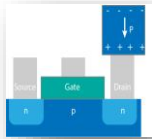




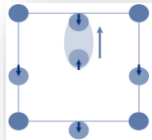
Ferroic electric and magnetic order - from fundamentals to novel nanoscale phenomena

Dennis Meier | Faculty of Physics

Ferroic electric and magnetic order - from fundamentals to novel nanoscale phenomena



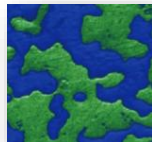
Ferroics-based applications



Fundamentals of ferroics



Improper ferroelectrics



Hyperferroelectrics



Antiferroelectrics

Technological progress in a transforming society



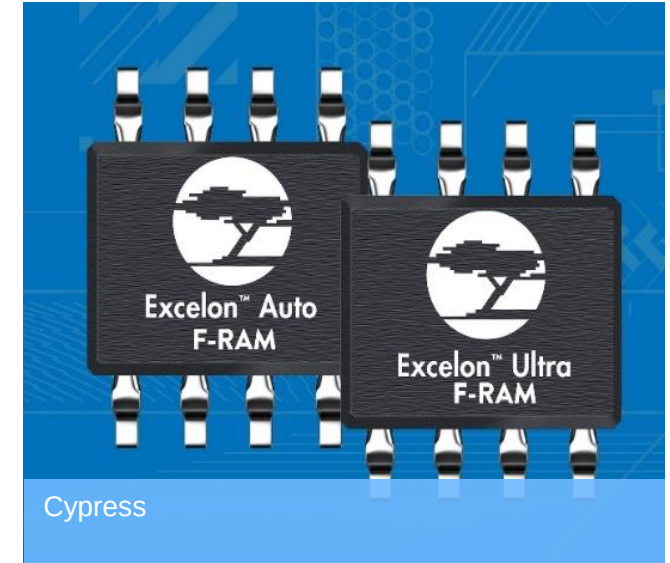
IBM 305 RAMAC (5 MB)

IBM (1956)



Toshiba MG08 (16 TB)

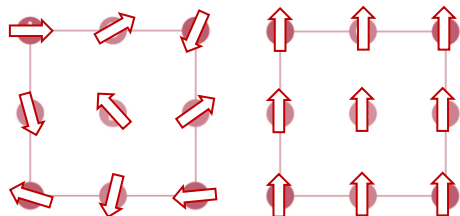
Toshiba (2019)



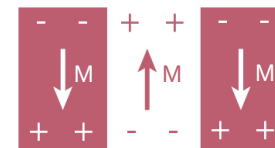
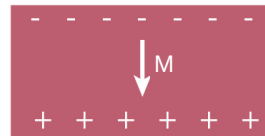
Cypress

Cypress (2019)

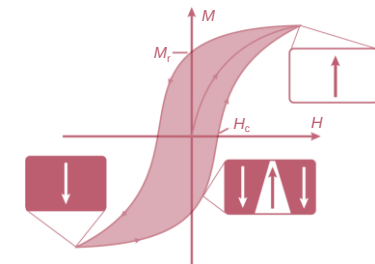
Ferromagnetism: spontaneous ordering of magnetic spins



Domains naturally form to minimize stray fields



Hysteretic switching under applied magnetic fields



Technological progress in a transforming society



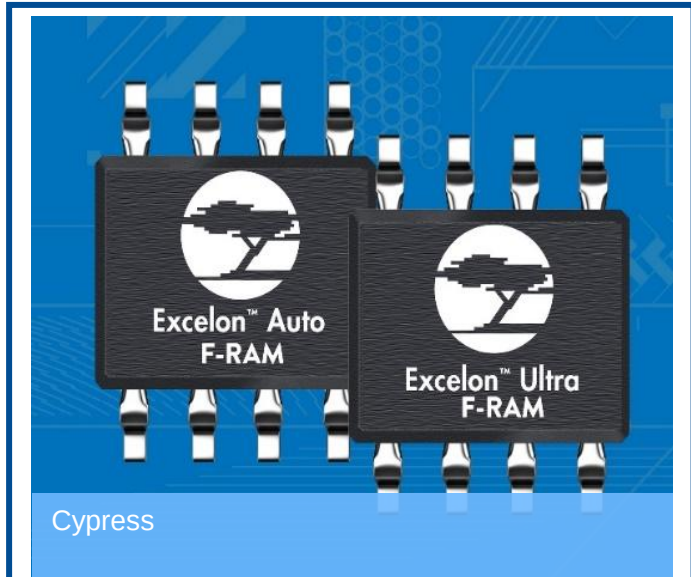
IBM 305 RAMAC (5 MB)

IBM (1956)



Toshiba MG08 (16 TB)

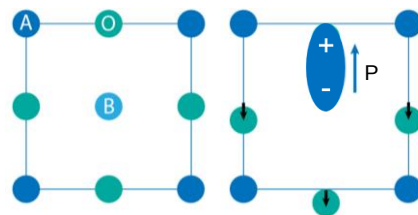
Toshiba (2019)



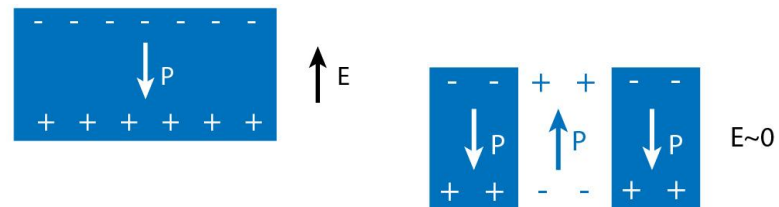
Cypress

Cypress (2019)

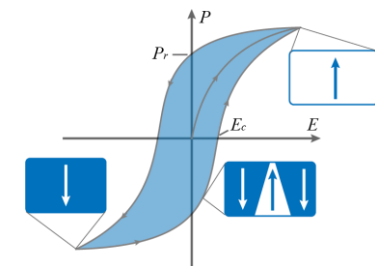
Ferroelectricity: spontaneous ordering of electric dipoles



Domains naturally form to minimize depolarizing fields



Hysteretic switching under applied electric fields



Random access memory and field effect transistors



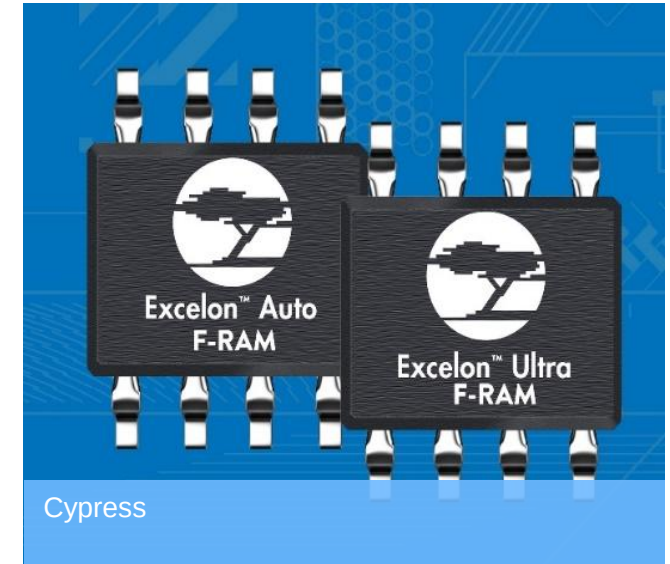
IBM 305 RAMAC (5 MB)

IBM (1956)



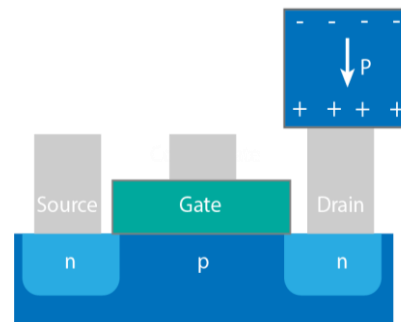
Toshiba MG08 (16 TB)

Toshiba (2019)



Cypress

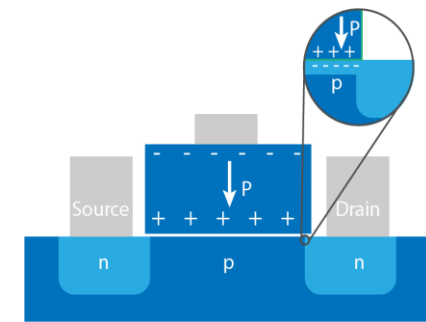
Cypress (2019)



Ferroelectric-RAM (FE-RAM)

Kim, et al., Nat. Nano. 18 (2023)

“Traditional applications require large, switchable polarization as weak polarization is more difficult to read and is easily masked by leakage currents.”



Ferroelectric FET (FE-FET)

Brandolini's law (aka. *bullshit* asymmetry principle)

“The amount of energy needed to refute bullshit is an order of magnitude bigger than that needed to produce it.”

Wikipedia

Improper ferroelectrics

General Consensus in Early Research: Historically, foundational literature (especially in the 1970s and 1980s dealing with materials like rare-earth molybdates and boracites) suggested that their low polarization values and high coercive fields rendered them unsuitable for standard memory applications or high-power electronics.

Lines, M. E., & Glass, A. M. (1977). Principles and Applications of Ferroelectrics and Related Materials.

Antiferroelectrics

Jim Scott about antiferroelectrics: “*antiferroelectricity is an ill-defined, almost useless concept*”

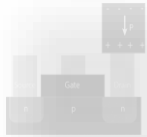
Rev. Mod. Phys. 46, 83–128 (1974)

Antiferromagnets

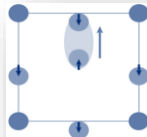
Louis Néel about antiferromagnets:
“*interesting but useless*”

1970 Nobel Prize Lecture

Ferroic electric and magnetic order - from fundamentals to novel nanoscale phenomena



State-of-the-art ferroics-based applications



Fundamentals of ferroics



Improper ferroelectrics

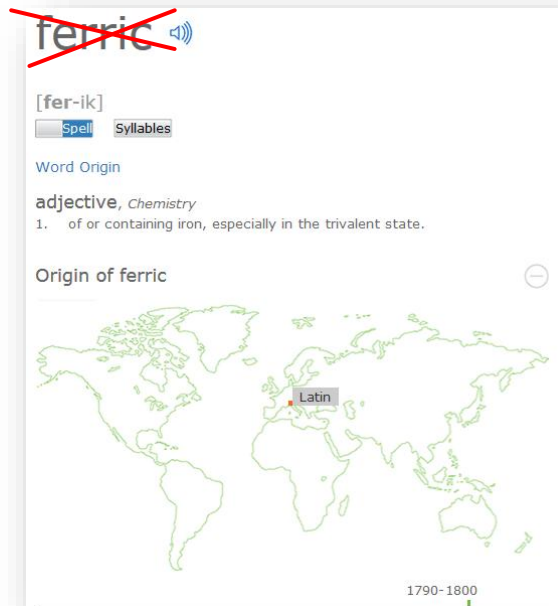


Hyperferroelectrics



Antiferroelectrics

What is a ferroic material?



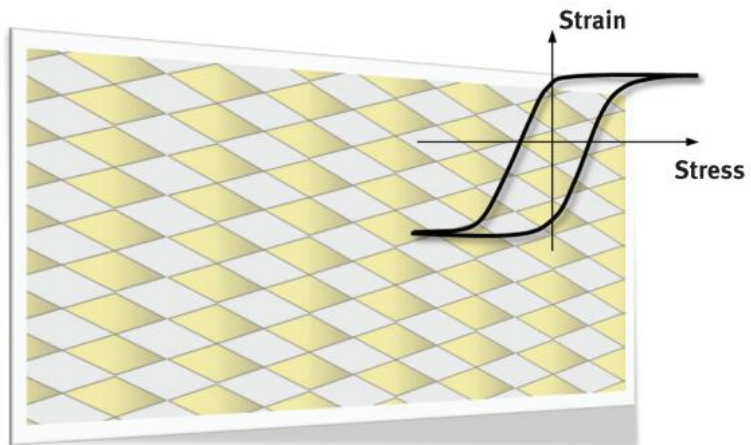
- Derived from *ferrum* („iron“)



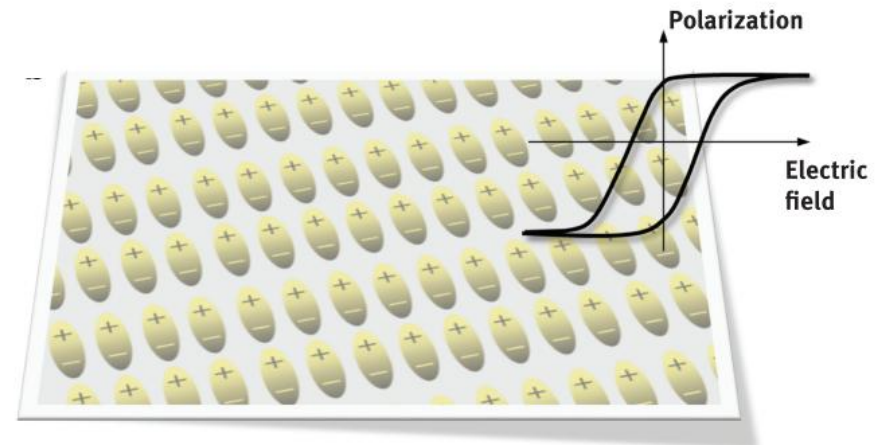
dowlingmagnets.com

- Iron-like behavior
- Broadly used beyond magnetism:
 - (anti-)ferroic
 - multiferroic
 - hyperferroic
 - ...

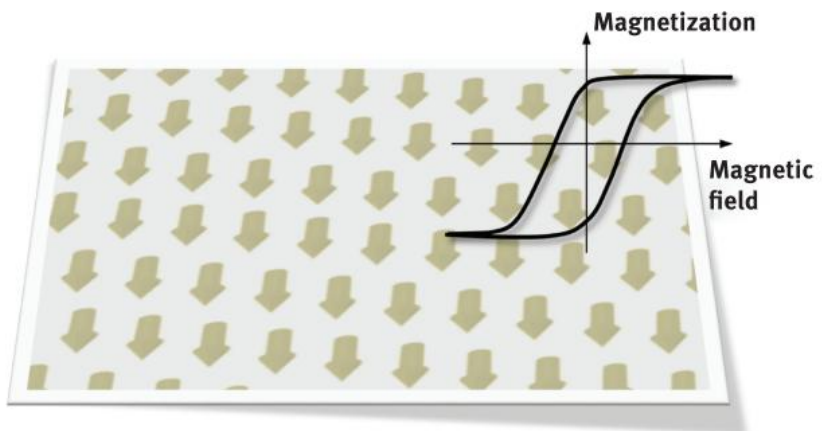
Primary Ferroics



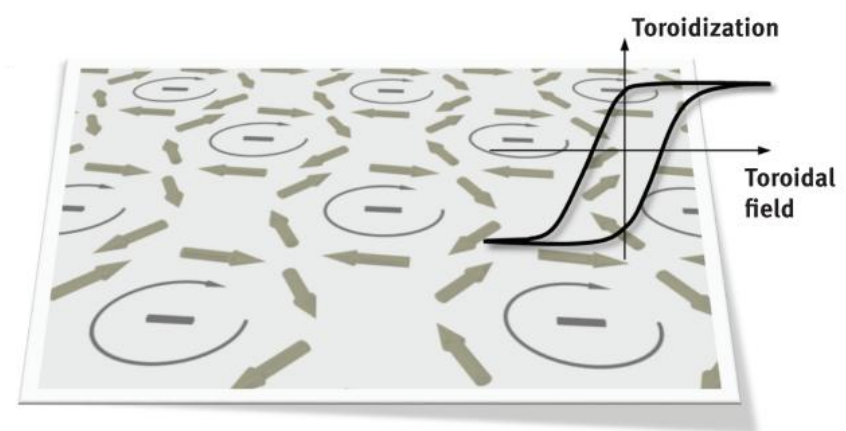
Ferroelastic



Ferroelectric



Ferromagnetic

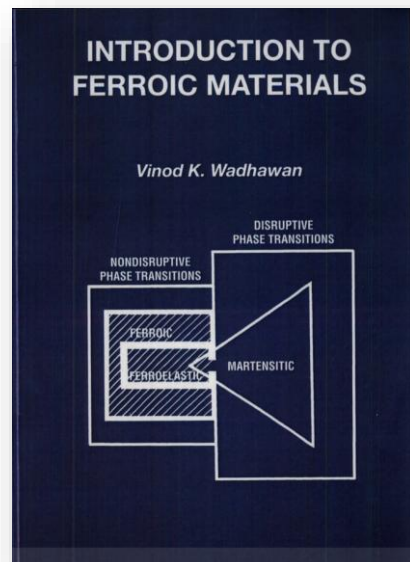


Ferrotoroidic

Primary Ferroics

Ferroic phase transition: **non-disruptive** phase transition that involves a change in **point-group symmetry**

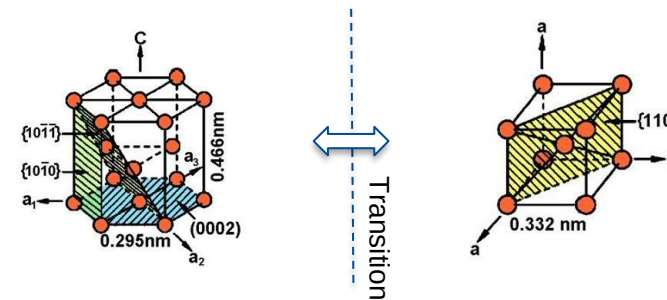
Wadhawan, Phase Trans. 64, 165 (1998)



Disruptive:

Both phases across the transition have at least one symmetry element not present in the other phase.

