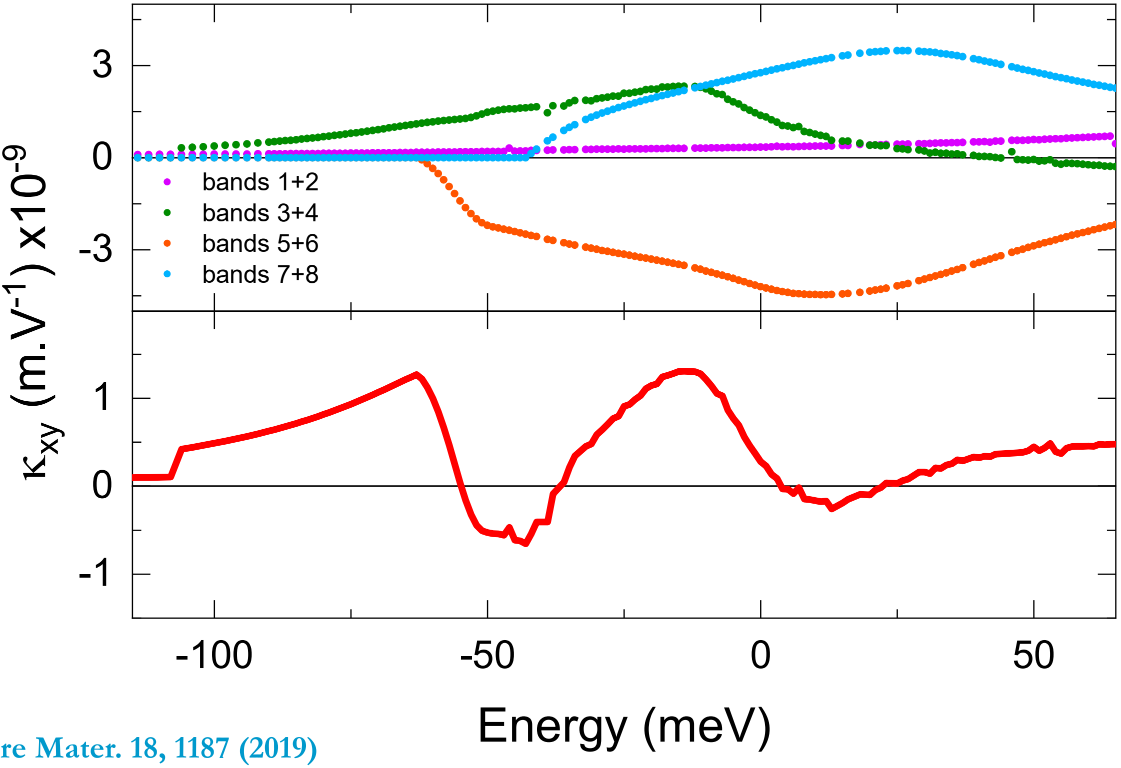


D.C. Vaz, MB et al, Nature Mater. 18, 1187 (2019)

Comparison with experiments

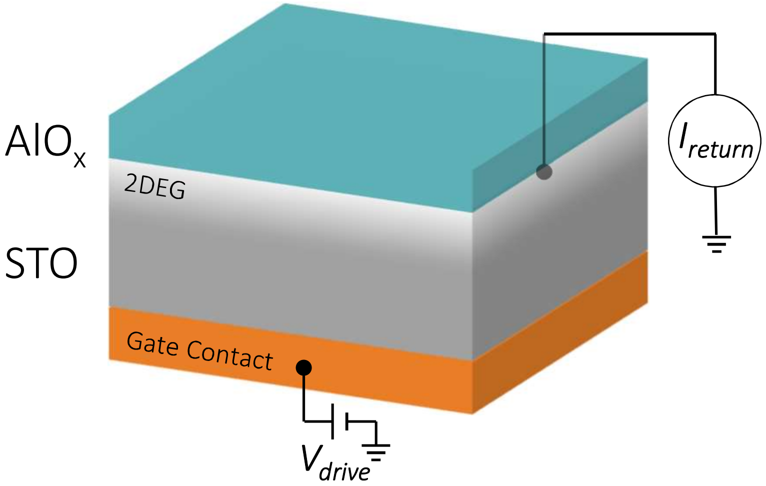




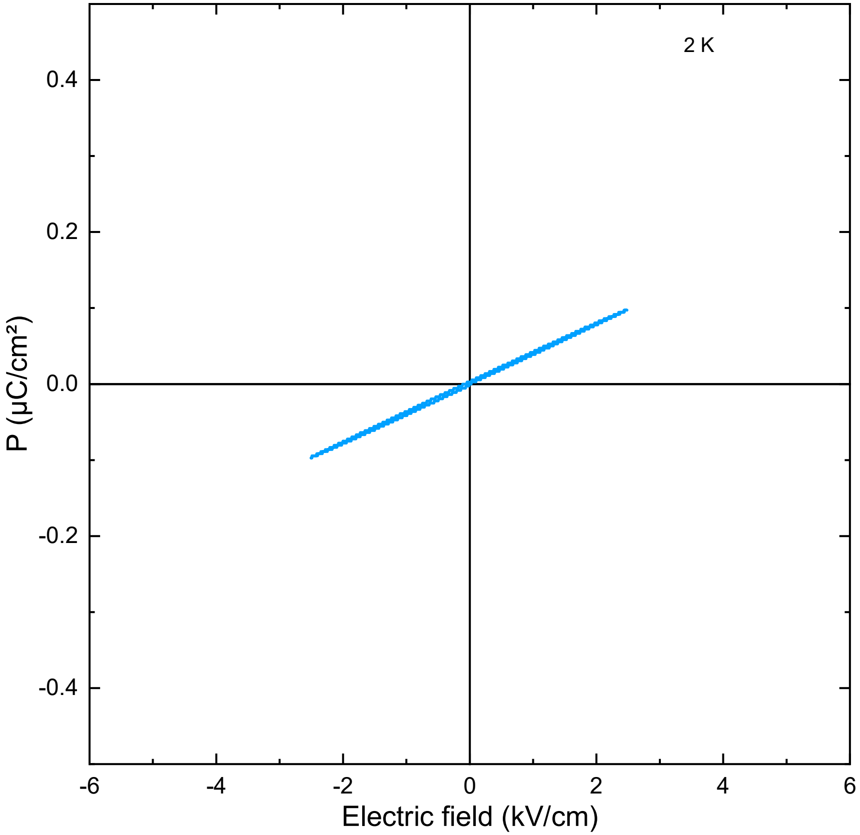
D.C. Vaz, MB et al, Nature Mater. 18, 1187 (2019)

E-field induced ferroelectricity in $SrTiO_3$

P(E) loops



$$I_r(t) = A_s \frac{dP_s}{dt} + C_s \frac{dV_d}{dt} + \frac{V_d}{R_s}$$



- After 2DEG formation by Al deposition, STO is thinned down to 200 µm, allowing to apply large electric fields

