Multiferroics and magnetoelectrics: towards industrial applications

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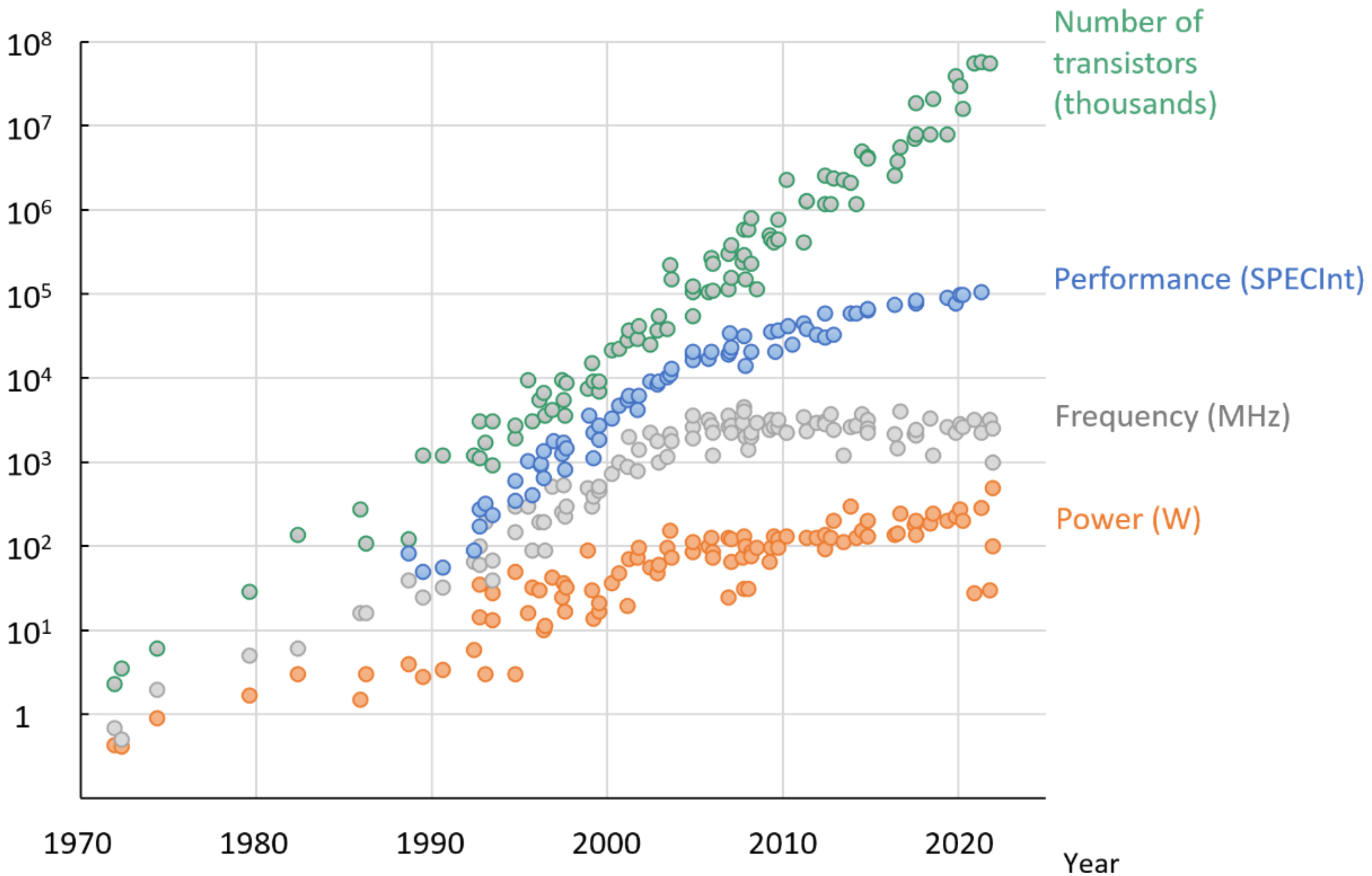
http://oxitronics.cnrs.fr

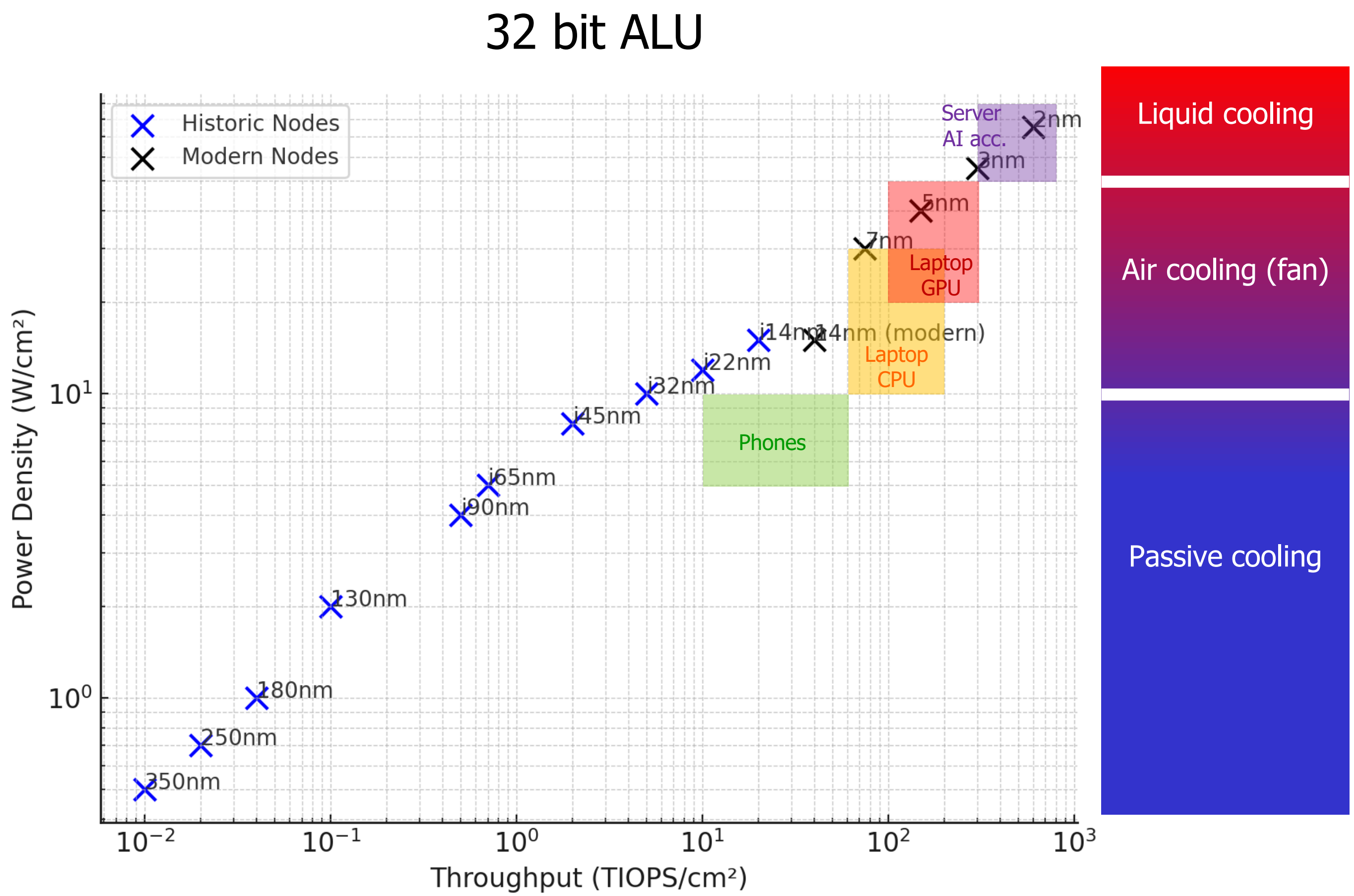
Moore’s law and Dennard scaling



- In the 1990’s the performance of computers increased by 100x
- In the 2010’s, only by 3x
- Chips performance is limited to mitigate heating

➔ **We need a new technology of chips operating at much lower power**

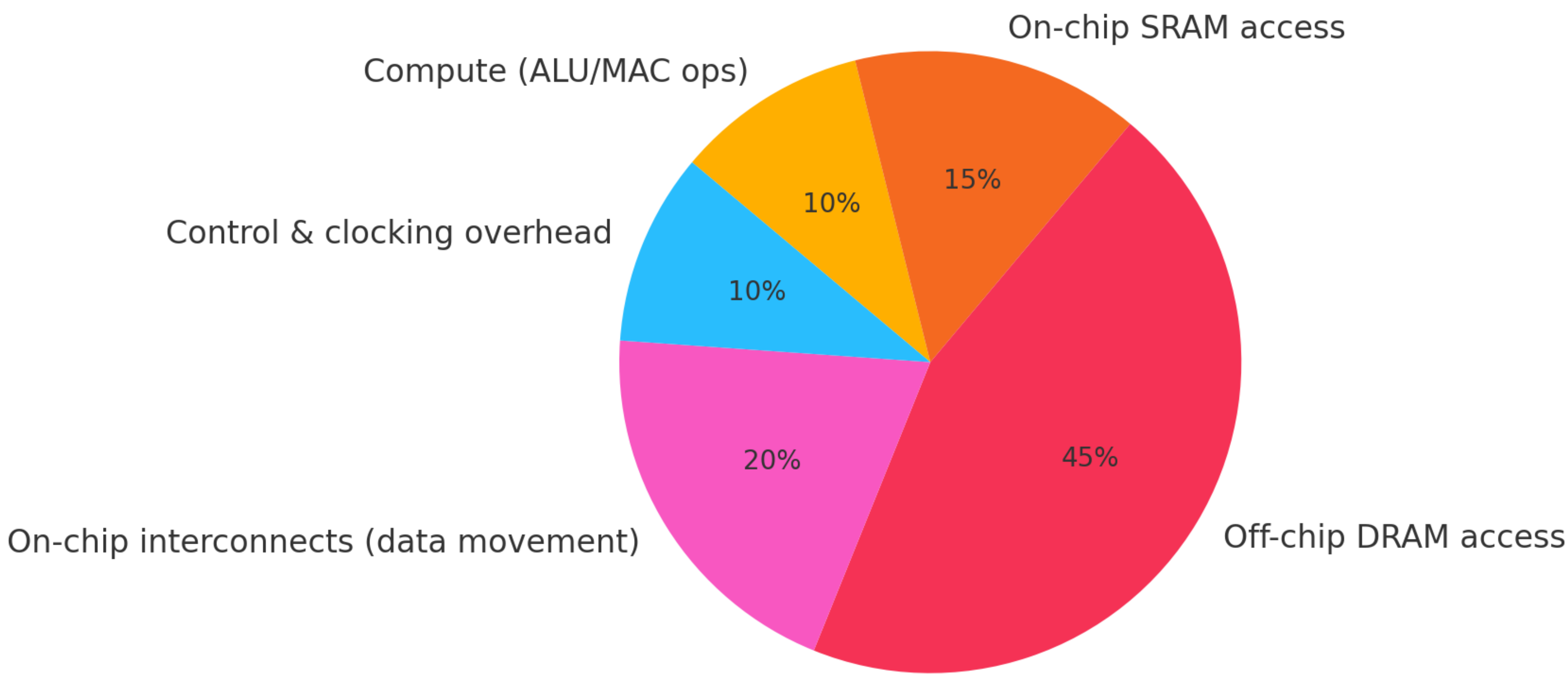
Chips can get very hot



- Current Iphone 16 A18 chip is based on TSMC 3 nm technology node
- It could operate at much higher performance if it did not heat so much…

➔ **New computing paradigms are needed to achieve low-power operation**

How is energy used in computing workloads ?

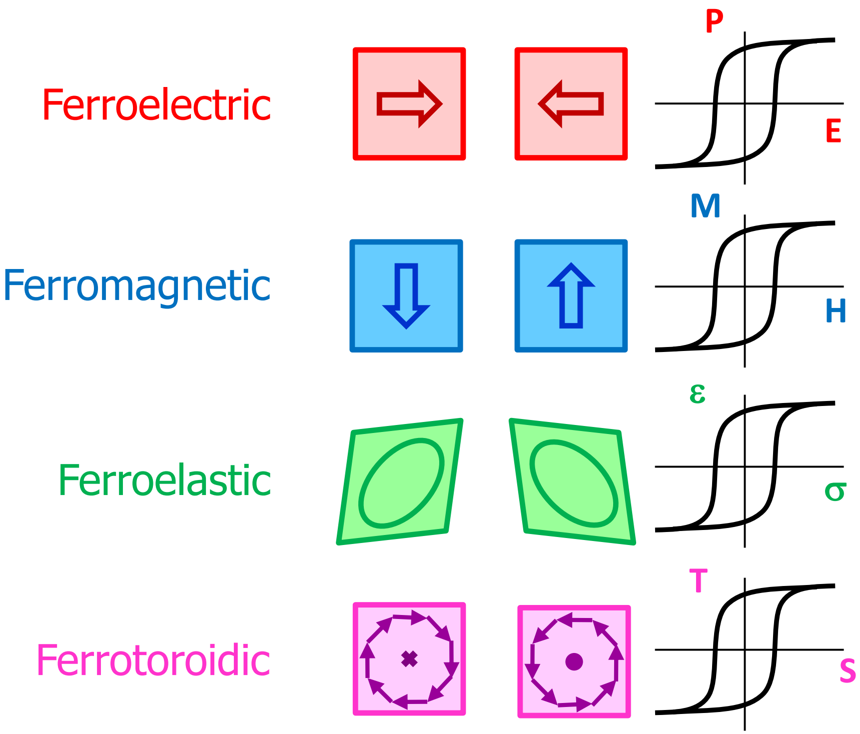


⊙ 60-70% of the energy is used to move data on chip and between CPU and DRAM chips
➔ Need for « logic-in-memory » computing
⊙ Bringing in **nonvolatility** would save an extra ~10% energy and increase performance by 20-50%
➔ Need for **nonvolatile memories** and **nonvolatile logic**, but how ?
➔ **Ferromagnetism and/or ferroelectricity**

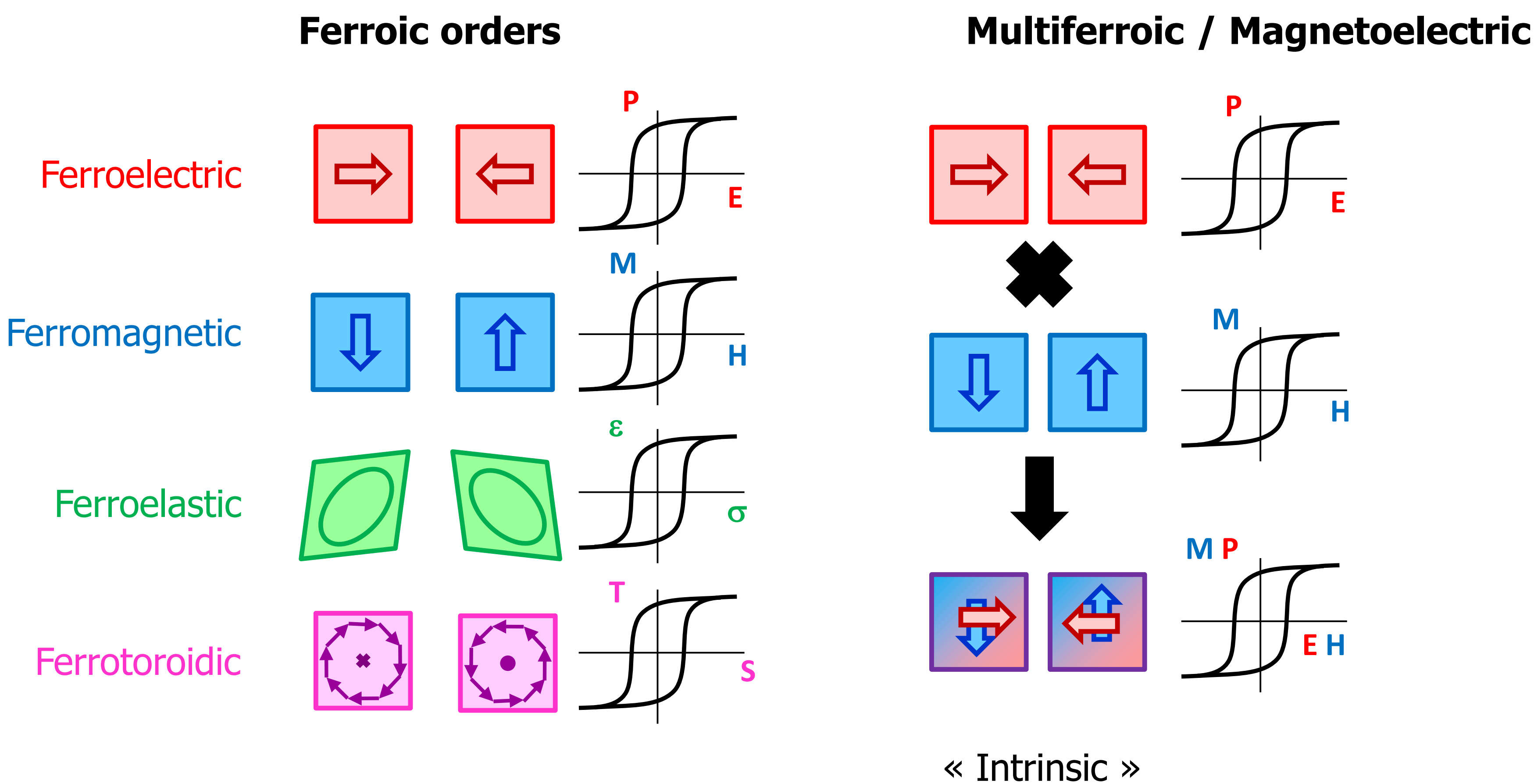
Outline

- Ferroic orders and magnetoelectric coupling
  - Intrinsic" magnetoelectric coupling
  - Field-effect-driven magnetoelectric coupling
  - Strain-driven magnetoelectric coupling
- Magnetoelectric spintronic devices
  - VCMA-MRAM
  - Magnetoelectric RAM
  - Magnetoelectric Spin orbit (MESO) devices
- Integration challenges

Ferroic orders



- Hysteretic dependence of order parameter : good for data storage



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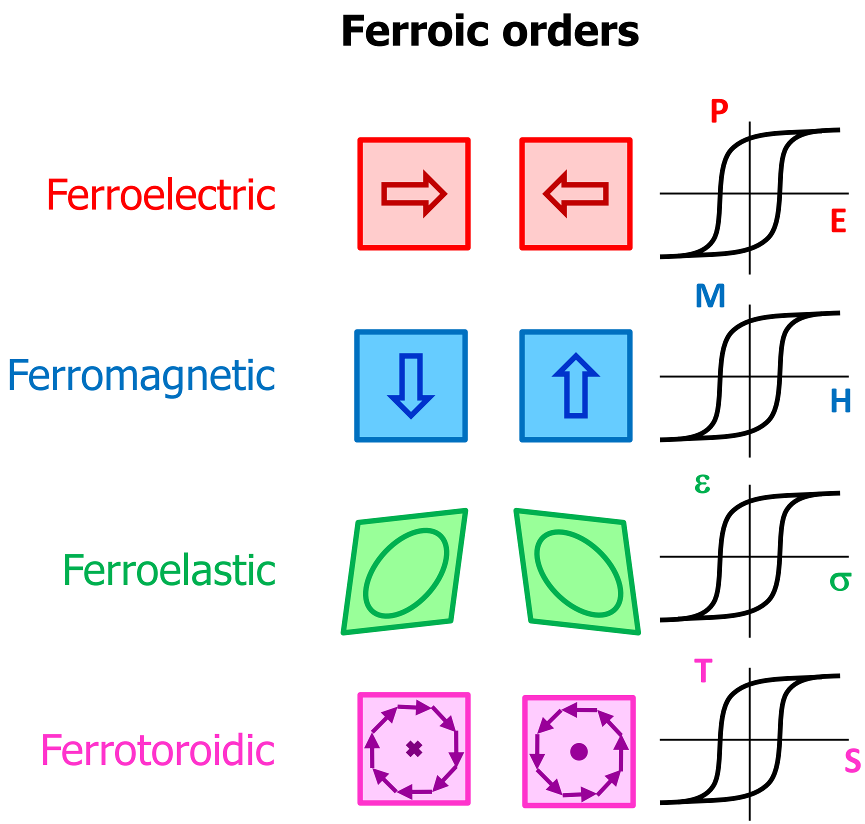
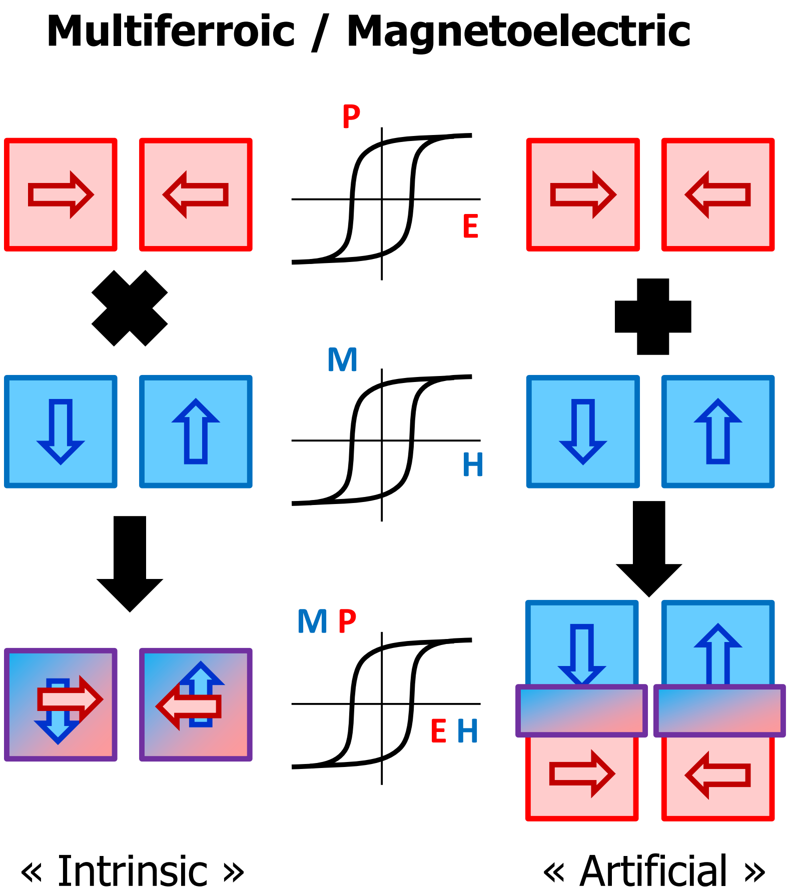
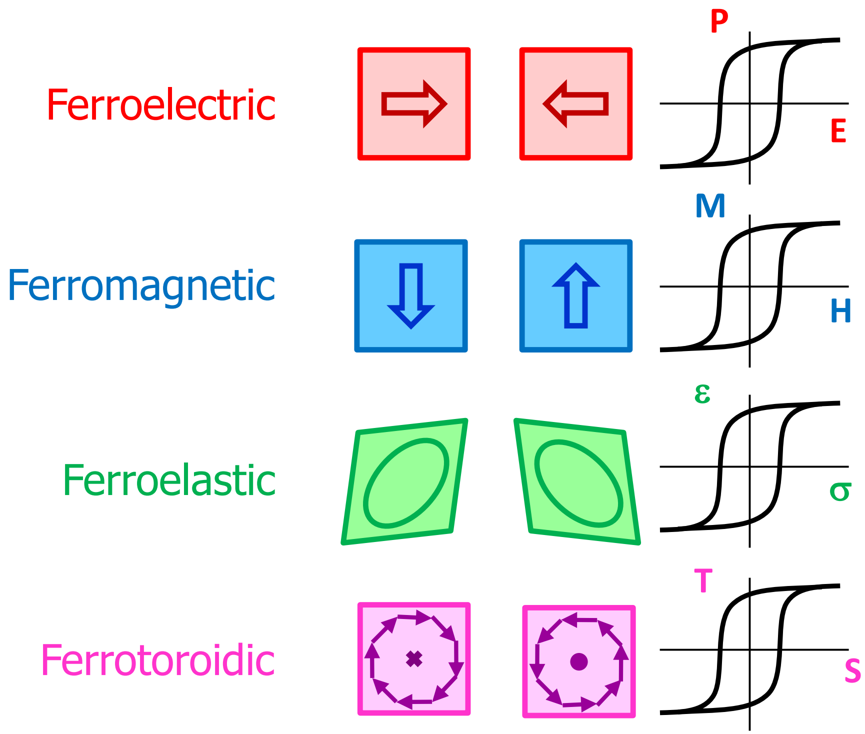


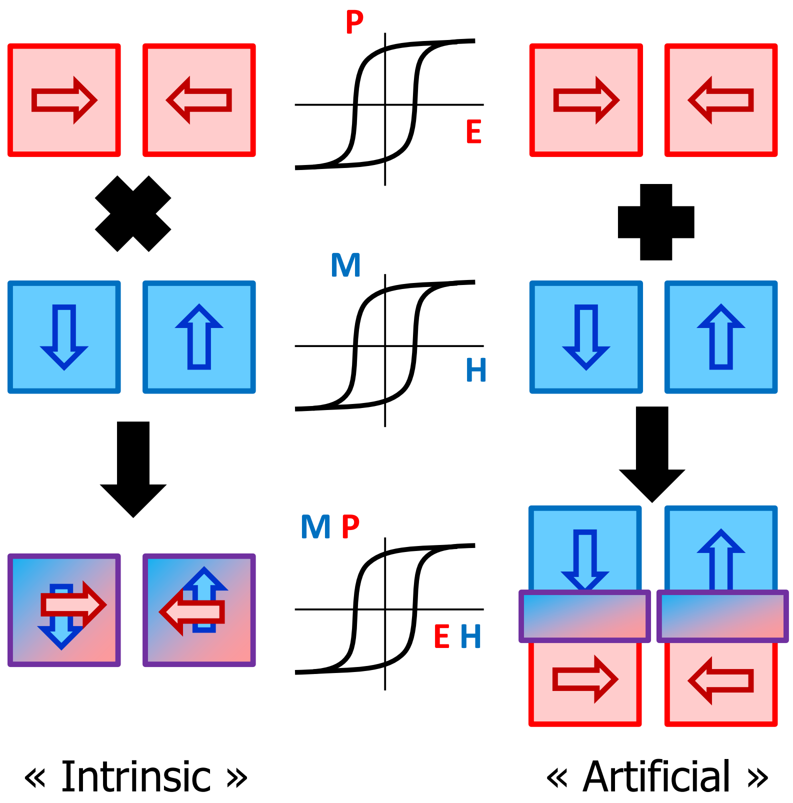


- Hysteretic dependence of order parameter : good for data storage

Ferroic orders



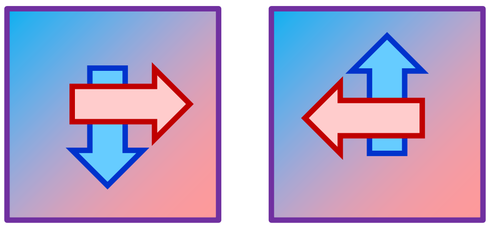
Multiferroic / Magnetoelectric



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

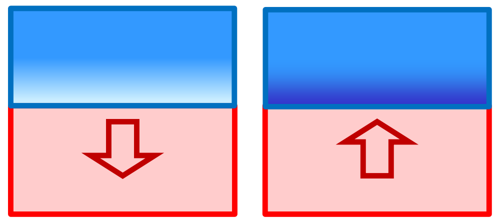
MB, Nature Mater. 11, 354 (2012)

Intrinsic magnetoelectric



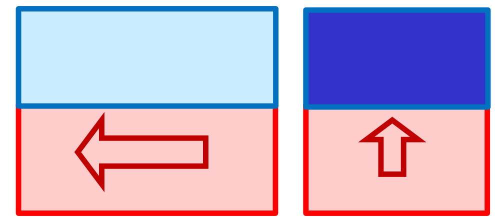
Use single-phase multiferroic material

Field-effect



Combine strong ferroelectric with carrier-mediated ferromagnet

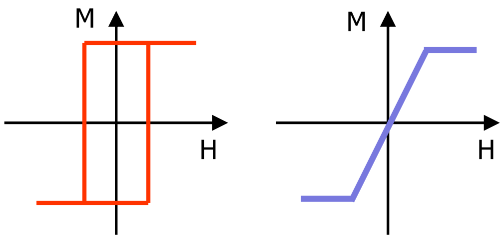
Strain-driven



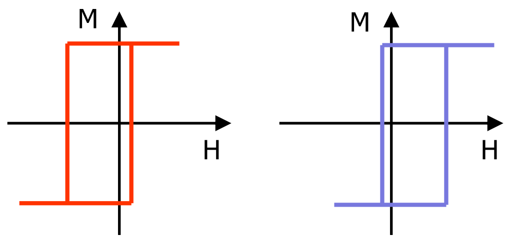
Combine piezoelectric or ferroelectric/ferroelastic with magnetostrictive ferromagnet