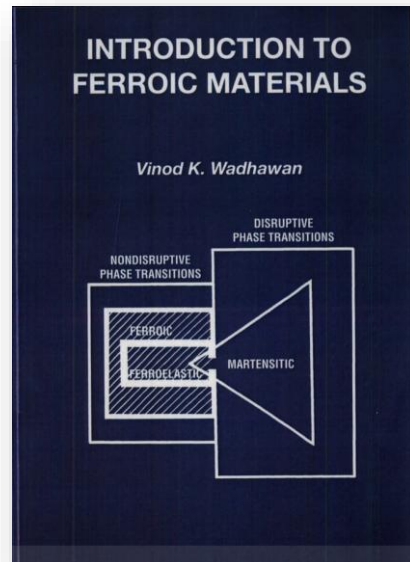
Severe change, not just in the space group, but in the space-group *type*.



Primary Ferroics

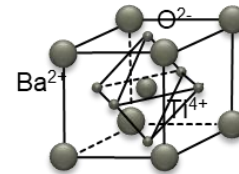
Ferroic phase transition: **non-disruptive** phase transition that involves a change in **point-group symmetry**

Wadhawan, Phase Trans. 64, 165 (1998)



Non-disruptive:

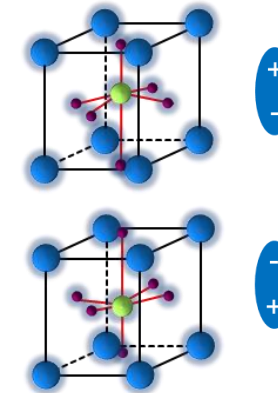
Cubic ($T > T_C$)



Centrosymmetric

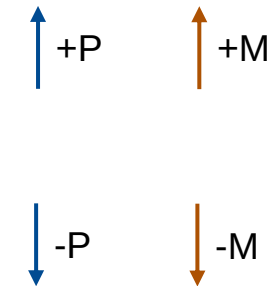


Tetragonal ($T < T_C$)



Non-centrosymmetric

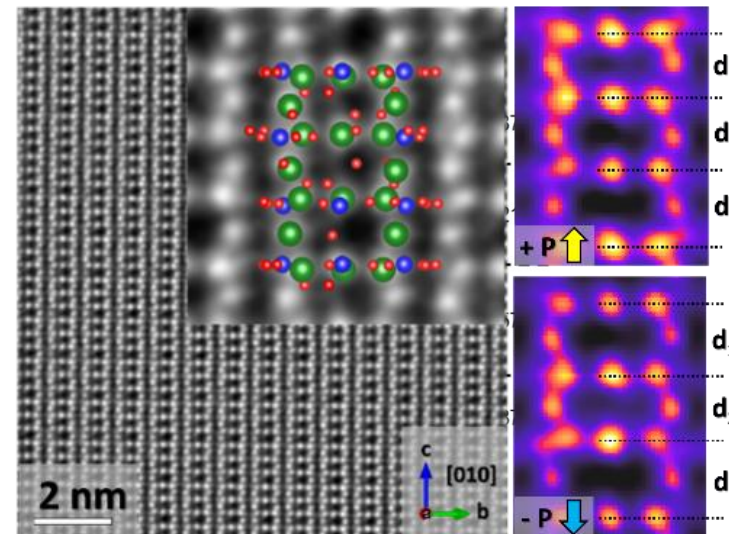
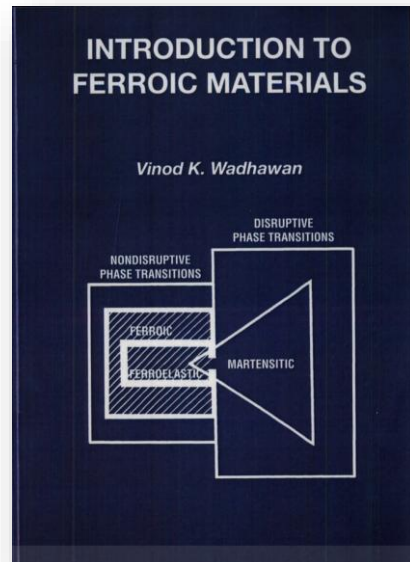
Analogy to magnetism



Primary Ferroics

Ferroic phase transition: **non-disruptive** phase transition that involves a change in **point-group symmetry**

Wadhawan, Phase Trans. 64, 165 (1998)



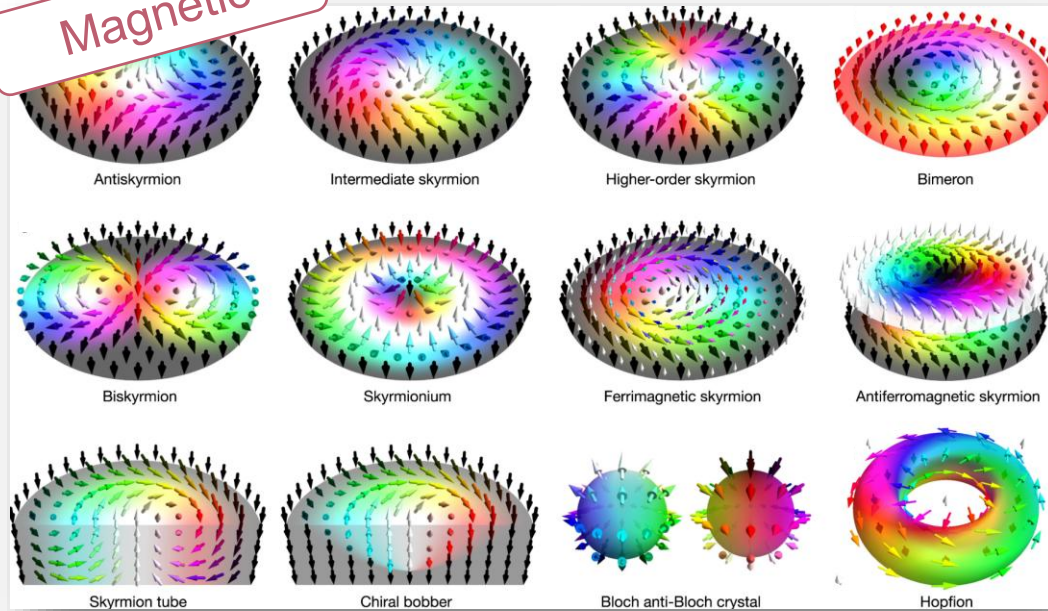
$$\begin{aligned} d_1 < d_2 &= +P \\ d_1 > d_2 &= -P \end{aligned}$$

$$d_3 = \text{const}$$

NOTE: Spins are quantized, whereas electric dipoles result from (3D) lattice distortions!

Topological textures in ferroelectrics and ferromagnets

Magnetic



Göbel et al. Phys. Rep. 895, 1-28 (2021)

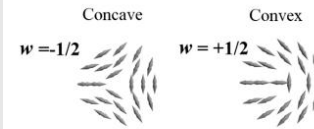
Electric

$w = +1$

Anti-vortex $w = -1$

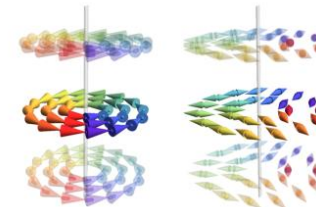
$\nabla \cdot \mathbf{P}$	> 0	$= 0$	< 0	$= 0$
$\nabla \times \mathbf{P}$	$= 0$	$= 0$	$= 0$	$= 0$

Disclinations

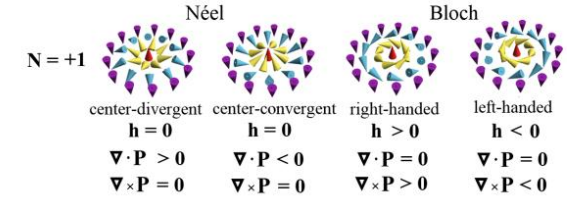


Vortex lines

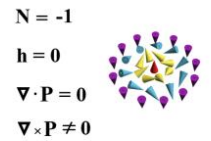
Disclination lines



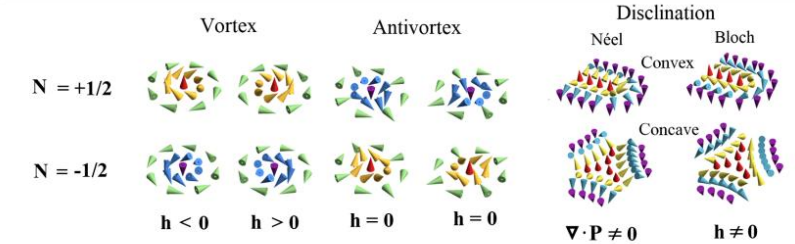
Skyrmions



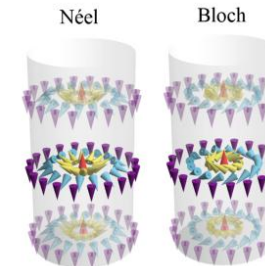
Antiskyrmion



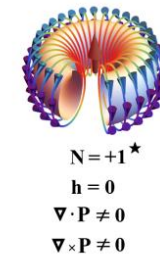
Merons



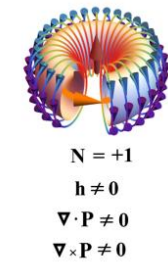
Skyrmion tubes



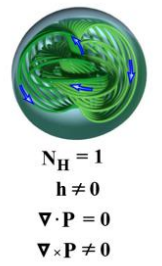
Bubbles



Bubble skyrmions

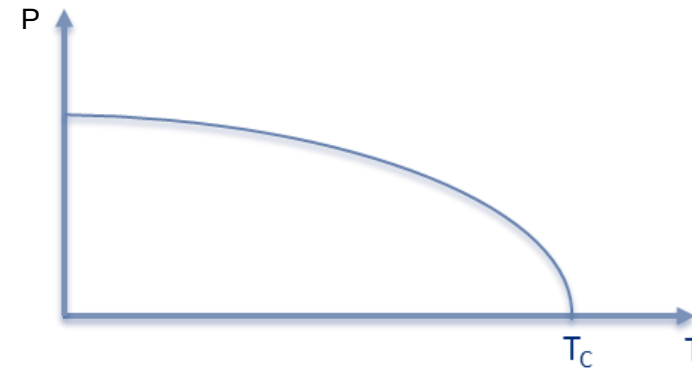
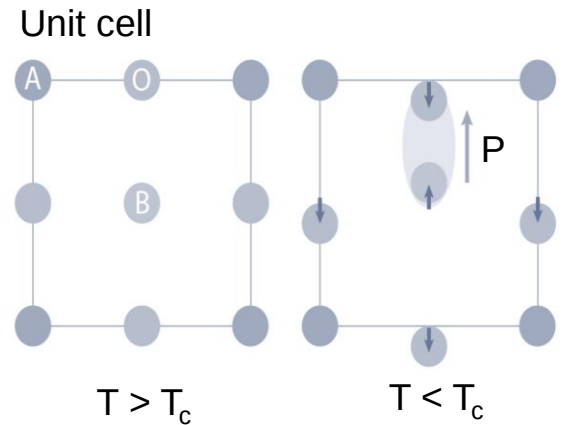


Hopfions



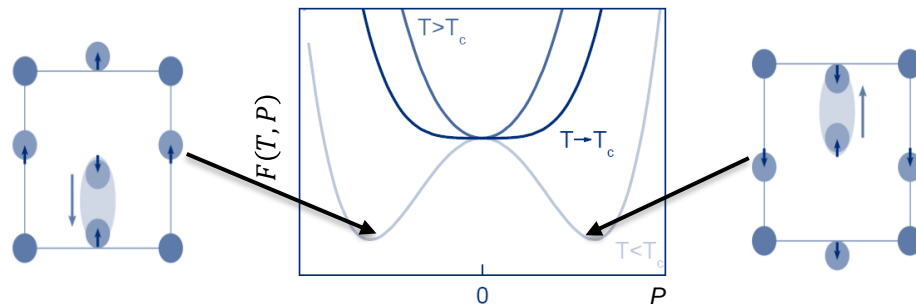
Junquera et al. Rev. Mod. Phys. 95, 2 (2023)

Ferroelectric phase transition

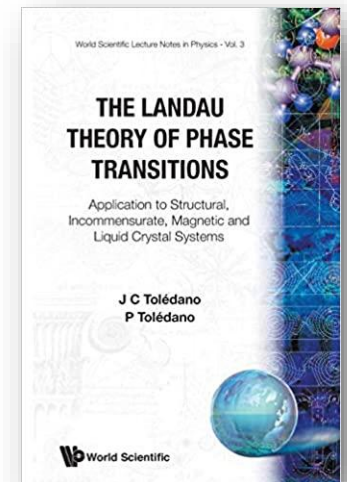


Mathematical description – Landau theory of phase transitions (2nd order):

$$F(T, P) = F_0(T) + \frac{a}{2}(T - T_c)P^2 + bP^4$$

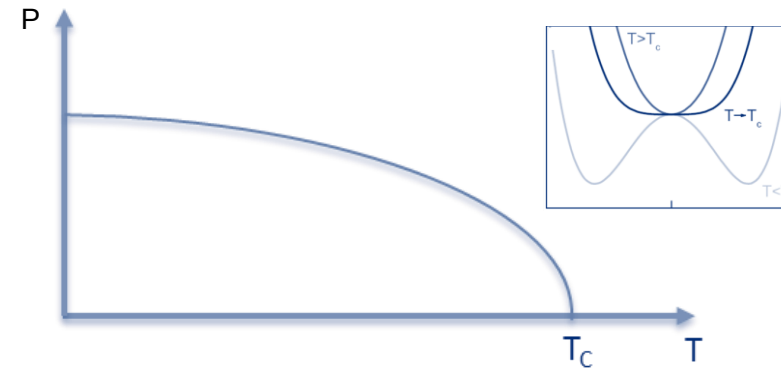
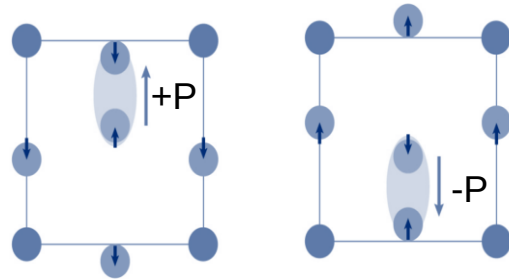


$$\frac{\partial F(T, P)}{\partial P} = 0 \quad \rightarrow P \propto \sqrt{T_c - T}$$

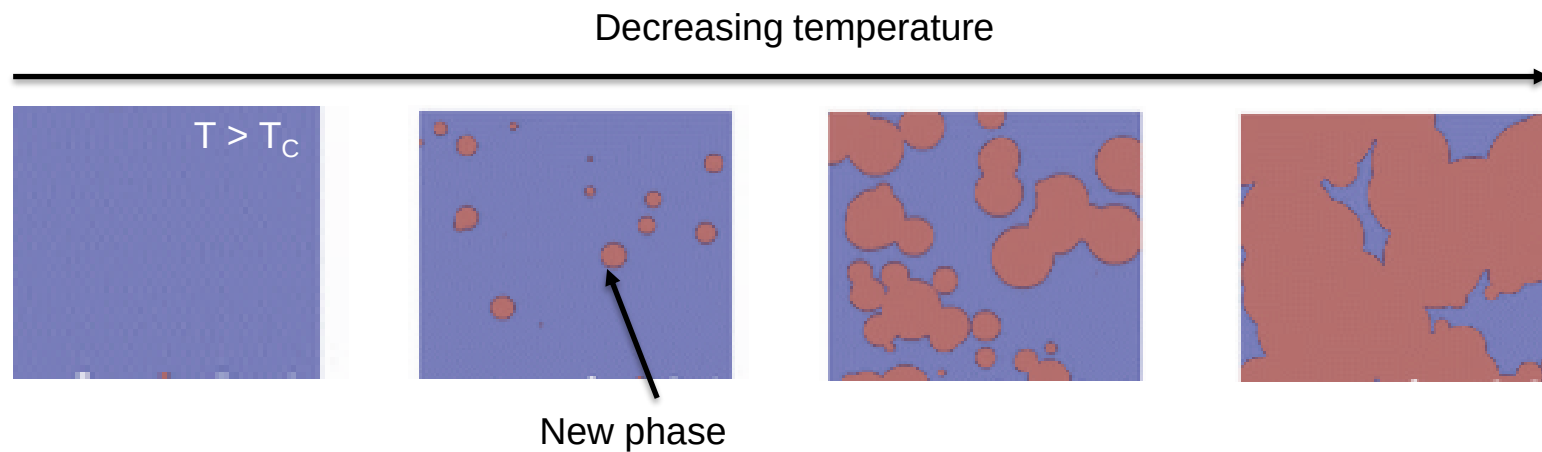


Formation of ferroelectric domains and domain walls

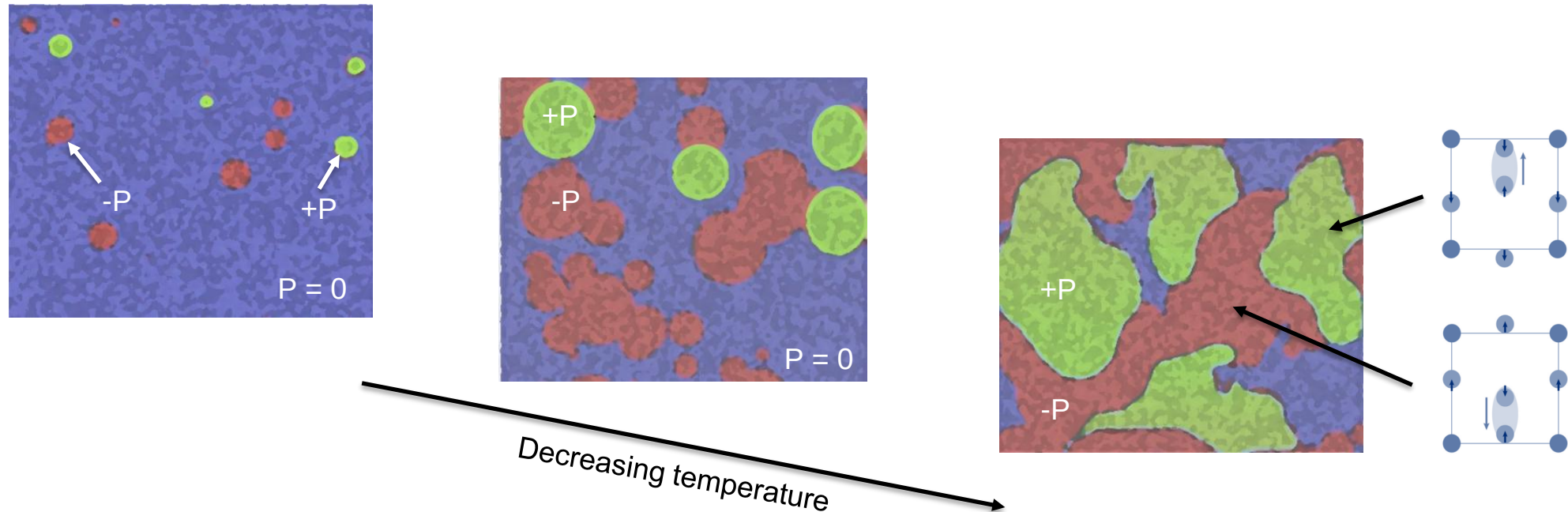
Two energy equivalent states:



Nucleation and growth:

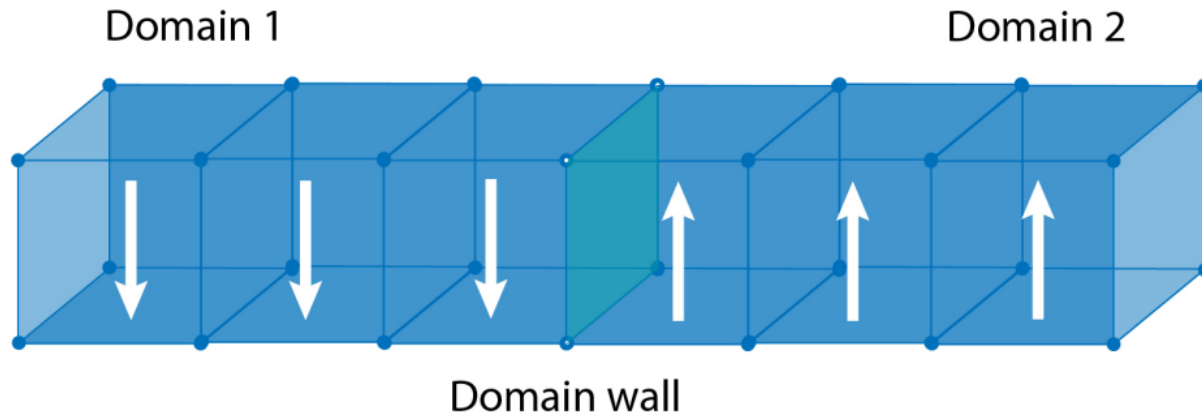


Formation of ferroelectric domains and domain walls



- **Ferroelectric domains:** Volumes of the same homogeneous crystalline structure but different spatial orientations of the electric order parameter P .
- Domains are an essential feature of **any ferroic system**. By breaking up into domains, ferromagnets and ferroelectrics substantially reduce their magnetostatic or electrostatic energy.
- Domains and domain walls naturally form at the ferroic phase transition

Ferroelectric domains and domain walls

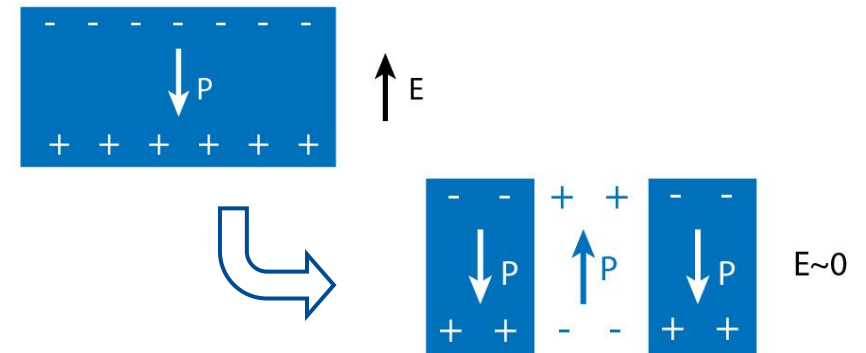


- Surface charge density = dipolar moment per unit volume

$$\Rightarrow E_{\text{depol}} = \frac{P}{\epsilon} \approx 10 - 100 \frac{\text{kV}}{\text{cm}}$$

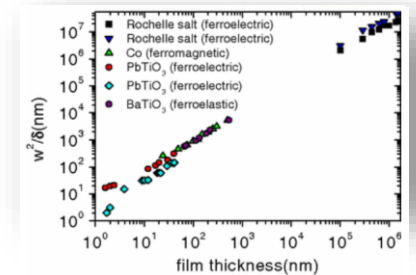
$$\left(P = 10 \frac{\mu\text{C}}{\text{cm}^2}, \epsilon_r = 100 - 1000 \right)$$

- $E_{\text{depol}} \gg E_{\text{coerc}}$



Kittel law

$$w = \sqrt{\frac{\sigma}{U}} d$$



σ : Energy density per unit area of the wall

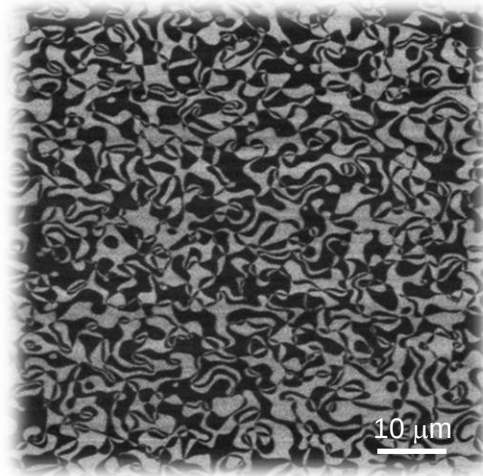
U : Volume energy density of domain

Catalan *et al.*, Rev. Mod. Phys. 84, 119 (2012)

Ferroelectric domains and domain walls

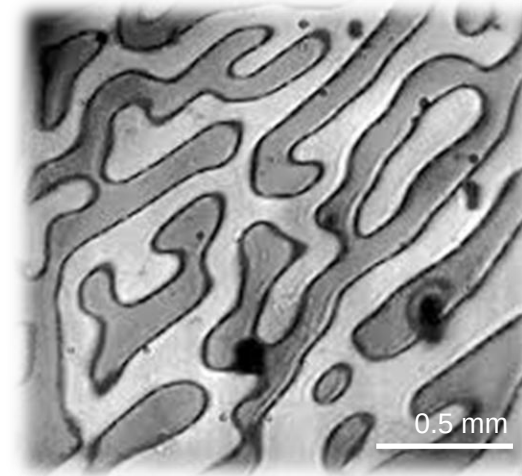
Hexagonal manganites (YMnO_3)

paraelectric $6/mmm$ $\longrightarrow$ ferroelectric $6mm$



Manganese tungstate (MnWO_4)

paraelectric $2/m$ $\longrightarrow$ ferroelectric 2



Domains and spin / lattice excitations

Phonons

PHYSICAL REVIEW LETTERS

2 AUGUST 1993

Phonon Scattering from Ferroelectric Domain Walls: Phonon Imaging in KDP

M. A. Weilert, M. E. Msall, A. C. Anderson, and J. P. Wolfe

Physics Department and Materials Research Laboratory, University of Illinois at Urbana-Champaign, Urbana, Illinois 61801
(Received 1 February 1993)

PHYSICAL REVIEW LETTERS

week ending
27 FEBRUARY 2015

Magnon-Driven Domain-Wall Motion with the Dzyaloshinskii-Moriya Interaction

Weiwei Wang,¹ Maximilian Albert,¹ Marijan Beg,¹ Marc-Antonio Bisotti,¹ Dmitri Chernyshenko,¹
David Cortés-Ortuño,¹ Ian Hawke,² and Hans Fangohr^{1,*}¹Engineering and the Environment, University of Southampton, SO17 1BJ Southampton, United Kingdom²Mathematical Sciences, University of Southampton, SO17 1BJ Southampton, United Kingdom

(Received 27 June 2014; published 26 February 2015)

Electromagnons

PHYSICAL REVIEW MATERIALS 6, 034403 (2022)

Domain-wall-induced electromagnons in multiferroics

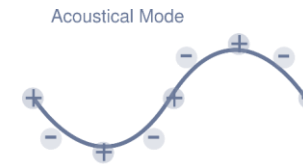
S. Omid Sayedaghaee¹, Sergey Prosandeev,¹ Sergei Prokhorenko,¹ Yousra Nahas,¹ Charles Paillard²,
Bin Xu³, and L. Bellaiche¹

Ferrons

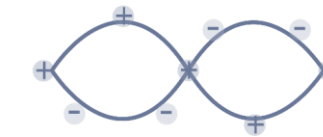
PHYSICAL REVIEW B 113, L220103 (2026)

Letter

Polarization transfer force on ferroelectric domain walls

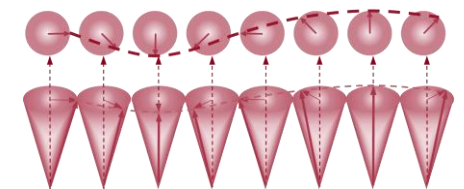
Huanhuan Yang^{1,2}, Peng Yan³, and Gerrit E. W. Bauer^{1,2,4,*}

Acoustical Mode

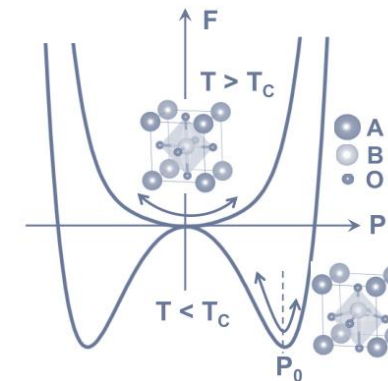


Optical Mode

Phonons



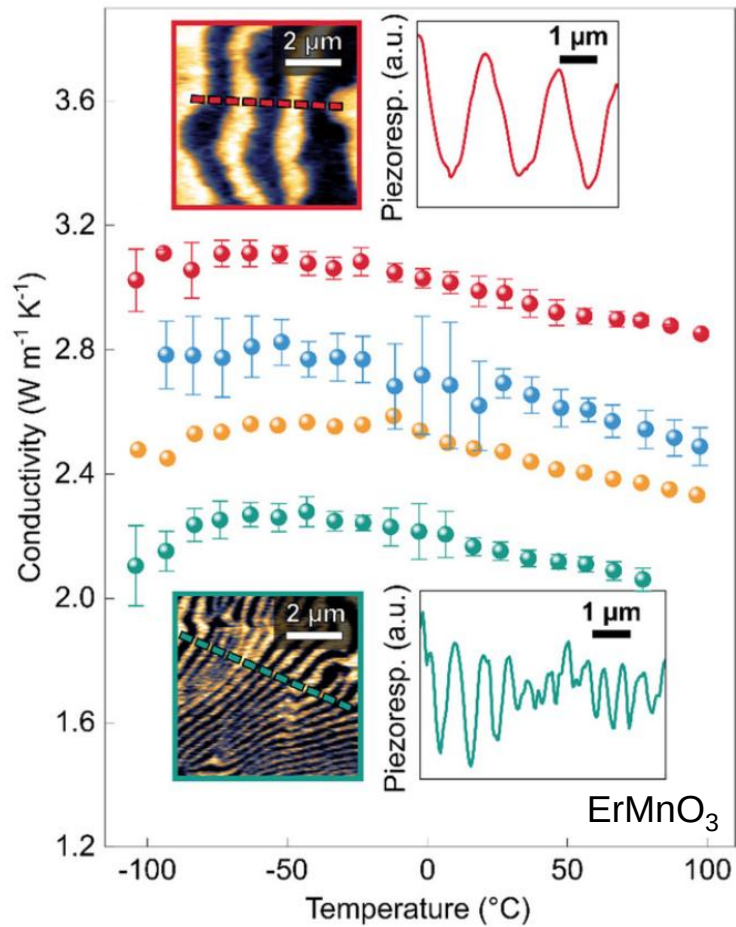
Magnons



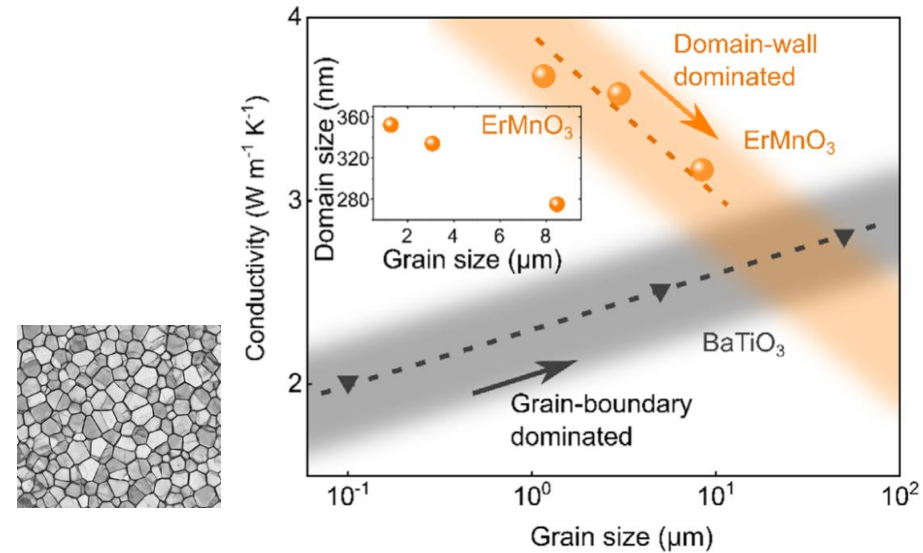
Ferrons

Take home message: When talking about excitations in ferroics, **domains cannot be ignored!**

Example: Relation between domain walls and thermal conductivity



Decreasing
domain size



Phonon scattering at ferroelectric domain walls suppresses thermal conductivity.

Belrhiti-Nejjar, DM *et al.*, Adv. Sci. E06931 (2025)

Ferroic electric and magnetic order - from fundamentals to novel nanoscale phenomena



State-of-the-art ferroics-based applications



Fundamentals of ferroics



Improper ferroelectrics



Hyperferroelectrics



Antiferroelectrics

Spontaneous polarization as a secondary effect

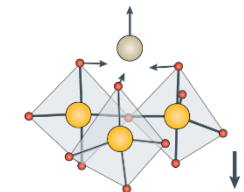
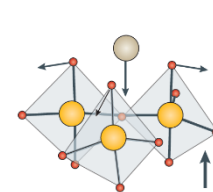
Improper ferroelectrics

A. P. Levanyuk and D. G. Sannikov

Usp. Fiz. Nauk 112, 561–589 (April 1974)

Improper ferroelectrics are considered in the review from a unified point of view on the basis of the phenomenological Landau theory of phase transitions. In such ferroelectrics, in contrast to the ordinary ones, the order parameter of the phase transition is not the polarization but another physical quantity whose transformation properties are different from those of the polarization. Spontaneous polarization arises in the phase transition as a secondary effect. Therefore, the dielectric anomalies in the improper ferroelectrics are significantly different from the dielectric anomalies in the ordinary ferroelectrics. In particular, the temperature dependence of the permittivity does not obey the Curie–Weiss law, an electric field does not suppress the phase transition, etc. The dielectric anomalies are derived by analyzing a definite form of the thermodynamic potential with a two-component order parameter. Such an analysis turns out to be sufficient for the discussion of the available experimental data. The domain structure of the improper ferroelectrics also possesses specific properties: In particular, there exist domains which do not differ in their polarizations. Since the loss of stability in an improper ferroelectric phase transition occurs not with respect to polarization, the soft mode in the nonpolar phase is inactive in the infrared spectrum. Other distinctive features of the phonon spectrum in the phase-transition region are also considered. The experimental data on improper ferroelectrics are discussed. For the rare-earth molybdates, the theory is in quantitative agreement with experiment. In certain other improper ferroelectrics the phase transitions are of first order and nowhere near to being of second order. The quantitative description of such transitions requires additional experimental data and further development of the theory.