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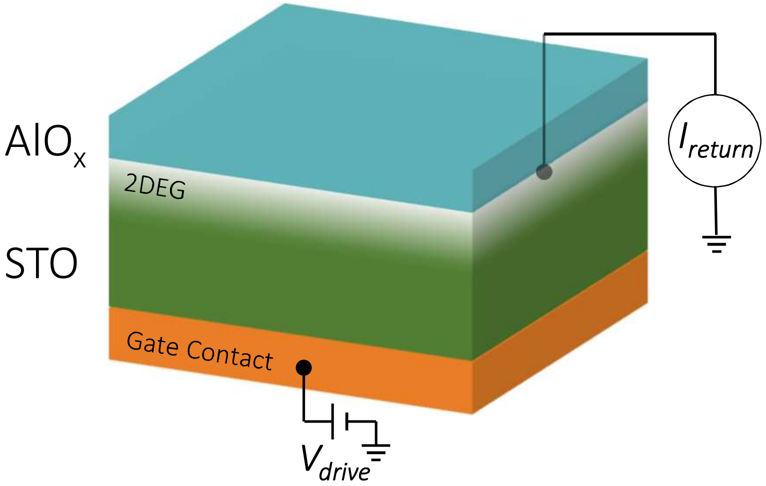

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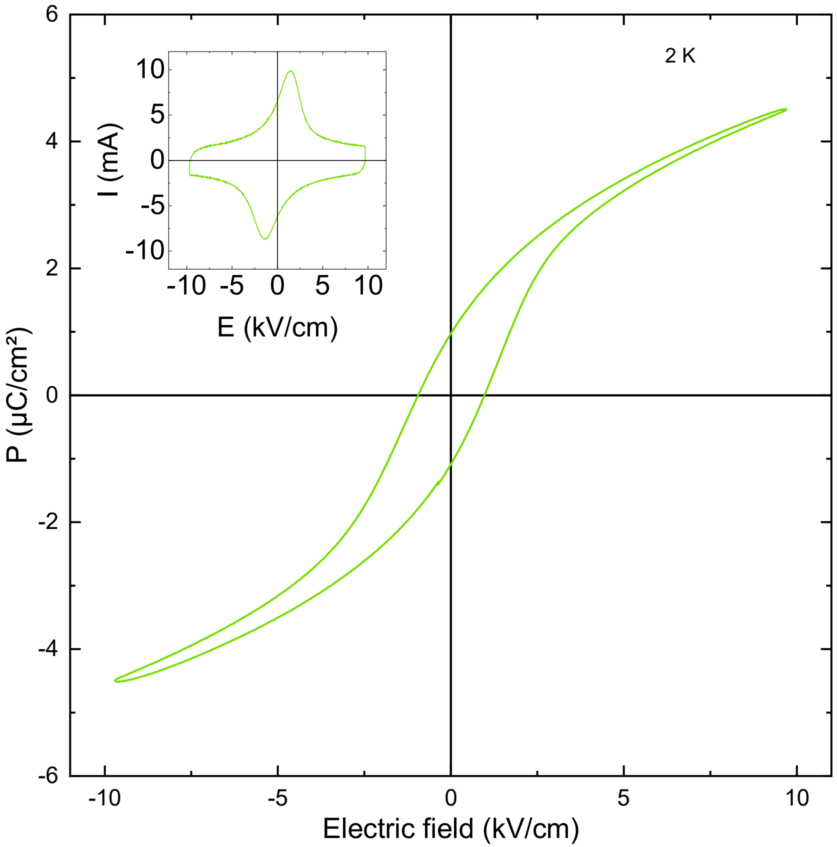
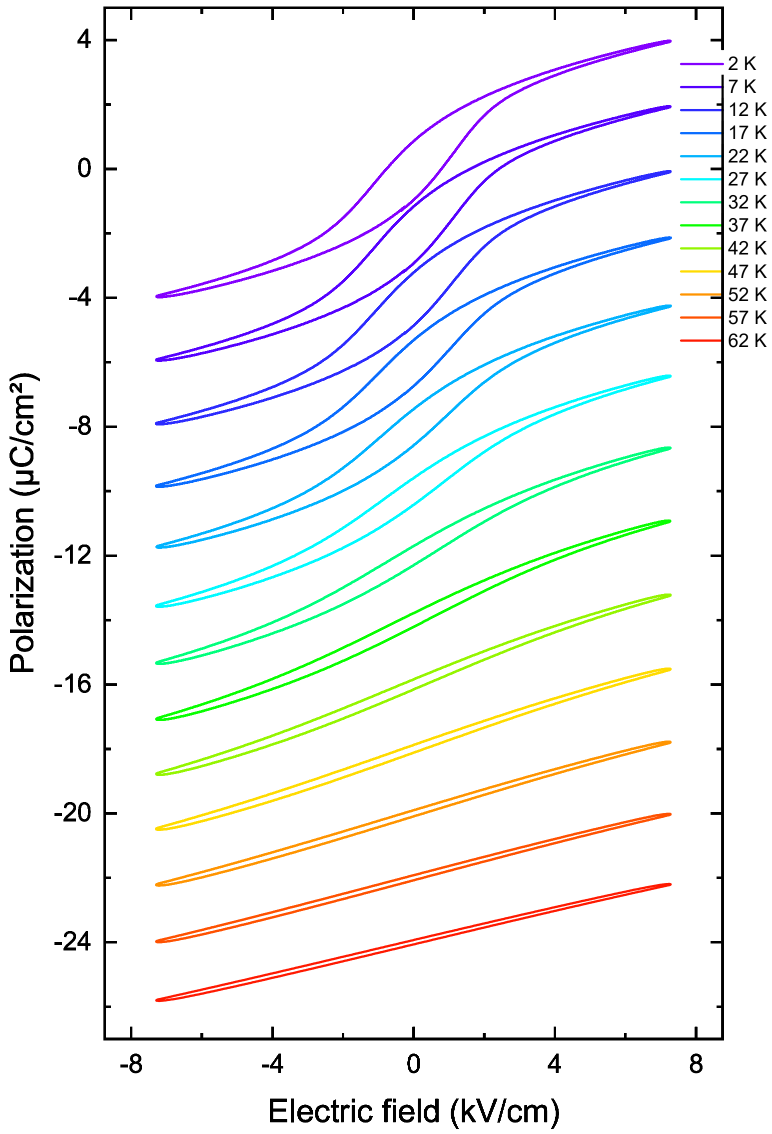
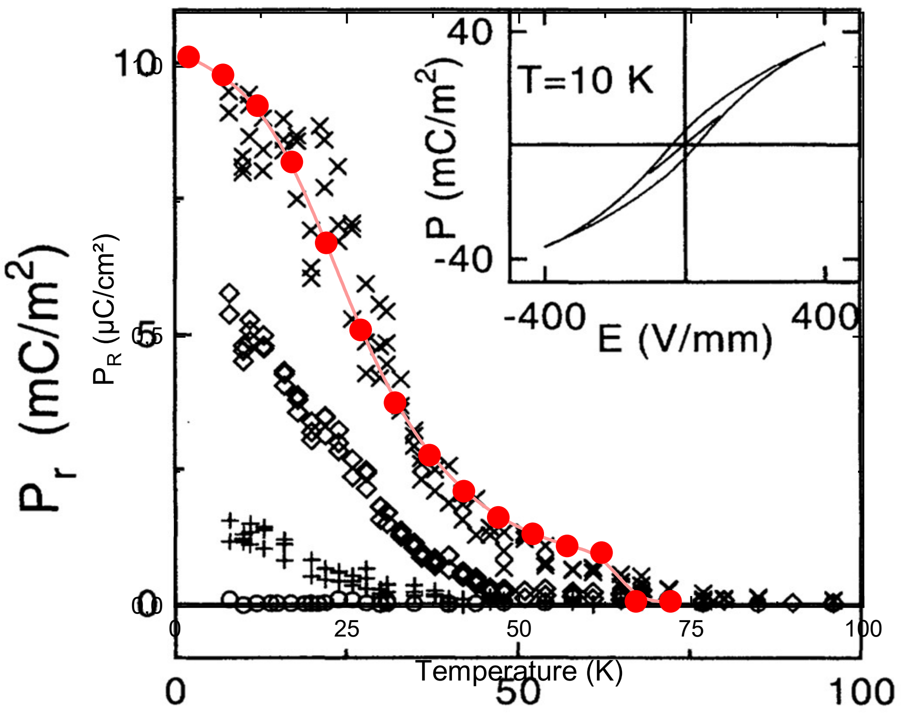