Controlling magnetism with electric fields

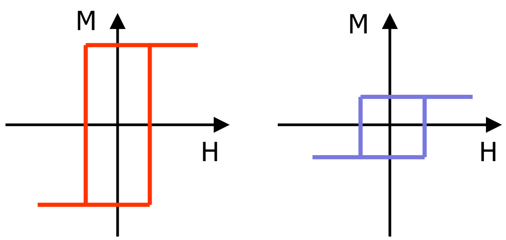
Magnetic anisotropy



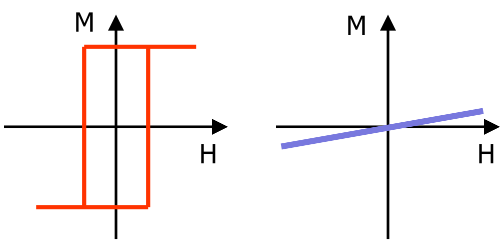
Exchange bias



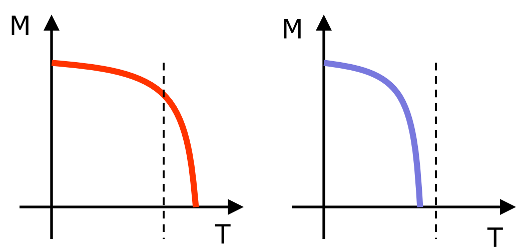
Magnetic moment



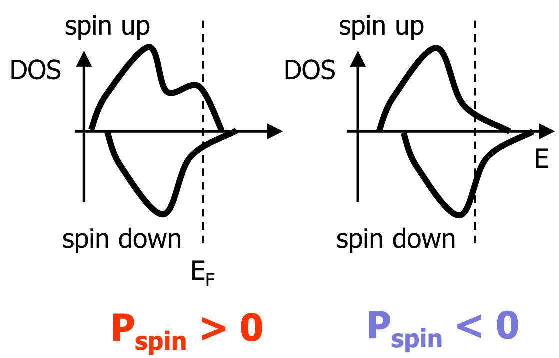
Magnetic order



Curie temperature

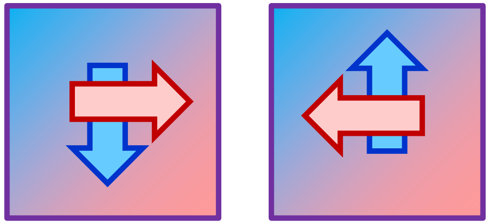


Spin polarization



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

Intrinsic magnetoelectric



Use single-phase multiferroic material

Field-effect

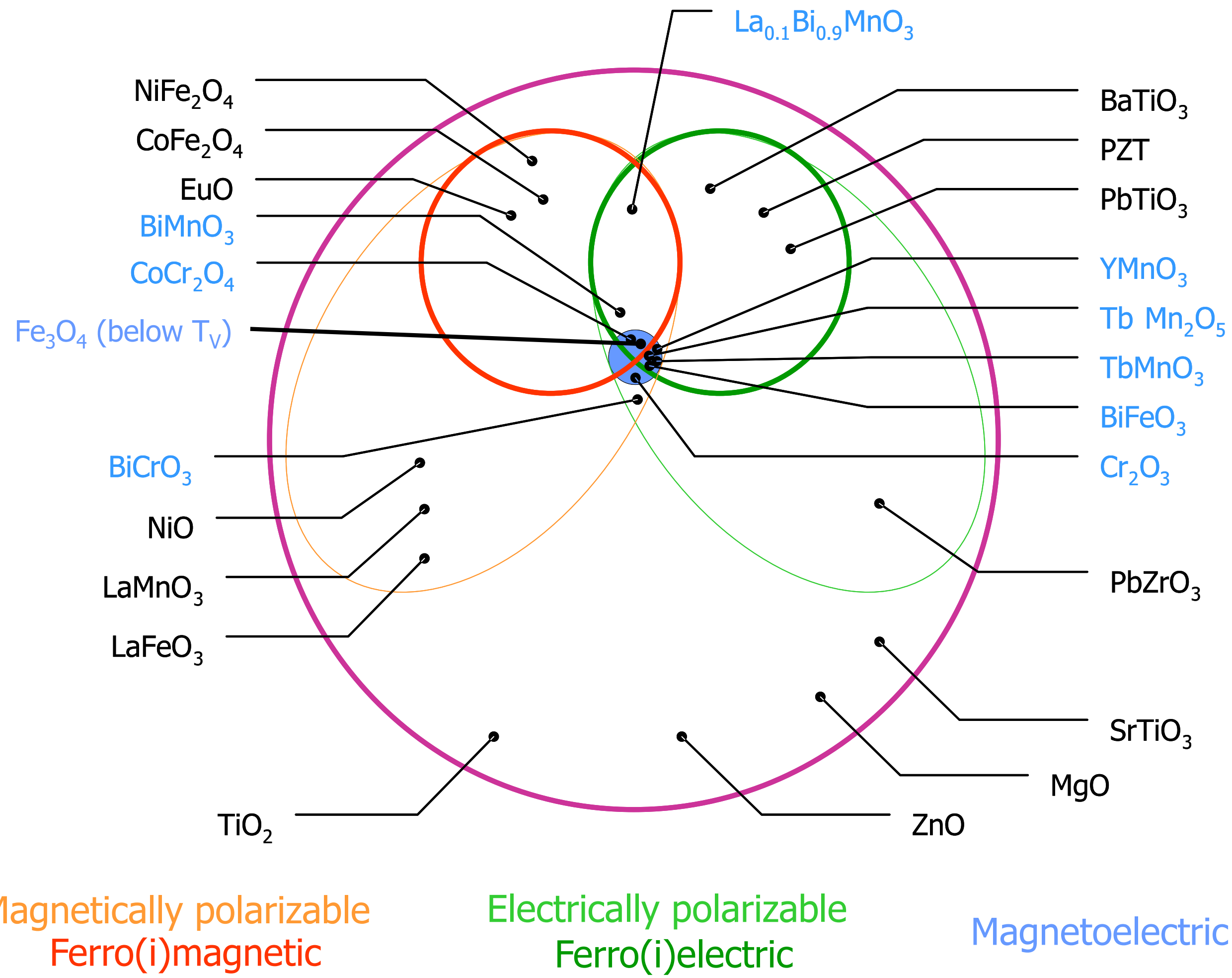
Combine strong ferroelectric with carrier-mediated ferromagnet

Strain-driven

Combine piezoelectric or ferroelectric/ferroelastic with magnetostrictive ferromagnet

E-field control of magnetism with intrinsic multiferroics

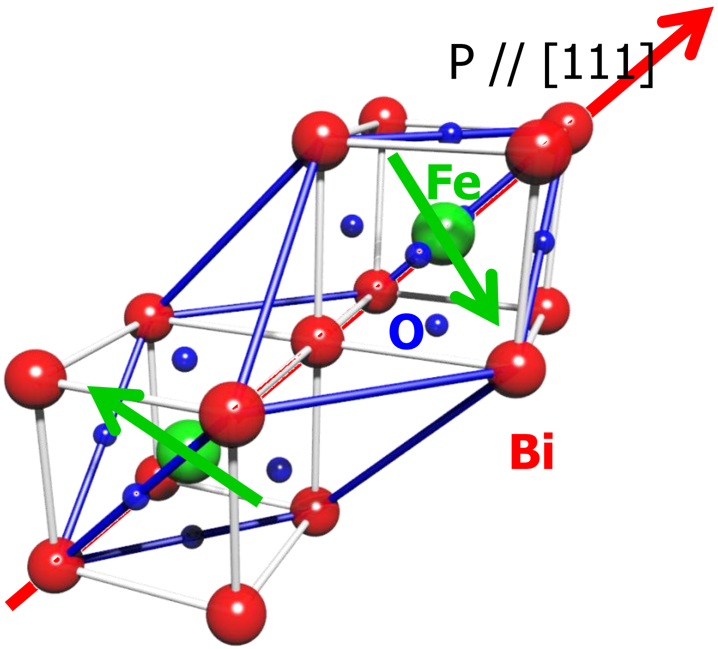
There are very few (room-temperature) multiferroics



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

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

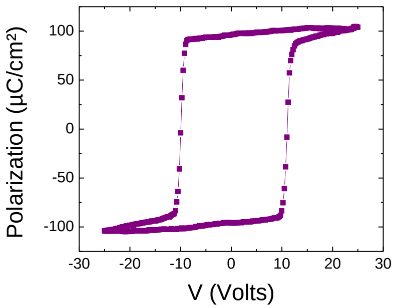
$BiFeO_3$: a room-temperature multiferroic



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)



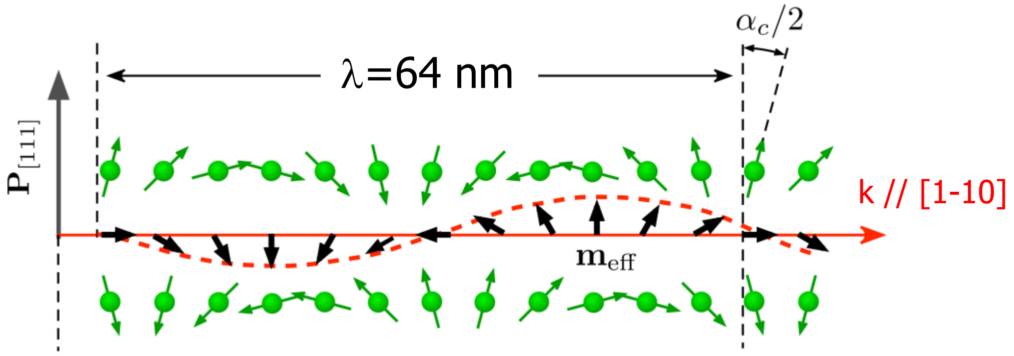
Magnetic properties

- G-type antiferromagnetic

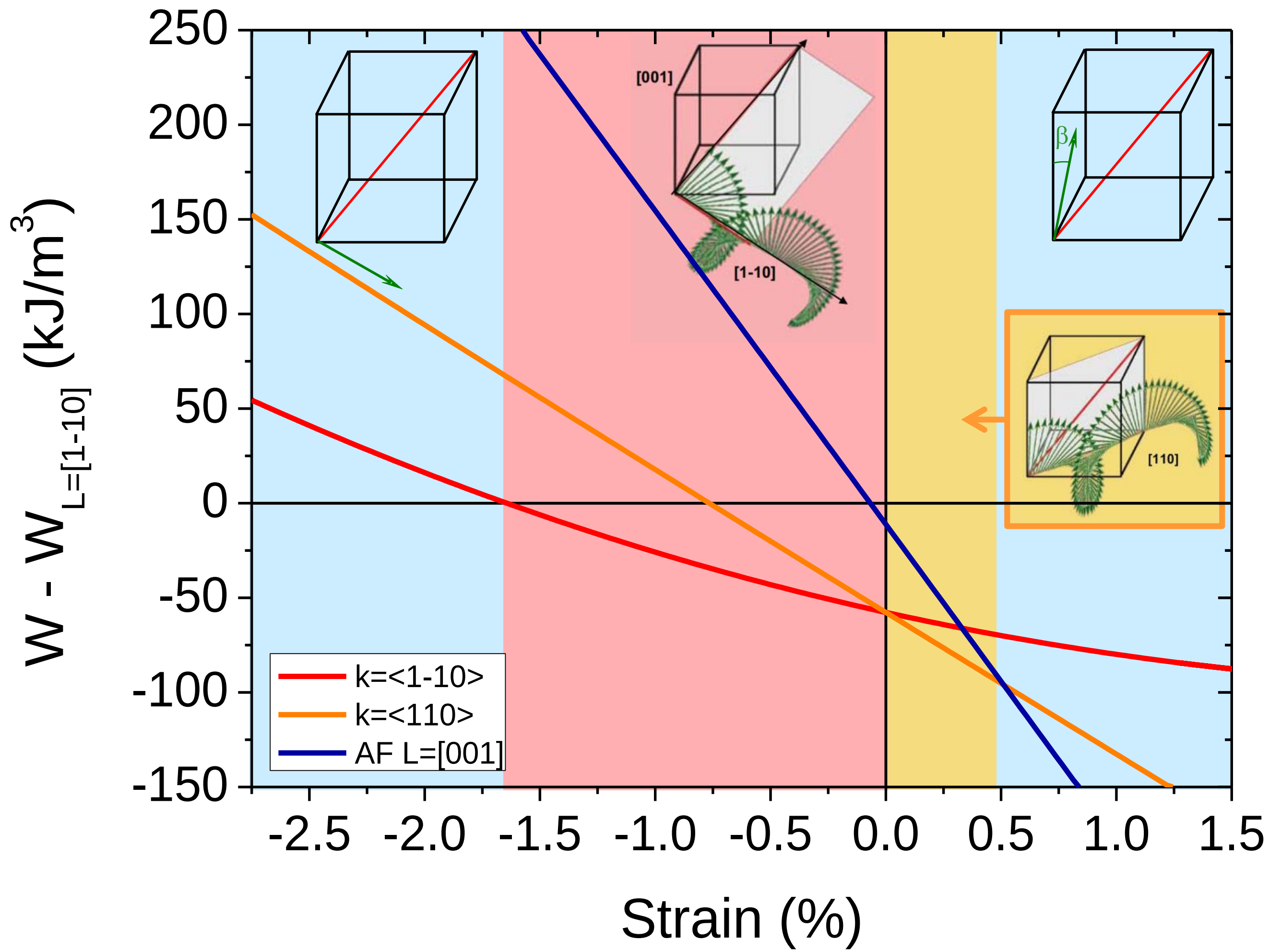
+ cycloidal modulation (λ=62 nm)

- 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 $BiFeO_3$

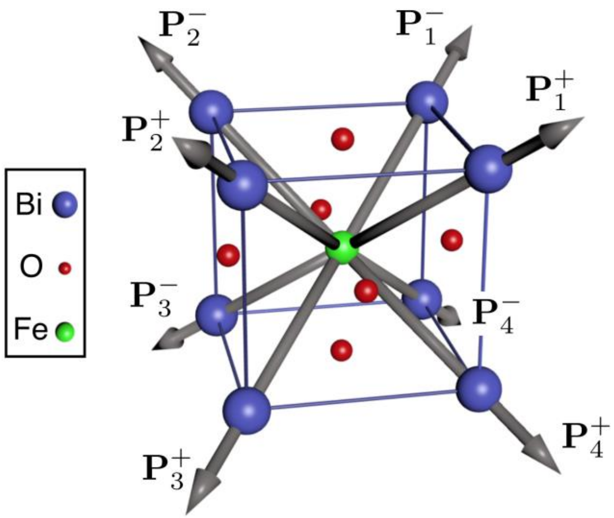


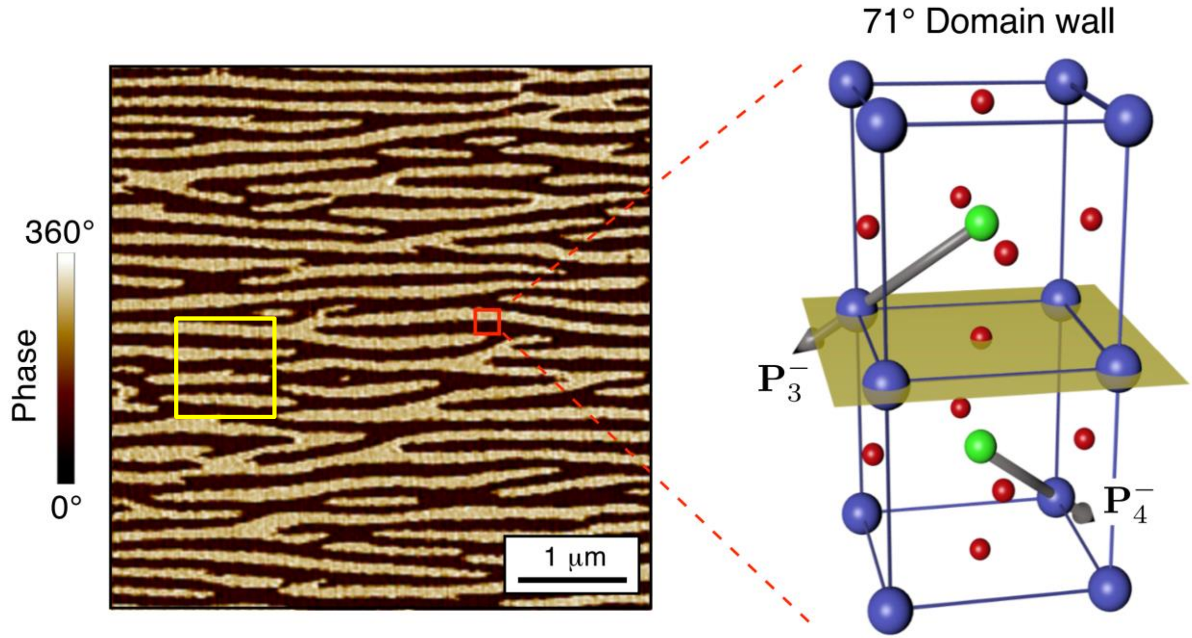
- Cycloidal state is destabilized by strain-induced (magnetoelastic) anisotropy
- Weak-FM state at high tensile or compressive state
- New cycloid stabilized at low tensile strain

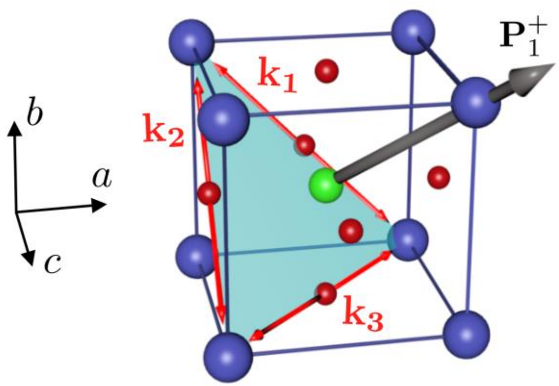
} Mössbauer spectroscopy + theory

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

Ferroelectric domain structure



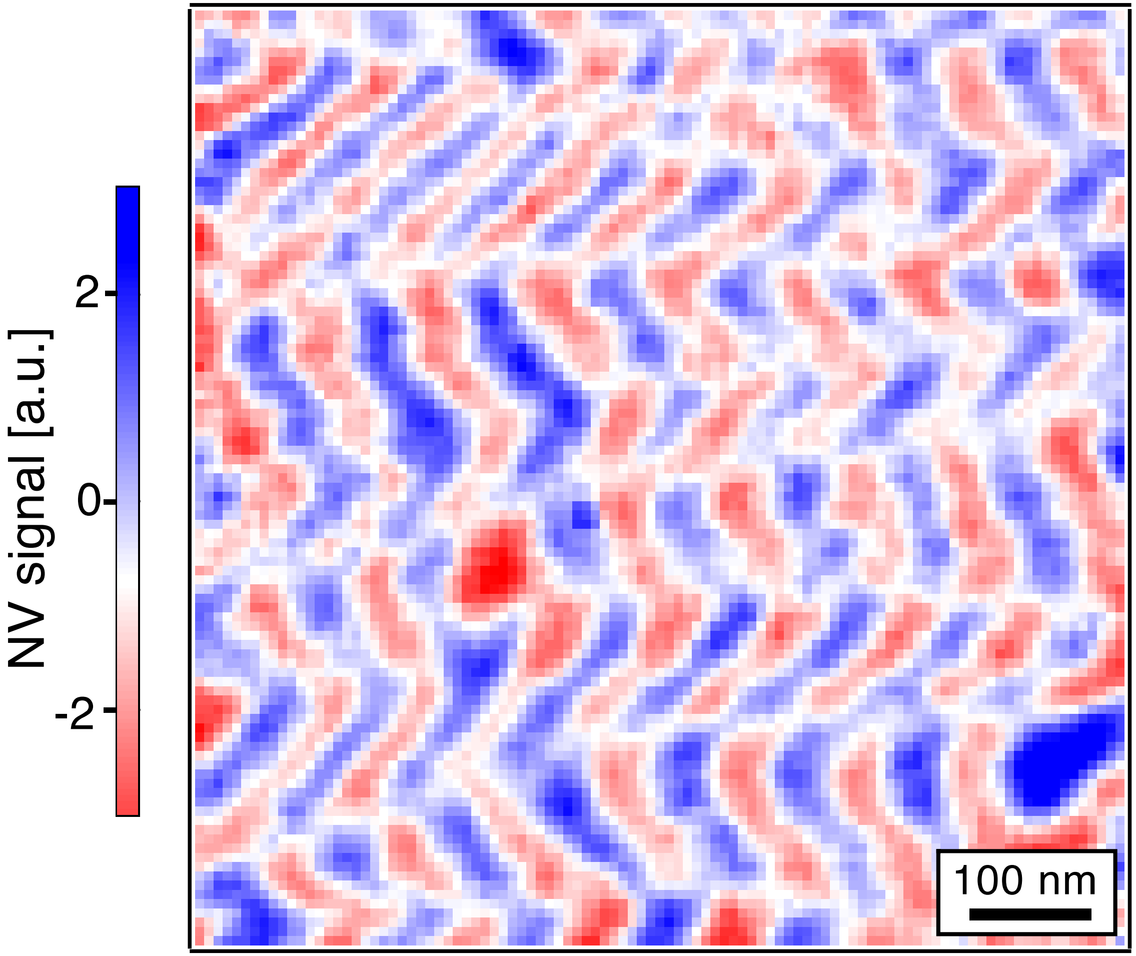




- BFO polarization can be oriented along 8 possible 111 directions
- Cycloid propagation vector is perpendicular to polarization
- Here we work with films with just 2 polarization variants
- Polarization domains typical size is 100-150 nm
- Magnetic imaging on regions 800 x 800 nm²

➔ Map the **spatial variation of the weak moment of Fe**

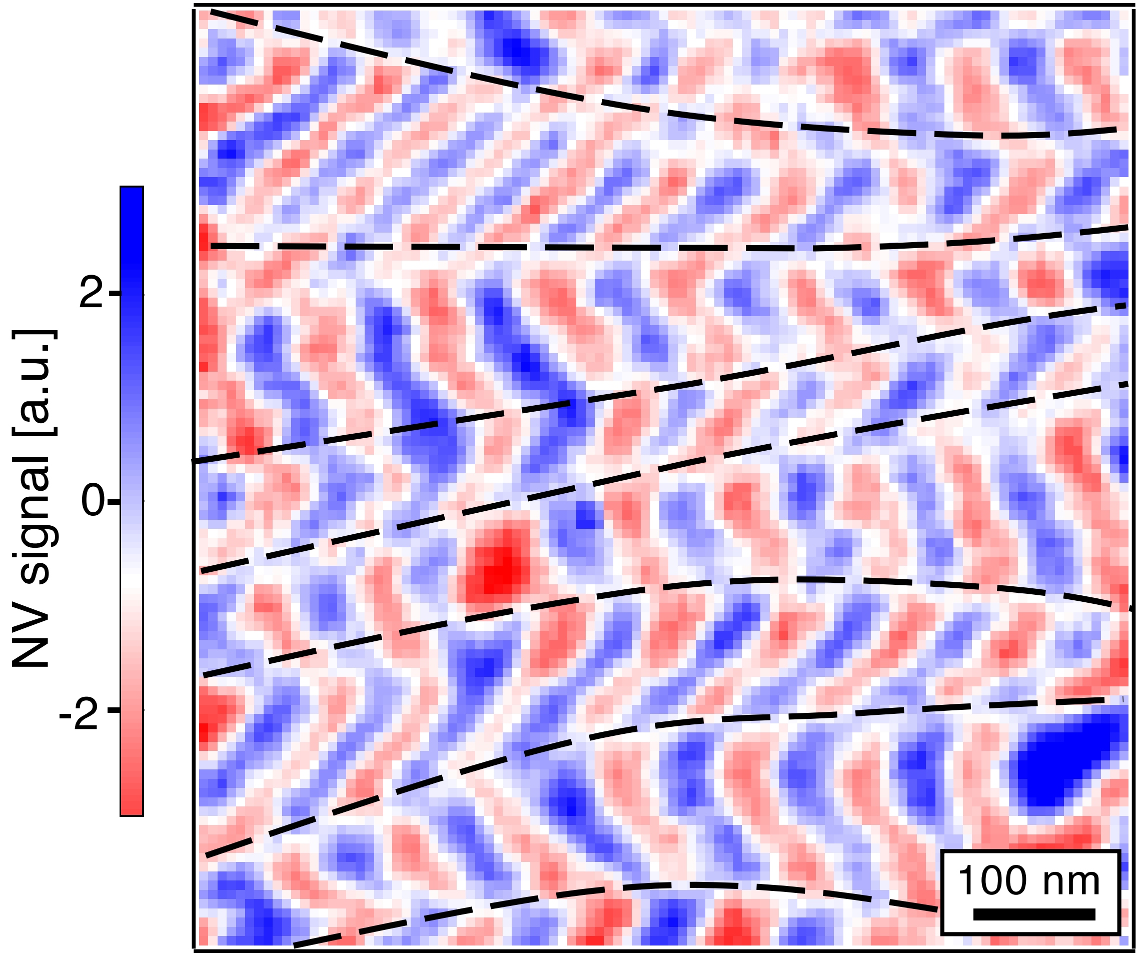
Magnetic imaging of BFO film at room temperature



Iso-B

- Clear « stripy » contrast of magnetic origin

Magnetic imaging of BFO film at room temperature

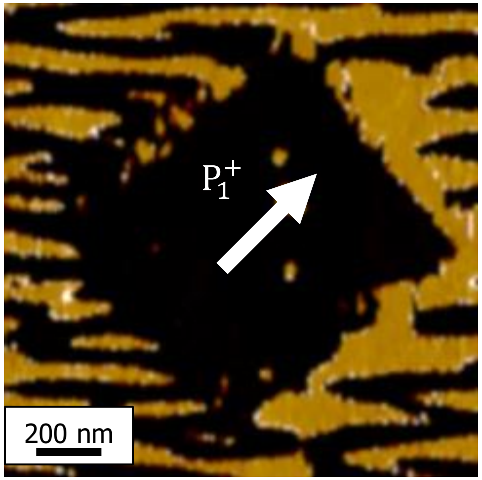


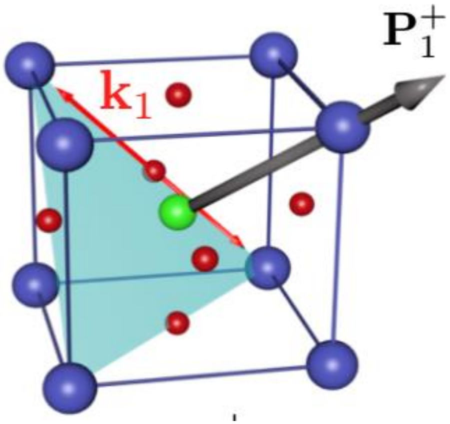
Iso-B

- Clear « stripy » contrast of magnetic origin
- Periodic modulation of weak moment, with period near 70 nm
- Additional zigzag pattern with size compatible with dimension of ferroelectric domains (100-150 nm)

Magnetic imaging of single ferroelectric domains

Ferroelectric domains imaged by PFM

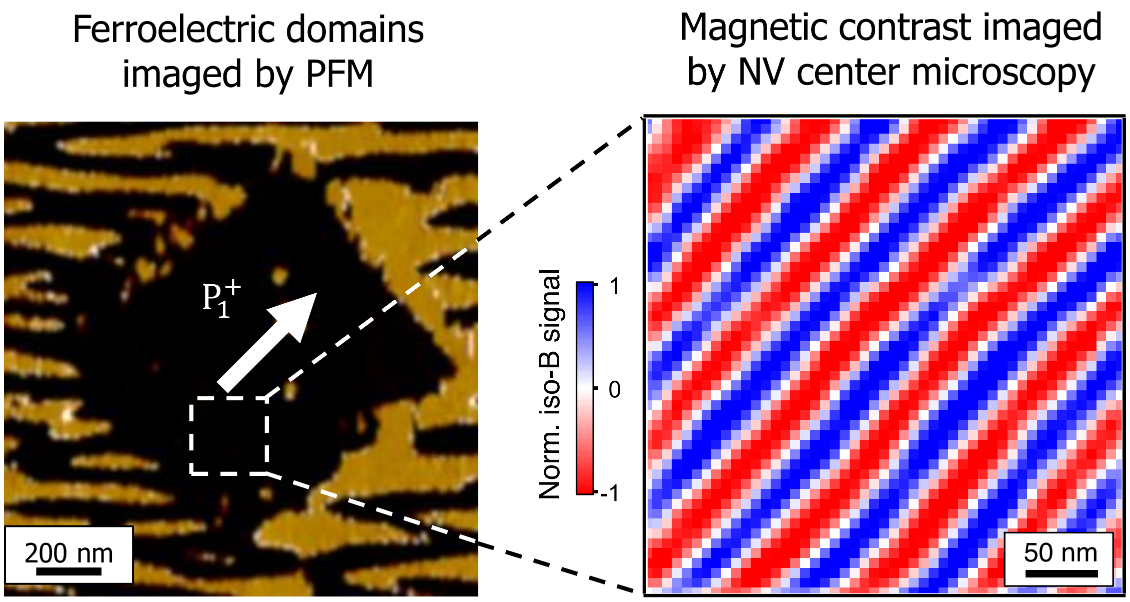




- Electric poling of BFO film : single ferroelectric and magnetic domain

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

Magnetic imaging of single ferroelectric domains



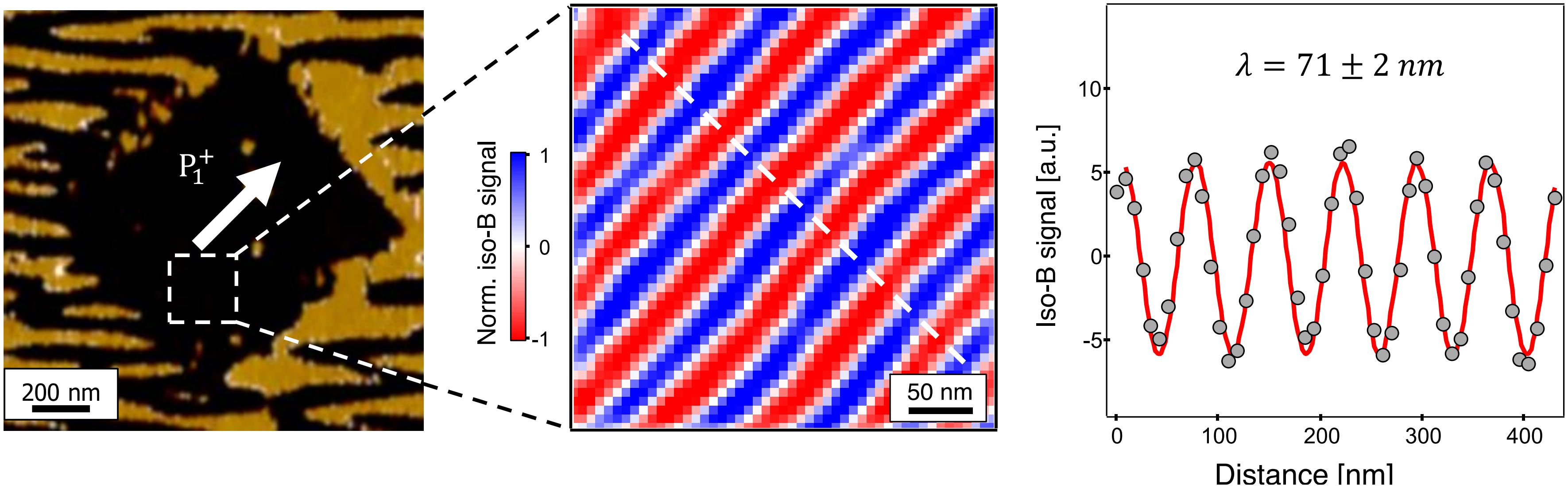
- Electric poling of BFO film : single ferroelectric and magnetic domain
- Periodic contrast with well-defined propagation direction and period