Structurally driven



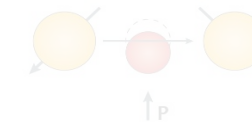
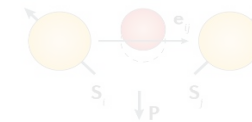
$$q = (q_1, q_2)$$

$$P_z \propto (q_1^3 - 3q_1q_2^2)$$

RMnO_3 ($R = \text{Sc, Y, In, Dy} - \text{Lu}$)

Van Aken *et al.*, Nat. Mater. 3, 164 (2004)

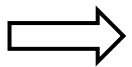
Magnetically driven



$$P_z \propto (q_1 \nabla_x q_2 - q_2 \nabla_x q_1)$$

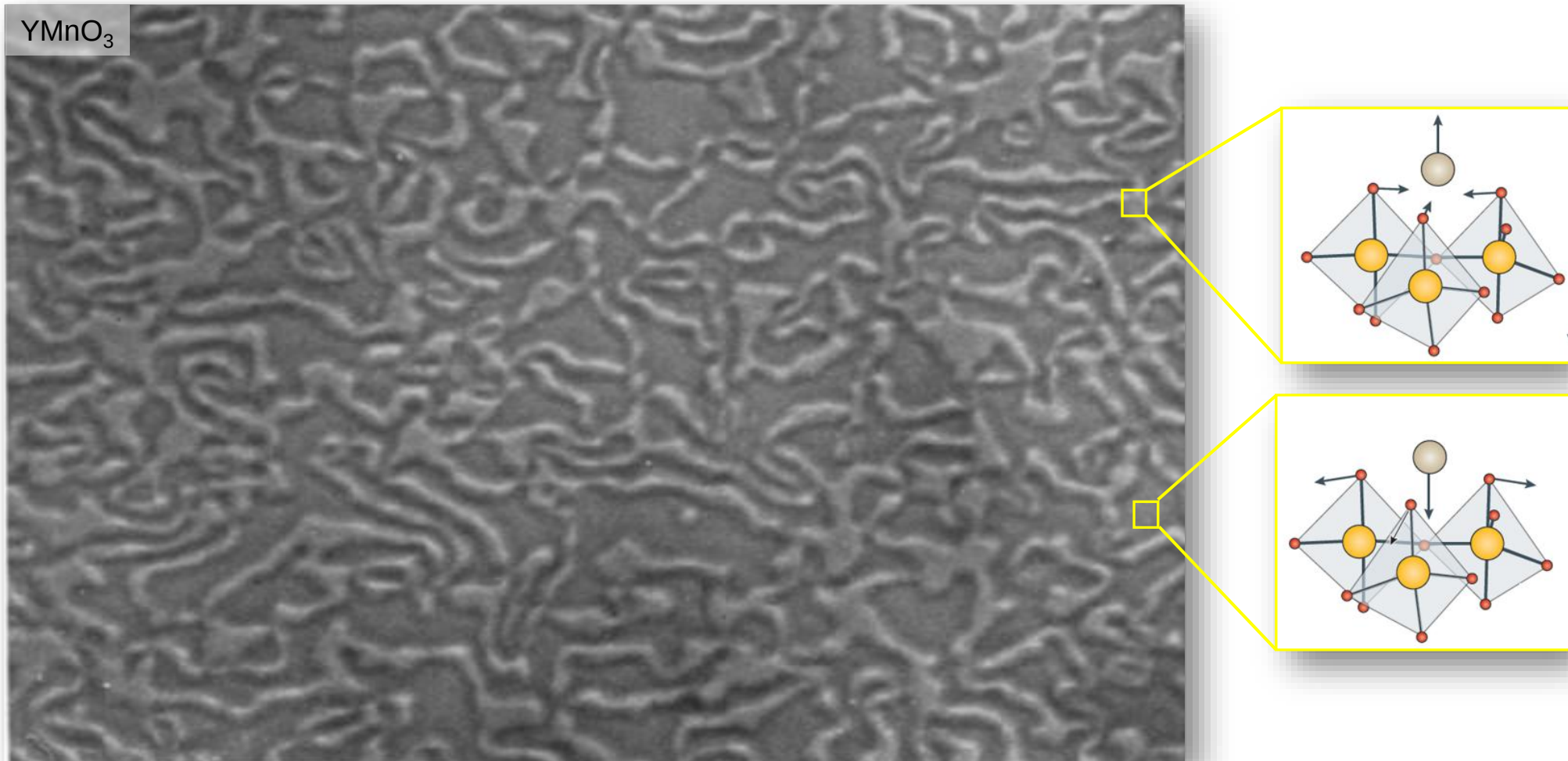
$\text{TbMnO}_3, \text{MnWO}_4$

Katsura *et al.* Phys. Rev. Lett. 95, 057205 (2005)



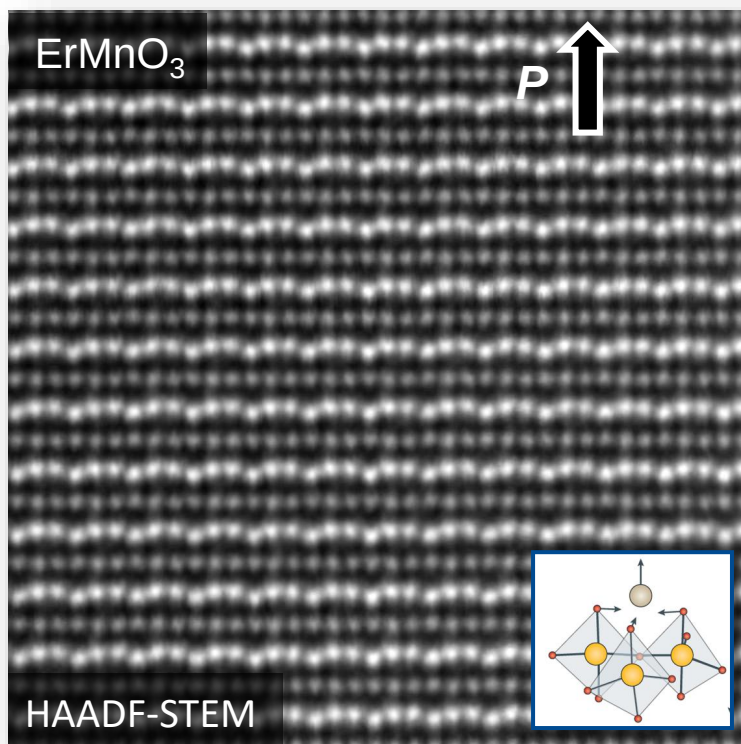
From the symmetry point of view, the primary order parameter of improper ferroelectrics always breaks more symmetries than the electric polarization P (otherwise the system is referred to as *pseudoproper*).

Structurally driven improper ferroelectric domain walls

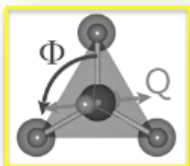
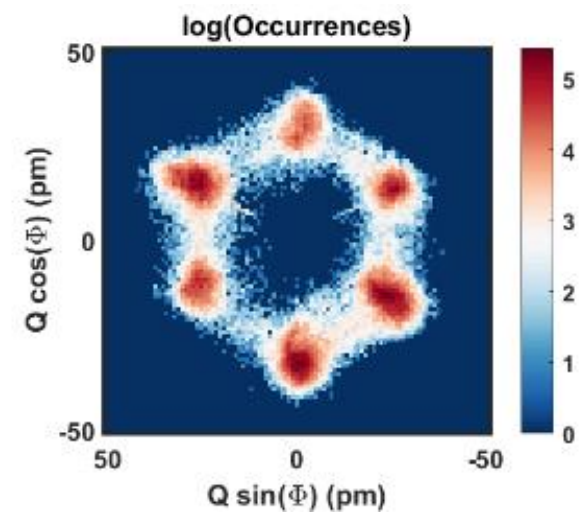
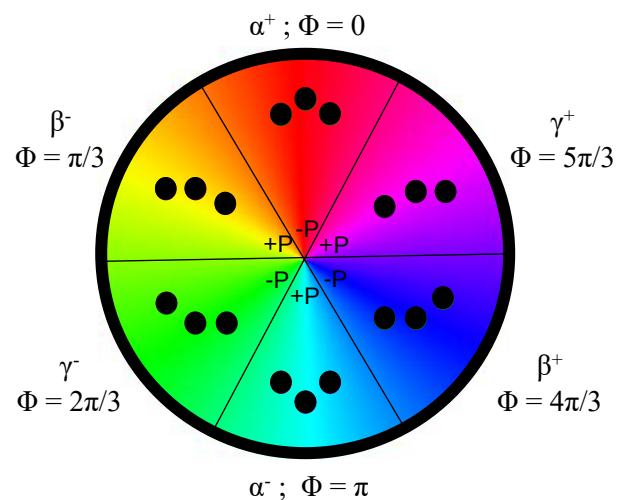


Safrankova *et al.*, Czech. J. Phys. B 17, 560 (1967)
Van Aken *et al.*, Nat. Mater. 3, 164 (2004)

Structural translation domains in hexagonal manganites



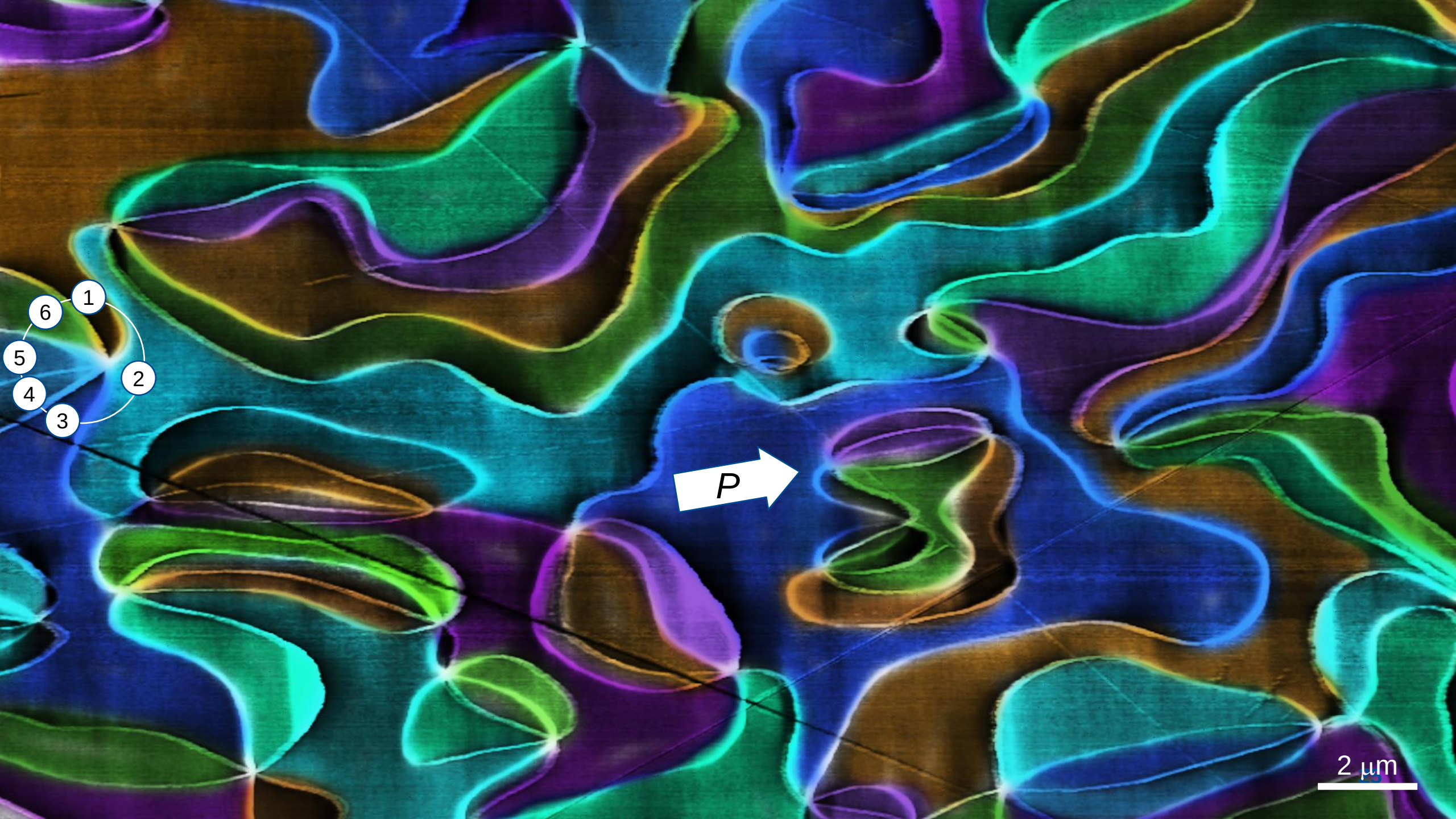
Holtz, DM *et al.*, Nano. Lett. 17, 5883 (2017)



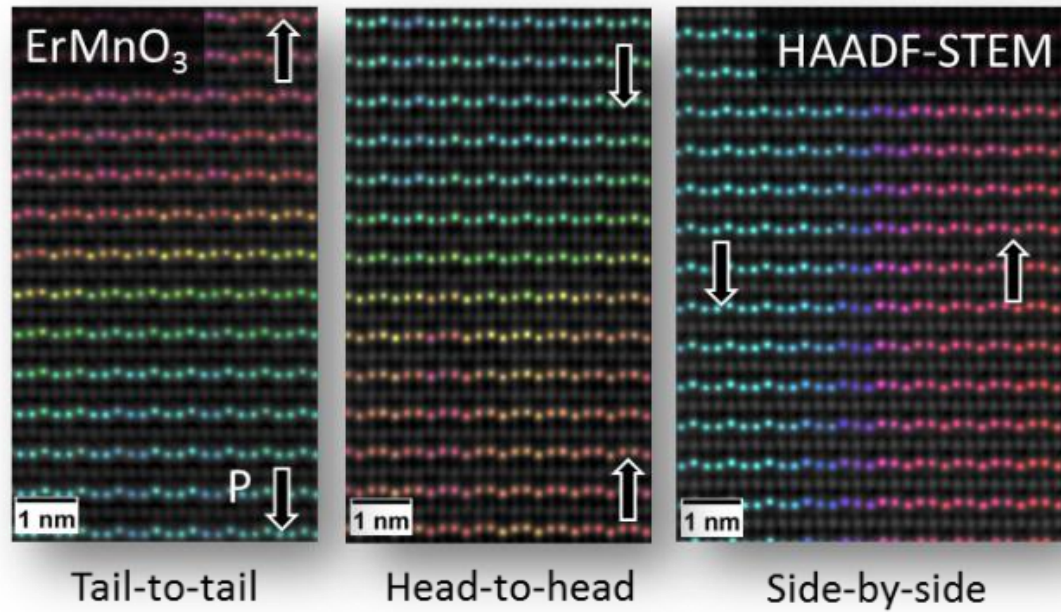
$$q = (q_1, q_2) \equiv (q \cos \Phi, q \sin \Phi) \Rightarrow P \sim q^3 \cos 3\Phi.$$

$$P \approx 5.6 \frac{\mu\text{C}}{\text{cm}^2}$$

Artyukhin *et al.*, Nature Mater. 13, 42 (2013)

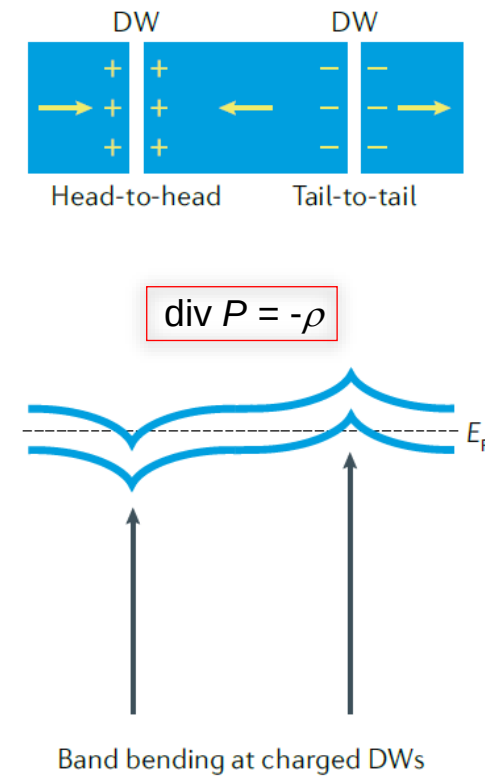


Stable charged domain walls



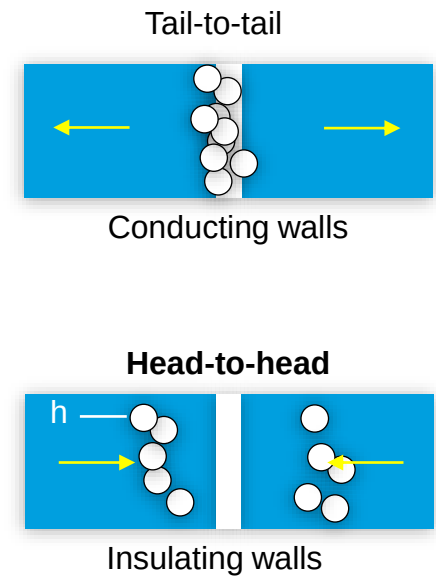
Neutral walls: $5.1 \pm 0.1 \text{ \AA}$
 Charged walls: $6.2 \pm 0.2 \text{ \AA}$