- After 2DEG formation by Al deposition, STO is thinned down to 200 µm, allowing to apply large electric fields
- Open hysteresis loops appear beyond a threshold E field, indicative of a **ferroelectric-like state**

E-field induced ferroelectricity in $SrTiO_3$

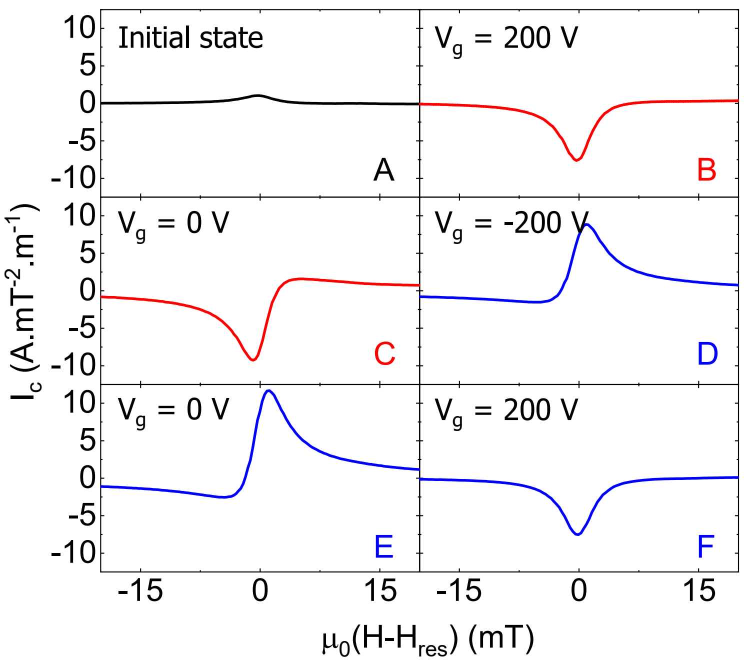


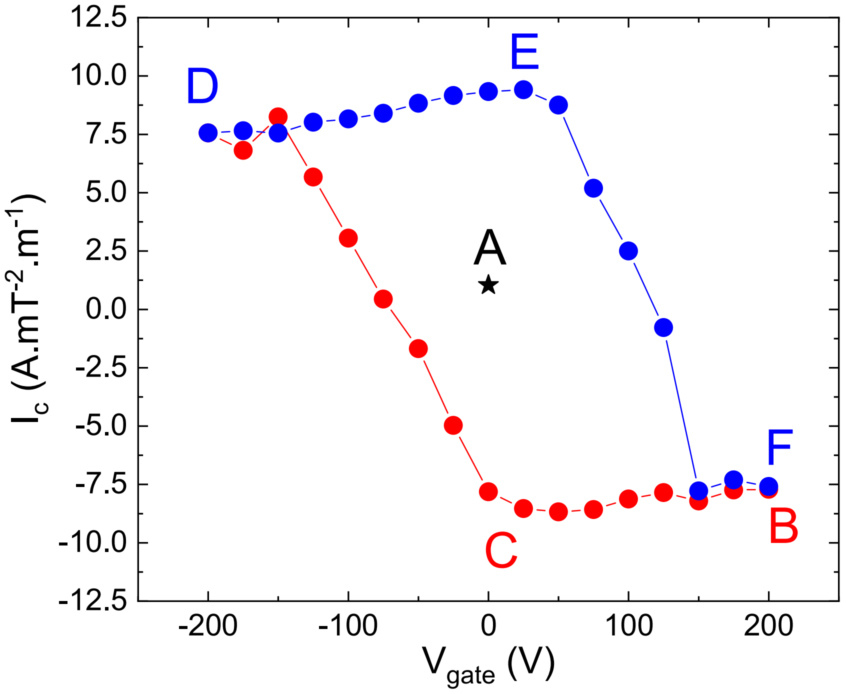


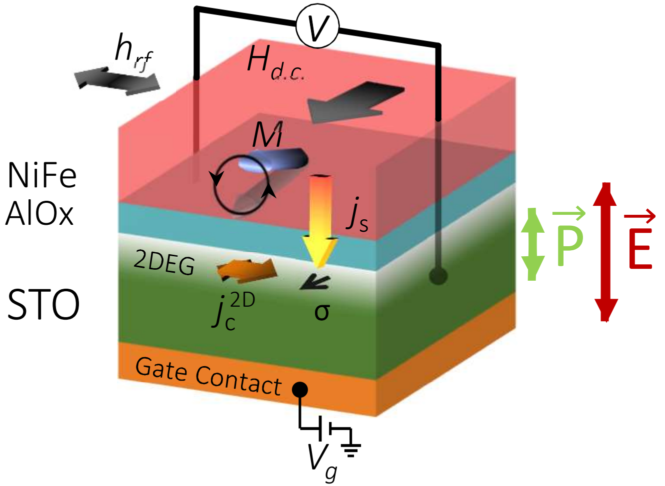
- Ferroelectric state disappears around 50 K

H. Gränicher, Helvetica Phys. Acta 29, 210 (1956) ;
J. Hemberger et al PRB 52, 13159 (1995) ;
J. Sidoruk, J. et al. JPCM 22, 235903 (2010) ;
H. Manaka, JPSJ. 86, 114702 (2017).