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

Magnetic imaging of single ferroelectric domains

Ferroelectric domains imaged by PFM

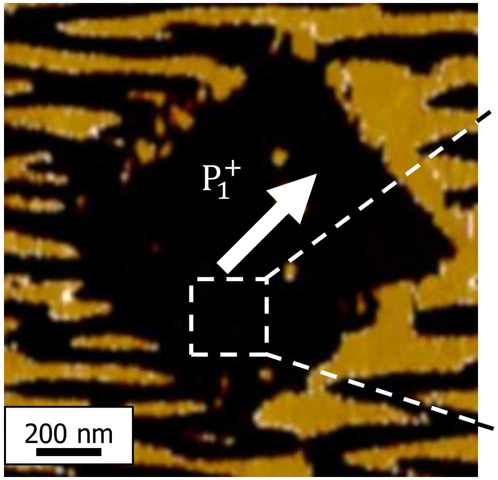
Magnetic contrast imaged by NV center microscopy

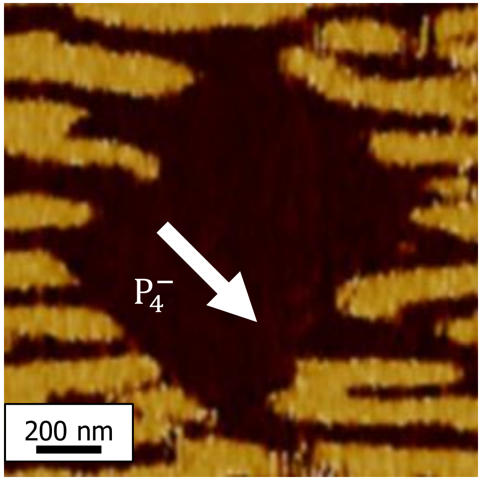


- Electric poling of BFO film : single ferroelectric and magnetic domain
- Periodic contrast with well-defined propagation direction and period
- Period is **71 nm**, slightly longer than in bulk (64 nm), likely due to epitaxial strain

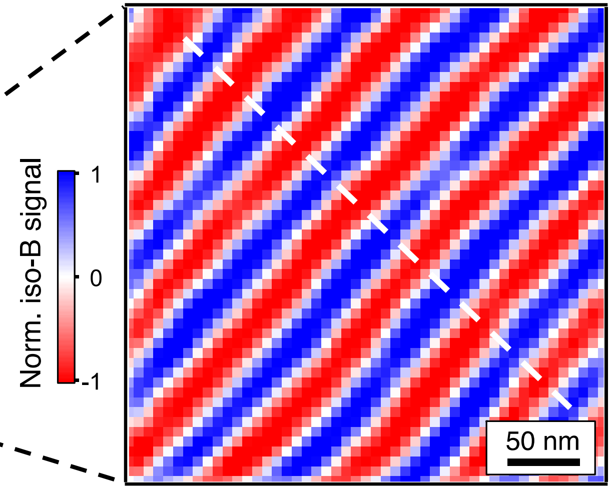
I. Gross, MB et al, Nature 549, 252 (2017)

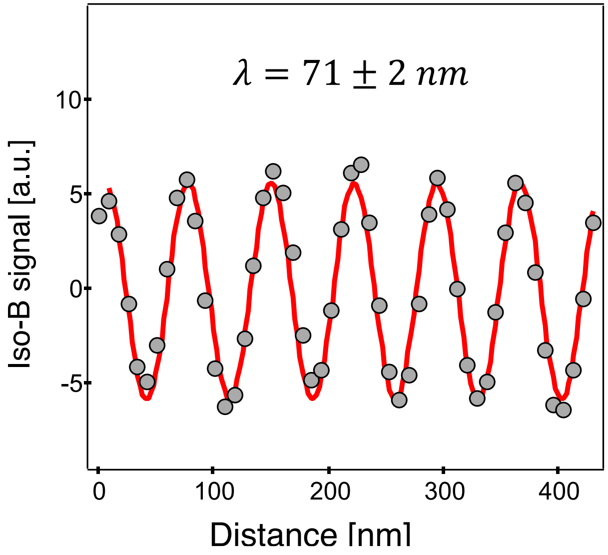
Ferroelectric domains imaged by PFM

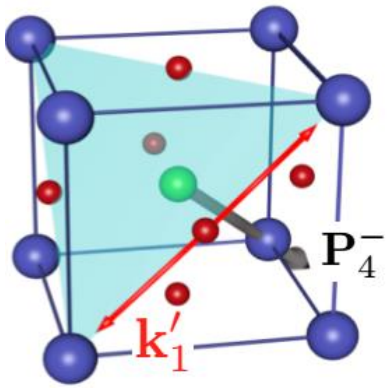




Magnetic contrast imaged by NV center microscopy







Magnetic imaging of single ferroelectric domains

Ferroelectric domains imaged by PFM

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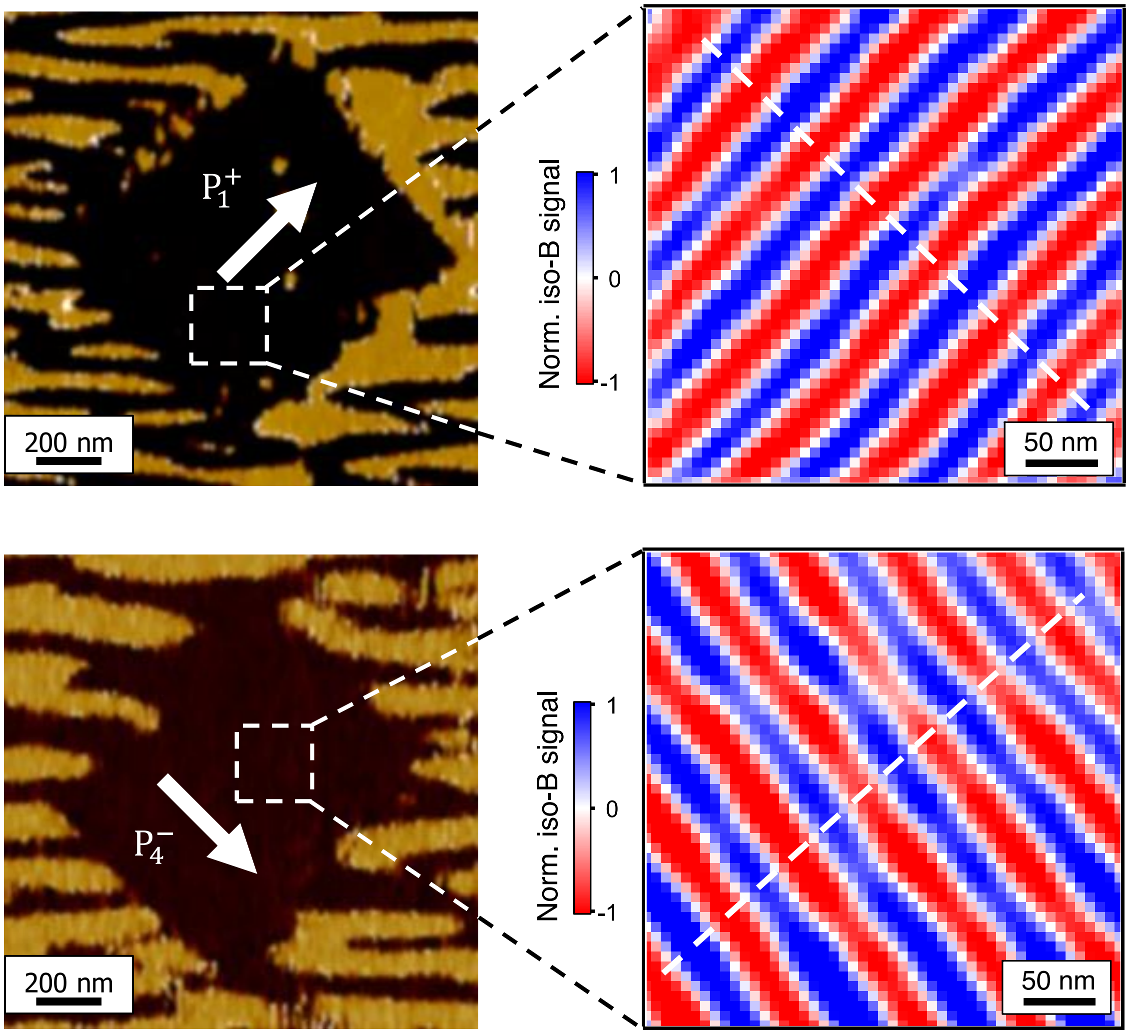
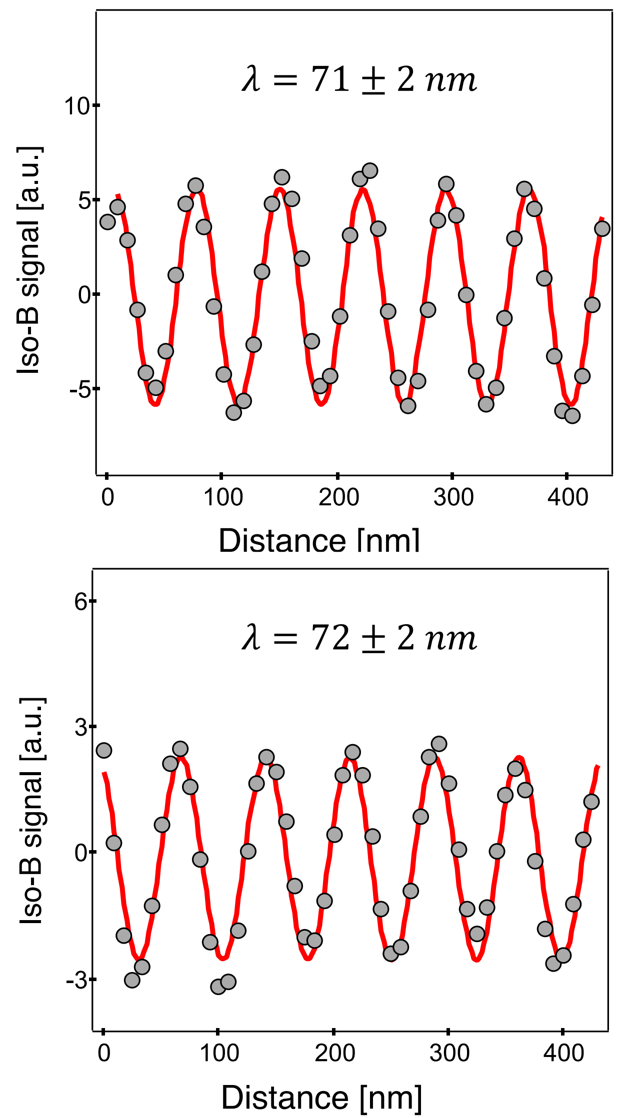


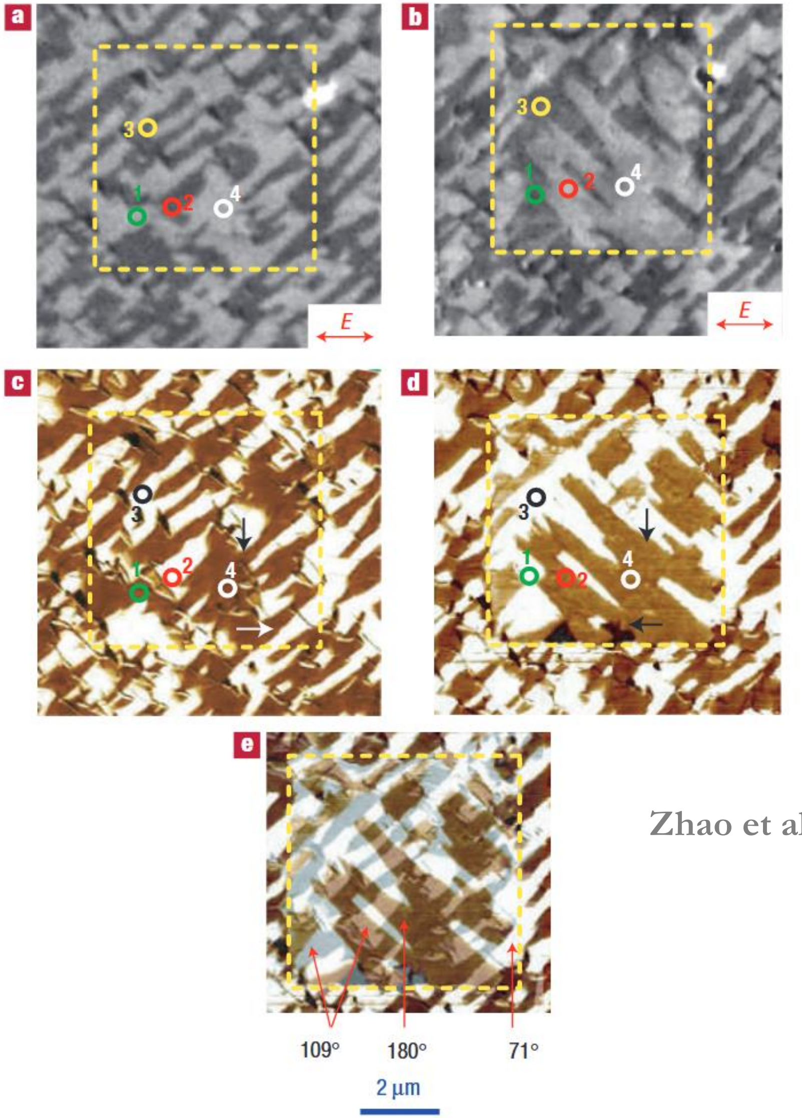


- **Electric-field control** of cycloid propagation direction

Electrical switching of antiferromagnetic domains

XMLD-PEEM
→ image AFM domains

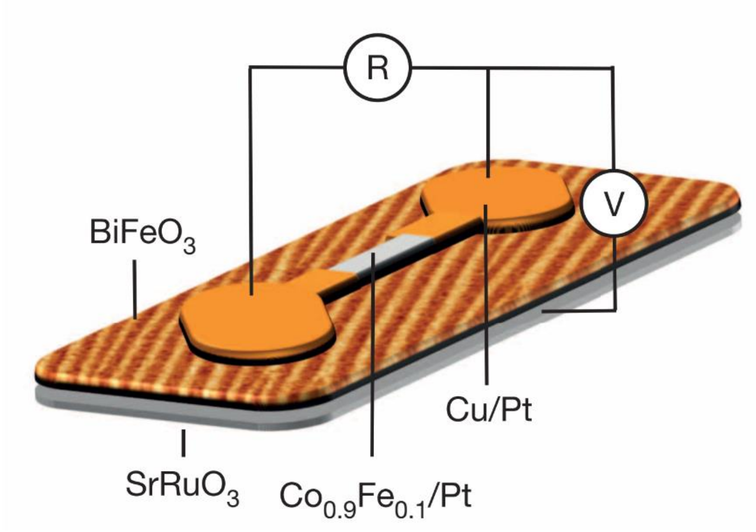
PFM
→ image FE domains



Zhao et al, Nature Mater (2006)

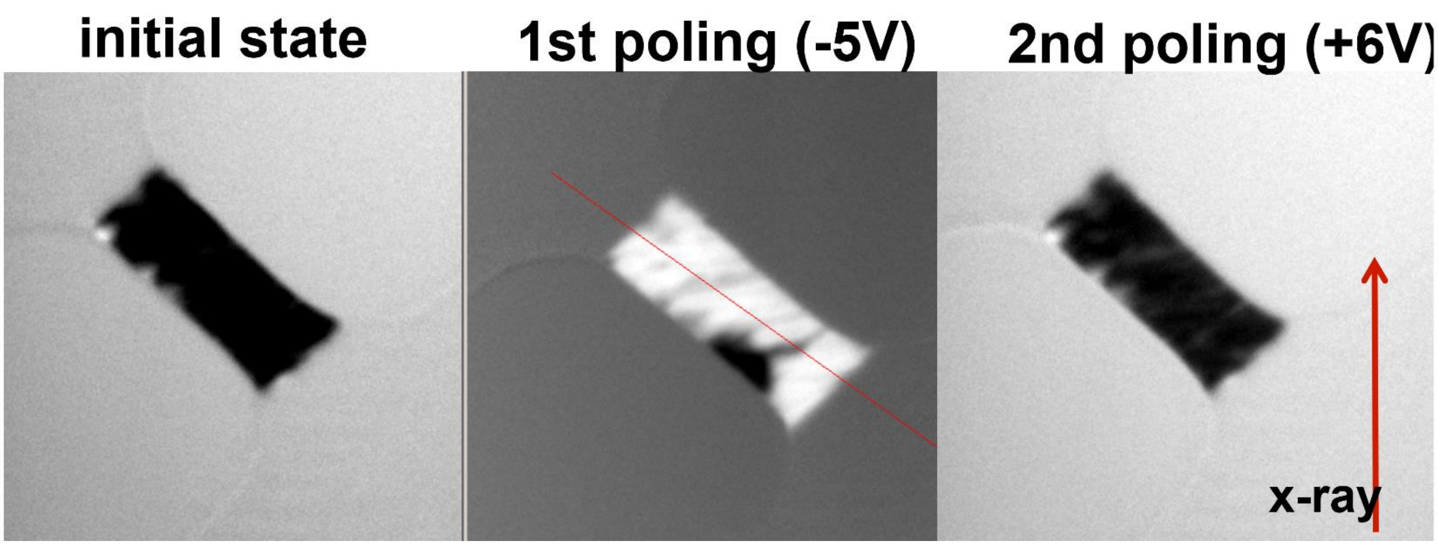
- Some AFM regions switch upon switching FE polarization

Magnetoelectric switching of magnetization with $BiFeO_3$



- Use $BiFeO_3$ thin film with just two families of ferroelectric domains with 71 deg DWs
- CoFe pad on top of BFO
- $BiFeO_3$ 180 degree polarization switching occurs in two steps (71° and 109°)
- Weak moment of BFO switches by 180 degrees
- Magnetization of CoFe switches

Heron et al, Nature 516, 370 (2014)



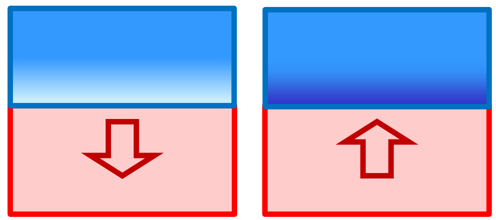
- XMCD-PEEM images at Co edge show electric-field driven magnetization reversal

Different approaches for E-field control of magnetism

Intrinsic magnetoelectric

Use single-phase multiferroic material

Field-effect

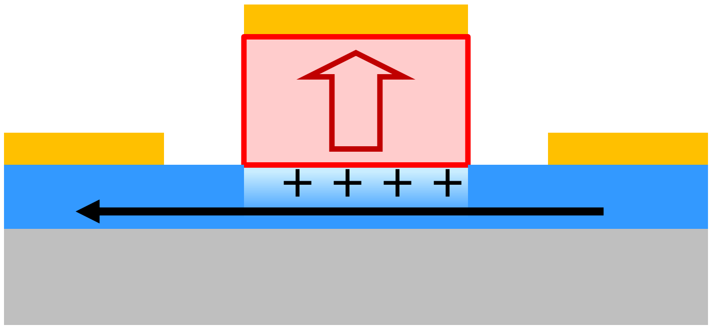


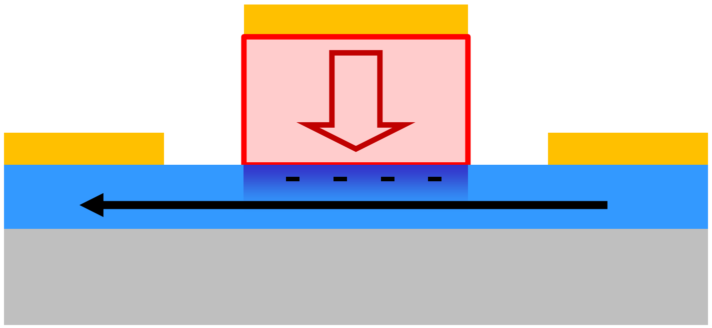
Combine strong ferroelectric with carrier-mediated ferromagnet

Strain-driven

Combine piezoelectric or ferroelectric/ferroelastic with magnetostrictive ferromagnet

Field-effect control of magnetism





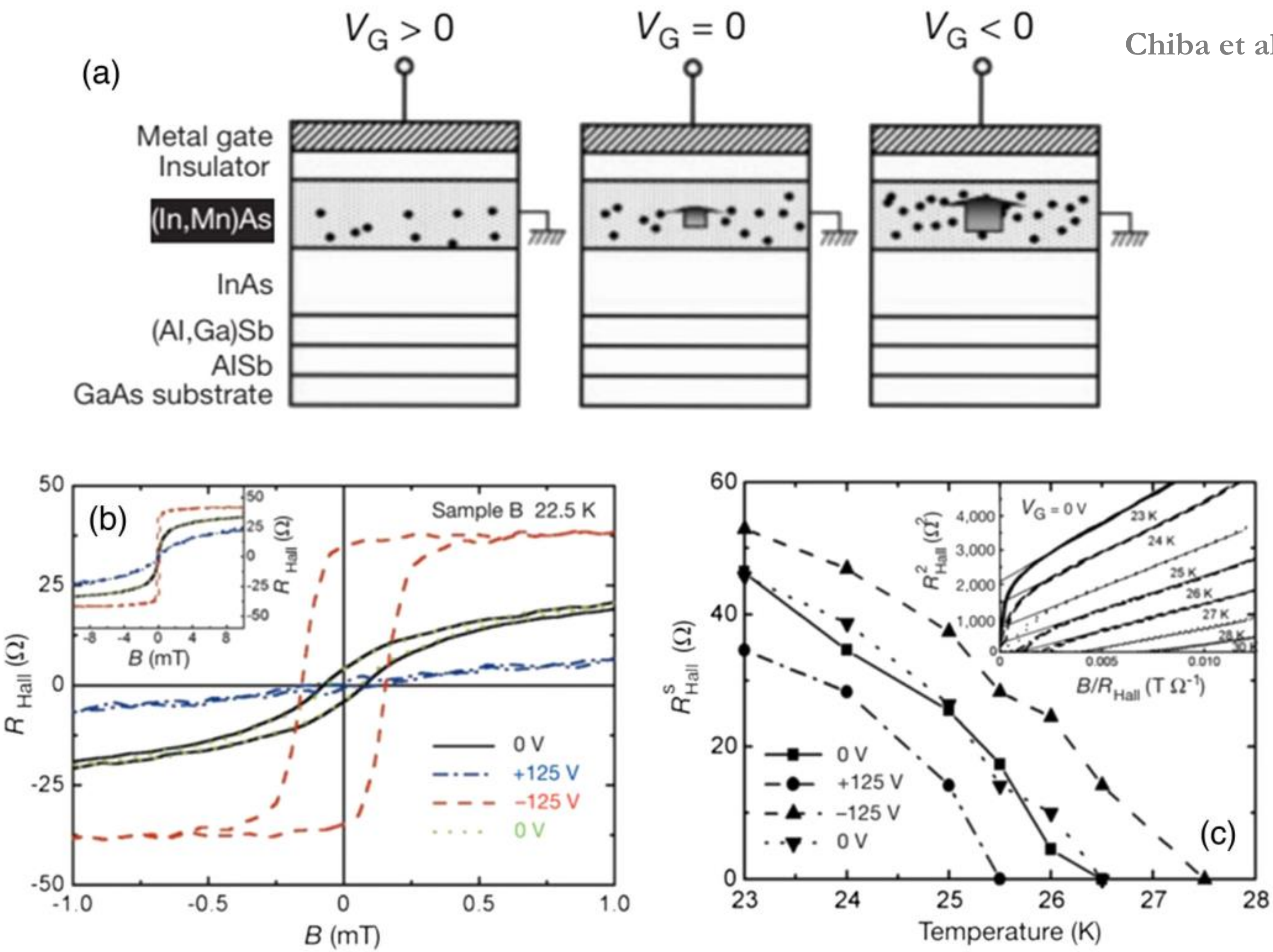
- Charge accumulation / depletion thanks to a dielectric or ferroelectric (non-volatile)
- If magnetism in channel material is (highly) sensitive to carrier density

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

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

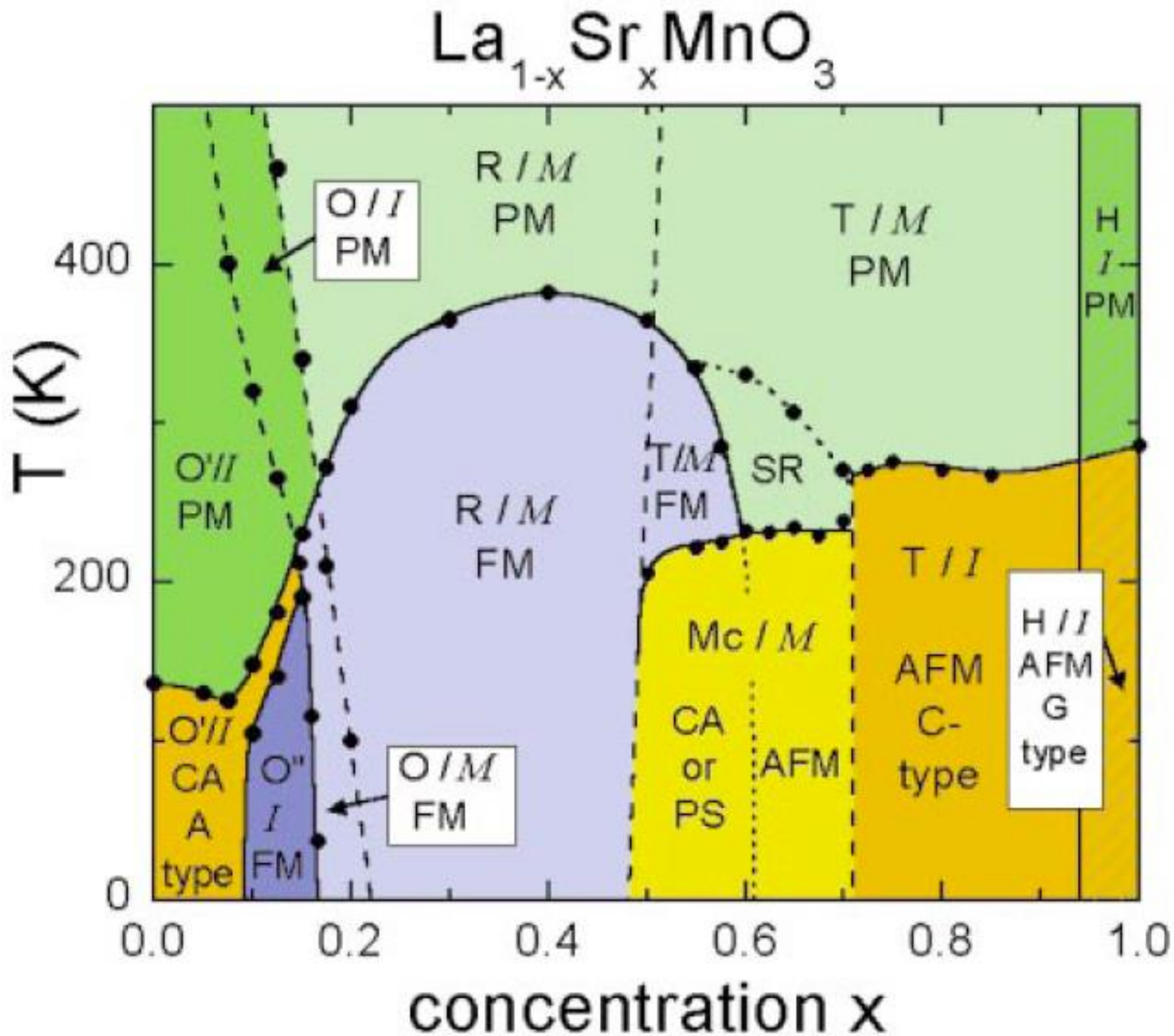
Field-effect control of magnetism in (In, Mn)As

Chiba et al, Nature (2000)



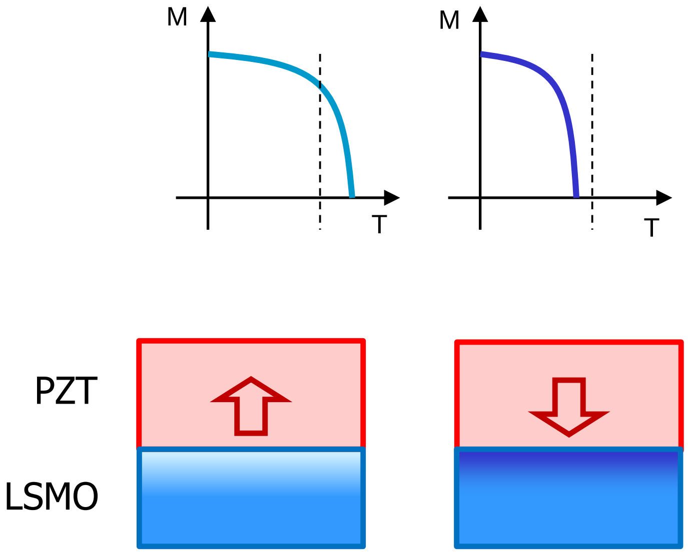
Dilute magnetic semiconductor : ferromagnetism mediated by free carriers