Holtz, DM *et al.*, Nano. Lett. 17, 5883 (2017)



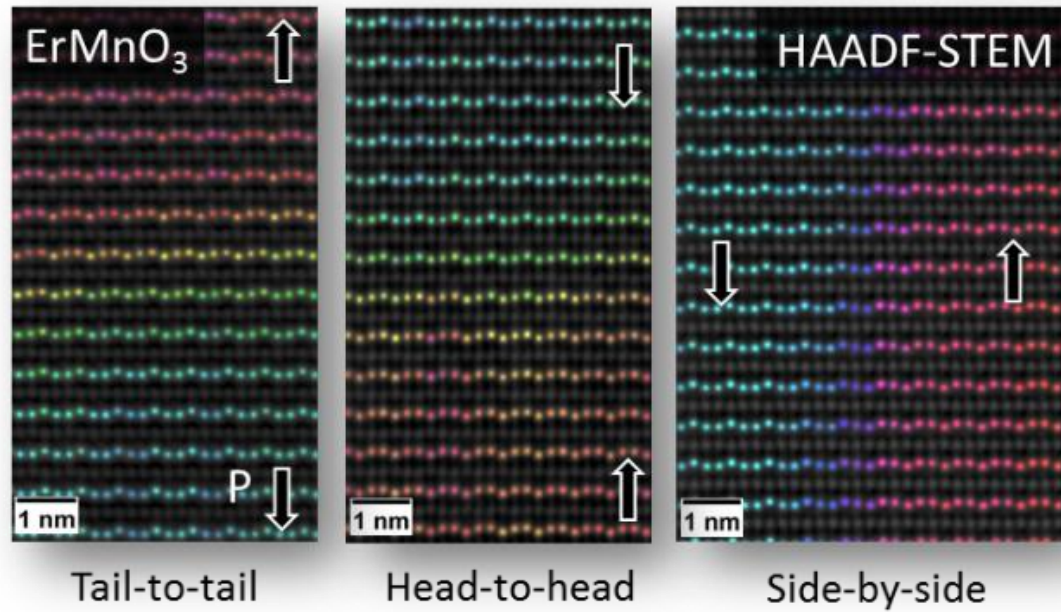
Nataf, DM *et al.*, Nat. Rev. Phys. 2, 634 (2020)

p-type semiconductor



Eliseev *et al.*, Phys. Rev. B 83, 235313 (2011)
 Gureev *et al.*, Phys. Rev. B 83, 184104 (2011)

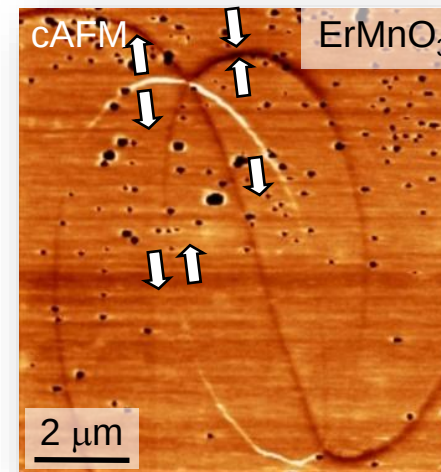
Stable charged domain walls



Neutral walls: $5.1 \pm 0.1 \text{ \AA}$
Charged walls: $6.2 \pm 0.2 \text{ \AA}$

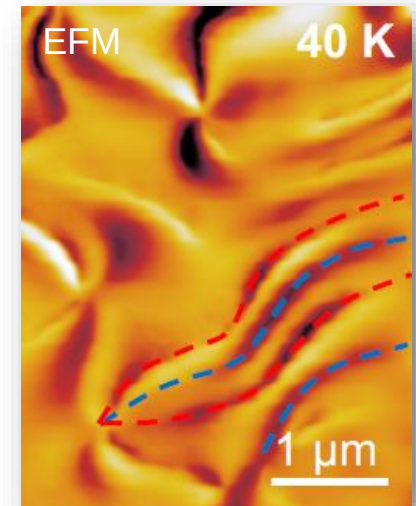
Holtz, DM *et al.*, Nano. Lett. 17, 5883 (2017)

Enhanced/reduced conduction



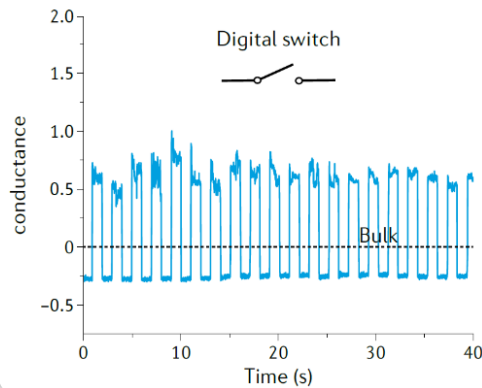
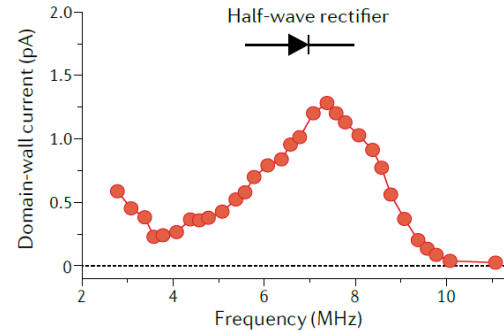
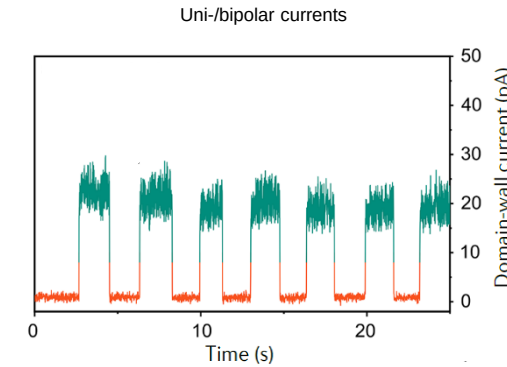
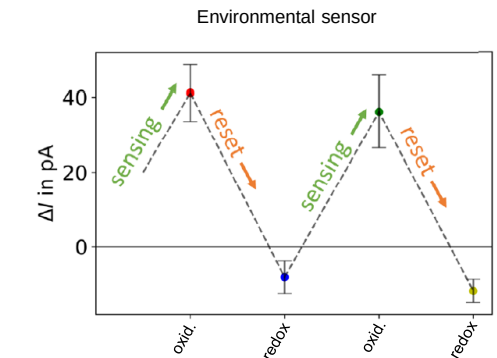
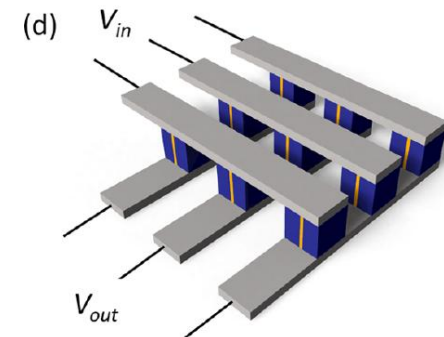
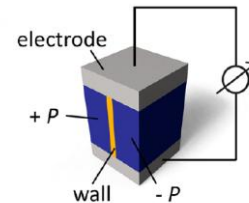
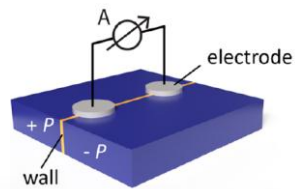
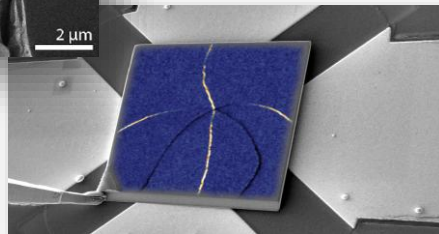
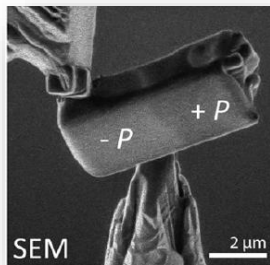
DM *et al.*, Nat. Mater. 11, 284 (2012)

Bound charges



Schoenherr, DM *et al.*, Nano. Lett. 19, 1659 (2019)

Controlling electronic signals using improper ferroelectric domain walls

Mundy, DM *et al.*, Nat. Mater. 16, 622 (2017)Schaab, DM *et al.*, Nat. Nano. 13, 1028 (2018)Schultheiß, DM, *et al.*, Nano Lett. 22, 9560 (2021)Richarz, DM, *et al.*, ACS Appl. Mater. Interfaces 17, 47576 (2025)

Spontaneous polarization as a secondary effect

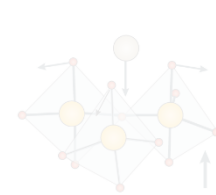
Improper ferroelectrics

A. P. Levanyuk and D. G. Sannikov

Usp. Fiz. Nauk 112, 561–589 (April 1974)

Improper ferroelectrics are considered in the review from a unified point of view on the basis of the phenomenological Landau theory of phase transitions. In such ferroelectrics, in contrast to the ordinary ones, the order parameter of the phase transition is not the polarization but another physical quantity whose transformation properties are different from those of the polarization. Spontaneous polarization arises in the phase transition as a secondary effect. Therefore, the dielectric anomalies in the improper ferroelectrics are significantly different from the dielectric anomalies in the ordinary ferroelectrics. In particular, the temperature dependence of the permittivity does not obey the Curie–Weiss law, an electric field does not suppress the phase transition, etc. The dielectric anomalies are derived by analyzing a definite form of the thermodynamic potential with a two-component order parameter. Such an analysis turns out to be sufficient for the discussion of the available experimental data. The domain structure of the improper ferroelectrics also possesses specific properties: In particular, there exist domains which do not differ in their polarizations. Since the loss of stability in an improper ferroelectric phase transition occurs not with respect to polarization, the soft mode in the nonpolar phase is inactive in the infrared spectrum. Other distinctive features of the phonon spectrum in the phase-transition region are also considered. The experimental data on improper ferroelectrics are discussed. For the rare-earth molybdates, the theory is in quantitative agreement with experiment. In certain other improper ferroelectrics the phase transitions are of first order and nowhere near to being of second order. The quantitative description of such transitions requires additional experimental data and further development of the theory.

Structurally driven



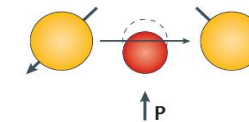
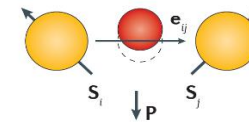
$$q = (q_1, q_2)$$

$$P_z \propto (q_1^3 - 3q_1q_2^2)$$

RMnO_3 ($R = \text{Sc, Y, In, Dy} - \text{Lu}$)

Van Aken *et al.*, Nat. Mater. 3, 164 (2004)

Magnetically driven

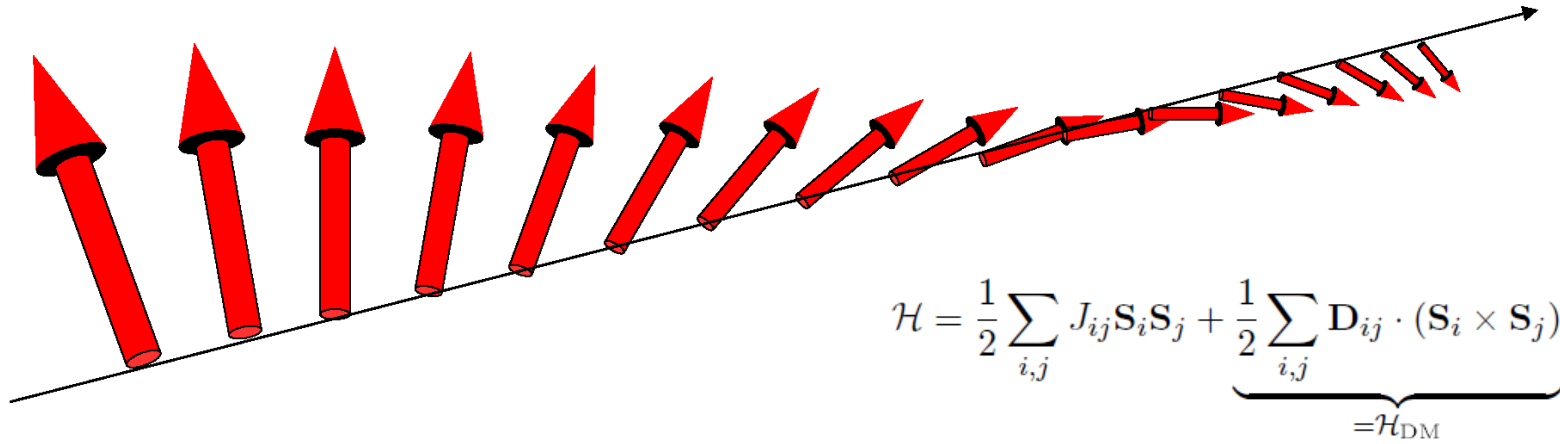


$$P_z \propto (q_1 \nabla_x q_2 - q_2 \nabla_x q_1)$$

$\text{TbMnO}_3, \text{MnWO}_4$

Katsura *et al.* Phys. Rev. Lett. 95, 057205 (2005)

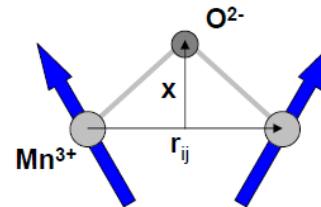
Dzyaloshinskii-Moriya interaction (DMI)



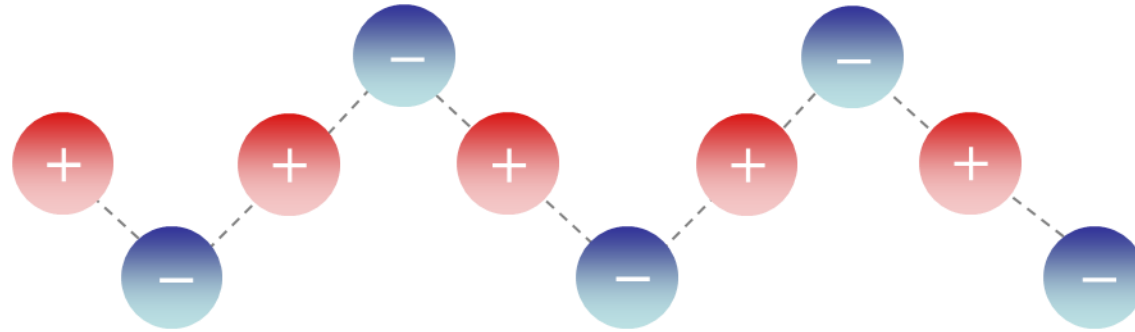
Dzyaloshinskii-Moriya vector $\mathbf{D}_{ij}$ ($\mathbf{D}_{ij} = -\mathbf{D}_{ji}$)