Spin-charge conversion in ferroelectric Al/STO 2DEGs





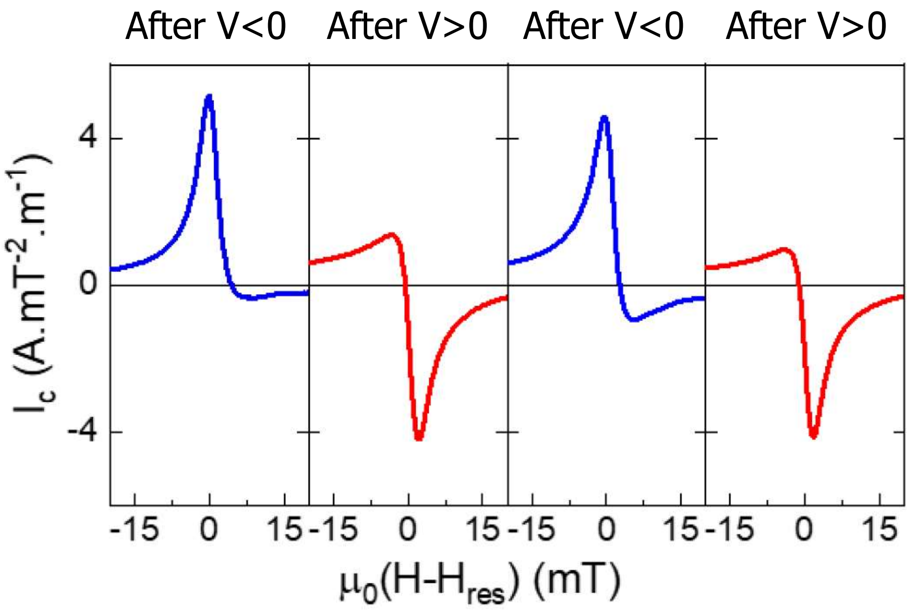


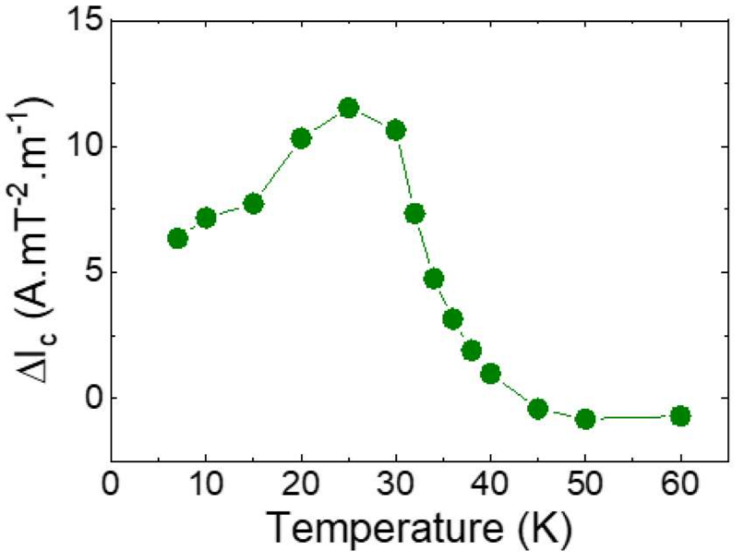
⊙ Charge current production by the inverse Edelstein effect shows a hysteretic dependence with the electric field, with two remanent states corresponding to positive and negative charge currents

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

manuel.bibes@cnrs-thales.fr

Spin-charge conversion in ferroelectric Al/STO 2DEGs



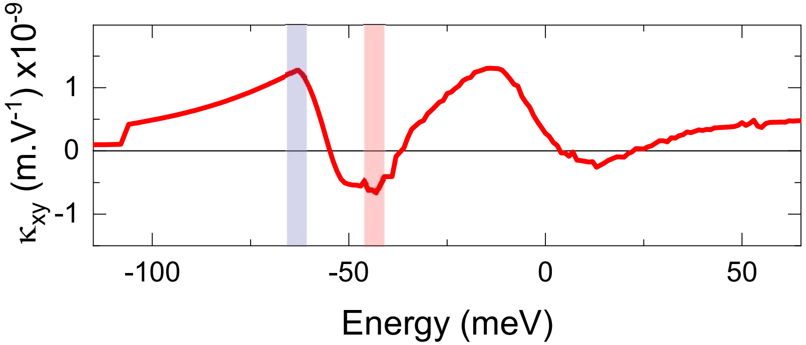


P. Noël, MB et al., Nature 580, 483 (2020)

- ⊙ Effect is reversible and disappears around 40-50 K just as the remanent polarization in the P-E loops
- ⊙ Strong indication that the electrical switching of spin-charge conversion is driven by ferroelectricity
- ⊙ **Control of spin-charge conversion by ferroelectricity**
- ⊙ **Huge potential for low-power logic-in-memory architectures beyond CMOS**

Possible mechanism ?

- ⊙ Modulation of carrier density and E_F by polarization direction
- ⊙ P_{up} : higher E_F ➔ negative conversion
- ⊙ P_{dn} : lower E_F ➔ positive conversion



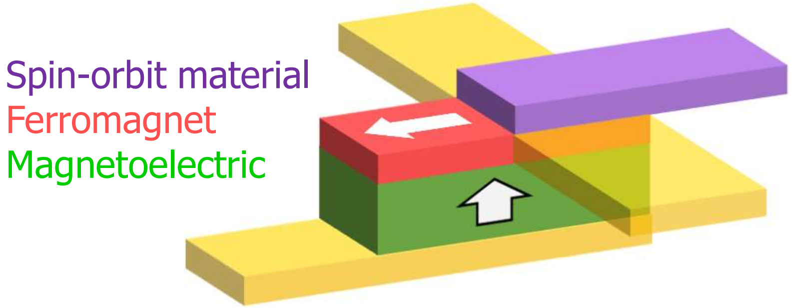
Outline

- ⦿ Ferroic orders, multiferroics and magnetoelectric coupling
- ⦿ Approaches for the electric-field control of magnetism
- ⦿ Electric-field control of spin-charge interconversion
- ➔ ⦿ Low-power spin-based devices for logic-in-memory

Magneto-electric spin-orbit transistor (MESO)

Original design by Intel

Manipatruni et al, Nature 565, 25 (2019)



Magneto-electric spin-orbit transistor (MESO)

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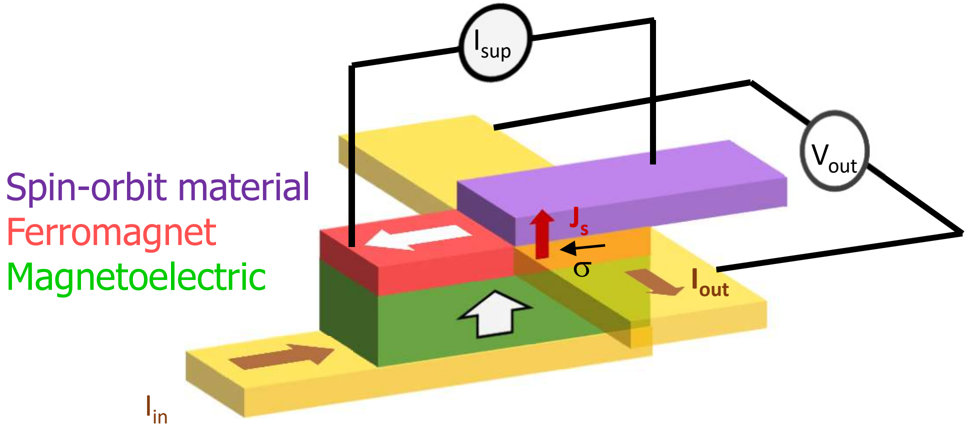