Mixed-valence manganites



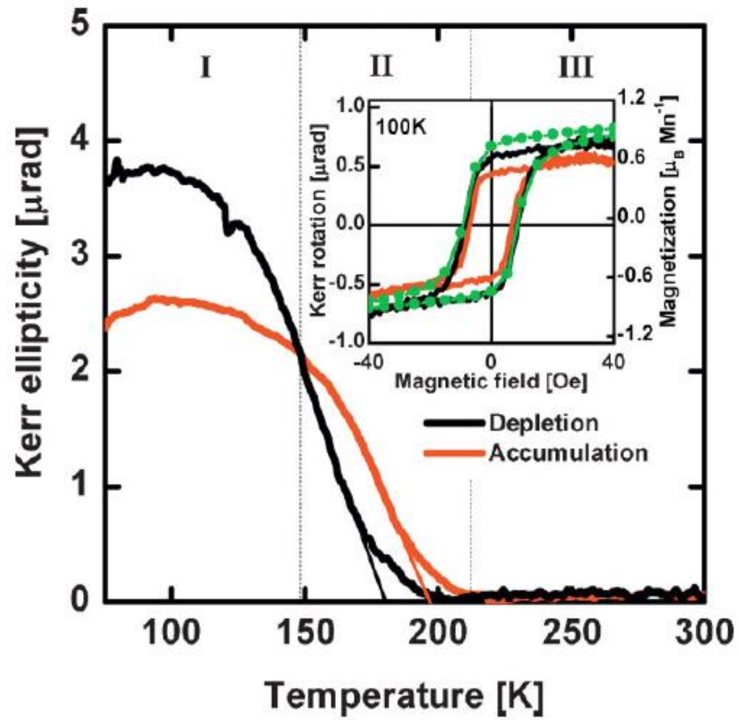
Hemberger et al., PRB, 66, 094410 (2002)

Field-effect control of magnetism in manganites



deplete electrons
accumulate holes
T_C increases

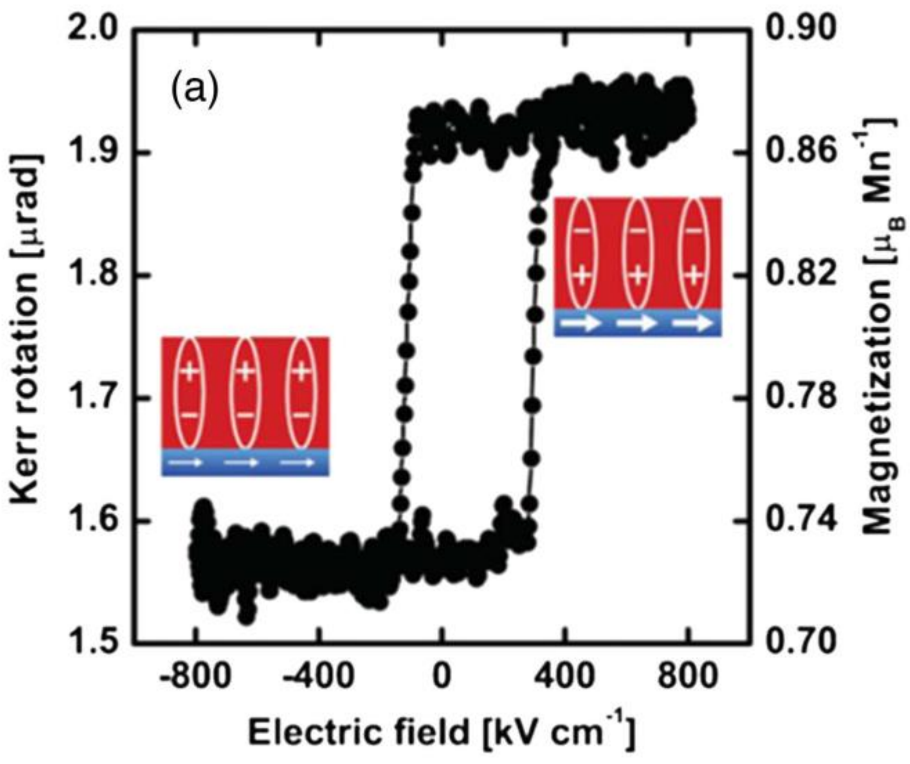
accumulate electrons
deplete holes
T_C decreases



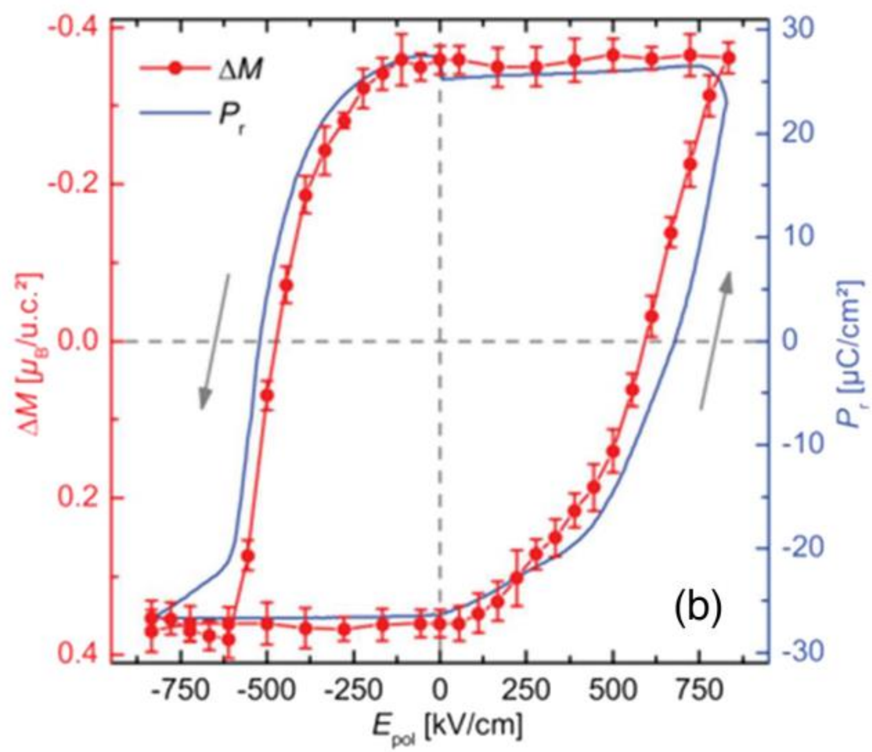
Vaz et al, PRL 104, 127202 (2010) & Molegraaf et al, Adv. Mater. 21, 3470 (2009)

- 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 or InMnAs)

PZT/LSMO bilayers



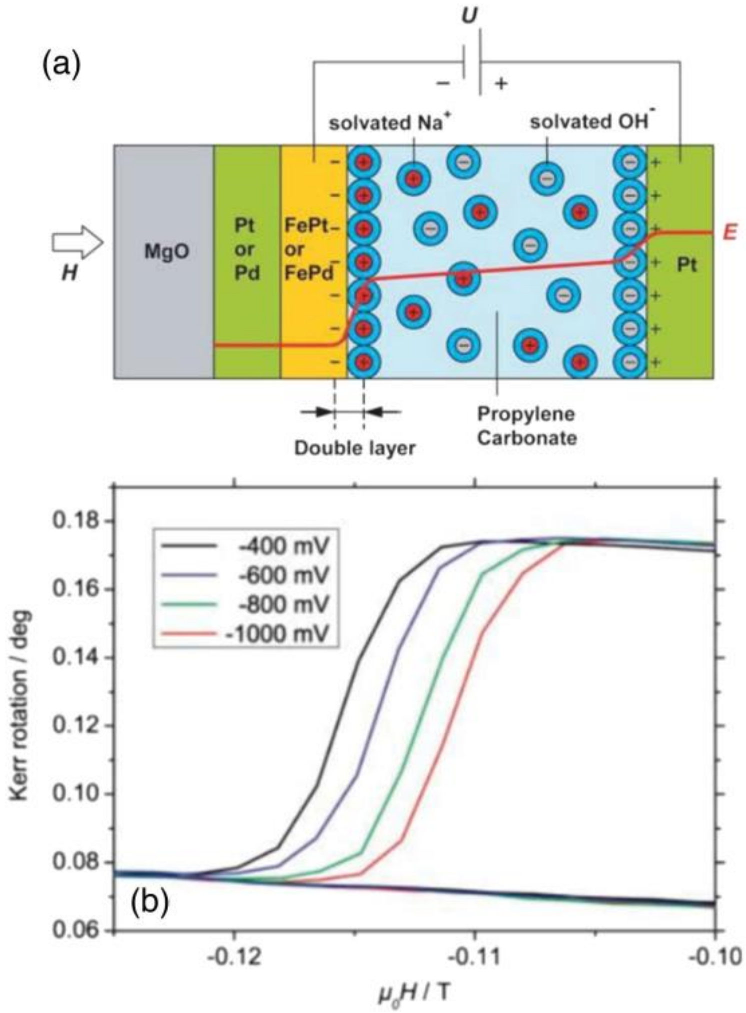
Molegraaf et al, Adv. Mater. 21, 3470 (2009)



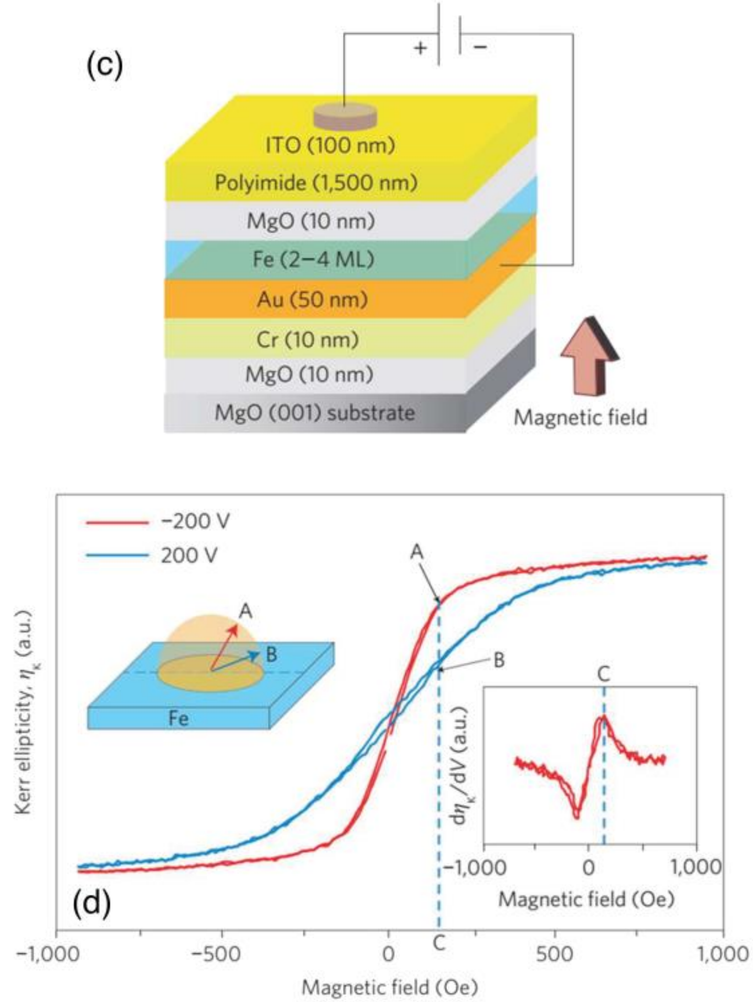
Leufke et al, PRB 87, 094413 (2013)

- Ferroelectric control of magnetization amplitude in PZT/LSMO at 50 K

Field-effect control of anisotropy in 3d ferromagnets



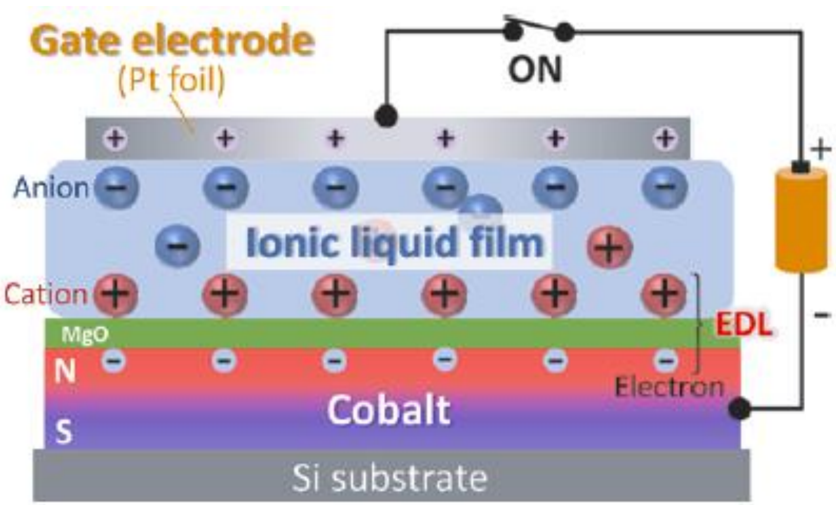
Weisheit et al, Science (2007)



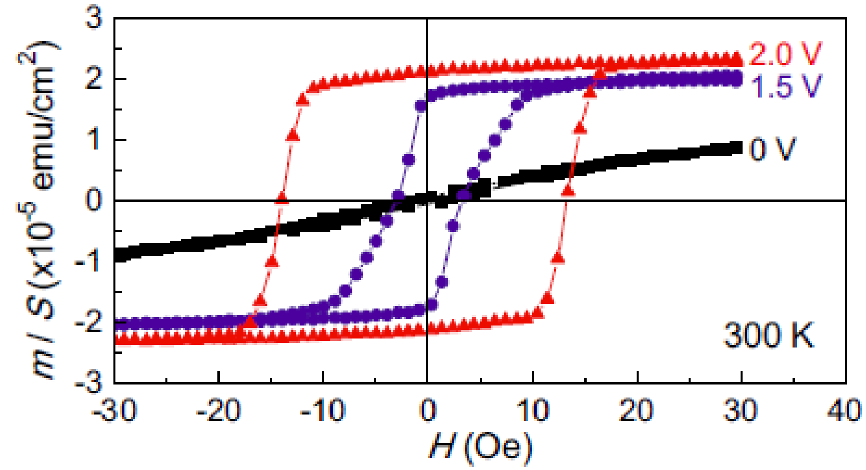
Maruyama et al, Nature Nano (2009)

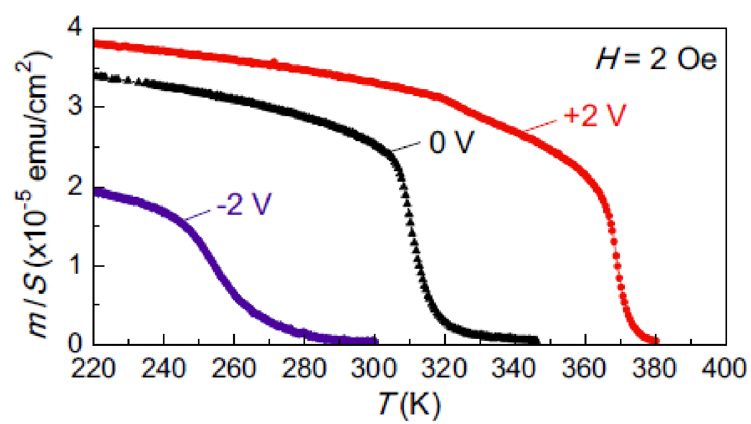
- E-field control of coercive field or magnetic easy axis

Increase accumulated charge density : ionic liquids



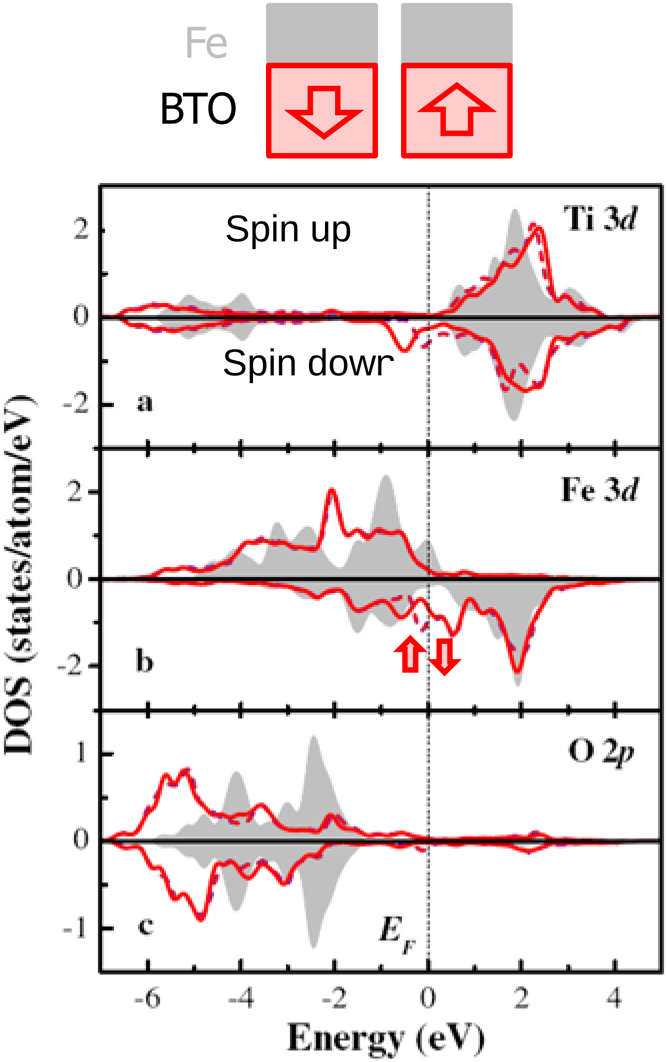
Chiba and Ono, J. Phys. D 46, 213001 (2013)





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

Ferroelectric control of spin polarization



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

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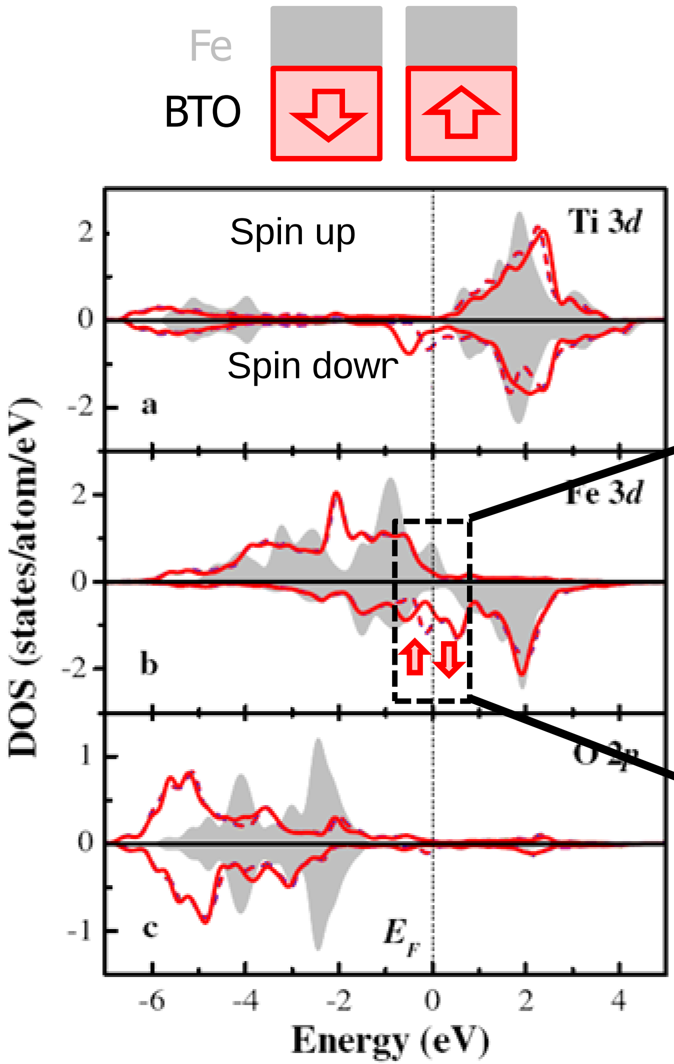
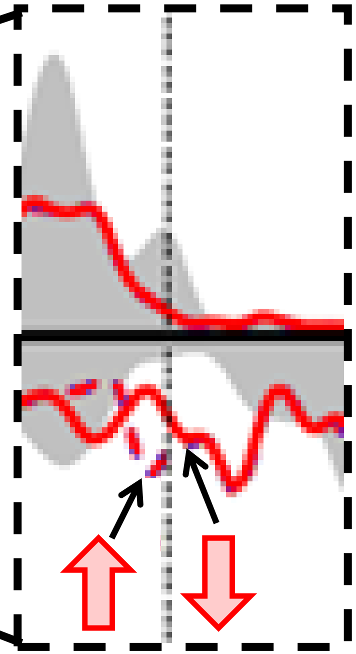


- Change of spin polarization of Fe depending on ferrolectric polarization direction
- ➔ Probe this effect in Fe/BTO/LSMO tunnel junctions



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Fechner et al, PRB 78, 212406 (2008)

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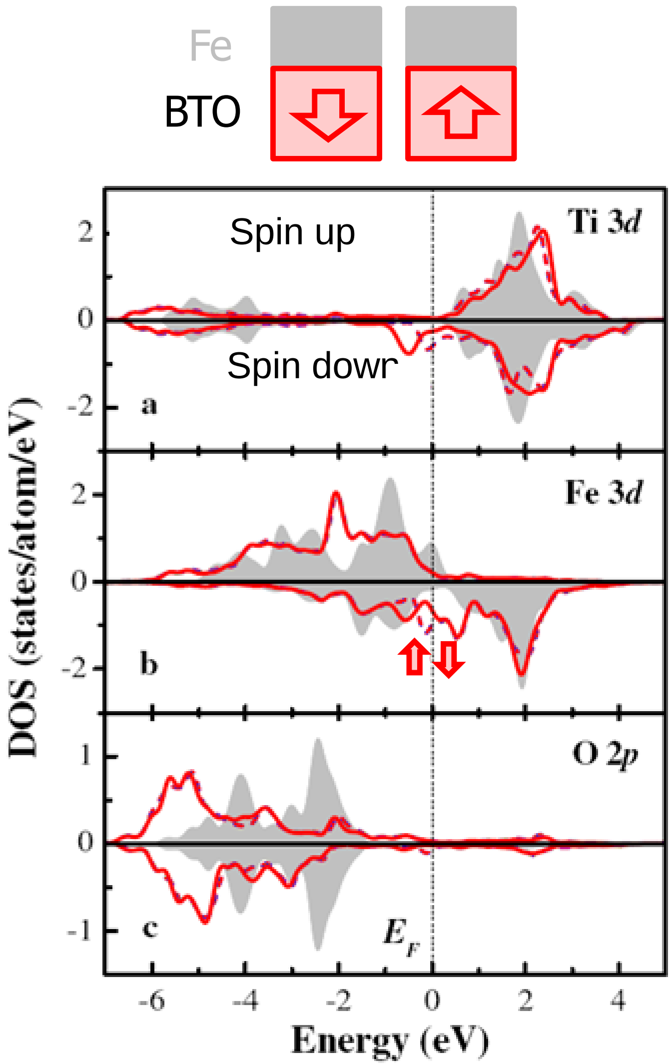

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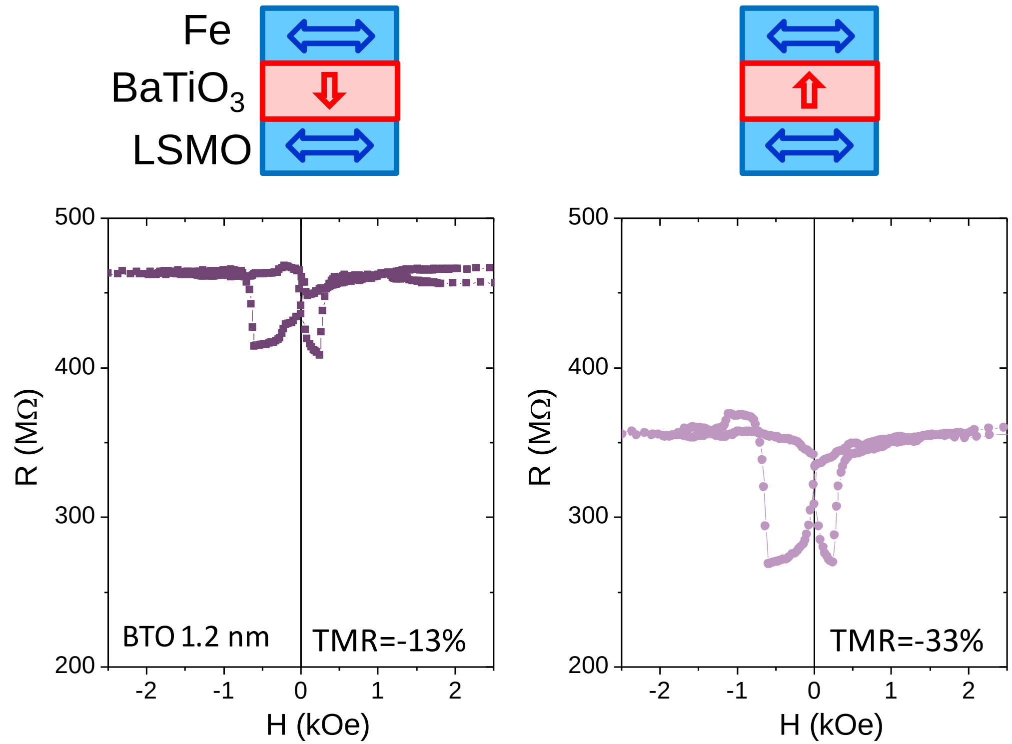


- TMR amplitude depends on direction of P
  → **Ferroelectric control of spin polarization**
- Combination of field-effect and hybridization changes

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

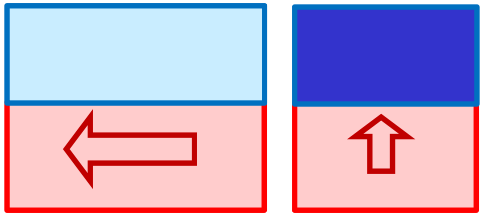
Intrinsic magnetoelectric

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

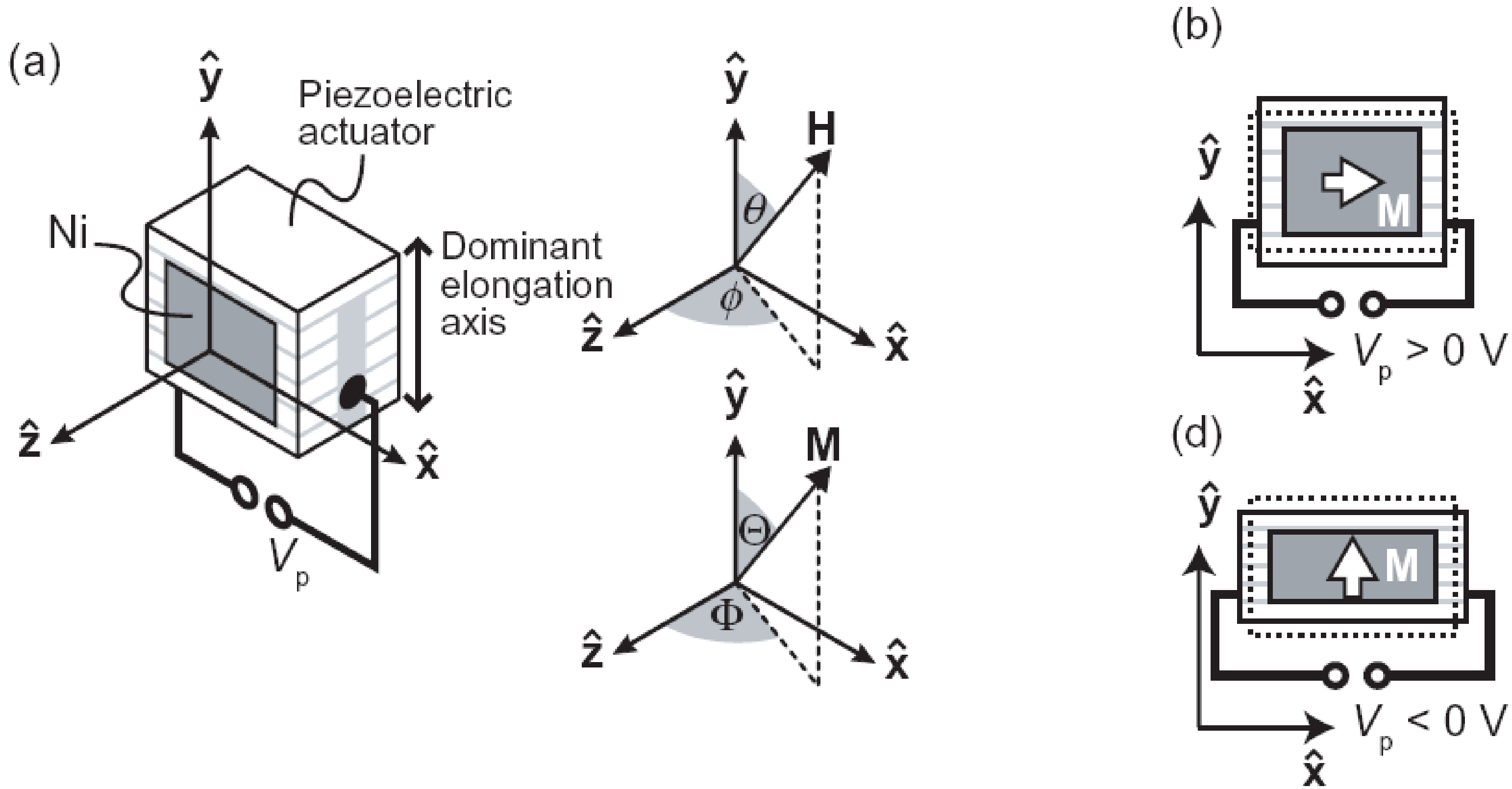
Example : experiments on PZT/Ni Weiler et al, New J. Phys 2009