- In low-symmetry systems the exchange interaction can contain an anisotropic term
- Arises due to spin orbit coupling (relativistic effect)

$$\mathbf{D}_{ij} \propto \mathbf{x} \times \mathbf{r}_{ij}$$



Magnetically induced ferroelectricity



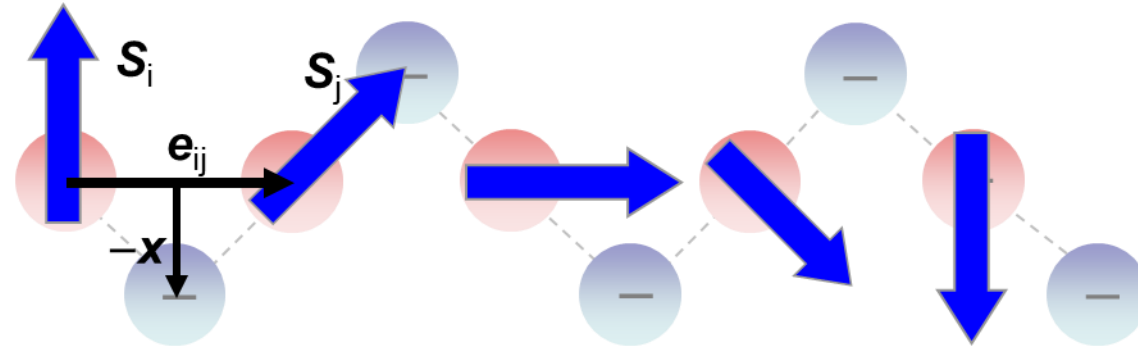
Dzyaloshinskii-Moriya:

$$\otimes \mathbf{S}_i \times \mathbf{S}_j$$

$$E_{\text{DM}} = \mathbf{D}_{ij} \cdot (\mathbf{S}_i \times \mathbf{S}_j)$$

$$\mathbf{D}_{ij} \sim \mathbf{x} \times \mathbf{e}_{ij}$$

Magnetically induced ferroelectricity



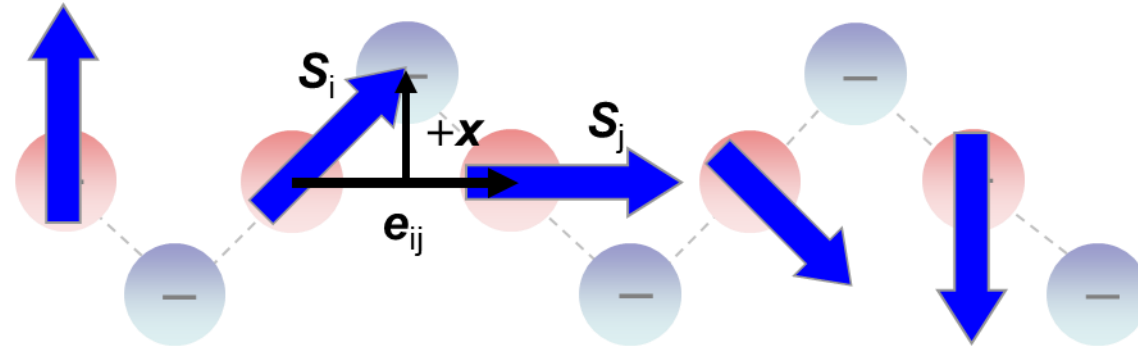
Dzyaloshinskii-Moriya:

$$\otimes \mathbf{S}_i \times \mathbf{S}_j$$

$$E_{\text{DM}} = \mathbf{D}_{ij} \cdot (\mathbf{S}_i \times \mathbf{S}_j)$$

$$\mathbf{D}_{ij} \sim \mathbf{x} \times \mathbf{e}_{ij}$$

Magnetically induced ferroelectricity



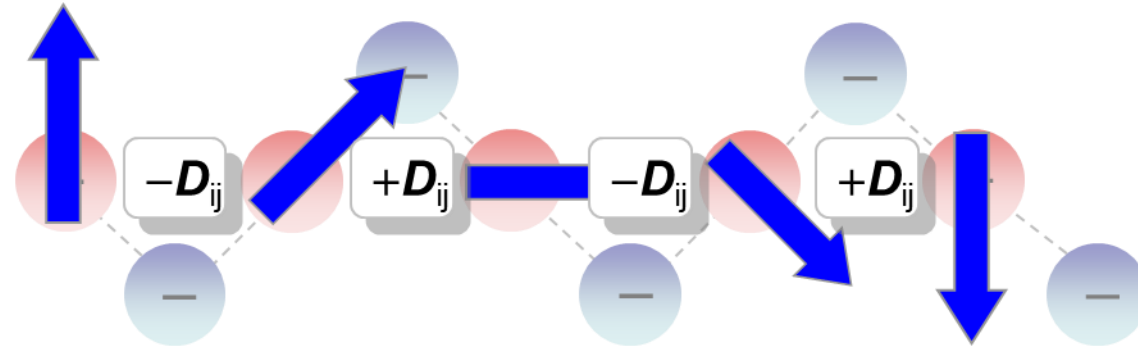
Dzyaloshinskii-Moriya:

$$\otimes \mathbf{S}_i \times \mathbf{S}_j$$

$$E_{\text{DM}} = \mathbf{D}_{ij} \cdot (\mathbf{S}_i \times \mathbf{S}_j)$$

$$\mathbf{D}_{ij} \sim \mathbf{x} \times \mathbf{e}_{ij}$$

Magnetically induced ferroelectricity



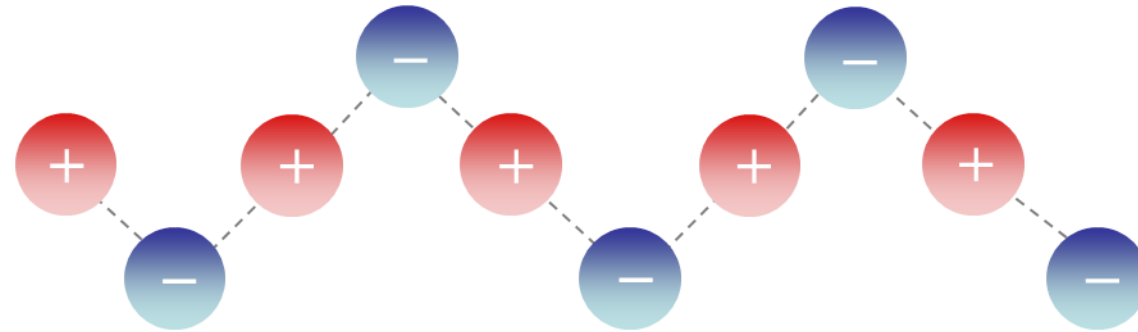
Dzyaloshinskii-Moriya:

$$\otimes \mathbf{S}_i \times \mathbf{S}_j$$

$$E_{\text{DM}} = \mathbf{D}_{ij} \cdot (\mathbf{S}_i \times \mathbf{S}_j)$$

$$\mathbf{D}_{ij} \sim \mathbf{x} \times \mathbf{e}_{ij}$$

Magnetically induced ferroelectricity



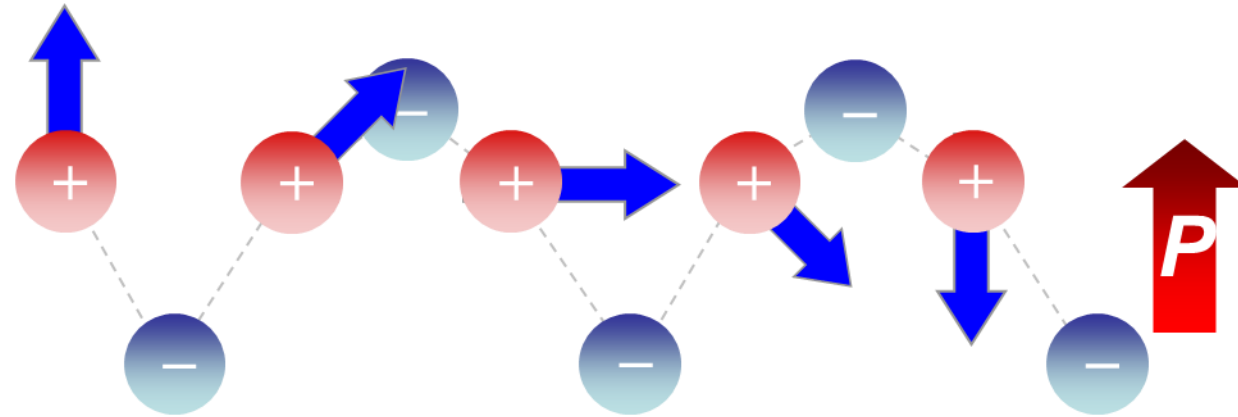
Dzyaloshinskii-Moriya:

$$\otimes \mathbf{S}_i \times \mathbf{S}_j$$

$$E_{\text{DM}} = \mathbf{D}_{ij} \cdot (\mathbf{S}_i \times \mathbf{S}_j)$$

$$\mathbf{D}_{ij} \sim \mathbf{x} \times \mathbf{e}_{ij}$$

Magnetically induced ferroelectricity



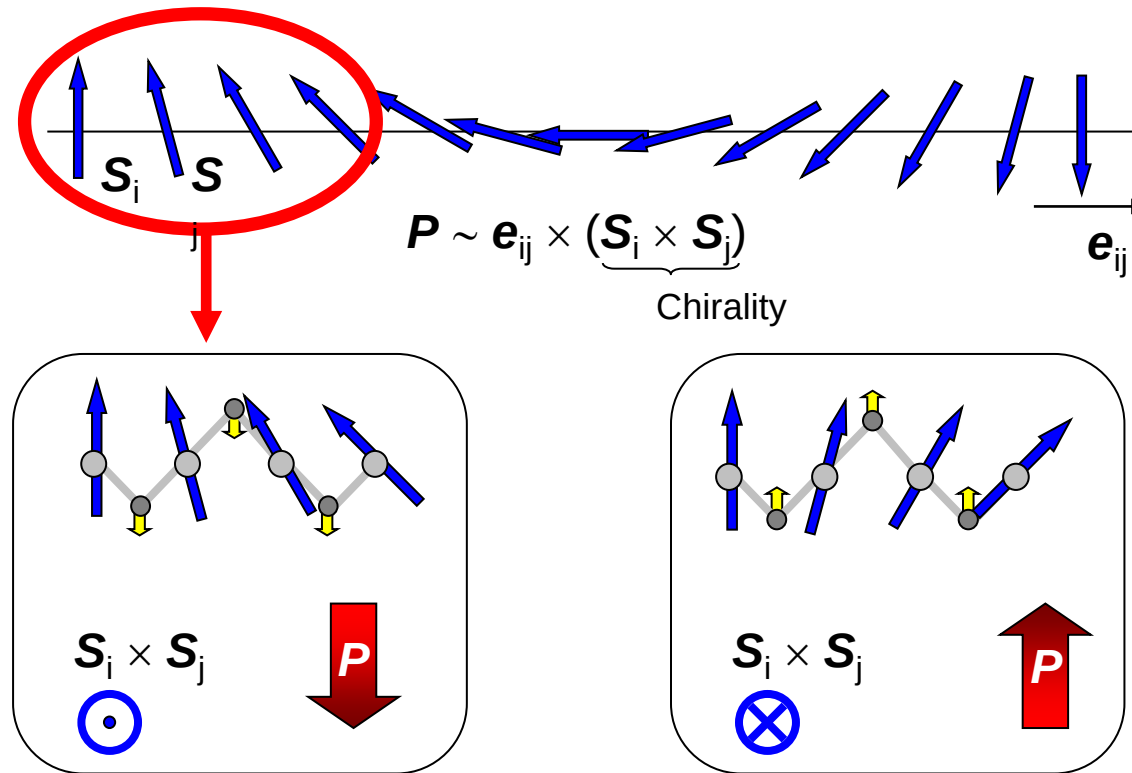
Dzyaloshinskii-Moriya:

$$\otimes \mathbf{S}_i \times \mathbf{S}_j$$

$$E_{\text{DM}} = \mathbf{D}_{ij} \cdot (\mathbf{S}_i \times \mathbf{S}_j)$$

$$\mathbf{D}_{ij} \sim \mathbf{x} \times \mathbf{e}_{ij}$$

Inverse Dzyaloshinskii-Moriya interaction



Magnetically induced ferroelectricity in TbMnO_3

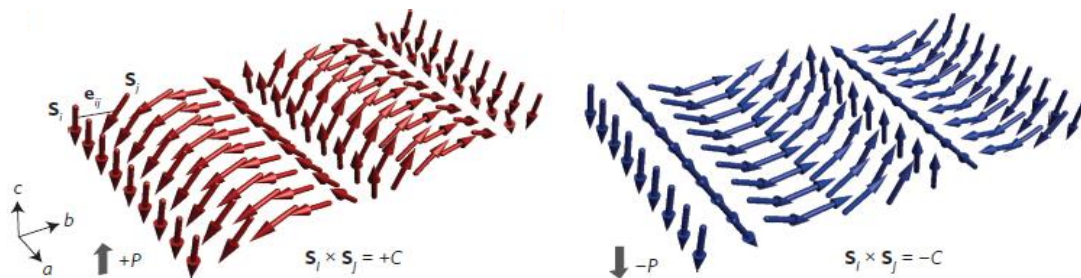
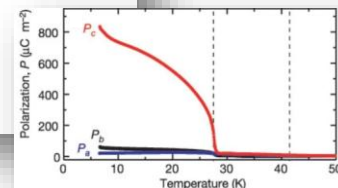
Letter | Published: 06 November 2003

Magnetic control of ferroelectric polarization

T. Kimura , T. Goto, H. Shintani, K. Ishizaka, T. Arima & Y. Tokura

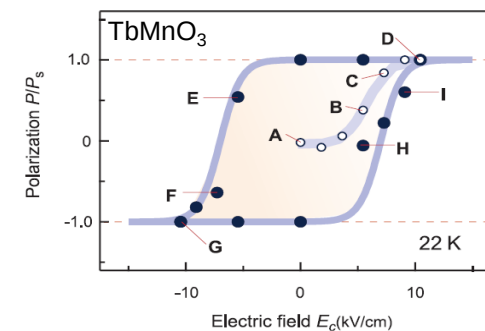
Nature **426**, 55–58 (2003) | [Cite this article](#)

34k Accesses | 4113 Citations | 12 Altmetric | [Metrics](#)

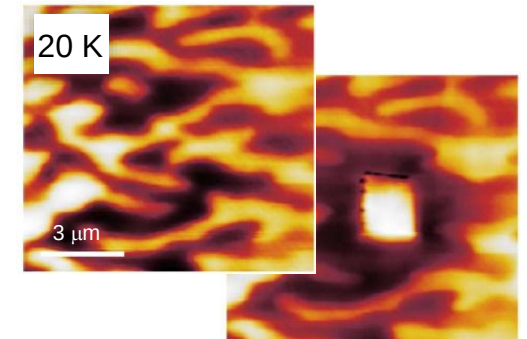


Manz *et al.*, *Nature Photonics* **10**, 653 (2016)

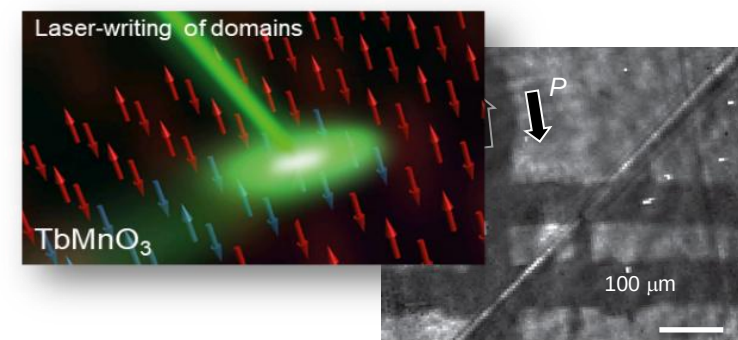
Controlling domain by electric fields, surface charges, and light



Matsubara, DM *et al.*, *Science* **3348**, 1112 (2015)



Schoenherr, DM *et al.*, *npj Quant. Mater* **5**, 86 (2020)



Manz, DM *et al.*, *Nat. Photon.* **10**, 653 (2016)

Ferroic electric and magnetic order - from fundamentals to novel nanoscale phenomena



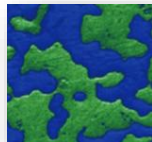
State-of-the-art ferroics-based applications



Fundamentals of ferroics



Improper ferroelectrics



Hyperferroelectrics



Antiferroelectrics

Hyperferroelectricity – persistent polarization under open circuit conditions

PRL 112, 127601 (2014)

Selected for a Viewpoint in *Physics*
PHYSICAL REVIEW LETTERS



Hyperferroelectrics: Proper Ferroelectrics with Persistent Polarization

Kevin F. Garrity, Karin M. Rabe, and David Vanderbilt

Department of Physics and Astronomy, Rutgers University, Piscataway, New Jersey 08854, USA

(Received 25 November 2013; published 26 March 2014)

All known proper ferroelectrics are unable to polarize normal to a surface or interface if the resulting depolarization field is unscreened, but there is no fundamental principle that enforces this behavior. In this work, we introduce **hyperferroelectrics**, a new class of proper ferroelectrics which polarize even when the depolarization field is unscreened, this condition being equivalent to **instability of a longitudinal optic mode** in addition to the transverse-optic-mode instability characteristic of proper ferroelectrics. We use first-principles calculations to show that several recently discovered hexagonal ferroelectric semiconductors have this property, and we examine its consequences both in the bulk and in a superlattice geometry.