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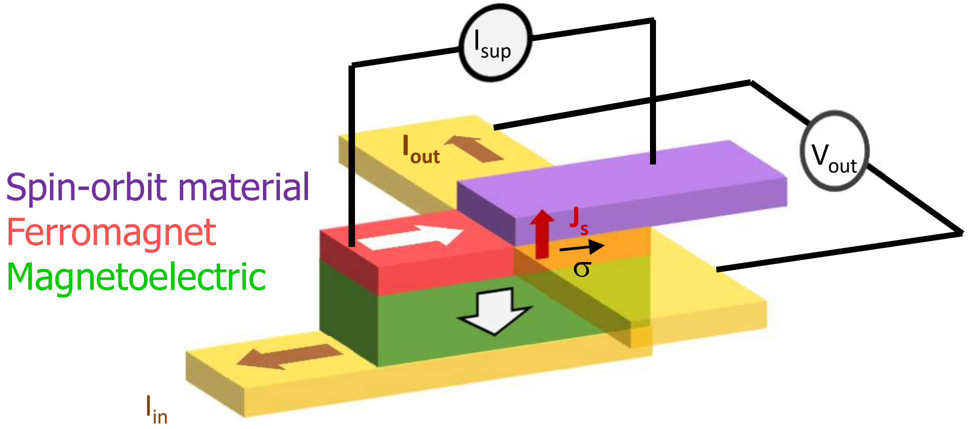

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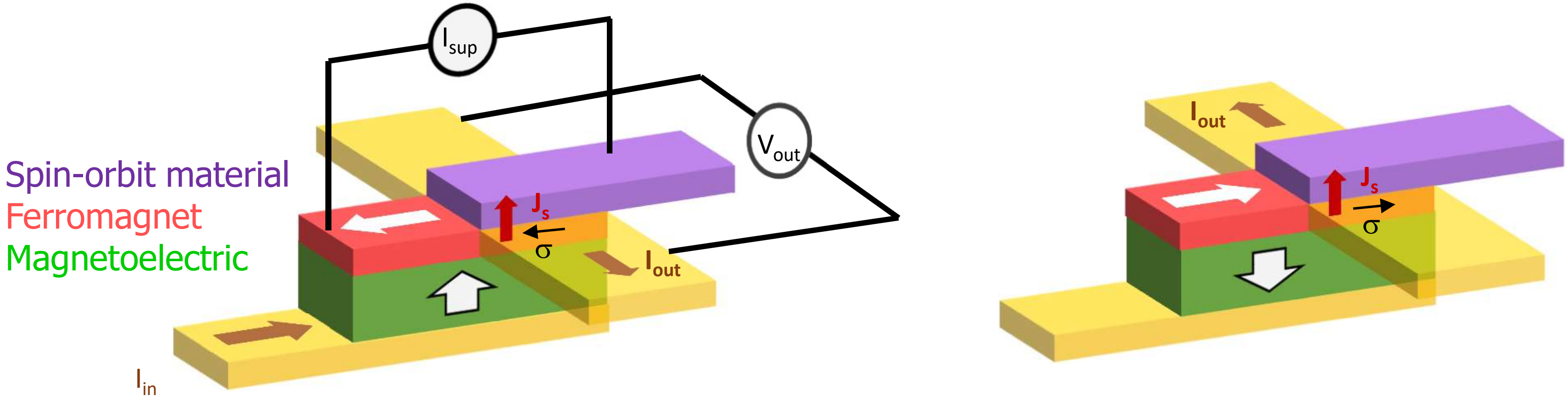

- New type of non-volatile spin-based transistor proposed by **Intel**
- Operates through **magnetoelectric coupling** (input) and **spin-orbit coupling** (output)
- Memory and logic embedded
- Scalable, concatenable, implementable as majority gate
- Low power (30 times less than CMOS for same size)
- 100 mV operating voltage (ME needs to switch with <100 mV ; SOC must generate >100 mV)

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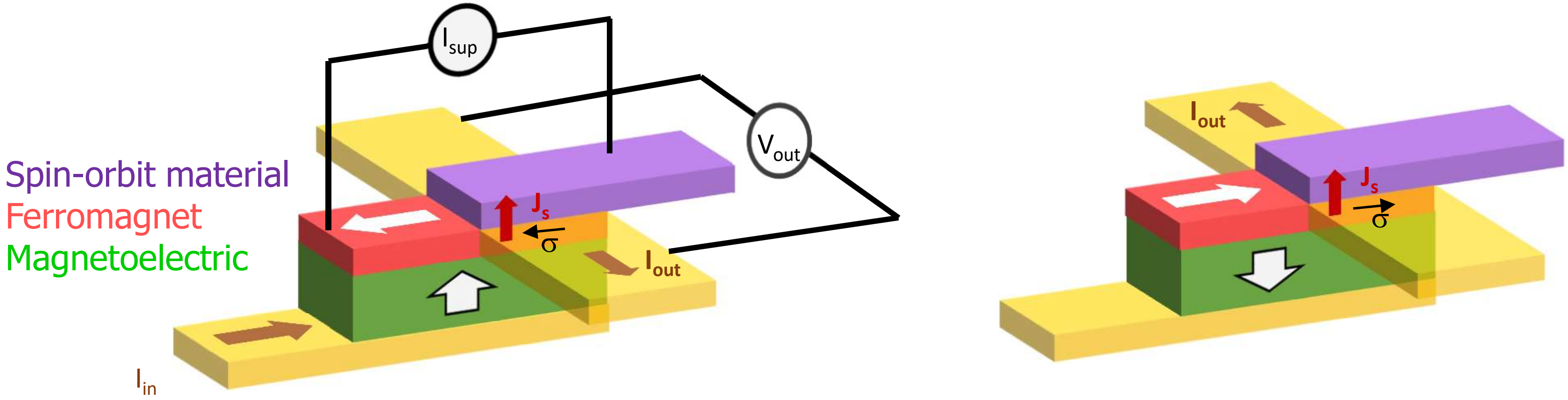
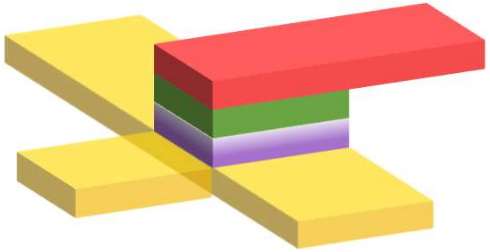