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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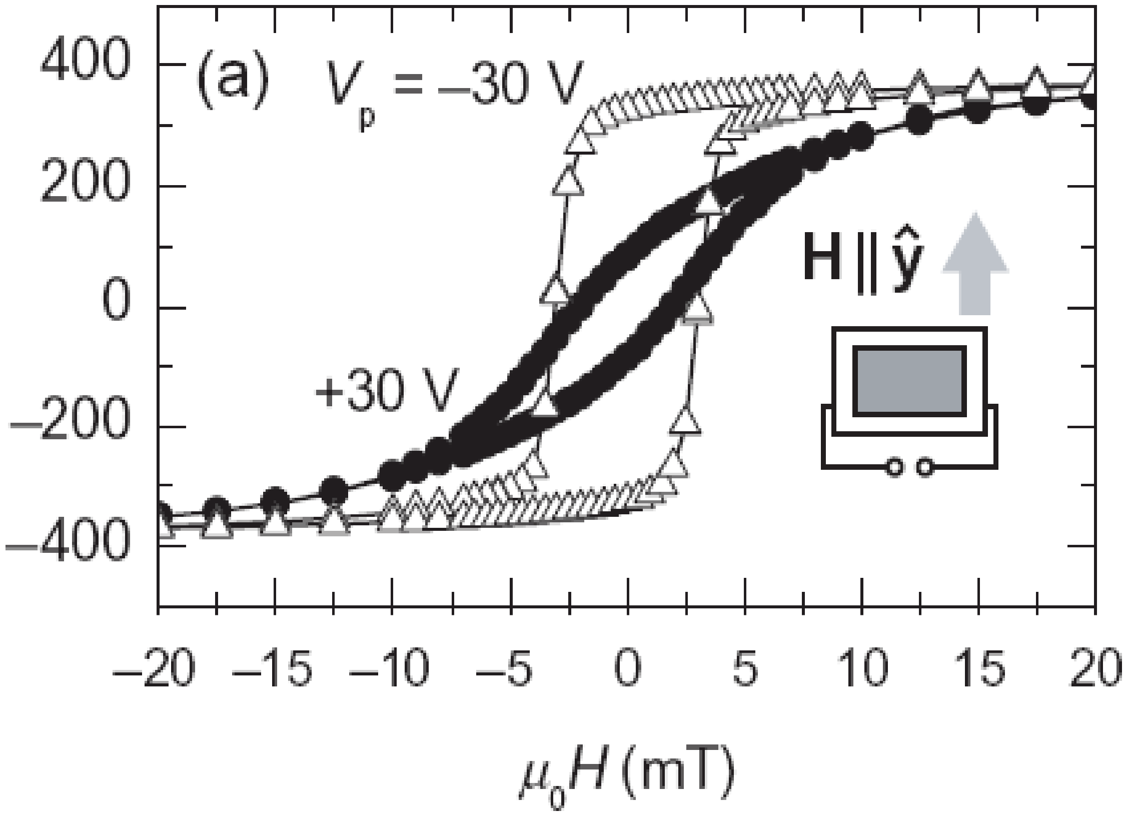
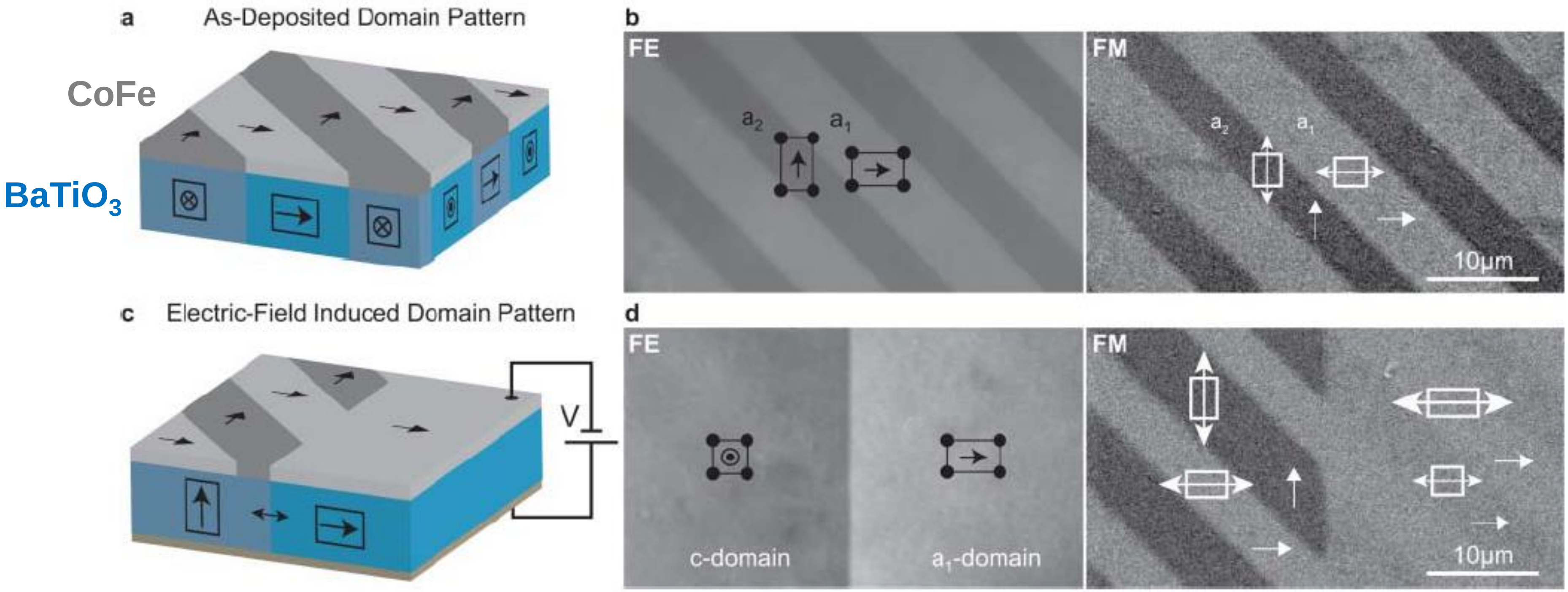


Weiler et al, New J. Phys 2009

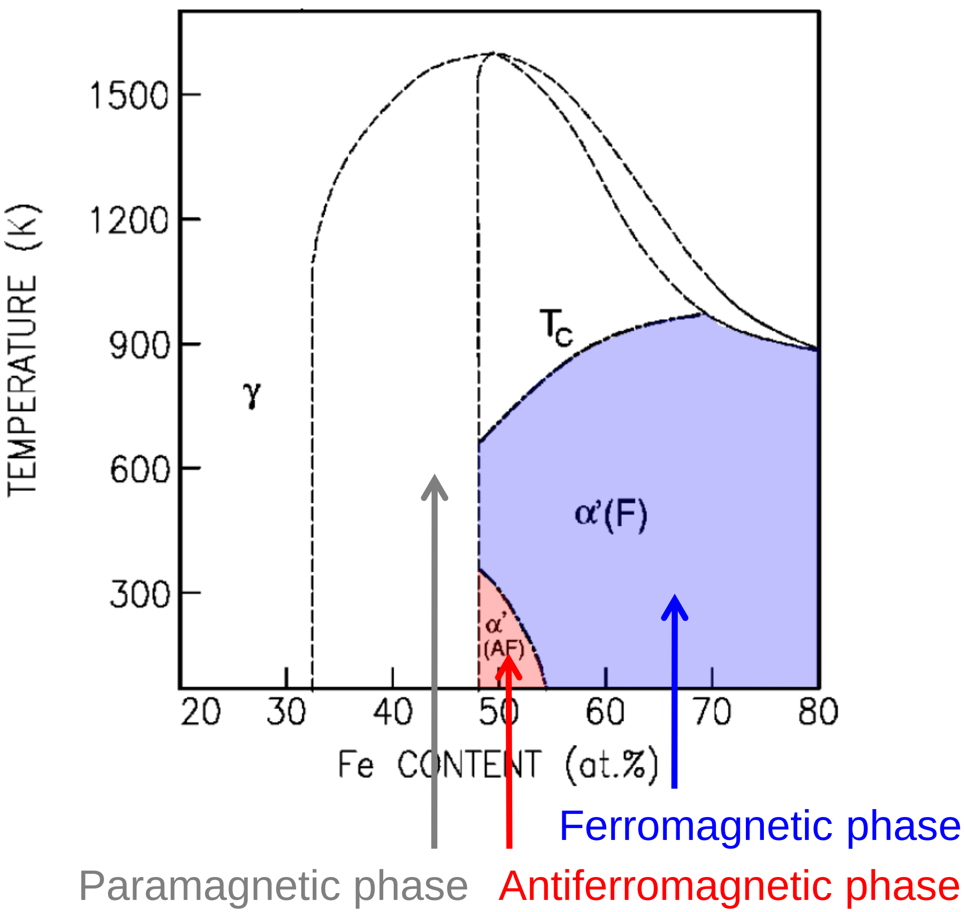
Electric-field induced control of magnetization easy axis

Electric-field control of magnetic domain wall motion and local magnetization reversal



Lahtinen et al, Sci. Rep. 2012

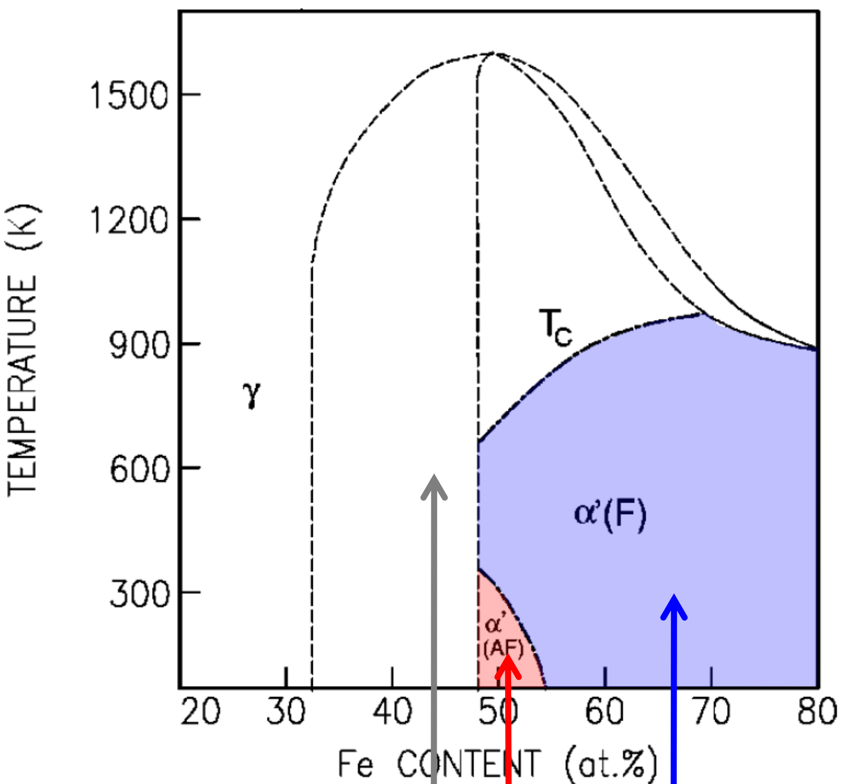
Strain-induced control of magnetic order



γ phase : fcc ; α phase : disordered bcc

α' phase : Fe/rh ordered bcc

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

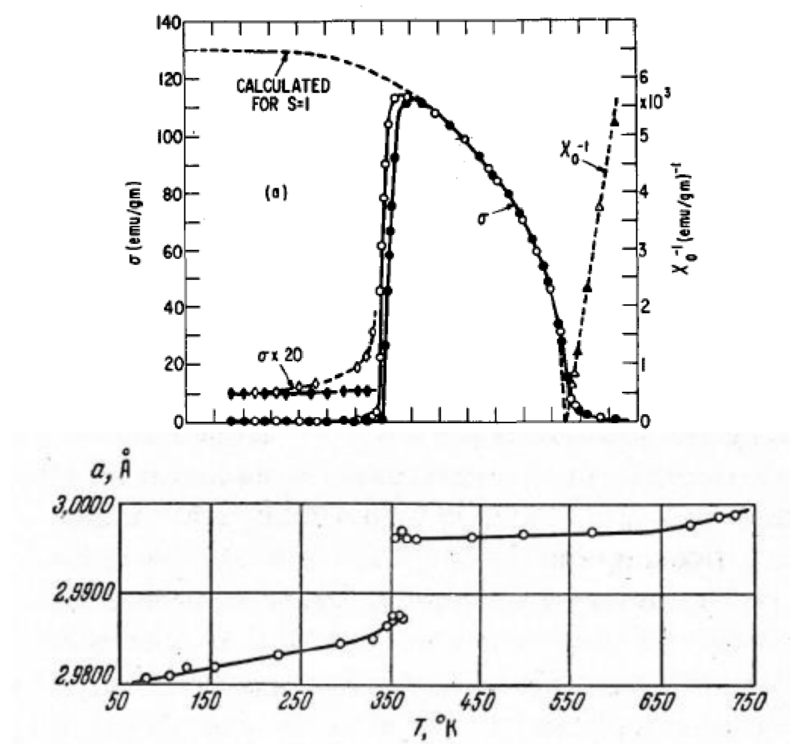


Ferromagnetic phase

Paramagnetic phase   Antiferromagnetic phase

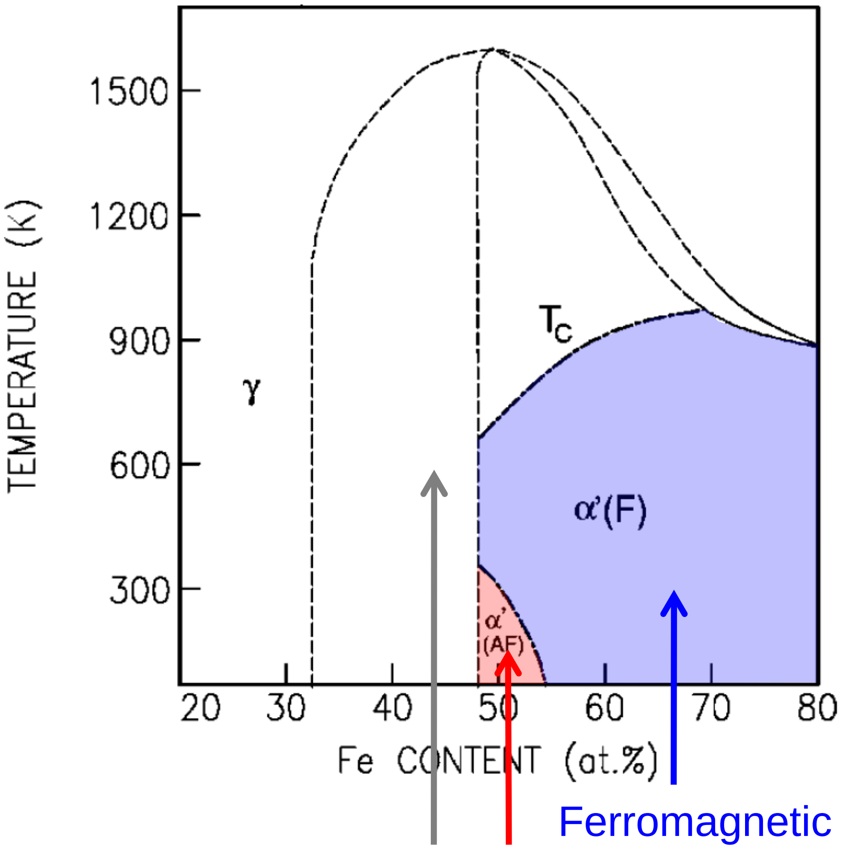
γ phase : fcc ; α phase : disordered bcc
α' phase : Fe/rh ordered bcc

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



- 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)



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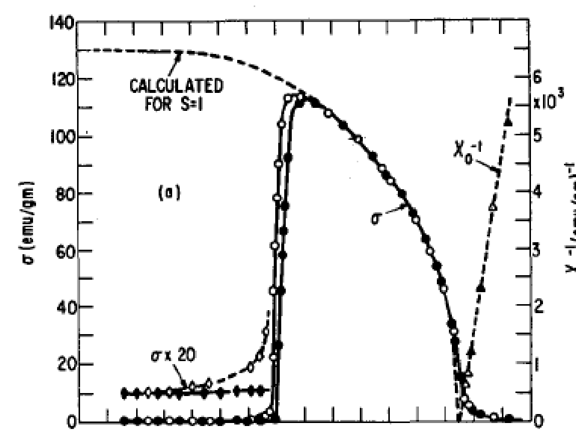

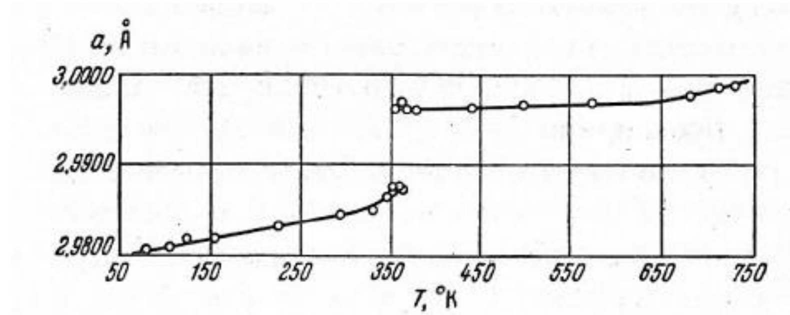

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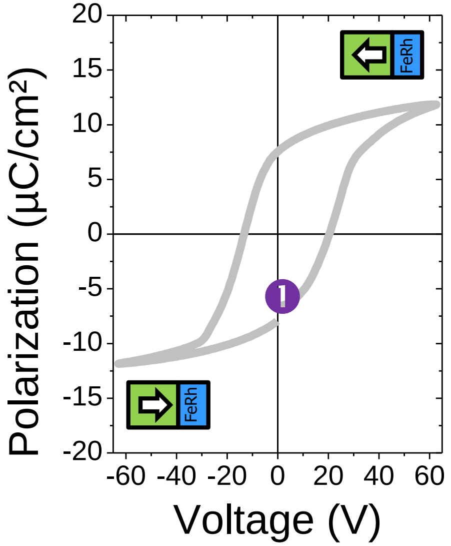
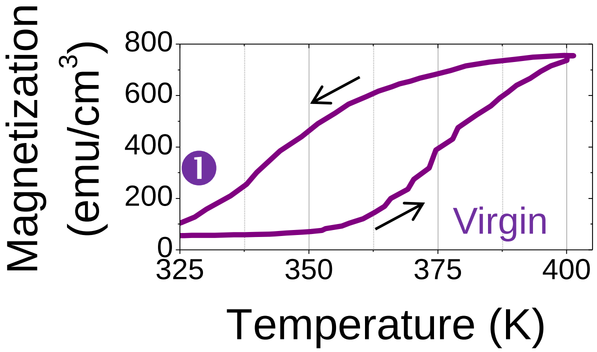
Zakharov et al, Sov. Phys. JETP 19, 1348 (1964)

- Magnetic state of FeRh is sensitive to pressure

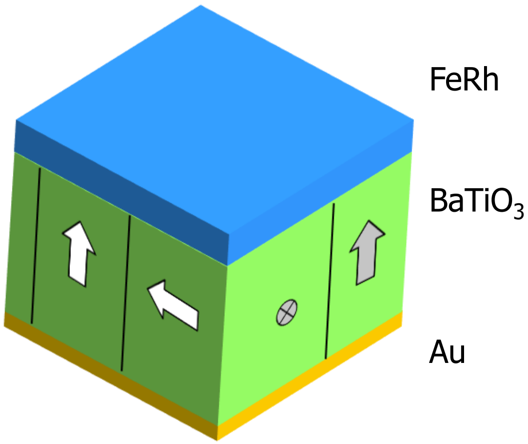
➔ Grow on **ferroelectric/ferroelastic $BaTiO_3$** substrate to achieve E-field control

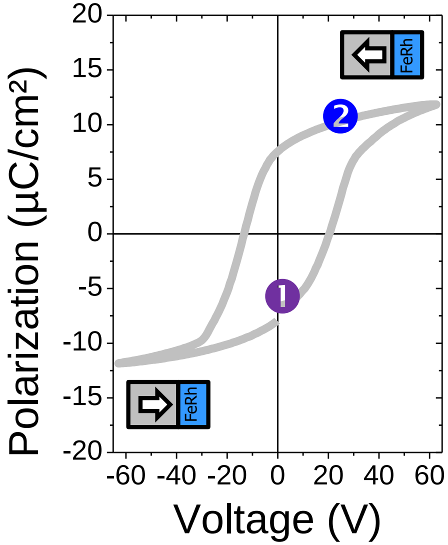
Strain-induced control of magnetic order

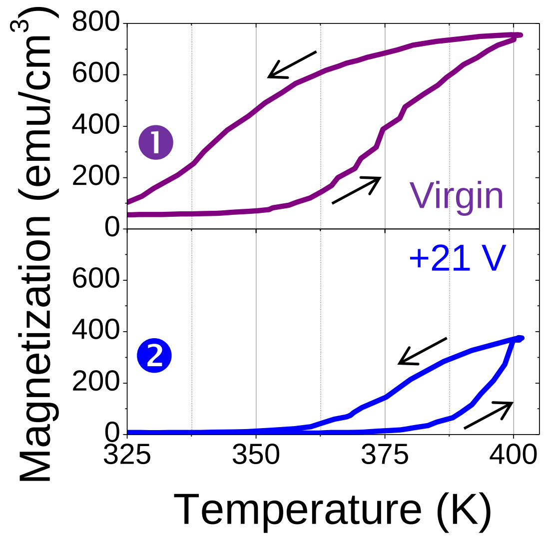




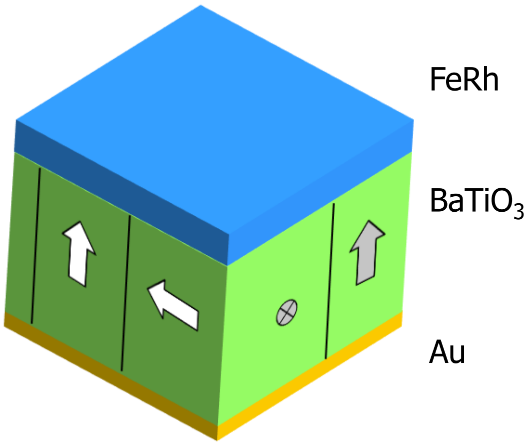
- At 0V at 20 kOe, T*≈360 K



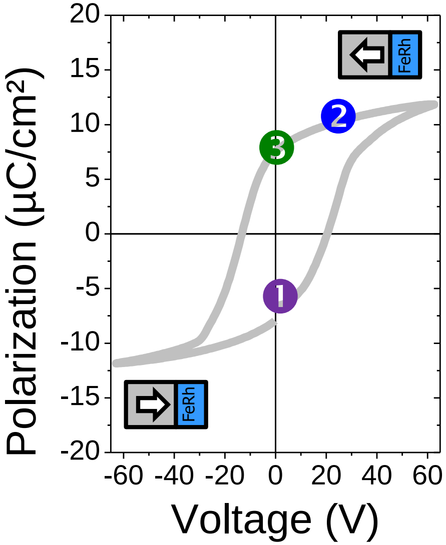


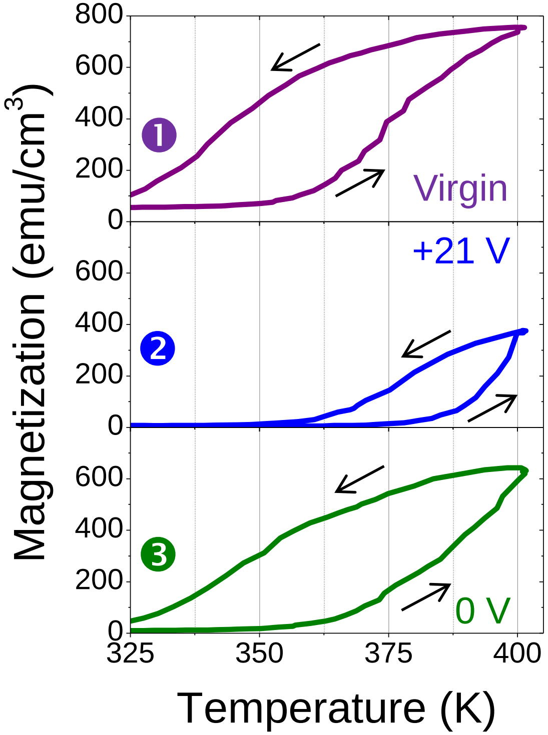


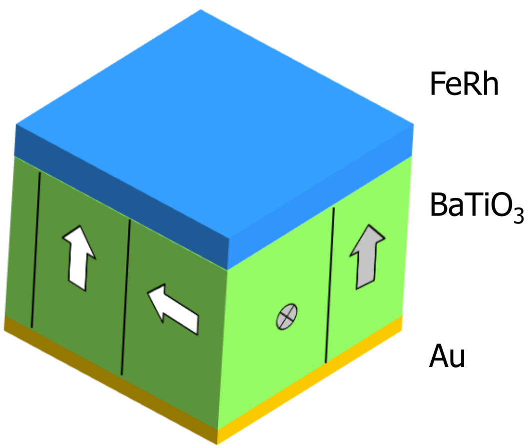
- At 0V at 20 kOe, T*≈360 K
- Voltage shifts T* by ~20K



Strain-induced control of magnetic order







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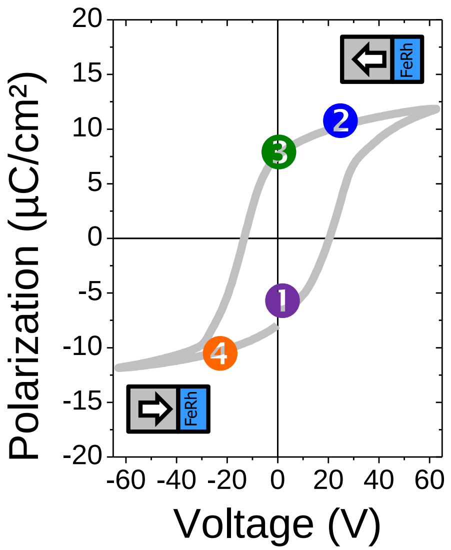
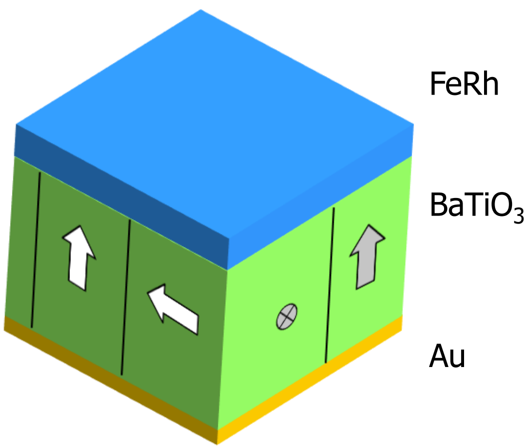
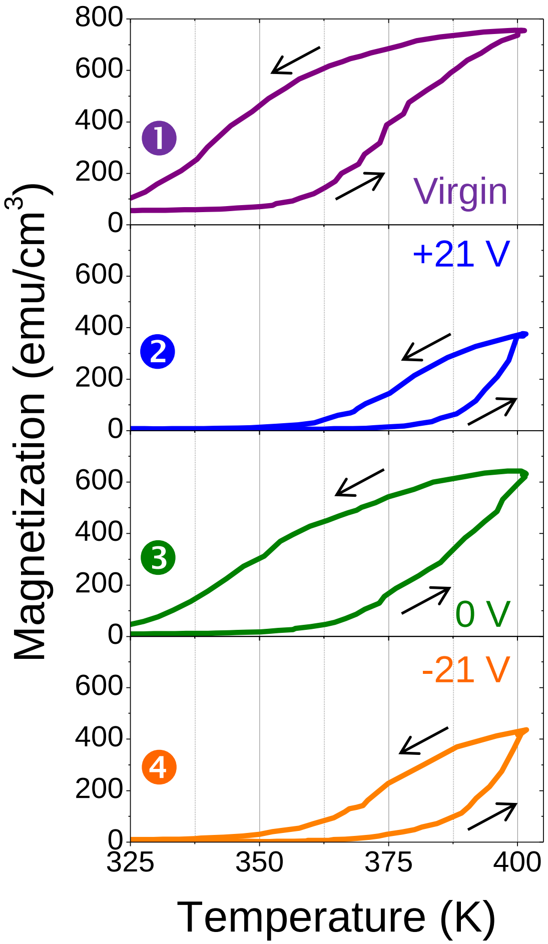
- Effect is reversible

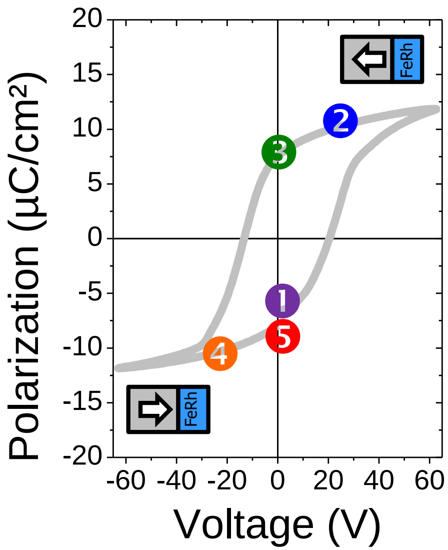
Strain-induced control of magnetic order