Stable charged antiparallel domain walls in hyperferroelectrics

S Liu and R E Cohen

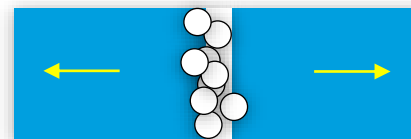
Published 18 May 2017 • © 2017 IOP Publishing Ltd

[Journal of Physics: Condensed Matter](#), Volume 29, Number 24

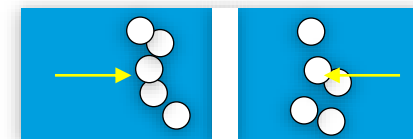
[Special Issue on Ferroelastics and Domain Walls](#)

Citation S Liu and R E Cohen 2017 *J. Phys.: Condens. Matter* 29 244003

Tail-to-tail



Head-to-head



Hyperferroelectric model systems

LiNbO_3 , LiBeSb , $\text{La}_2\text{Ti}_2\text{O}_7$, $\text{Sr}_2\text{Nb}_2\text{O}_7$, $\text{Ca}_3\text{Ti}_2\text{O}_7$,
 $\text{Pb}_5\text{Ge}_3\text{O}_{11}$

Garrity *et al.* Phys. Rev. Lett. 112, 127601 (2014)

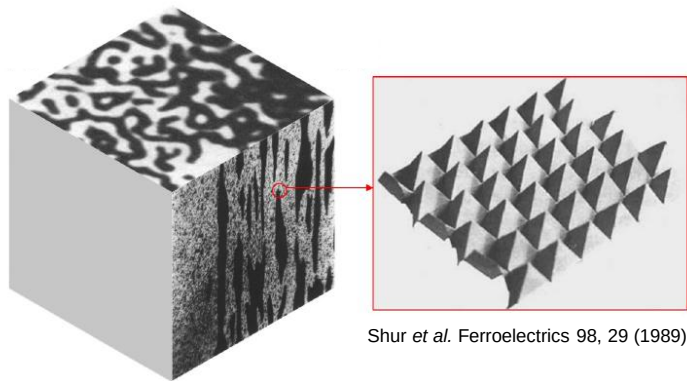
Liu *et al.* J. Phys.: Condens. Matter 29, 244003 (2017)

Zhan *et al.*, Phys. Rev. B 97, 054107 (2018)

Fava *et al.*, Phys. Rev. B 109, 024113 (2024)

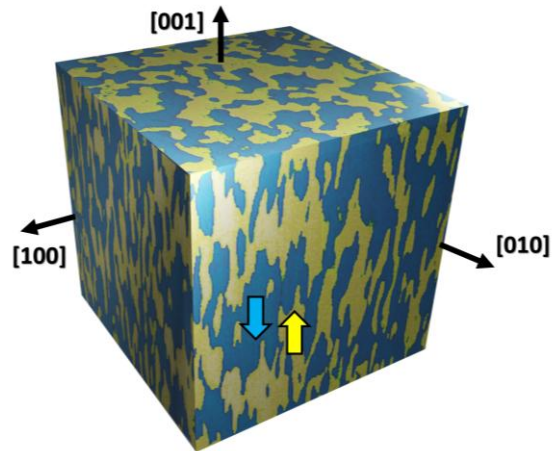
Conroy, DM *et al.*, Adv. Mater. 36, 2405150 (2024)

Unusual ferroelectric behavior in $\text{Pb}_5\text{Ge}_3\text{O}_{11}$



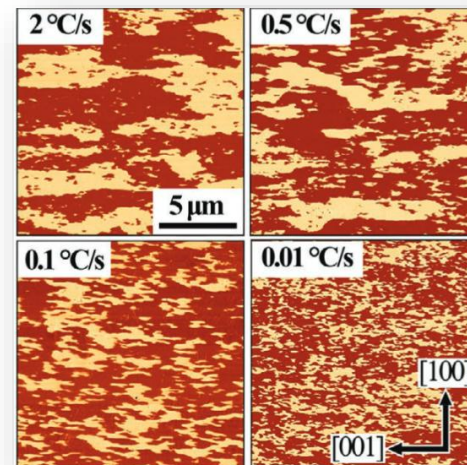
Shur et al. Ferroelectrics 98, 29 (1989)

Uniaxial ferroelectric $P \approx 4.8 \frac{\mu\text{C}}{\text{cm}^2}$



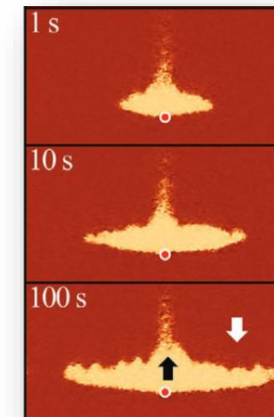
Bak, DM et al. Adv. Funct. Mater. 30, 2000284 (2020)

Domain scaling



Bak, DM et al. Adv. Funct. Mater. 30, 2000284 (2020)

Domain wall dynamics

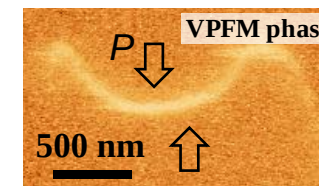


Tikhonov, DM, et al. Adv. Mater. 34, 2203028 (2022)

Domain shape

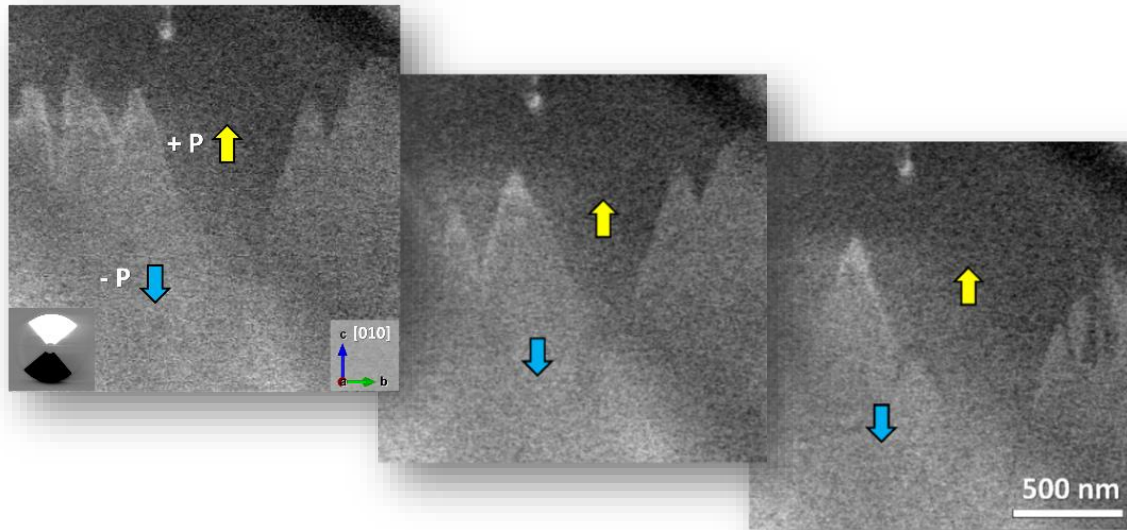


Piezoresponse

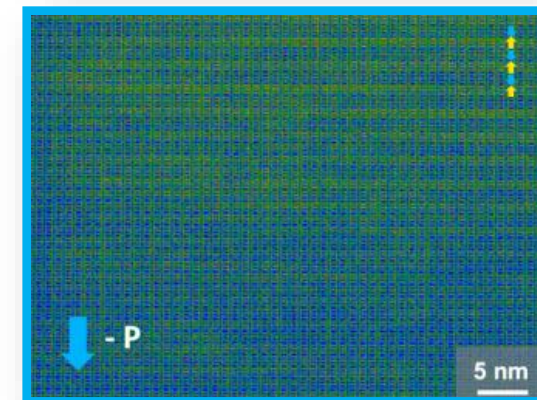
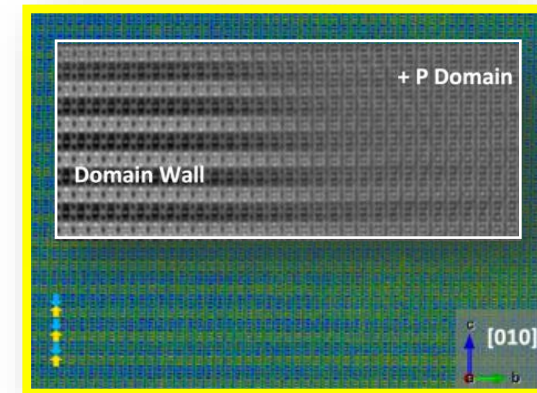
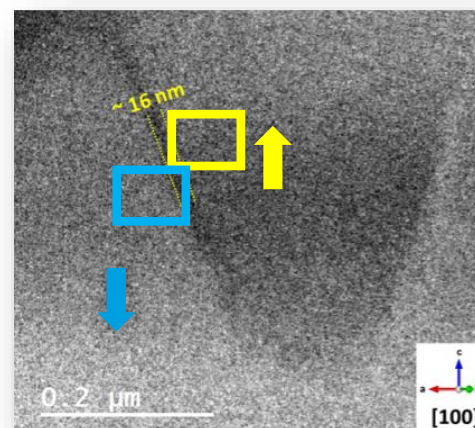


Lu, DM et al. Adv. Funct. Mater. 33, 2213684 (2023)

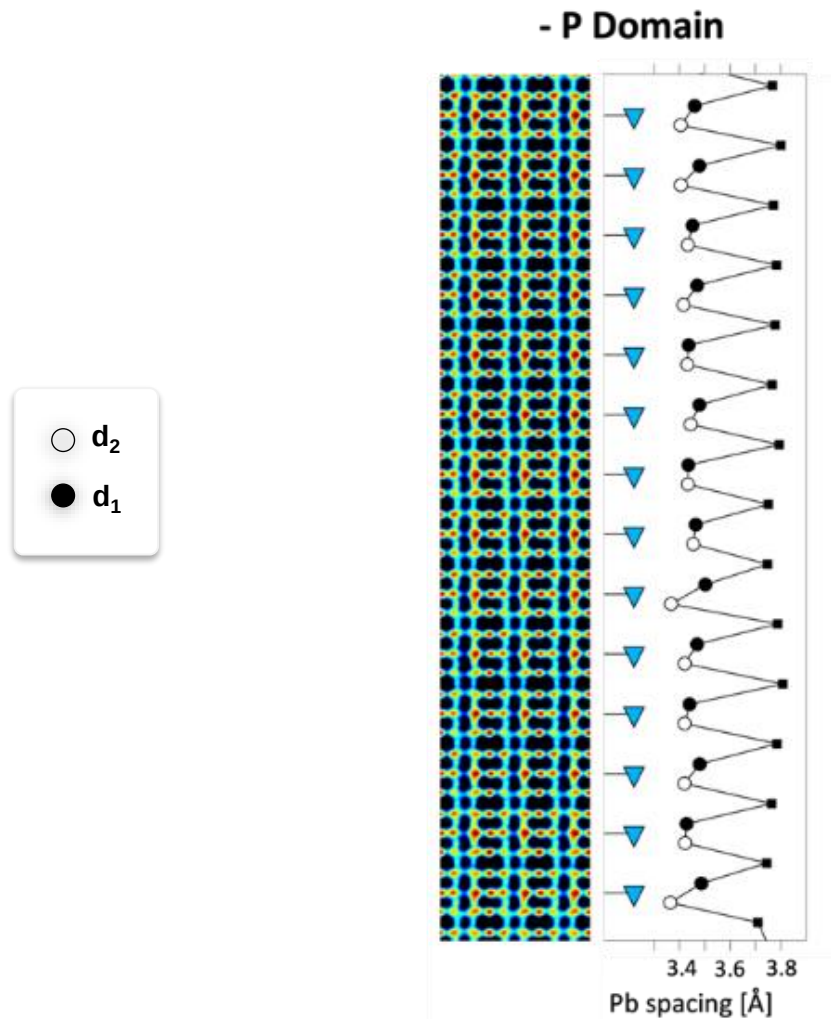
Domain wall properties and anti-polar structure



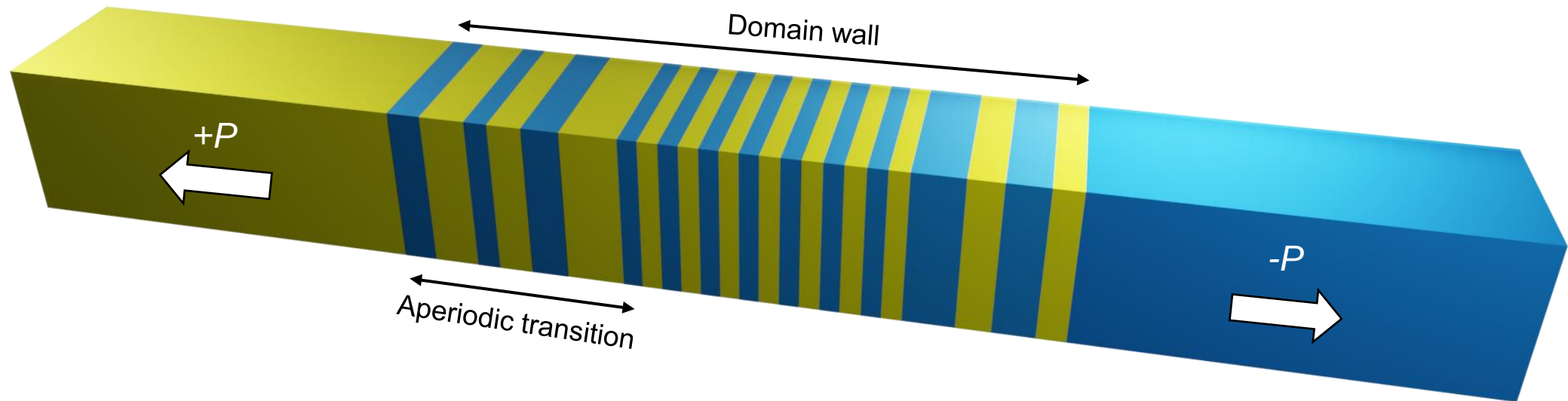
Highly mobile
and broad 180°
domain walls



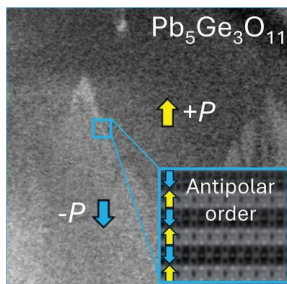
Evolution of 180° dipole flip within the wall



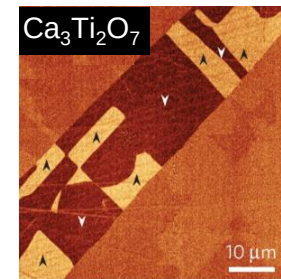
Modulated anti-polar order – an exception to the rule?



Conroy, DM et al., Adv. Mater. 36, 2405150 (2024)



- “Building blocks” enabled by hyperferroelectricity
- **BUT**: simple head-to-head or tail-to-tail still energetically favorable → **excited state**?
- To be continued...



Oh et al. Nature Mater. 14, 407 (2015)

Ferroic electric and magnetic order - from fundamentals to novel nanoscale phenomena



State-of-the-art ferroics-based applications



Fundamentals of ferroics



Improper ferroelectrics



Hyperferroelectrics



Antiferroelectrics

Antiferroelectrics revisited

Theory of Antiferroelectric Crystals

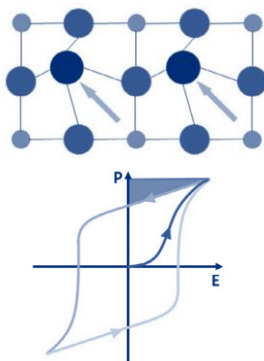
C. KITTEL

Department of Physics, University of California, Berkeley, California

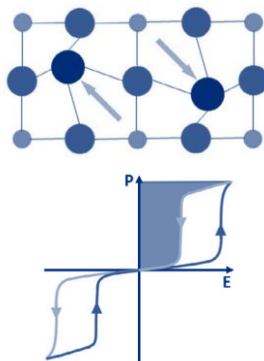
(Received January 10, 1951)

An antiferroelectric state is defined as one in which lines of ions in the crystal are spontaneously polarized, but with neighboring lines polarized in antiparallel directions. In simple cubic lattices the antiferroelectric state is likely to be more stable than the ferroelectric state. The dielectric constant above and below the antiferroelectric curie point is investigated for both first- and second-order transitions. In either case the dielectric constant need not be very high; but if the transition is second order, ϵ is continuous across the Curie point. The antiferroelectric state will not be piezoelectric. The thermal anomaly near the Curie point will be of the same nature and magnitude as in ferroelectrics. A susceptibility variation of the form $C/(T+\theta)$ as found in strontium titanate is not indicative of antiferroelectricity, unlike the corresponding situation in antiferromagnetism.

Ferroelectric



Antiferroelectric



Randall et al. Jour. Amer. Cer. Soc. 104, 8, 3775 (2021)

Examples of antipolar order

Collinear

Simple modulations

Sinusoidal

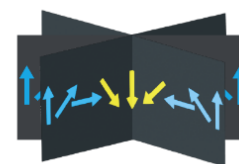
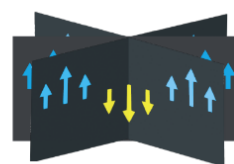


Non-collinear

Cycloidal, conical, ...