Alternative design CNRS/Thales/Spintec

MB et al, patent FR18 74319 ; Nature 580, 483 (2020)



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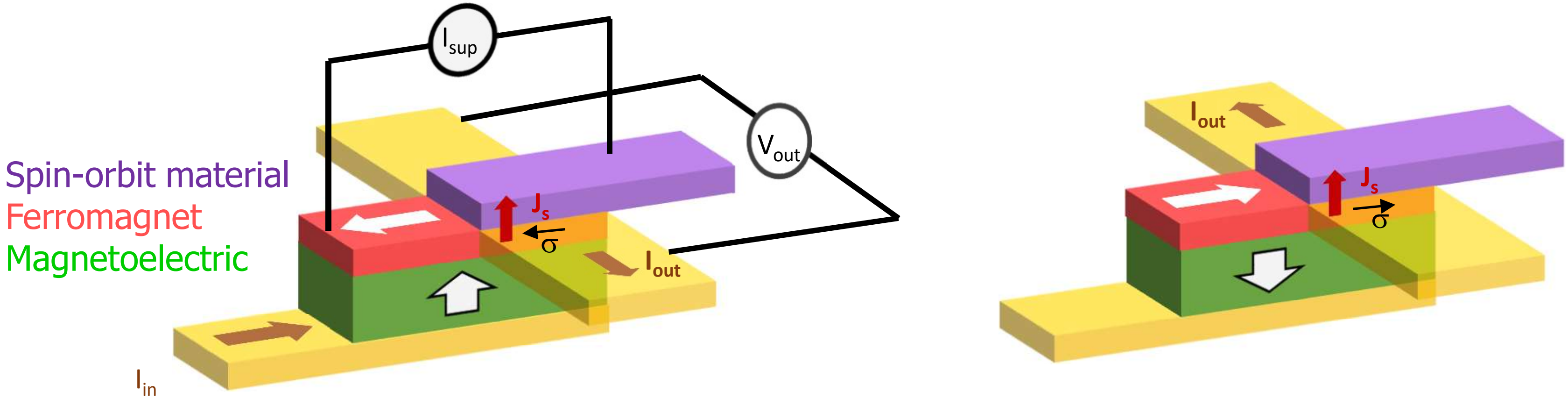

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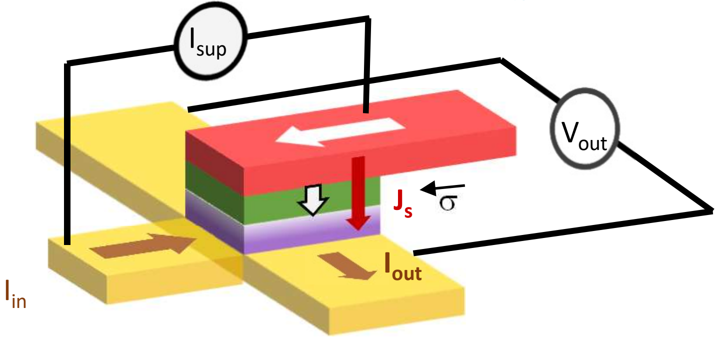

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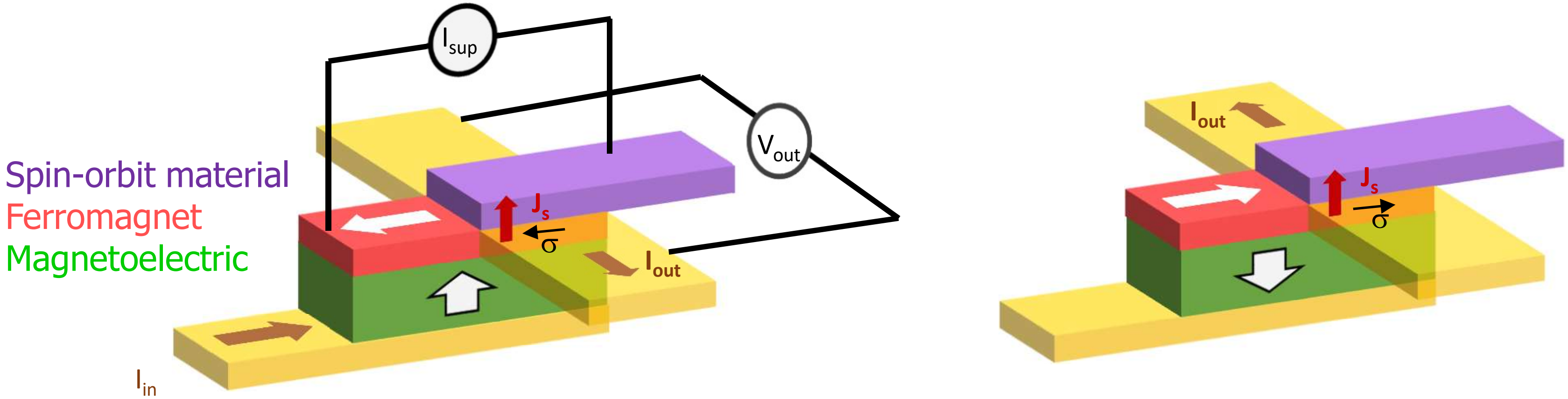

Spin-orbit material
Ferromagnet
Magnetoelectric

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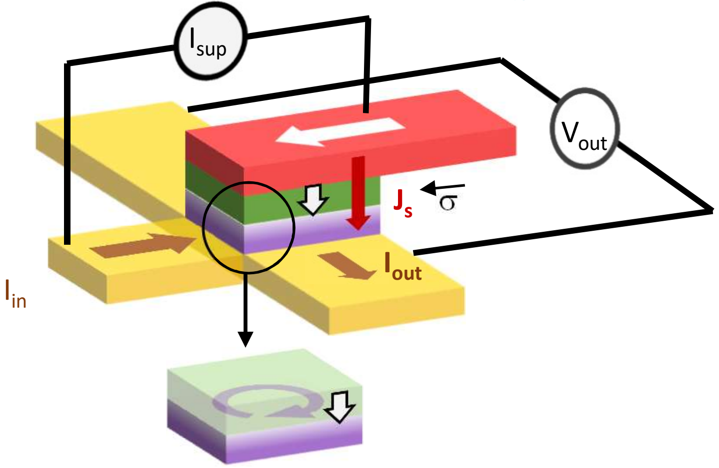
MB et al, patent FR18 74319 ; Nature 580, 483 (2020)