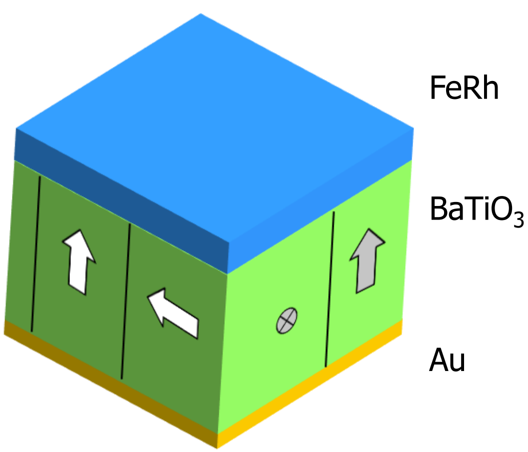


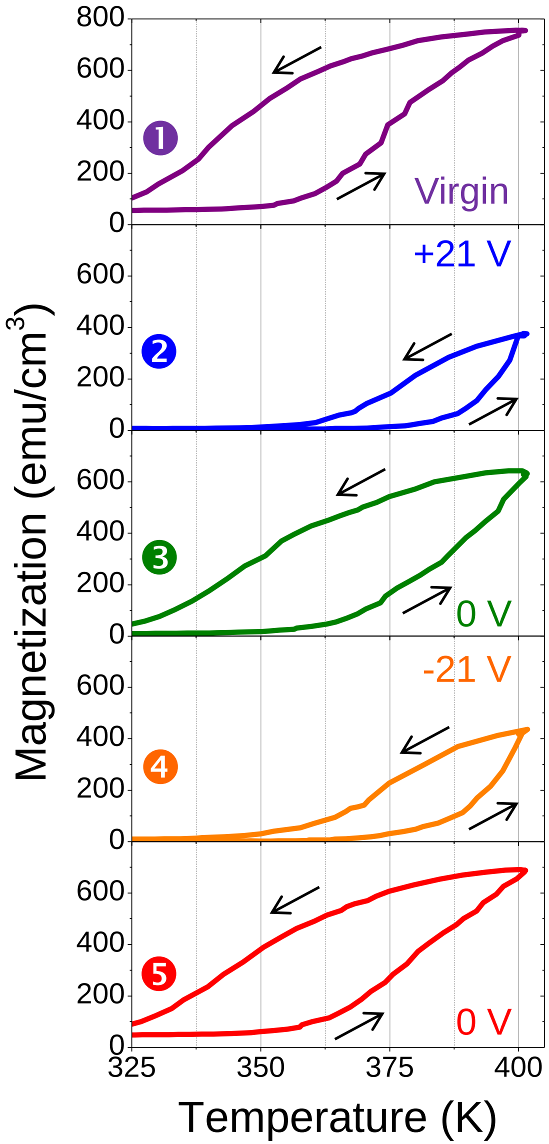




- At 0V at 20 kOe, T*≈360 K
- Voltage shifts T* by ~20K
- Effect is reversible
- Positive or negative voltages give roughly similar effect







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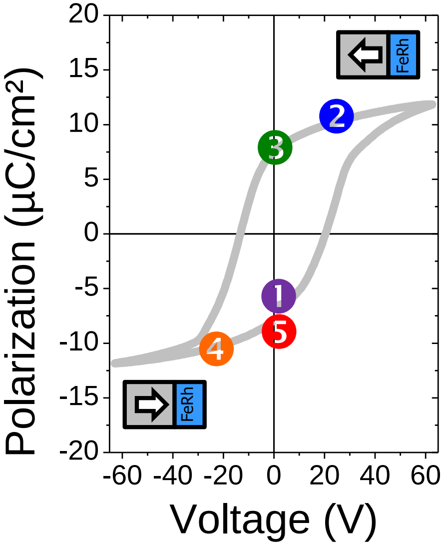

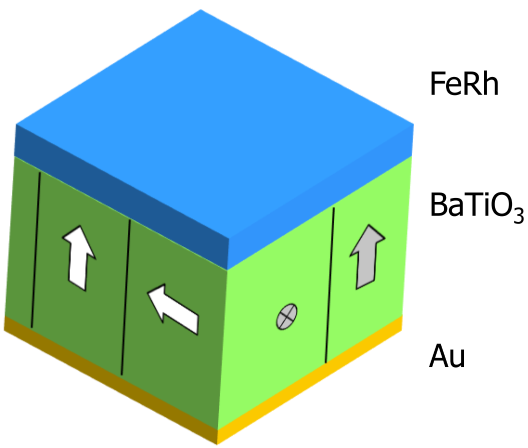

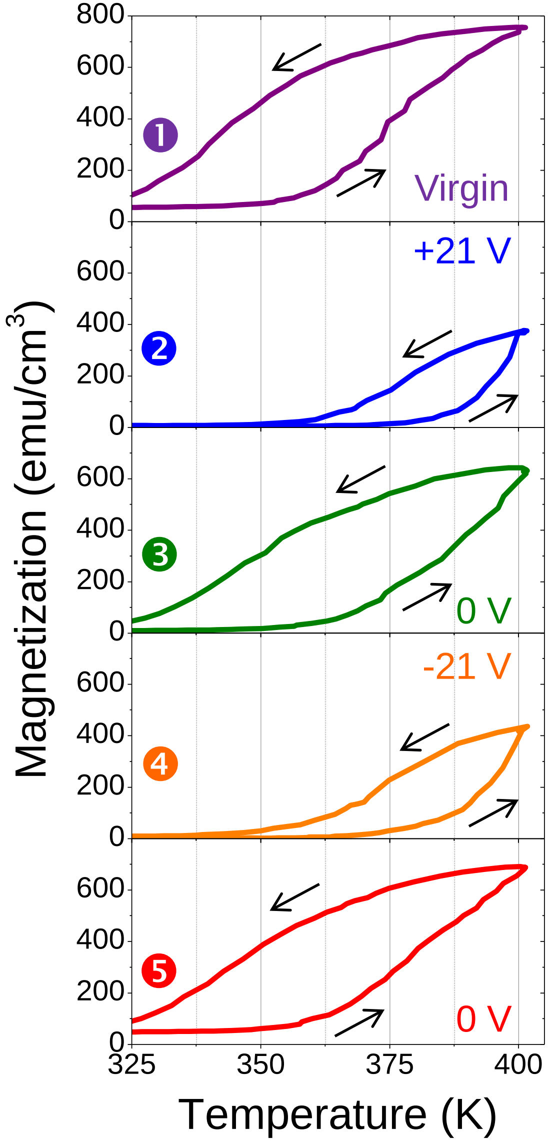

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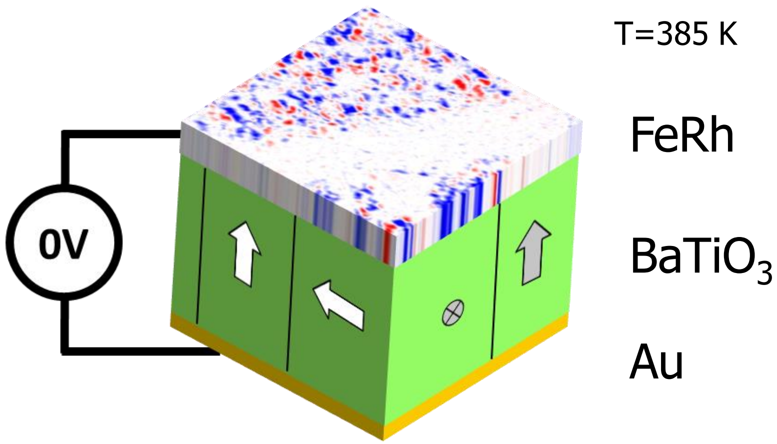
- Max magnetization change ~600 emu/cm^3
- ME coupling α=1.6.10^{-5} s/m
- Larger than in any single phase material by 5 orders
- Larger than in any artificial multiferroic by factor >10

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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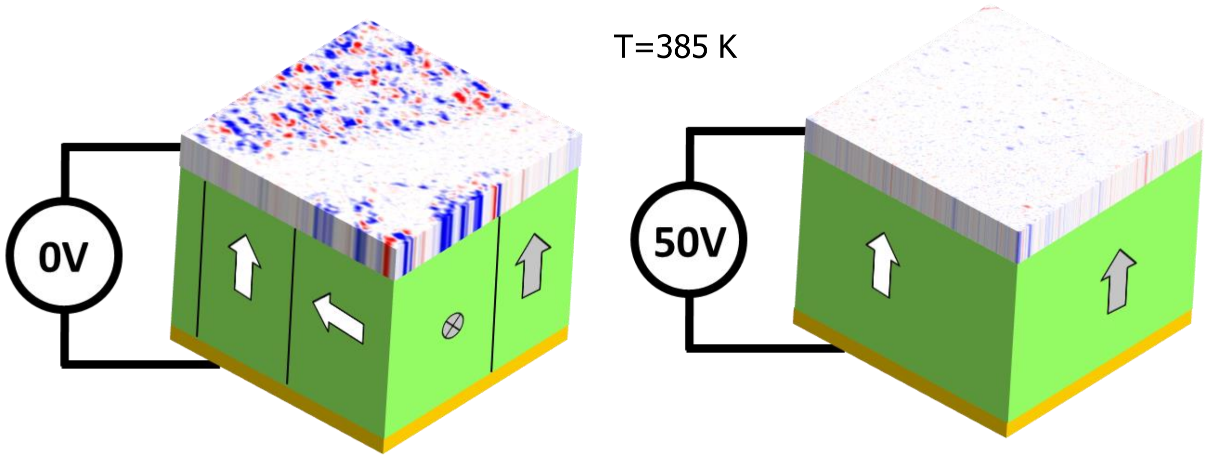

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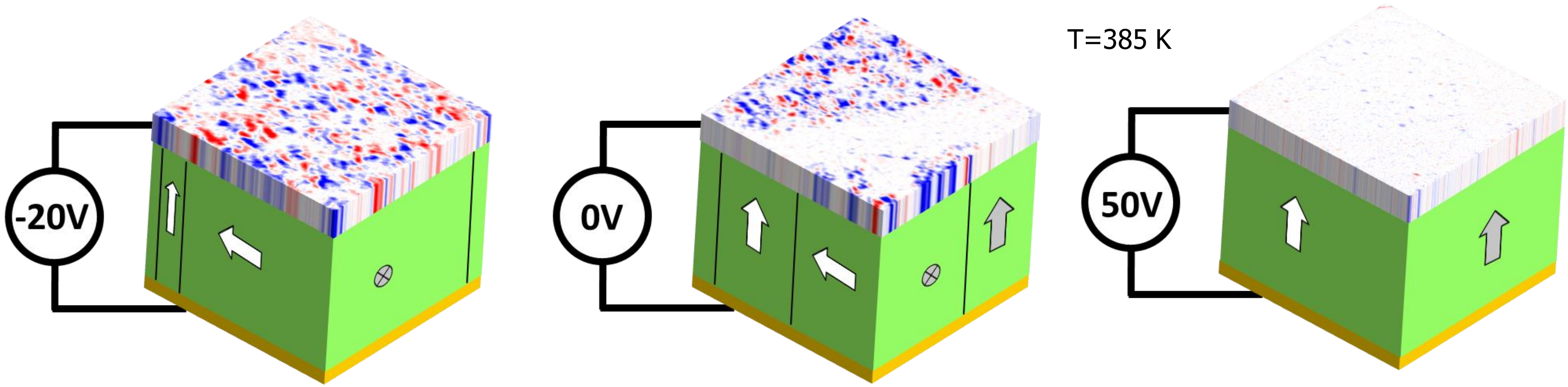


Ferromagnetic state

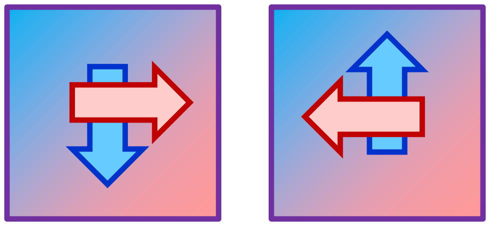
Mixed ferro/ antiferromagnetic state

Antiferromagnetic state

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

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

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)
- ✗ Needs very large fields

Strain-driven

Combine piezoelectric or ferroelectric/ferroelastic with magnetostrictive ferromagnet

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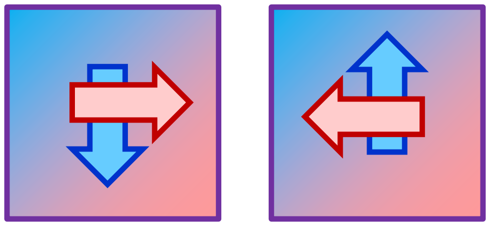

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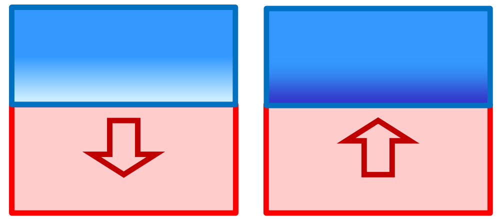

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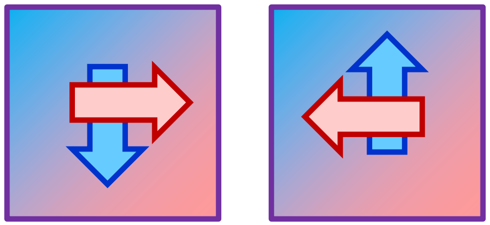
Different approaches for E-field control of magnetism

Intrinsic magnetoelectric



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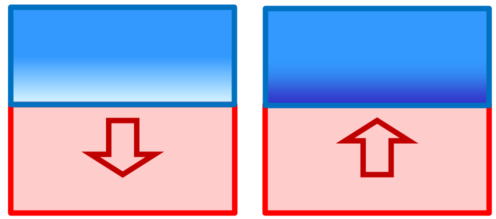

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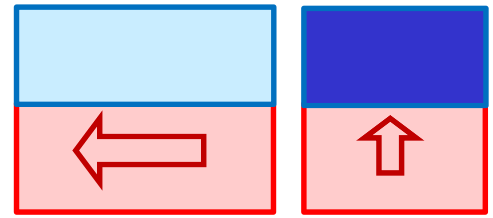

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Outline

- Ferroic orders and magnetoelectric coupling
  - Intrinsic" magnetoelectric coupling
  - Field-effect-driven magnetoelectric coupling
  - Strain-driven magnetoelectric coupling

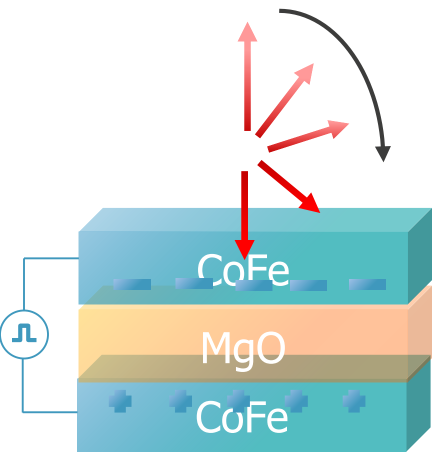
- Magnetoelectric spintronic devices :
  - VCMA-MRAM
  - Magnetoelectric RAM
  - Magnetoelectric Spin orbit (MESO) devices

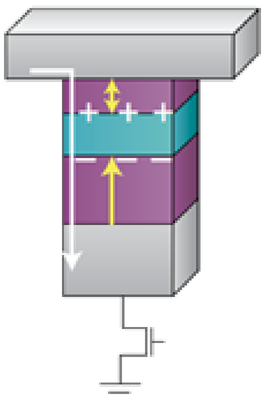
- Integration challenges

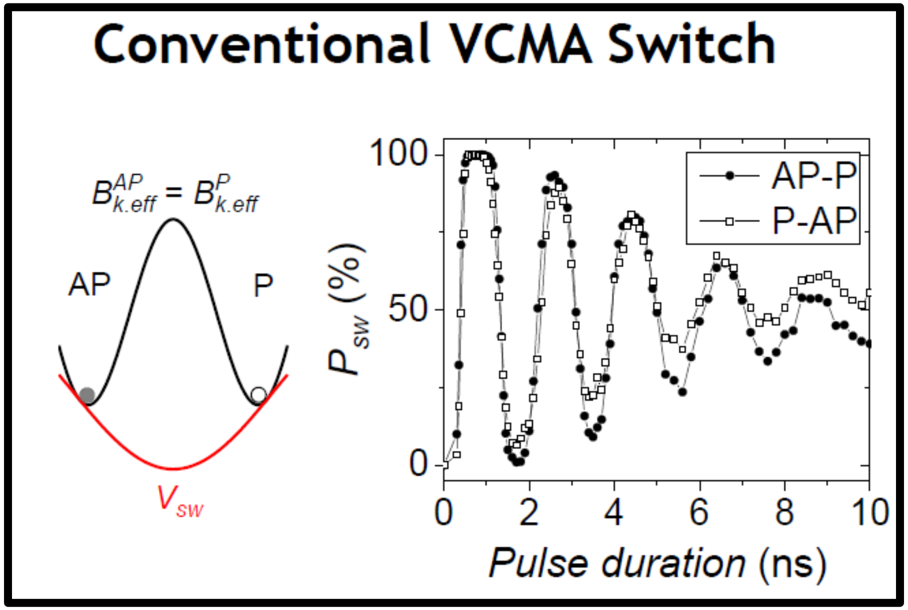
Technology readiness level

Voltage-controlled magnetic anisotropy (VMCA)

Voltage controlled device
(instead of current controlled)



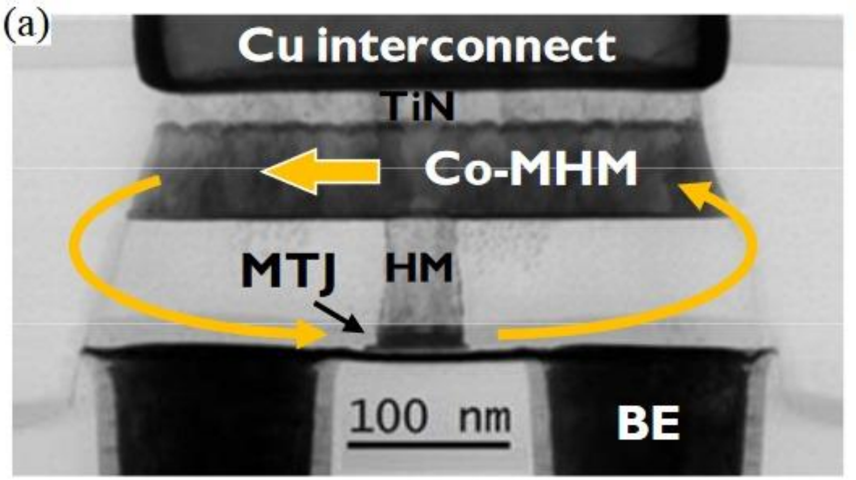


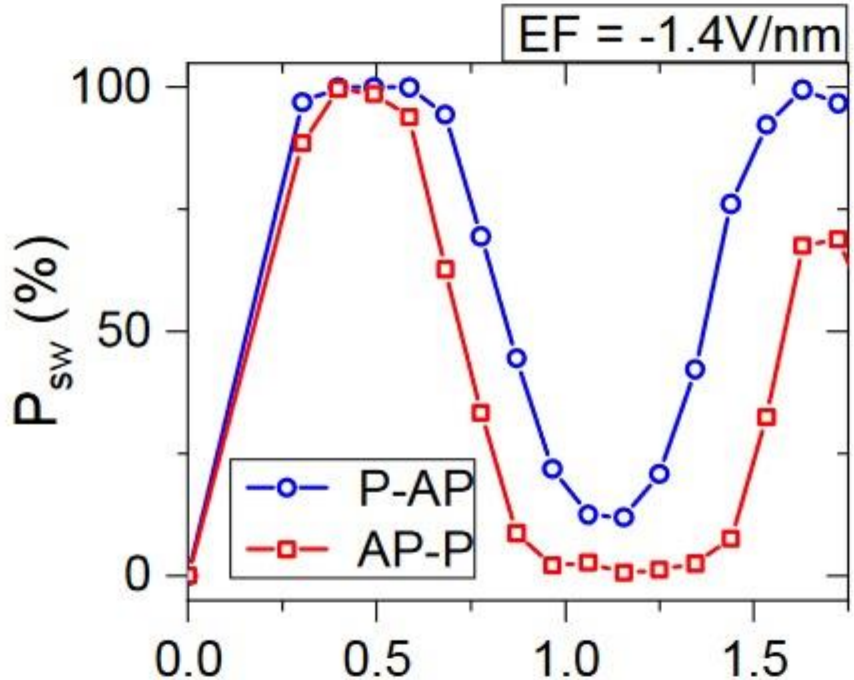


- Voltage control: Ultra low power at GHz speed
- Precessional switching, sub-ns dynamics

- Non deterministic: requires external field
- RA >100Ω.µm² required
- Read time penalty at large resistances

Y. Shiota, Nat. Mater., vol. 11, no. 1, pp. 39 (2012), C. Grezes, Appl. Phys. Lett., vol. 108, pp. 012403 (2016)

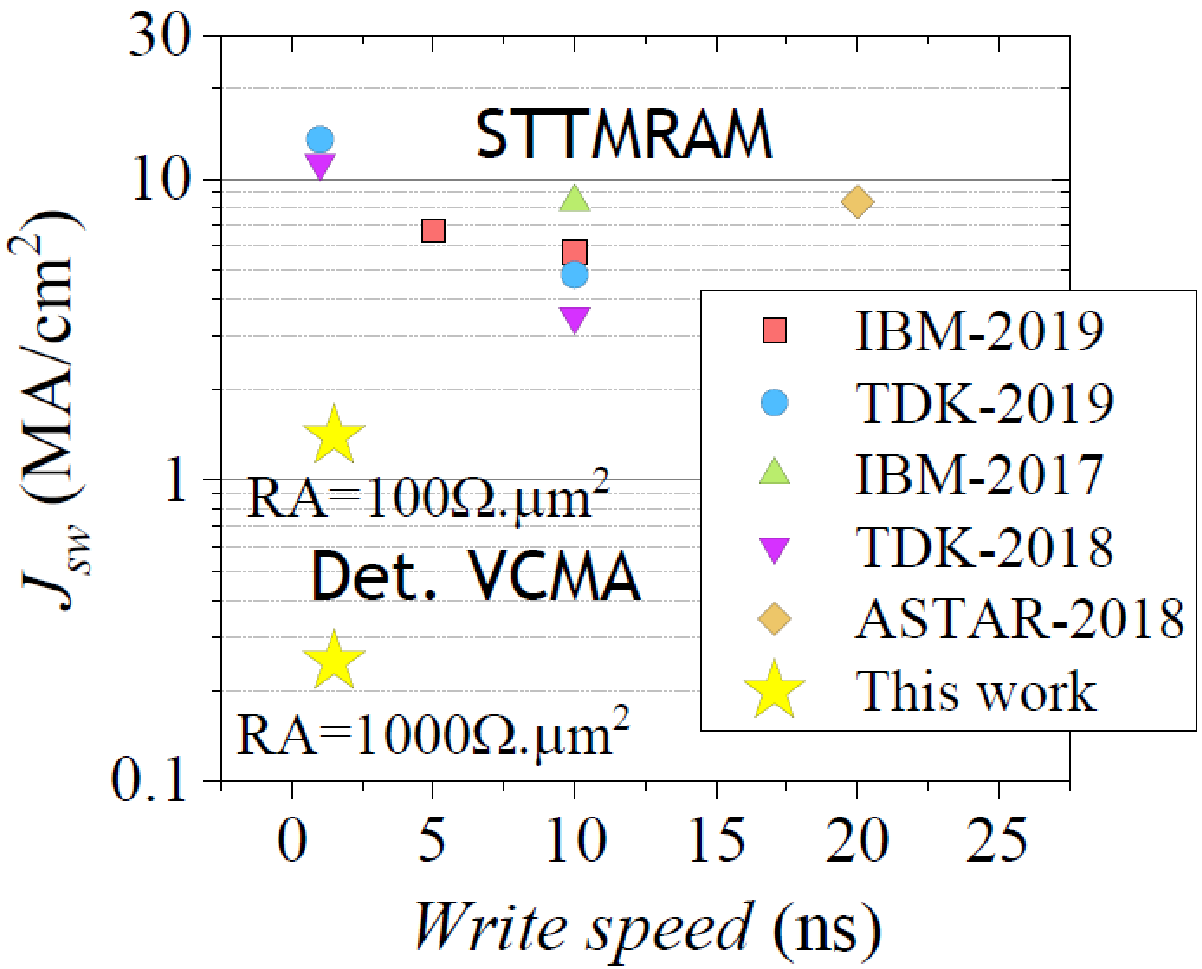




K. Garello, Spintec

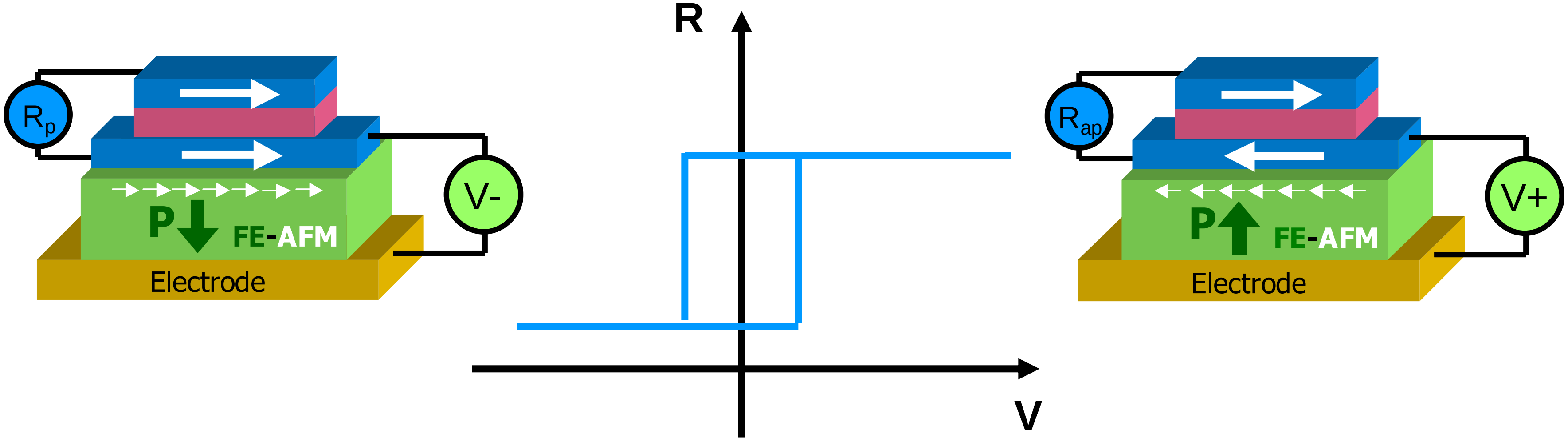
- Replace external field by hard magnetic layer onto of MTJ (→ generates stray field)
- Depending on pulse duration, switch from P to AP or AP to P

VCMA-MRAM



- Lower switching current density compared to STT MRAM
- Current challenges : improve bit error rate and device to device variations

Y.C. Yu, IEEE Symposium of VLSI Technology (2020)



MB & A.Barthélémy, Nature Materials 7, 425 (2008)

Prerequisites :

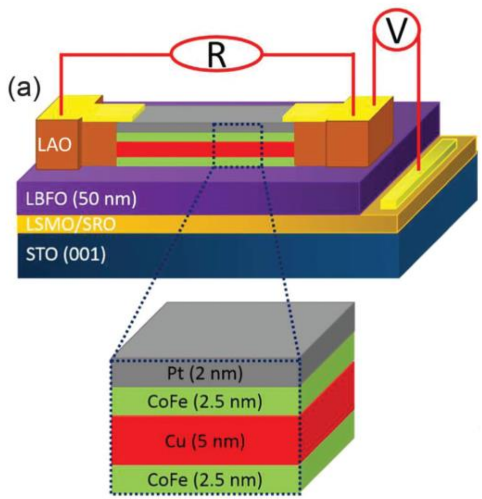
1. observe robust exchange coupling at room-temperature
2. no leakage through FE layer
3. observe GMR on the trilayer
4. control exchange coupling by E-field (via the magnetoelectric coupling)

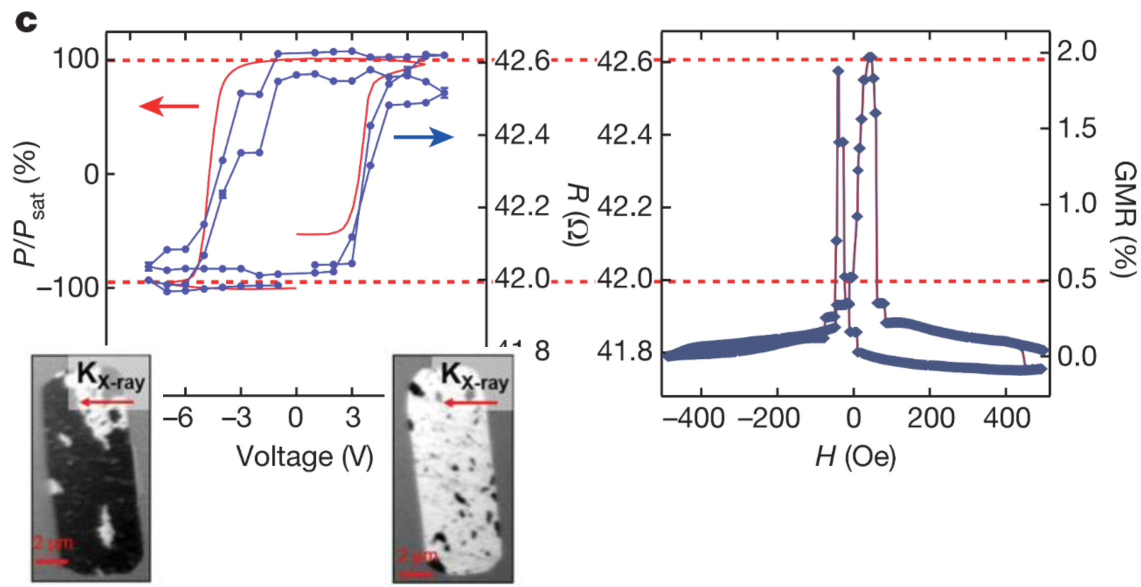
Magnetoeletric random access memory (MERAM)