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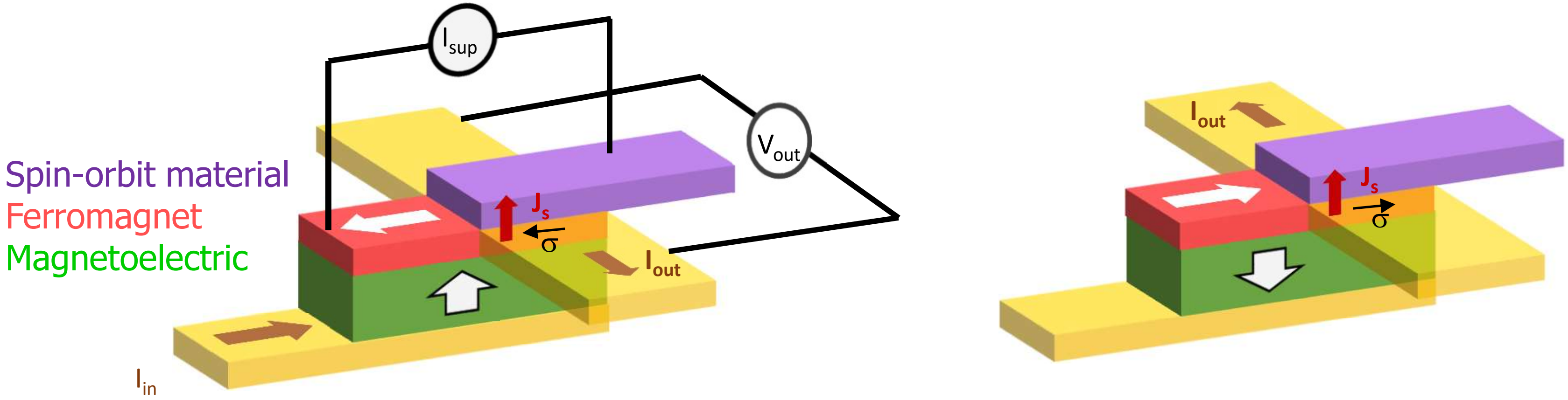

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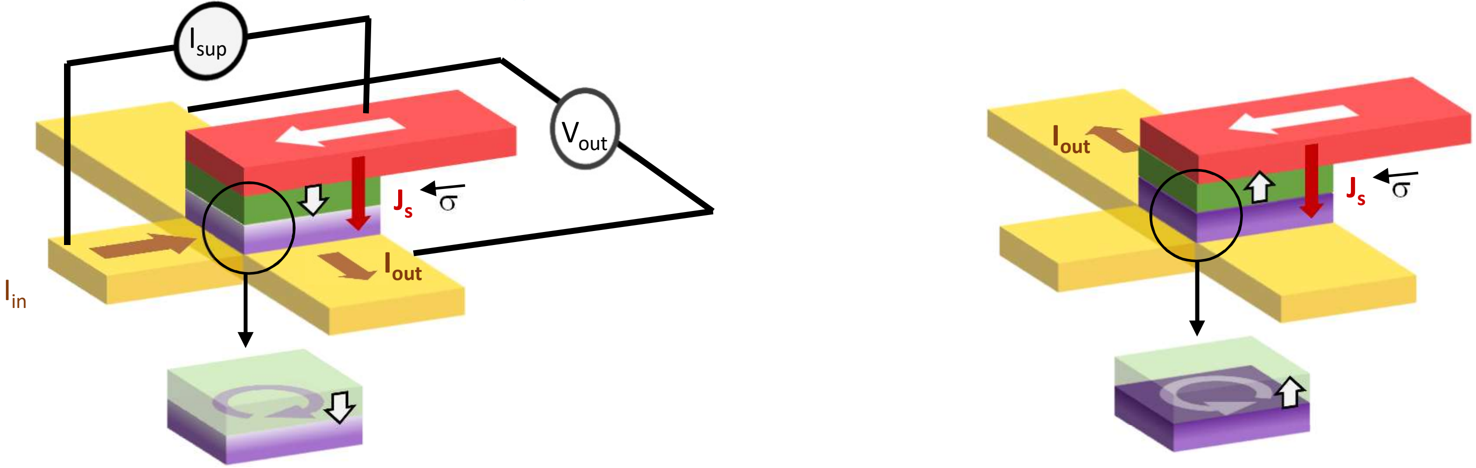
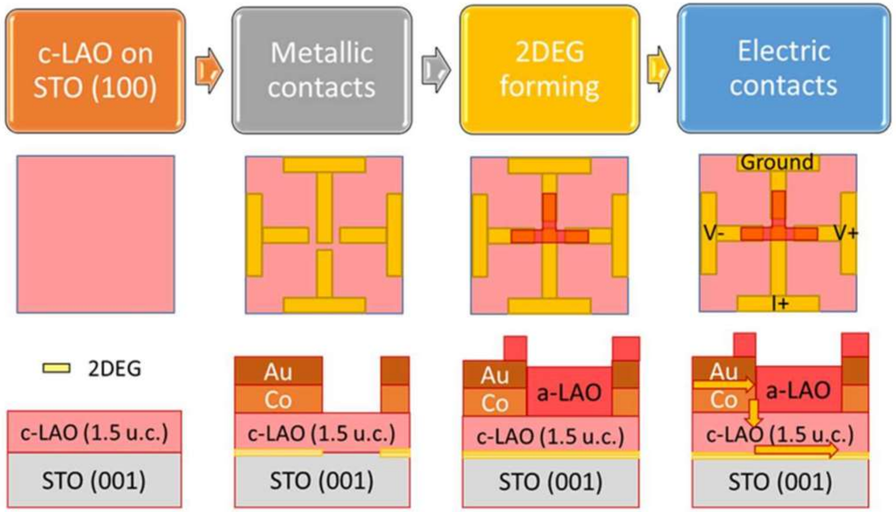
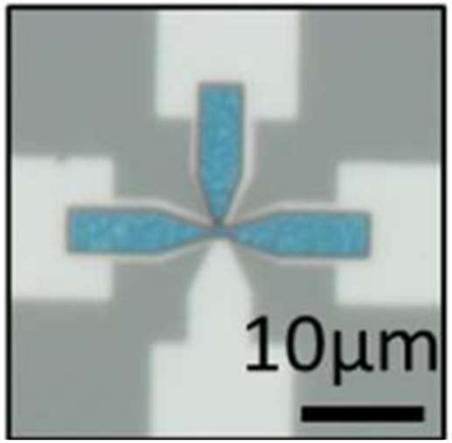


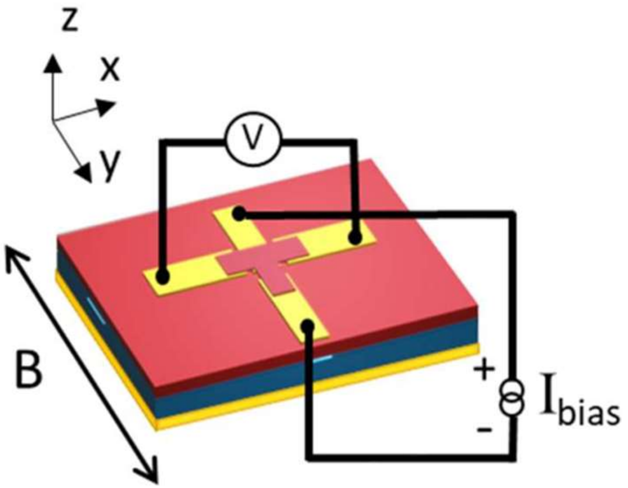
- Magnetoelectric replaced by non-magnetic ferroelectric
- No need for magnetization switching
- Ferroelectricity controls Rashba state at interface with spin-orbit material