Metric	STT-MRAM	SOT-MRAM	VCMA-MRAM	MERAM
Write Energy (fJ)	500	250	50	5
Write Speed (ns)	10	3	3	5
Read Energy (fJ)	50	50	50	50
Endurance (cycles, log10)	15	15	14	14
	Demonstrated	Demonstrated	Demonstrated	Projected

- STT-MRAM are commercial products
- Next in development are SOT-MRAM, and VCMA-MRAM
- MERAM would yield a 100x gain in write energy vs STT-MRAM and 10x vs VCMA-MRAM

Towards MERAM based on $BiFeO_3$



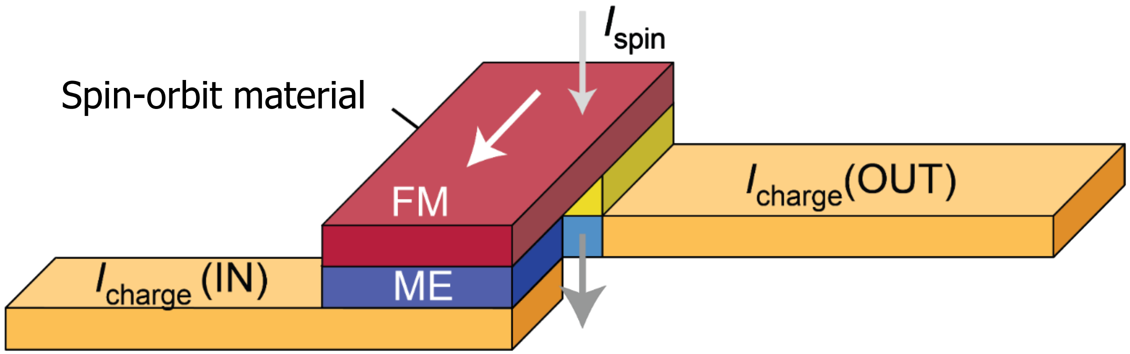


- Here CoFe single layer is replaced by CoFe/Cu/CoFe trilayer (GMR spin valve)
- Trilayer resistance is switched by electric field, suggesting magnetization in bottom CoFe layer switched by 180 degrees

Heron et al, Nature 516, 370 (2014)

Scalable energy-efficient magnetoelectric spin–orbit logic

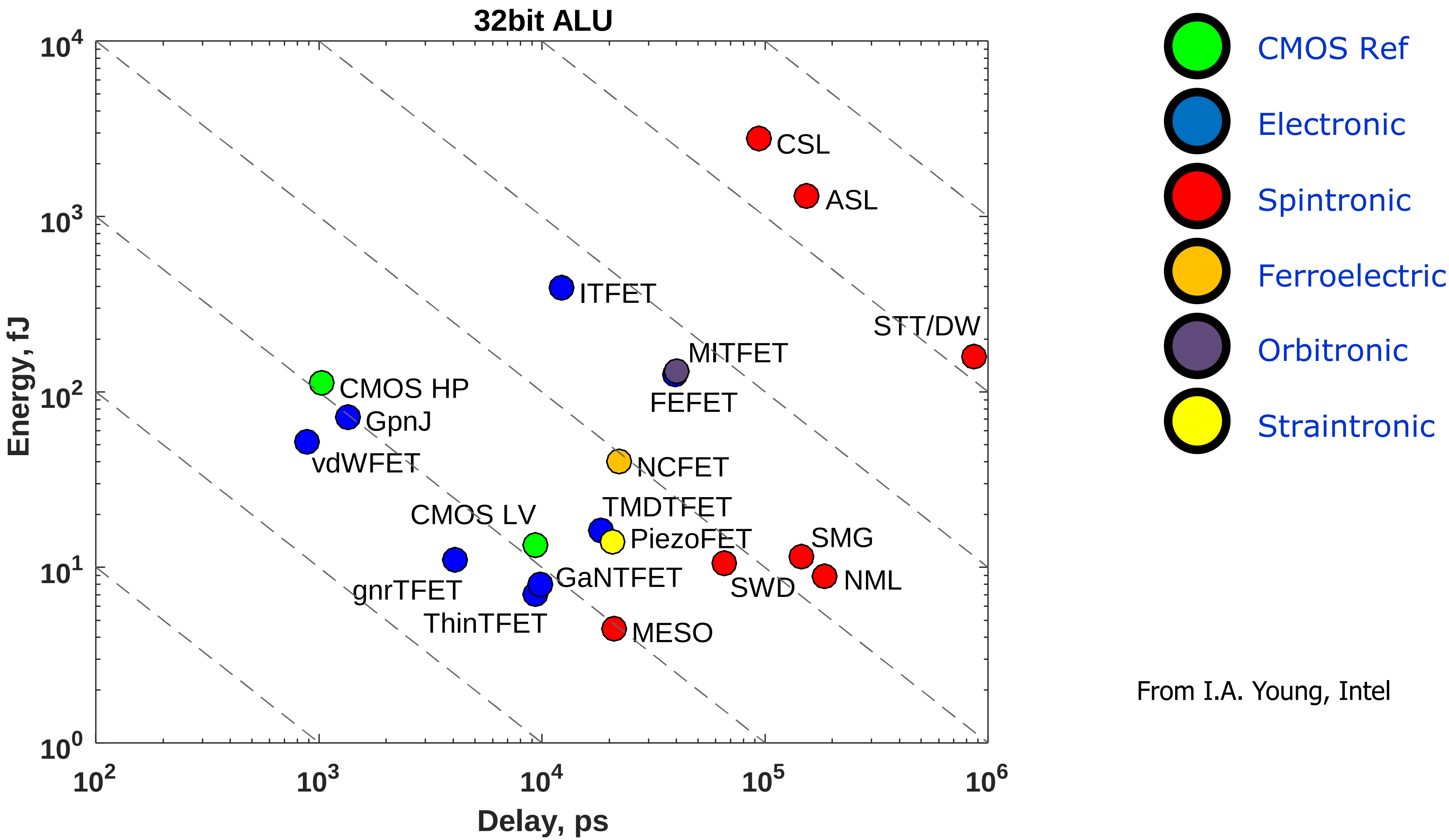
Sasikanth Manipatruni[1]*, Dmitri E. Nikonov[1], Chia-Ching Lin[1], Tanay A. Gosavi[1], Huichu Liu[2], Bhagwati Prasad[3], Yen-Lin Huang[3,4], Everton Bonturim[3], Ramamoorthy Ramesh[3,4,5] & Ian A. Young[1]



- 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)

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

Magneto-electric spin-orbit transistor (MESO)

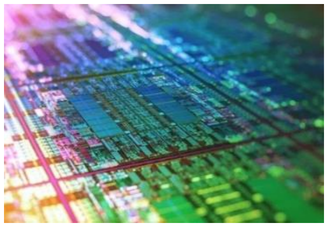


From I.A. Young, Intel

- MESO slightly slower than advanced CMOS but lower energy and non-volatile

Magneto-electric spin-orbit transistor (MESO)

CMOS +
Von Neumann
architecture



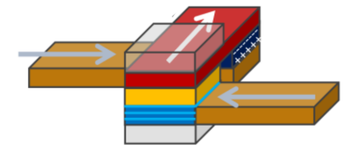
Energy consumption

Memory and logic in a single component
x2 - x3

Non-volatility
x1.3 - x1.5

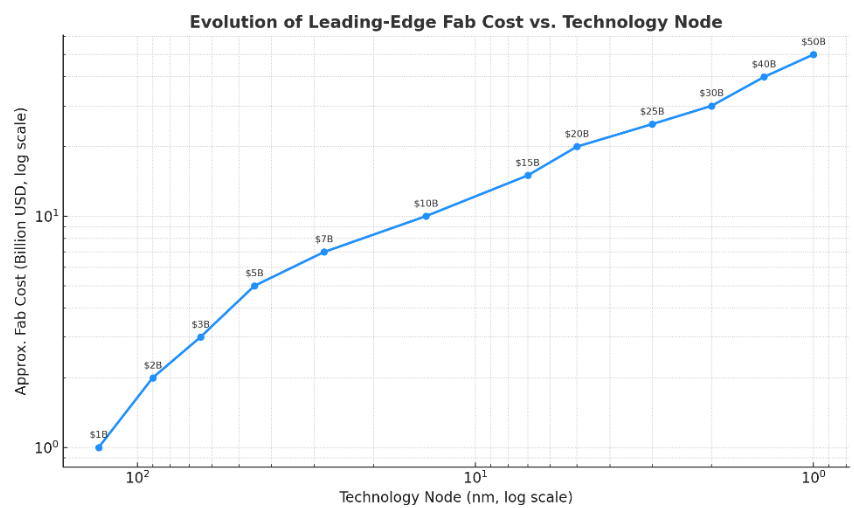
Ferroelectricity & low-voltage operation
× 10 – 100

MESO



Decrease by a factor 100-1000

- Optimized MESO architectures have potential to yield huge gains in energy consumption and performance
- As a reminder, between two consecutive technology nodes, today gain is 20-25%, and new fab costs ~$40B (a number that is only going to increase)



Magneto-electric spin-orbit transistor (MESO)

CMOS +
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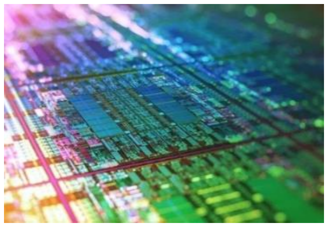
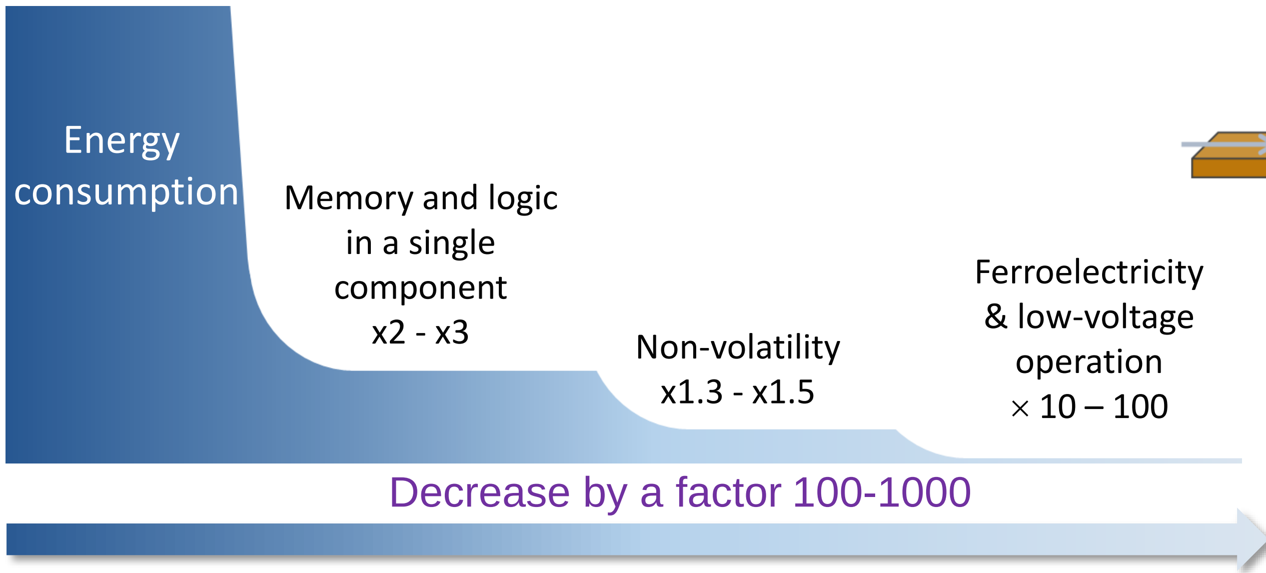
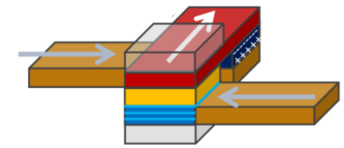
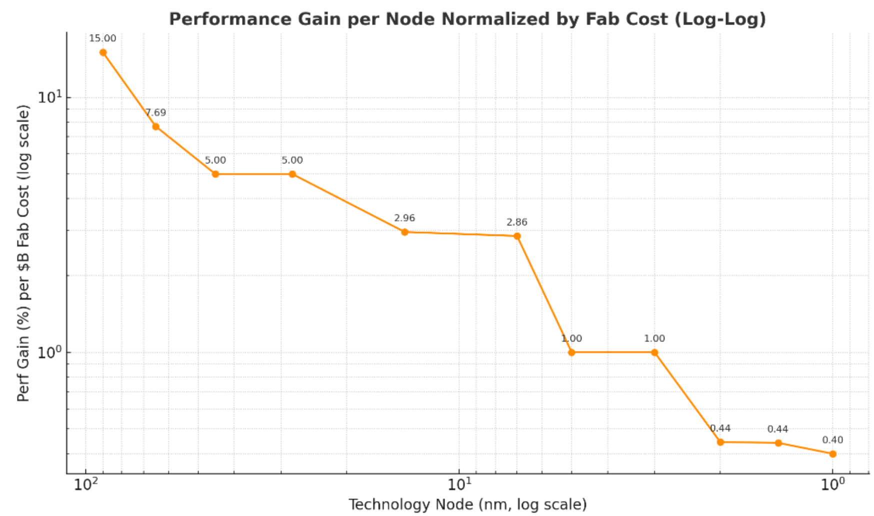




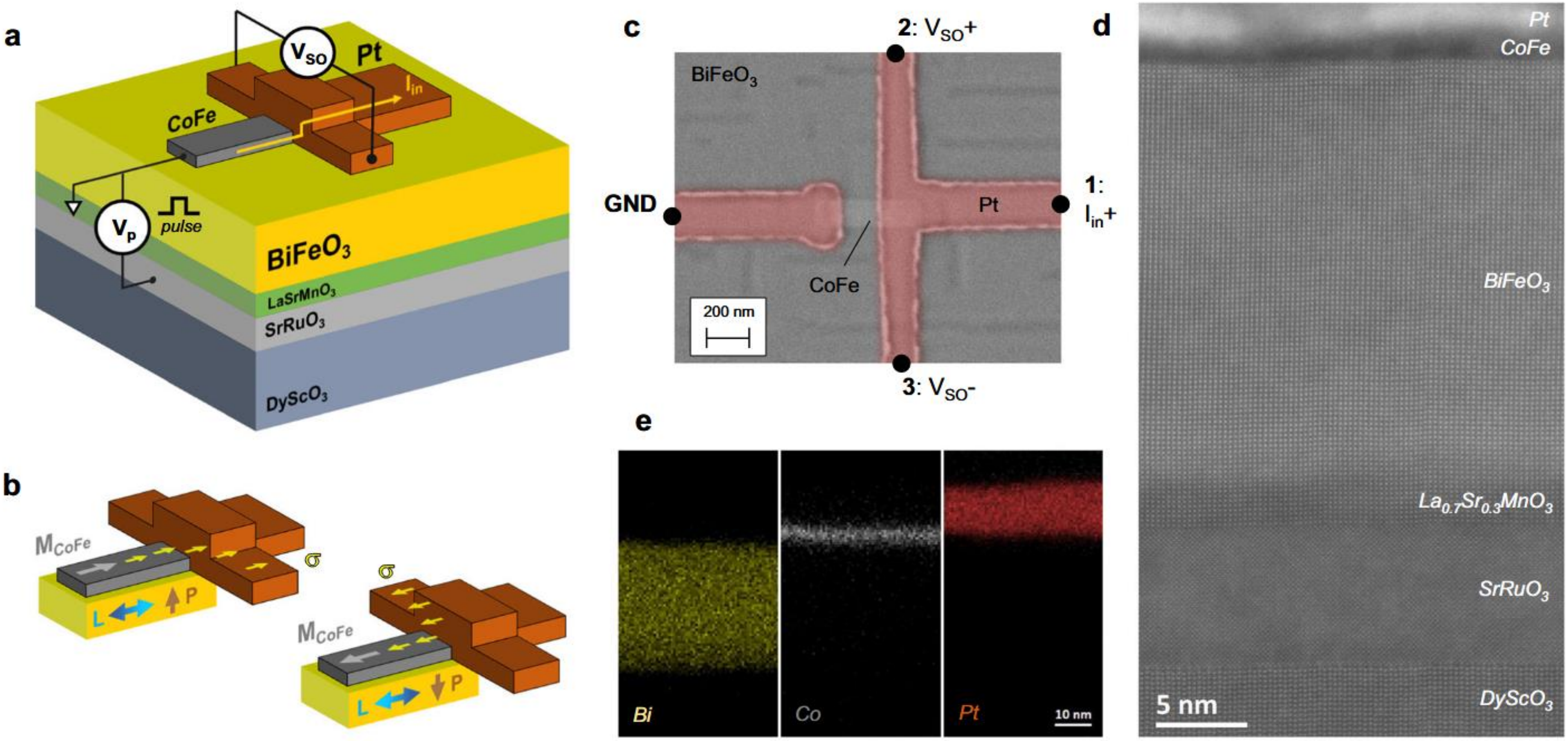
MESO



- Optimized MESO architectures have potential to yield huge gains in energy consumption and performance
- As a reminder, between two consecutive technology nodes, today gain is 20-25%, and new fab costs ~$40B (a number that is only going to increase)
- With latest nodes, for $1B spent only 0.4% improvement in performance

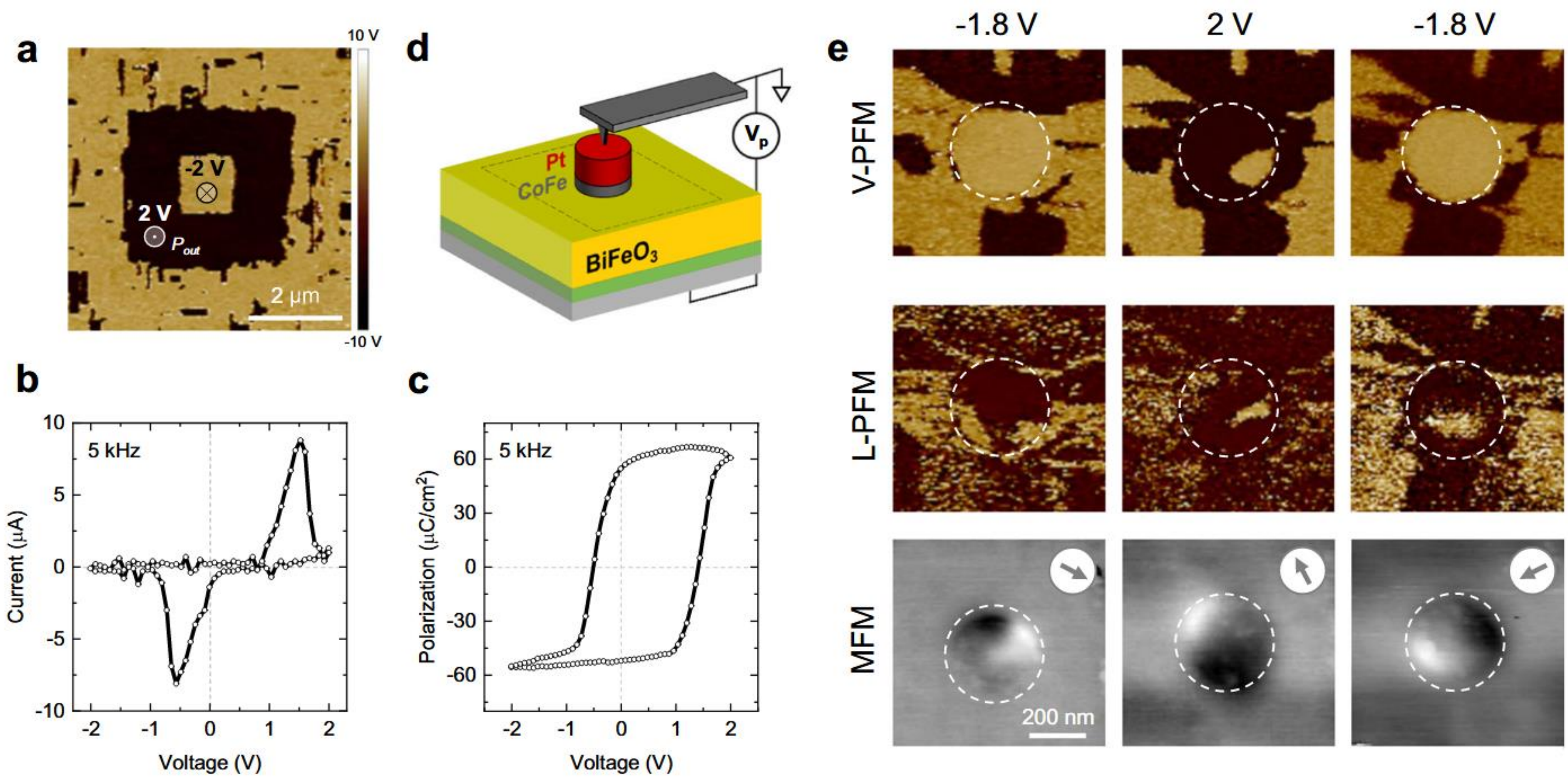


MESO development status



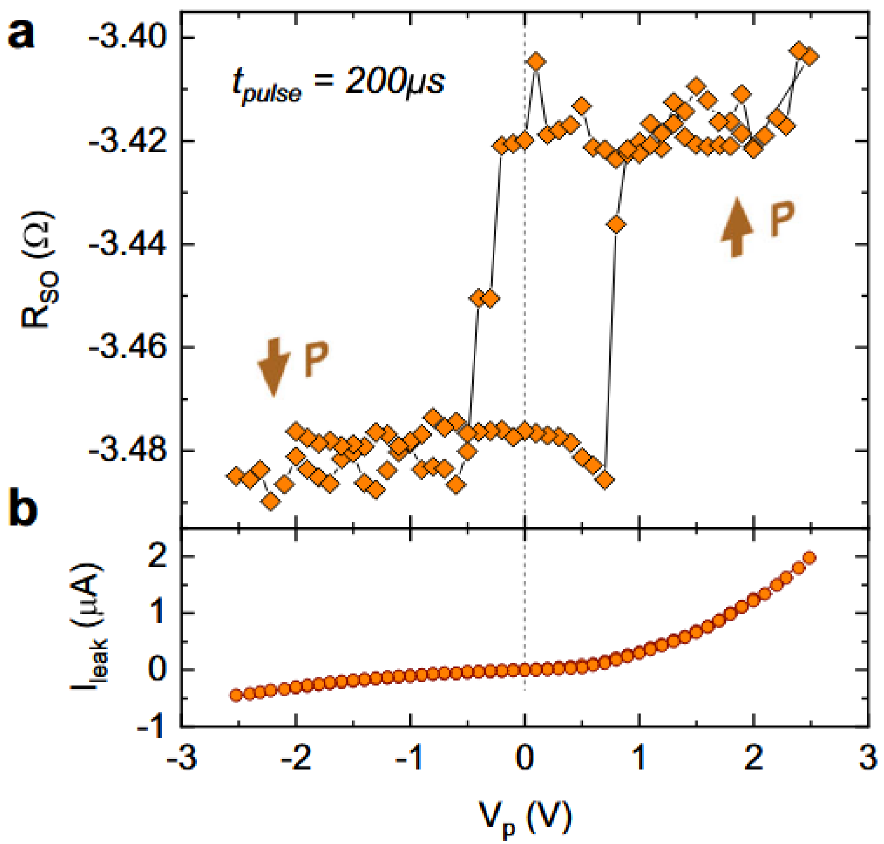
- MESO stack based on BFO grown by PLD and sputtering; substrate is $DyScO_3$
- Readout by inverse SHE in Pt (will lead small output signal because of low SHE angle and low R of Pt)

D.C. Vaz, MB et al, Nature Comm. 15, 1902 (2024)



- BFO switches at about 1 V
- Co magnetization switching by E field but not very clean

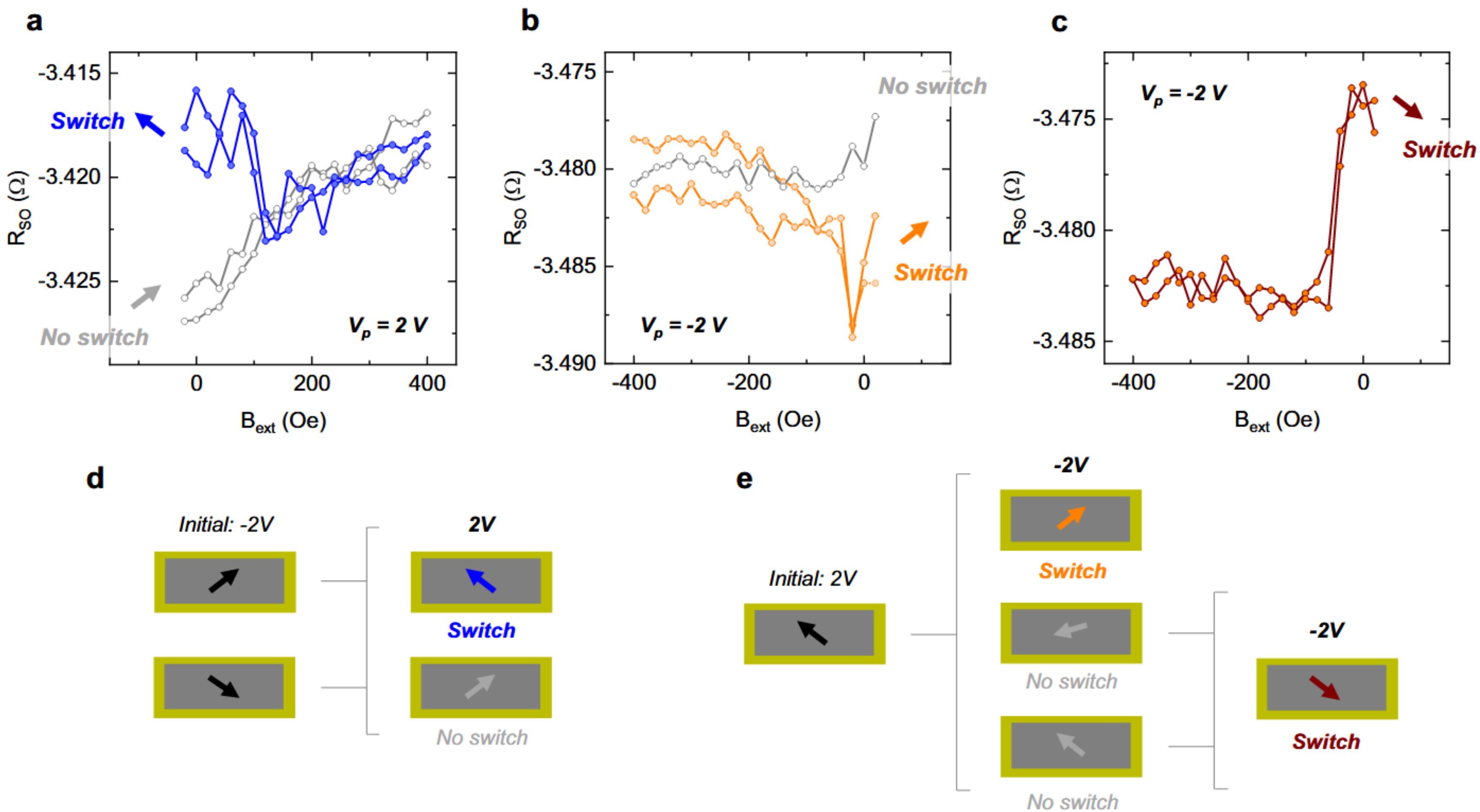
D.C. Vaz, MB et al, Nature Comm. 15, 1902 (2024)



- Baseline resistance (with B field applied) shows switching → just small field effect from BFO on Co (no magnetization switching here)
- Low leakage

D.C. Vaz, MB et al, Nature Comm. 15, 1902 (2024)

MESO development status



- Nondeterministic switching behavior of output signal
- Questions potential of BFO-based MESO…

D.C. Vaz, MB et al, Nature Comm. 15, 1902 (2024)

MESO development status

TRL 1	**Basic principles observed** — ME switching and SOC interconversion shown on ideal single crystals (e.g., $BiFeO_3$ on $GdScO_3$, STO). Physics of multiferroic control and spin current generation confirmed.	✓
TRL 2	**Concept formulated** — Conceptual device structure includes: multiferroic layer, SOC channel, interconnect stack. Early models assume ideal lattice matching, ignoring integration stress.	✓
TRL 3	**Proof of concept on ideal substrates** — Lab-scale MESO devices built on small oxide substrates (5–10 mm^2). Key figures of merit (voltage, retention, interconversion efficiency) measured under ideal strain conditions.	?
TRL 4	**Validation on small chips, but no CMOS flow** — Small arrays fabricated on single-crystal substrates; first attempts to transfer to Si using buffer layers, direct wafer bonding, or seed layers, but mismatch, defects, or leakage remain major issues.	
TRL 5	**Relevant environment: heterointegration on Si** — Demonstration that $BiFeO_3$ (or substitute ME layer) can be grown or transferred onto 300 mm Si wafers with acceptable quality: minimal misfit dislocations, good ferroelectric and magnetic order, compatible thermal budget for BEOL. Still likely limited to test coupons or bonded wafers.	
TRL 6	**Prototype logic circuits on 300 mm wafers** — Small-scale MESO logic gates fabricated in 300 mm pilot lines. Validate patterning, etching, alignment with standard CMOS modules. Early test of CMOS–MESO hybrid chips to benchmark interconnect, power, noise margins.	
TRL 7	**Functional sub-blocks in operational environment** — Functional logic sub-blocks (e.g., in-memory logic, ALUs) integrated in test SoCs using standard EDA flows and back-end design. Reliability under thermal cycling and standard packaging tested.	
TRL 8	**Pilot-line qualification for real applications** — Volume-fabricated wafers with reliable MESO layers at acceptable defectivity, yield, and uniformity. Full process flow qualified for stress, contamination, thermal budgets. Test in real system workloads.	
TRL 9	**Commercial product deployment** — MESO devices mass-manufactured in foundries with stable process windows, qualified supply chain for oxide targets, and standard test/repair flows. Proven benefit over advanced CMOS nodes at product scale.	