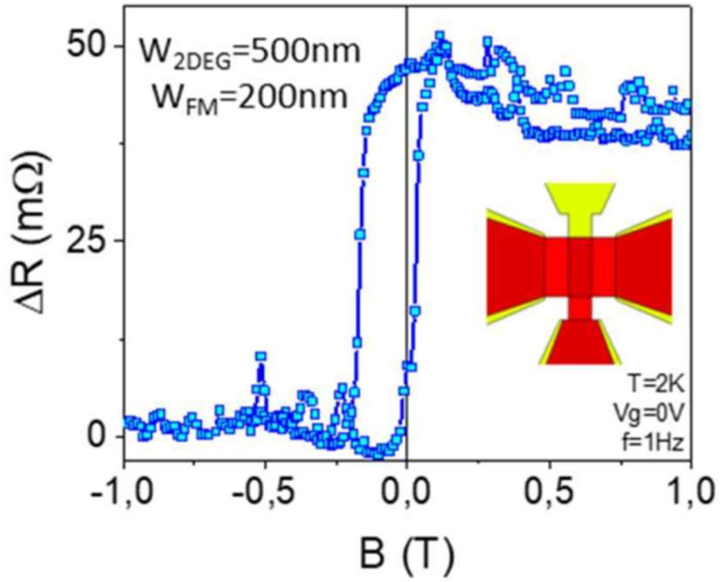
All electrical detection of spin-charge conversion in STO nanodevices



Patterning of T-shape devices by e-beam lithography





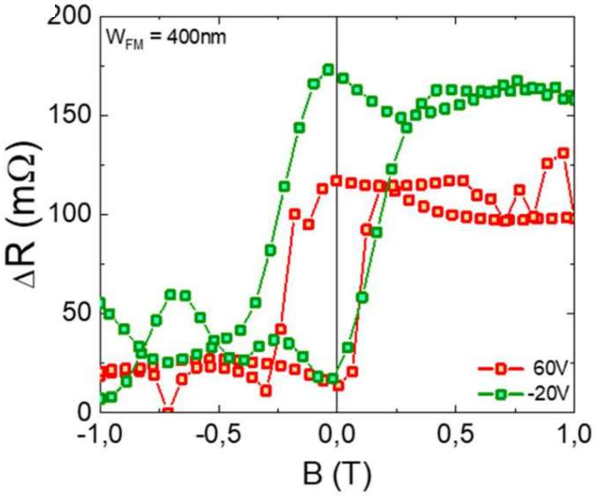


Direct evidence for spin-charge conversion from magnetotransport in STO 2DEGs

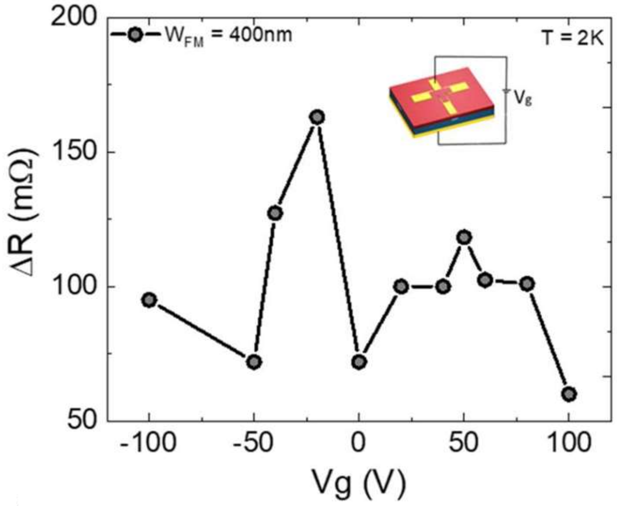
F. Gallego, MB et al, Adv. Func. Mater. 34, 2307474 (2024)

All electrical detection of spin-charge conversion in STO nanodevices

Gate dependence

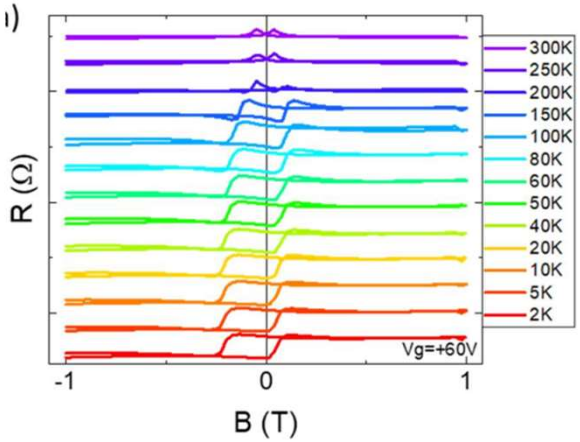


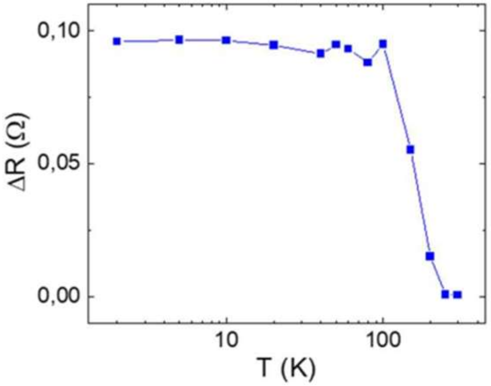
Signal amplitude depends on gate voltage

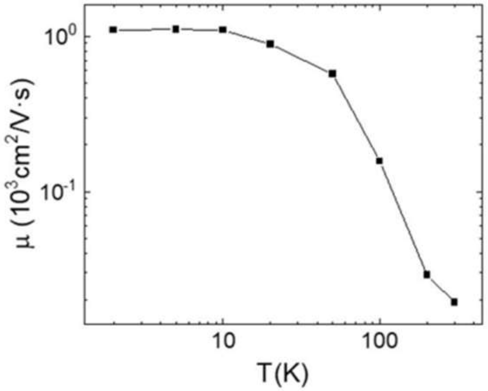


Non-monotonic gate depedence as in spin-pumping

Temperature dependence







Most devices show exchange bias, probably due to CoOx at Co/LAO interface
Signal disappears > 200 K, probably due to decrease in conversion efficiency / scattering time

Conclusions and perspectives

There are many possibilities for E-field control of magnetism

- With multiferroics (works but at room temperature limited to $BiFeO_3$)
- Through field effect (limited efficiency, requires ultrathin films and large fields)
  - Find better materials combinations between FE and FM → ferroelectric nitrides (e.g. AlScN)?
- Through field-controlled strain (efficient but hard to miniaturize + poor endurance)
- New possibilities for spin/charge interconversion at oxide interfaces with Rashba SO coupling
  - FE control demonstrated
  - Need reliable, low leakage demonstration at room temperature
  - Implementation in FESO-type nanoscale devices in under way

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Thank you !