ChatGPT

Comparison of development status

TRL Category	VCMA MRAM	MERAM	MESO
1. Fundamental Physics & Materials	TRL 6 — VCMA effect at CoFeB/MgO interfaces is well understood and reproducible.	TRL 3–4 — Magnetoelectric coupling shown in multiferroics ($BiFeO_3$, Cr_2O_3) at lab scale; robust switching at RT demonstrated in small samples.	TRL 3–4 — ME switching + SOC interconversion demonstrated in lab; materials well studied but mostly on ideal substrates (e.g., single crystals).
2. Device-Level Prototype	TRL 5–6 — Single cells & small arrays (kb–Mb scale) with VCMA-assisted switching fabricated; clear write energy benefit.	TRL 3 — Single cells demonstrated; readout via GMR verified.	TRL 3 — Single MESO switches built; early lab demos of logic-level operation under ideal conditions.
3. Integration & Process Compatibility	TRL 5–6 — Fully compatible with STT-MRAM process flows; no exotic layers; standard BEOL thermal budgets.	TRL 2–3 — Robust multiferroic integration on 300 mm Si remains unsolved; buffer layers, wafer bonding, or stress control still in lab R&D.	TRL 2–3 — No robust CMOS-compatible flow yet; same oxide–Si integration bottlenecks; buffer layers or wafer bonding needed.
4. System-Level Demonstration & Application Readiness	TRL 5–6 — Pilot-line arrays built; EDA tools and PDK flows adapted from mature STT-MRAM; production scaling feasible.	TRL 1–2 — No large test chips; no proven yield, reliability, or lifetime data; purely academic for now.	TRL 1–2 — No system-level blocks or co-integrated logic circuits demonstrated on real wafers; only conceptual architectures and simulations.

Outline

- Ferroic orders and magnetoelectric coupling
  - Intrinsic" magnetoelectric coupling
  - Field-effect-driven magnetoelectric coupling
  - Strain-driven magnetoelectric coupling

- Magnetoelectric spintronic devices :
  - VCMA-MRAM
  - Magnetoelectric RAM
  - Magnetoelectric Spin orbit (MESO) devices

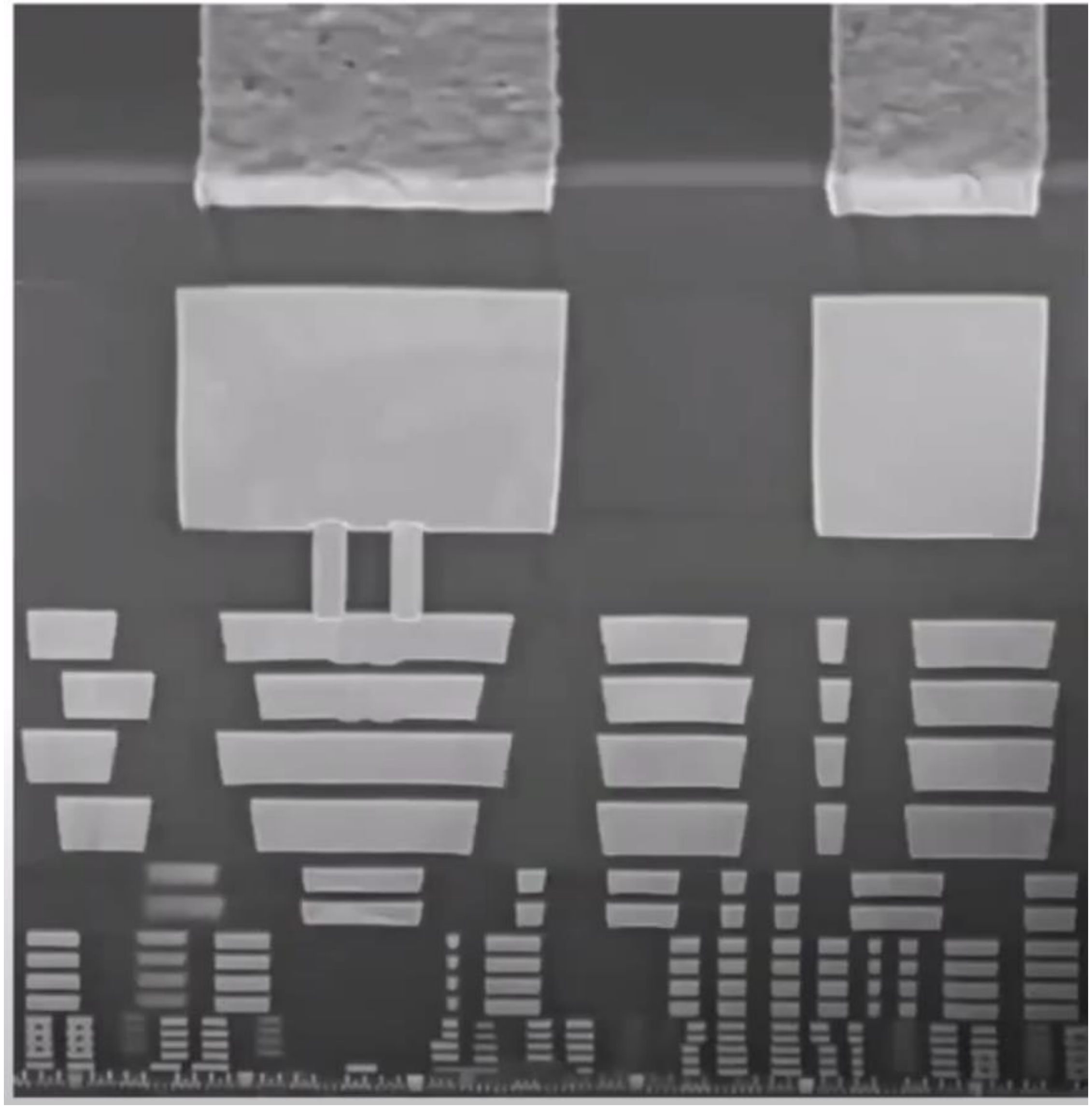
- Integration challenges

Integration challenges

BEOL
(17 metal
level stack)

MEOL

FEOL



Global Foundries

FEOL/MEOL/BEOL : Front/middle/back end of line

Integration challenges

- To integrate a material in the BEOL, its growth conditions must be compatible with CMOS, i.e. not damage the CMOS circuits underneath

- Plus, with perovskite oxides, need a perovskite template (top of BEOL part is amorphous SiOx, Cu, etc)

- One solution : grow epitaxial perovskite stack onto epitaxial Si wafer, and then transfer onto CMOS wafer

- But then, perovskite stack must be grown onto 200 or 300 mm Si wafer

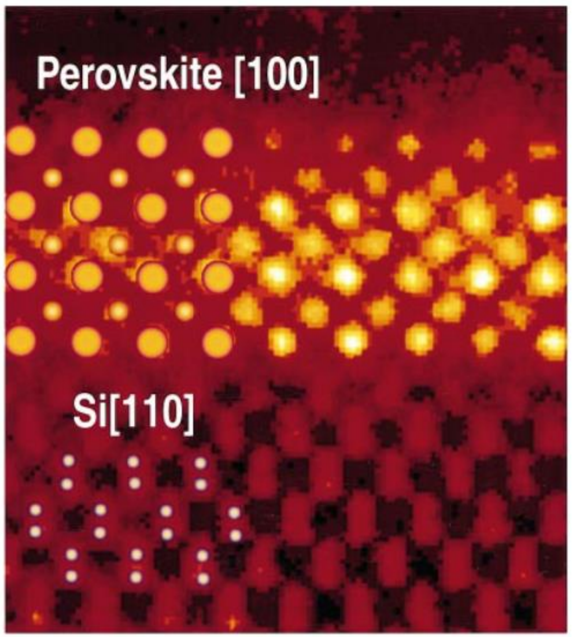
- There are now tools to grow oxide on Si 300 wafers by
  - Sputtering
  - MBE
  - PLD

Epitaxy of perovskites on Si

VOLUME 81, NUMBER 14 PHYSICAL REVIEW LETTERS 5 OCTOBER 1998

Crystalline Oxides on Silicon: The First Five Monolayers

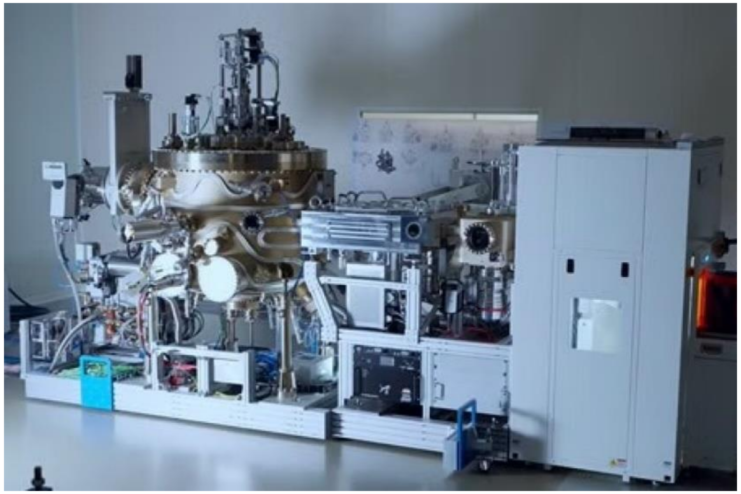
R. A. McKee, F. J. Walker, and M. F. Chisholm
Oak Ridge National Laboratory, Oak Ridge, Tennessee 37831-6118
(Received 8 June 1998)



- Epitaxy of $SrTiO_3$ on Si(001) by MBE
- 45 deg rotation of STO unit cell with respect to Si (then lattice mismatch is just 1.7%)

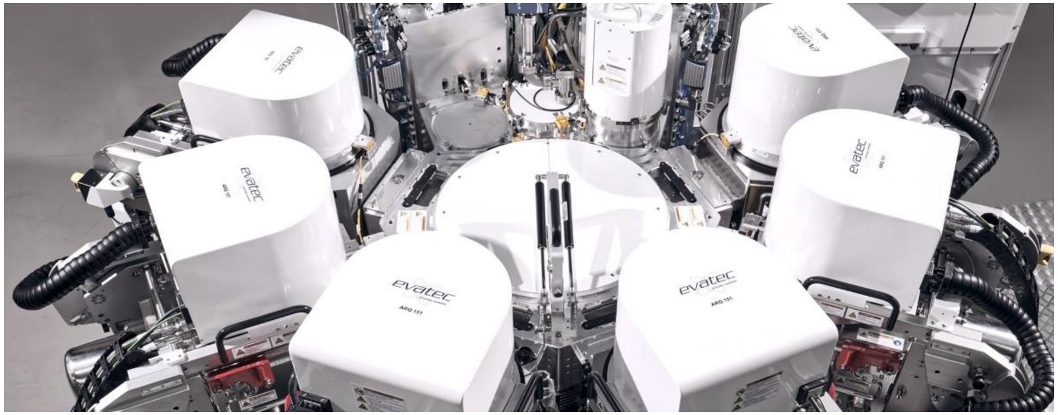
Industrial tools for oxide epitaxy on 300 mm Si

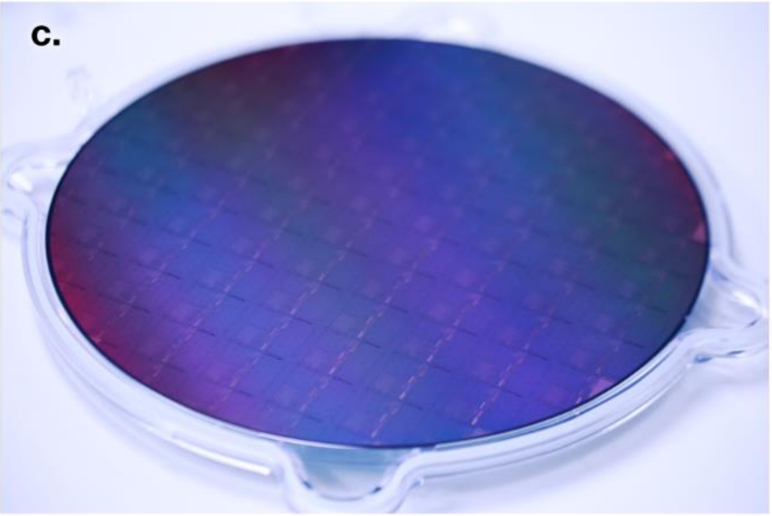
Solmates B.V / Lam Research (PLD)

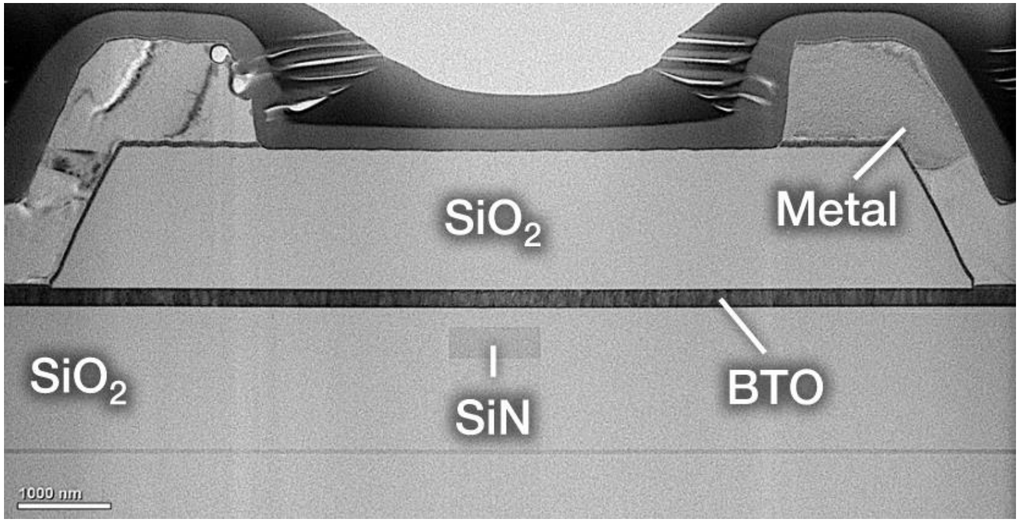


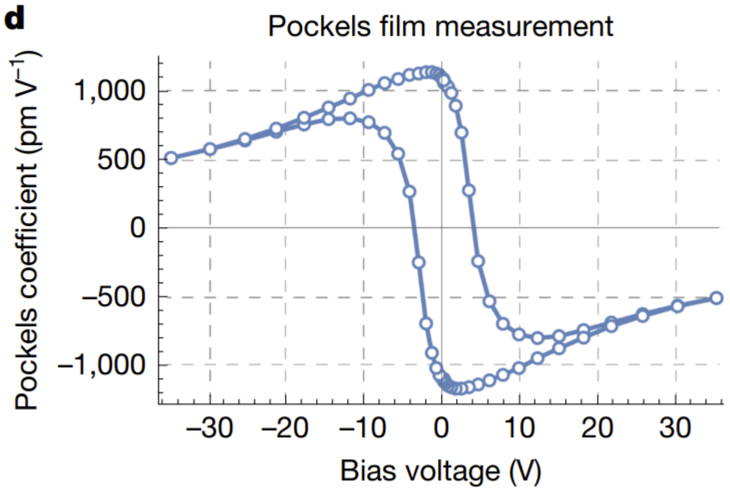
RIBER Rosie pilot line (MBE)

Evatec (sputtering)









- Demonstration of high-quality epitaxial $BaTiO_3$ on 300 mm Si wafer by **PsiQuantum** @ Global Foundries for a fully integrated quantum photonic platform
- Technique: molecular beam epitaxy, compatible with foundry processes
- BTO quality evidence by giant, record-high electo-optical Pockels coefficient (with better than 1% uniformity)

Nature (2025) ; ArXiv:2404.17570v1

Conclusions

- Still a long way to go for multiferroics or magnetoelectrics to be used in industrial applications for information and communication technology
- Perhaps most promising are VCMA-MRAM, with very low write energyu
- Issues to be solved:
  - We need more room temperature multiferroics, with strong ME coupling
  - For MESO, need SOC systems with larger spin-charge conversion efficiency
  - Integration into CMOS (may benefit from progress for integrated optics with BTO on Si 300 mm)
- Multiferroics and magnetoelectrics can perhaps bring solutions for other information processing paradigms, like magnonics

Conclusions

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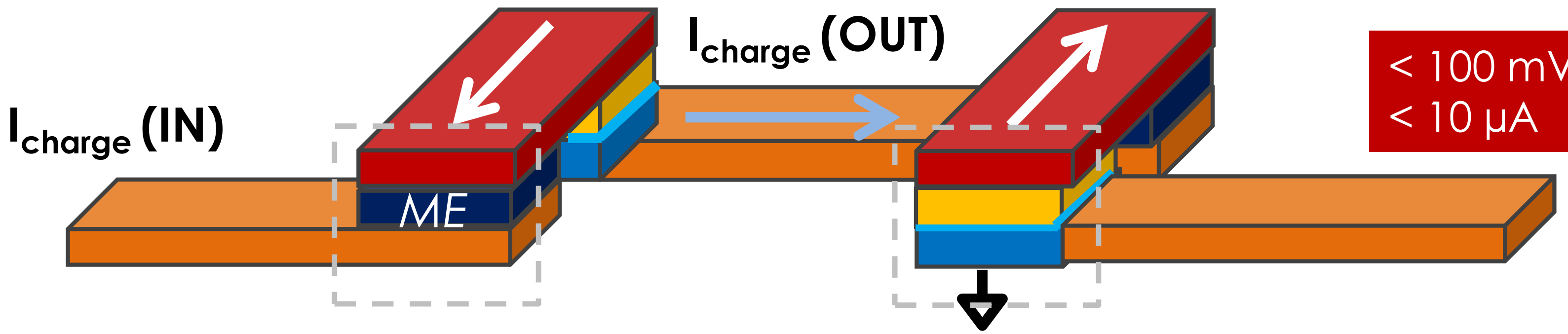
Ferroelectric spin-orbit device : FESO



aJ switching.

< 100 mV
< 10 μA

Voltage Controlled Magnetization

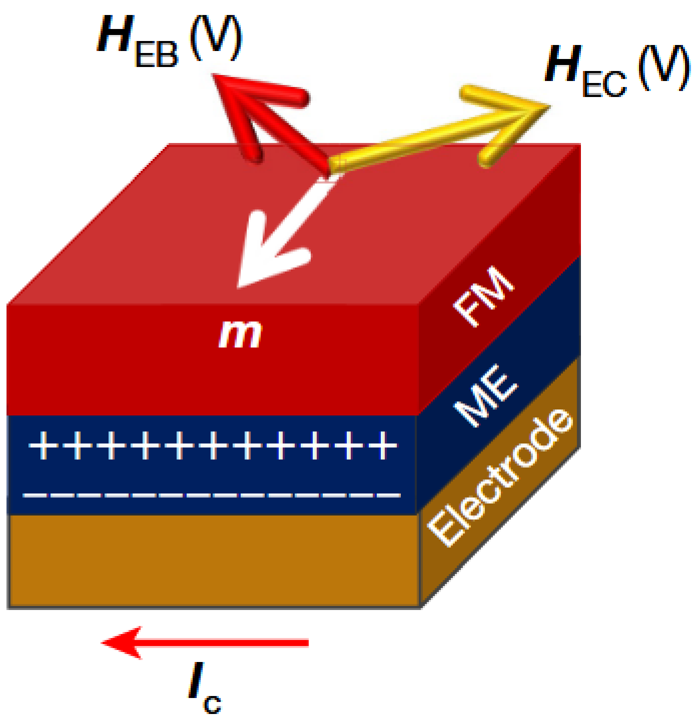
Multiferroic – e.g. $BiFe0_3$

Magnetization to Voltage

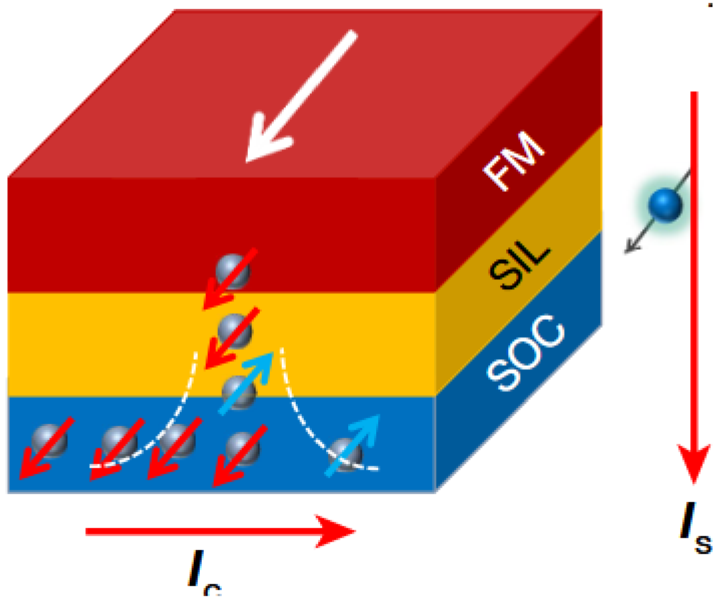
Inverse Spin Orbit – e.g. Ag/Bi, Bi_2Se_3

Magnet	20 x 32 nm
Δ (stability)	45 kT
Interconnect	12 X 45 nm
R_{ic}, C_{ic}	4.5 Ω, 4 aF
Energy per bit	(600 kT) 2.5 aJ

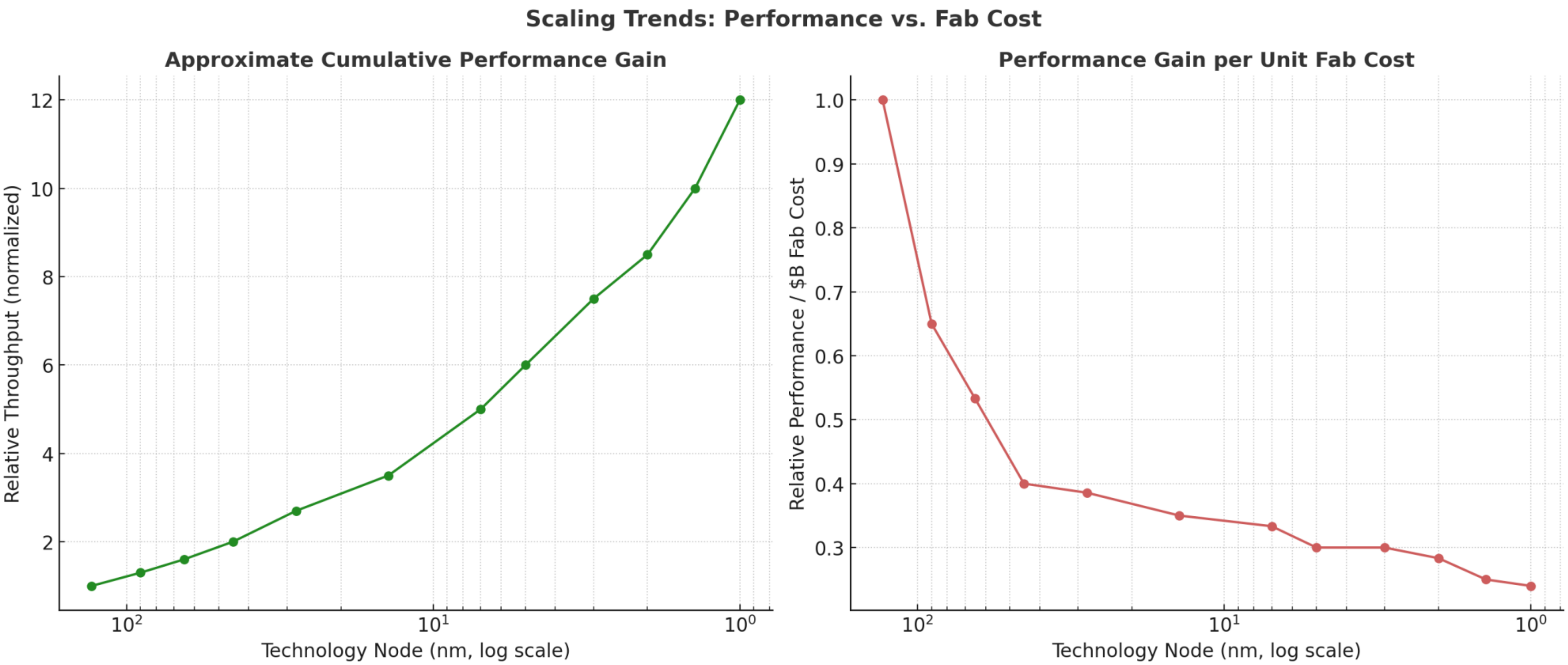
Input

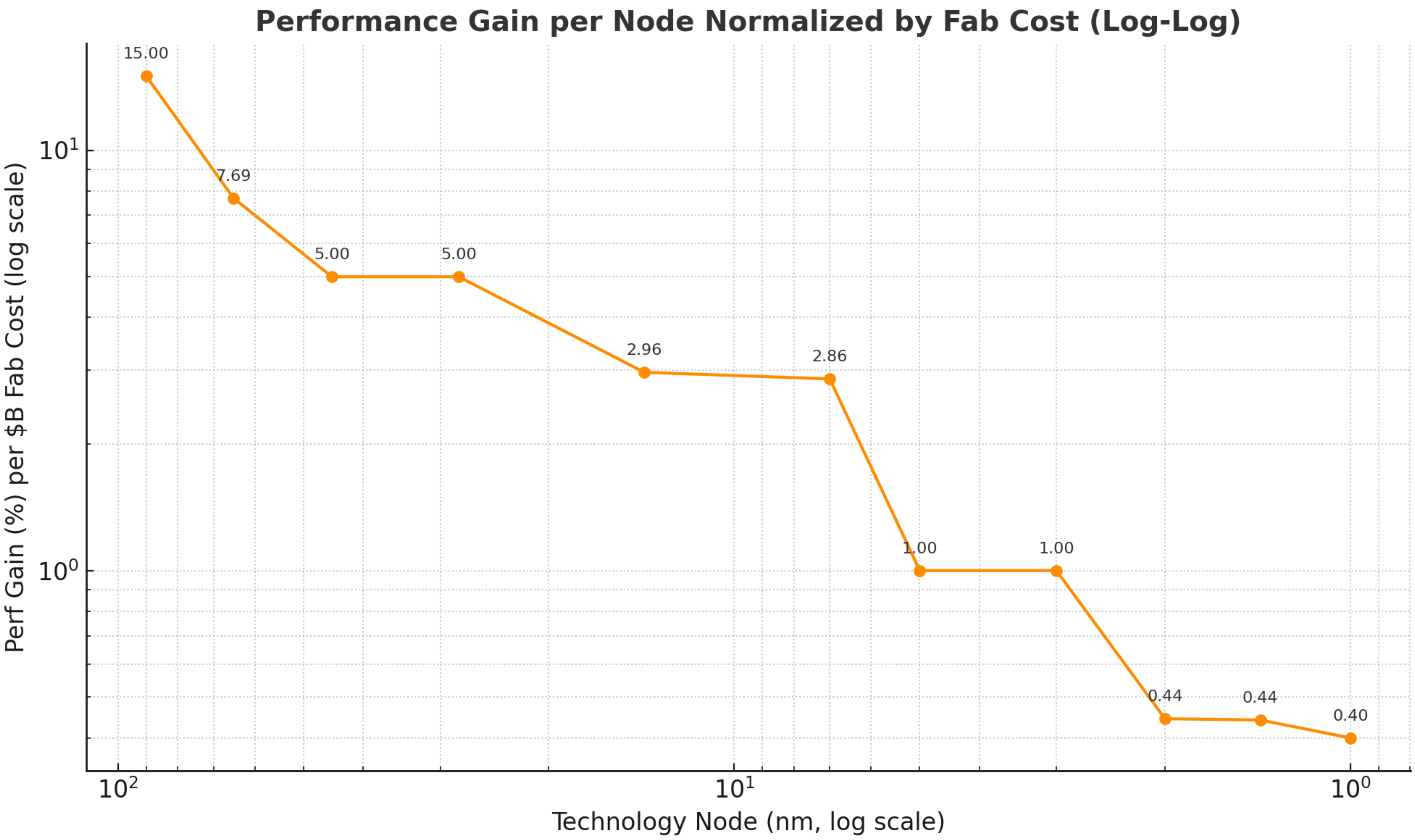


Output



Magnetoelectric switching of FM magnetization


Scaling Trends: Performance vs. Fab Cost
Approximate Cumulative Performance Gain
Relative Throughput (normalized)
12
10
8
6
4
2
10^2
10^1
10^0
Technology Node (nm, log scale)
Performance Gain per Unit Fab Cost
Relative Performance / $B Fab Cost
1.0
0.9
0.8
0.7
0.6
0.5
0.4
0.3
10^2
10^1
10^0
Technology Node (nm, log scale)


Performance Gain per Node Normalized by Fab Cost (Log-Log)
Perf Gain (%) per $B Fab Cost (log scale)
Technology Node (nm, log scale)
15.00
7.69
5.00
5.00
2.96
2.86
1.00
1.00
0.44
0.44
0.40
10^1
10^0
10^2
10^1
10^0

Magnetoelectric switching in BFO