Multiple modulations



Long-range
commensurate/
incommensurate

Uncompensated

Uneven



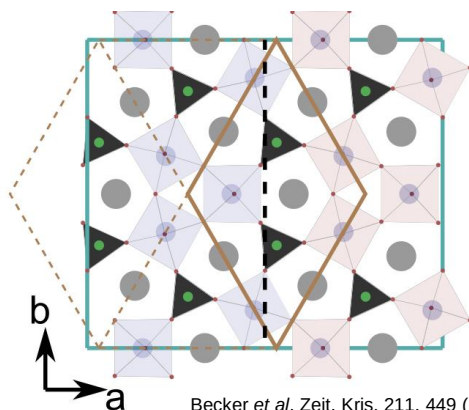
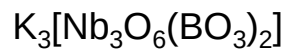
Canted



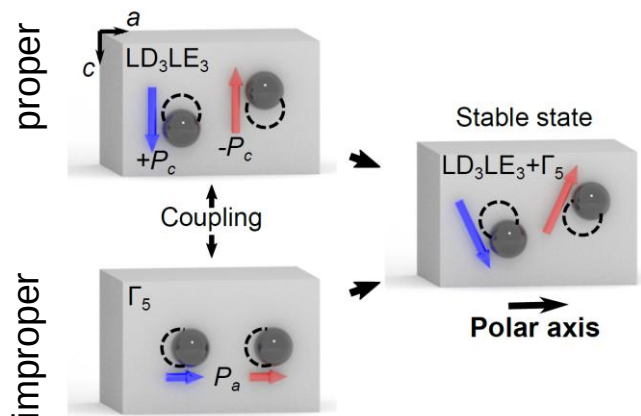
Hybrid
polar + antipolar

Catalan, Gruverman, Íñiguez-González, DM, and Trassin, Nat. Mater. 25, 557 (2026)

Domain formation in potassium niobate borate



Becker et al. Zeit. Kris. 211, 449 (1996)

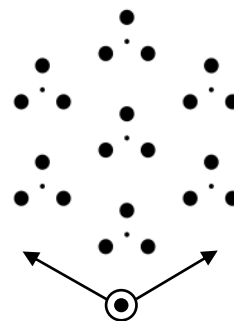


$$P_a \approx 0.03 \frac{\mu\text{C}}{\text{cm}^2}$$

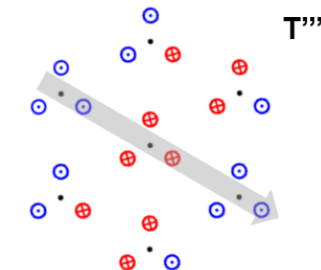
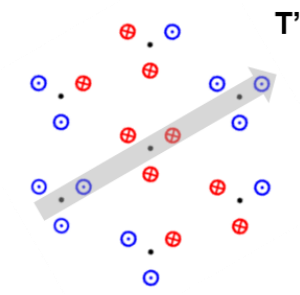
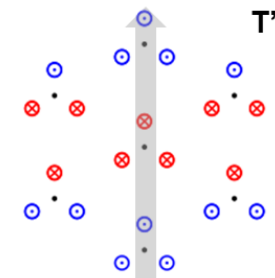
$$\pm P_c \approx 19 \frac{\mu\text{C}}{\text{cm}^2}$$

Ushakov, DM et al., Nat. Nano. 21, 648 (2026)

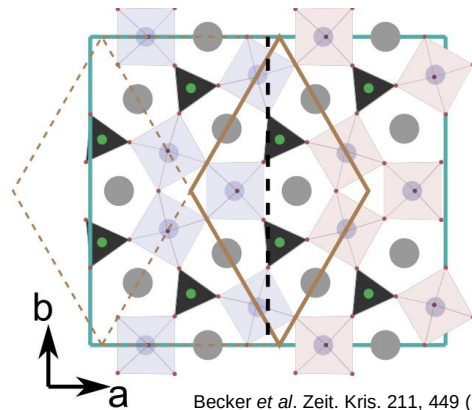
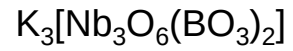
Proto phase ($P6\bar{2}m$)



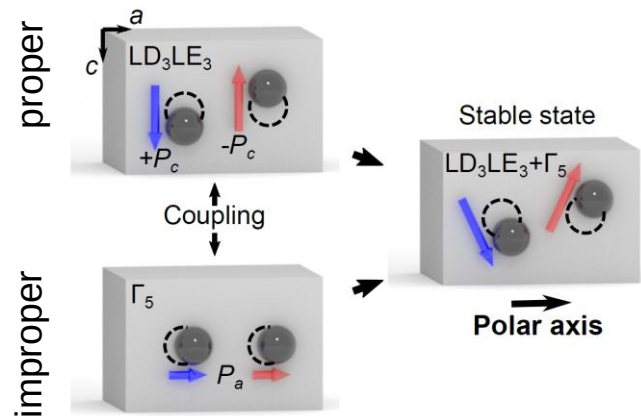
Antipolar (LD_3LE_3)



Domain formation in potassium niobate borate



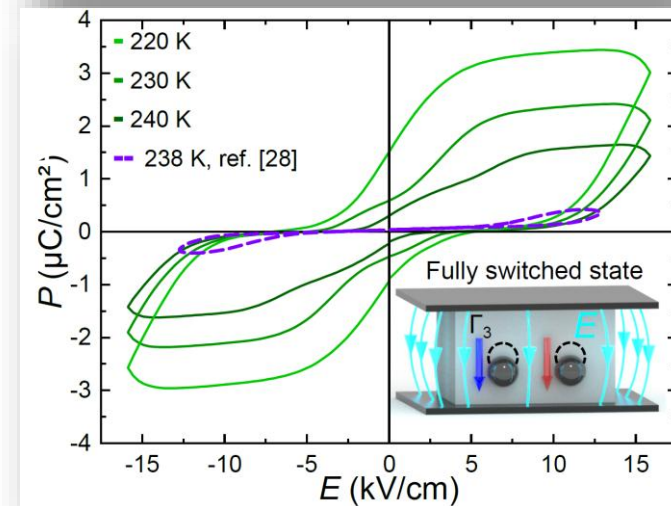
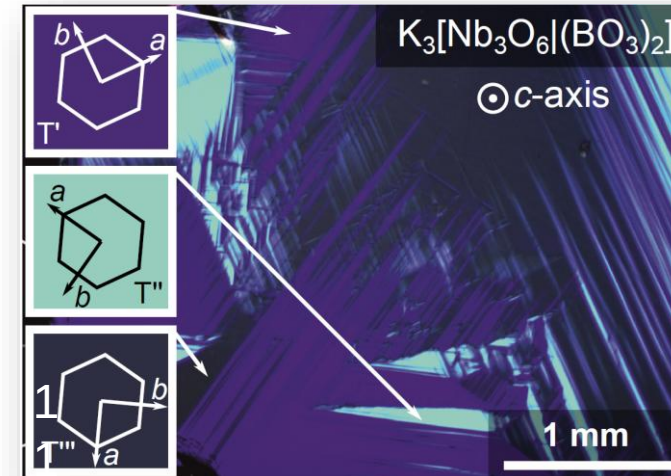
Becker et al. Zeit. Kris. 211, 449 (1996)



$$P_a \approx 0.03 \frac{\mu\text{C}}{\text{cm}^2}$$

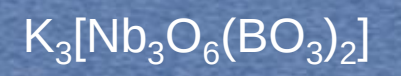
$$\pm P_c \approx 19 \frac{\mu\text{C}}{\text{cm}^2}$$

Ushakov, DM et al., Nat. Nano. 21, 648 (2026)



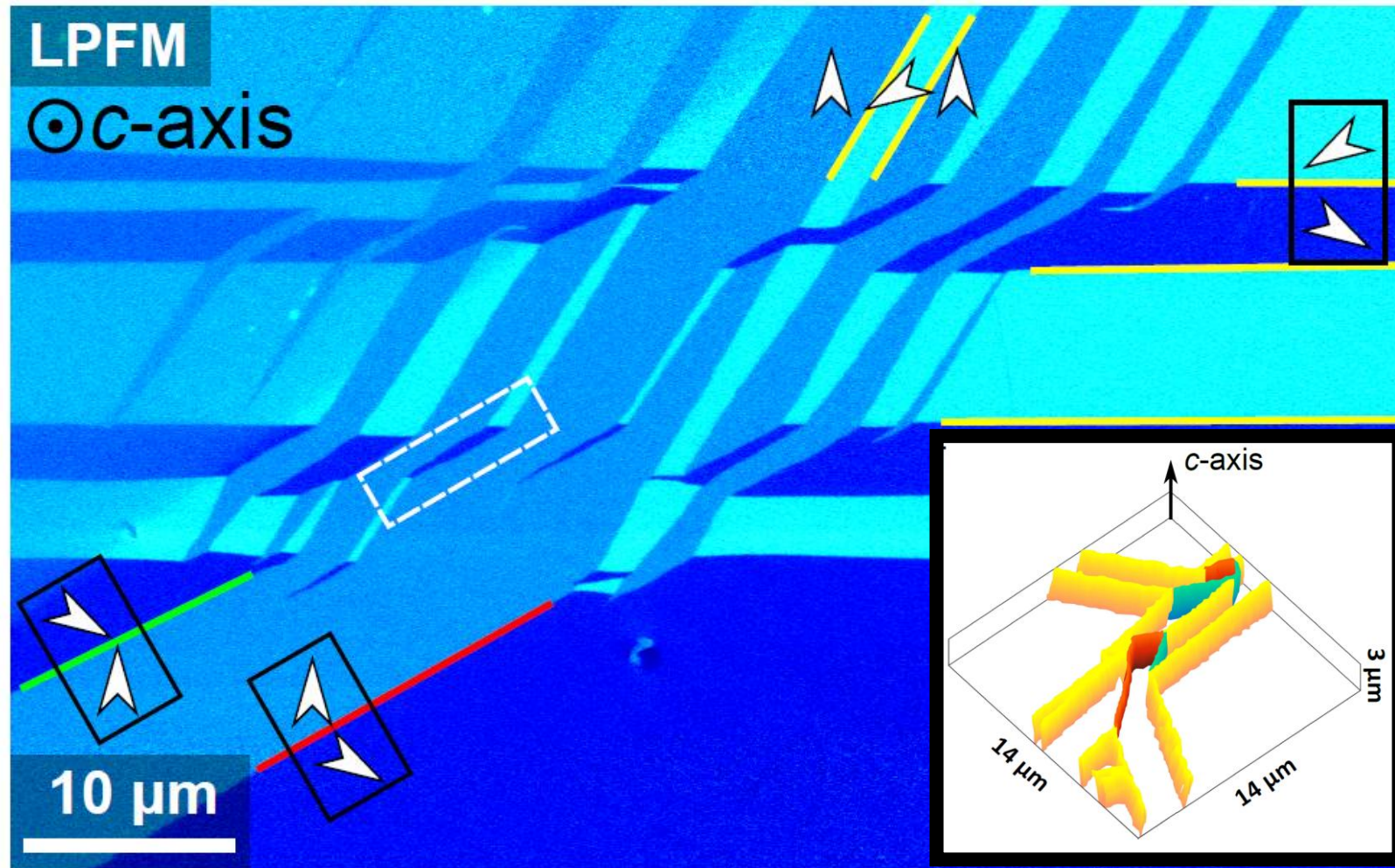
Becker et al. Zeit. Kris. 211, 449 (1996)

Ushakov, DM et al., Nat. Nano. 21, 648 (2026)

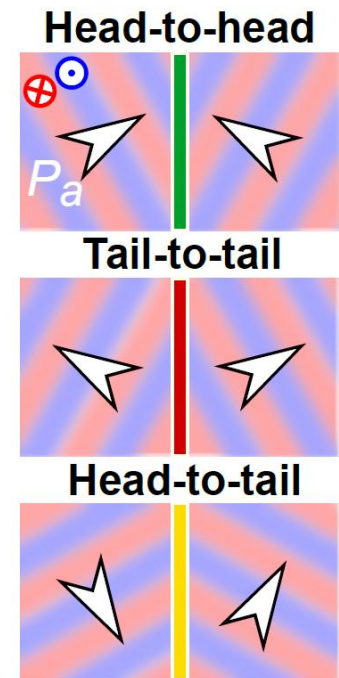


5 μm

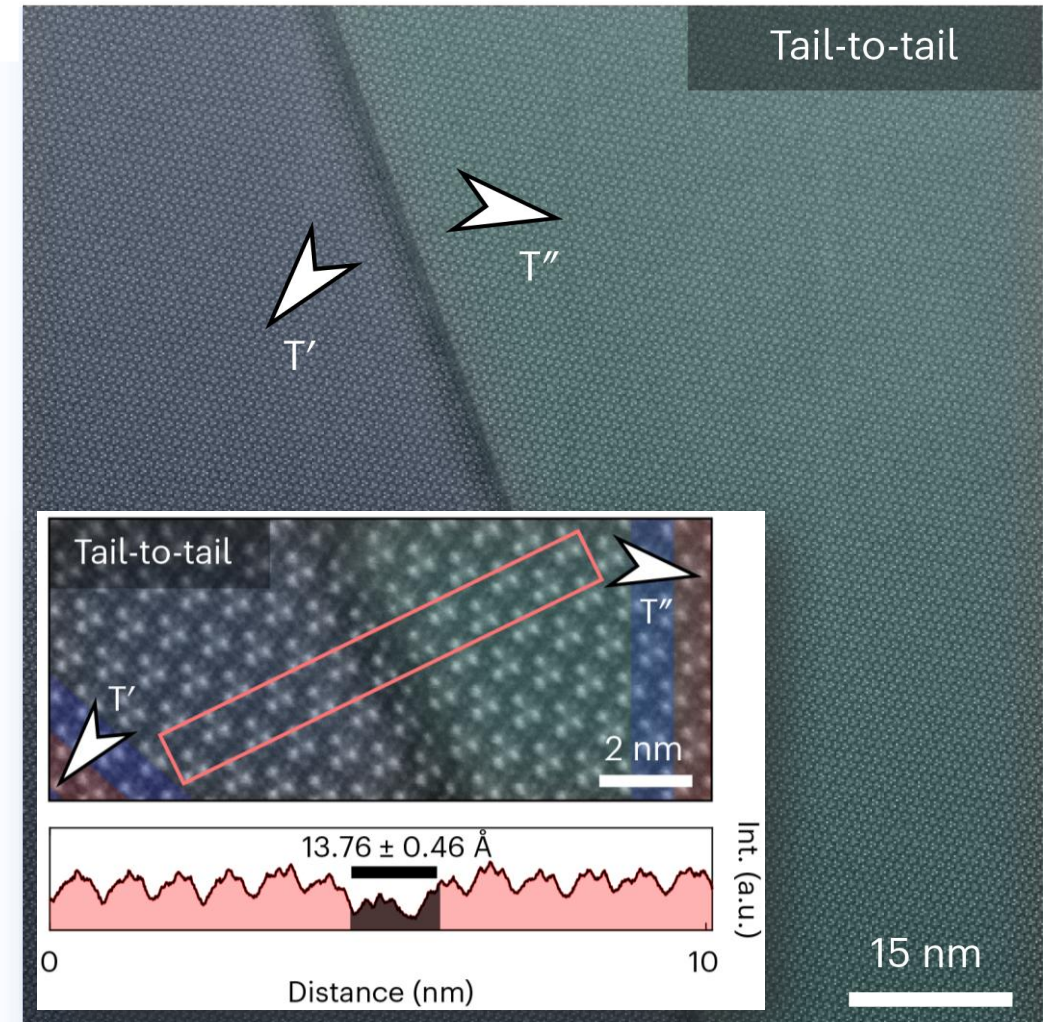
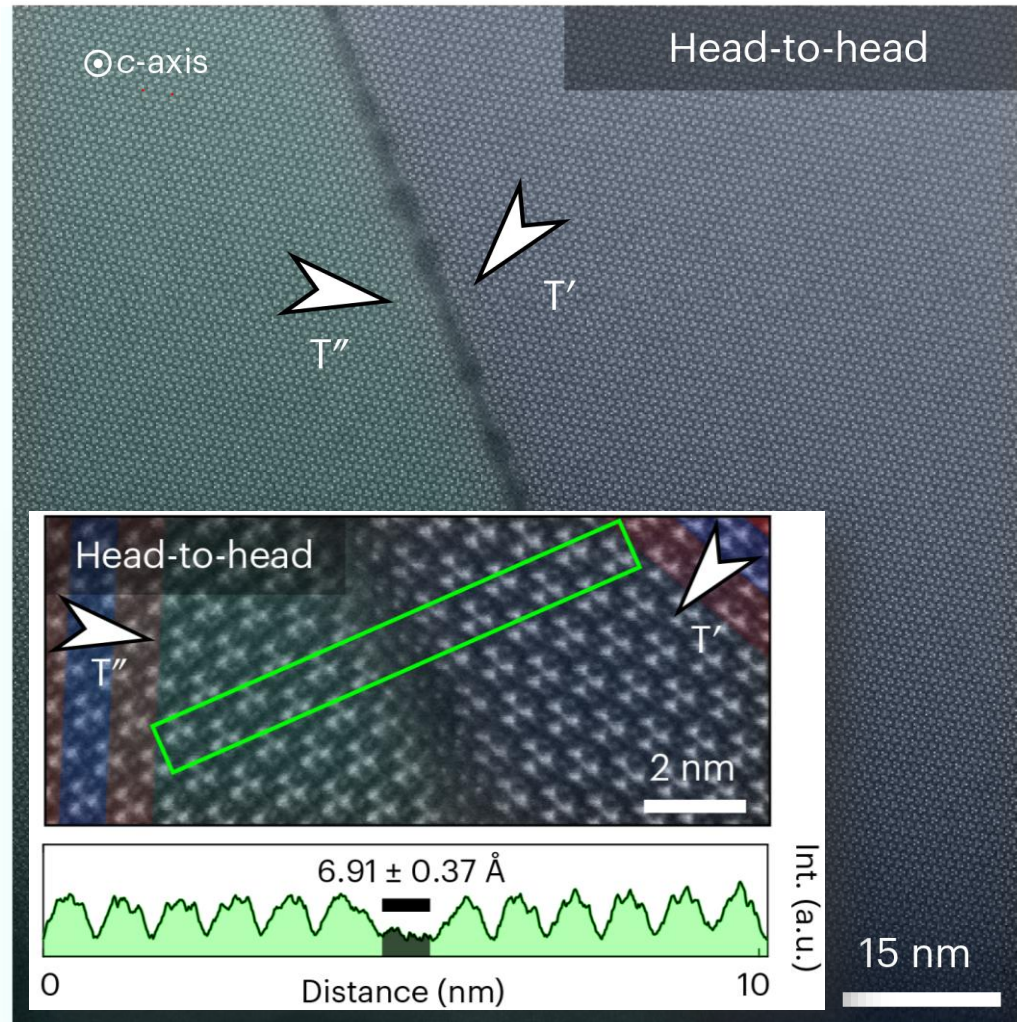
Charged hybrid antiferroelectric-ferroelectric domain walls



Ushakov, DM et al., Nat. Nano. 21, 648 (2026)



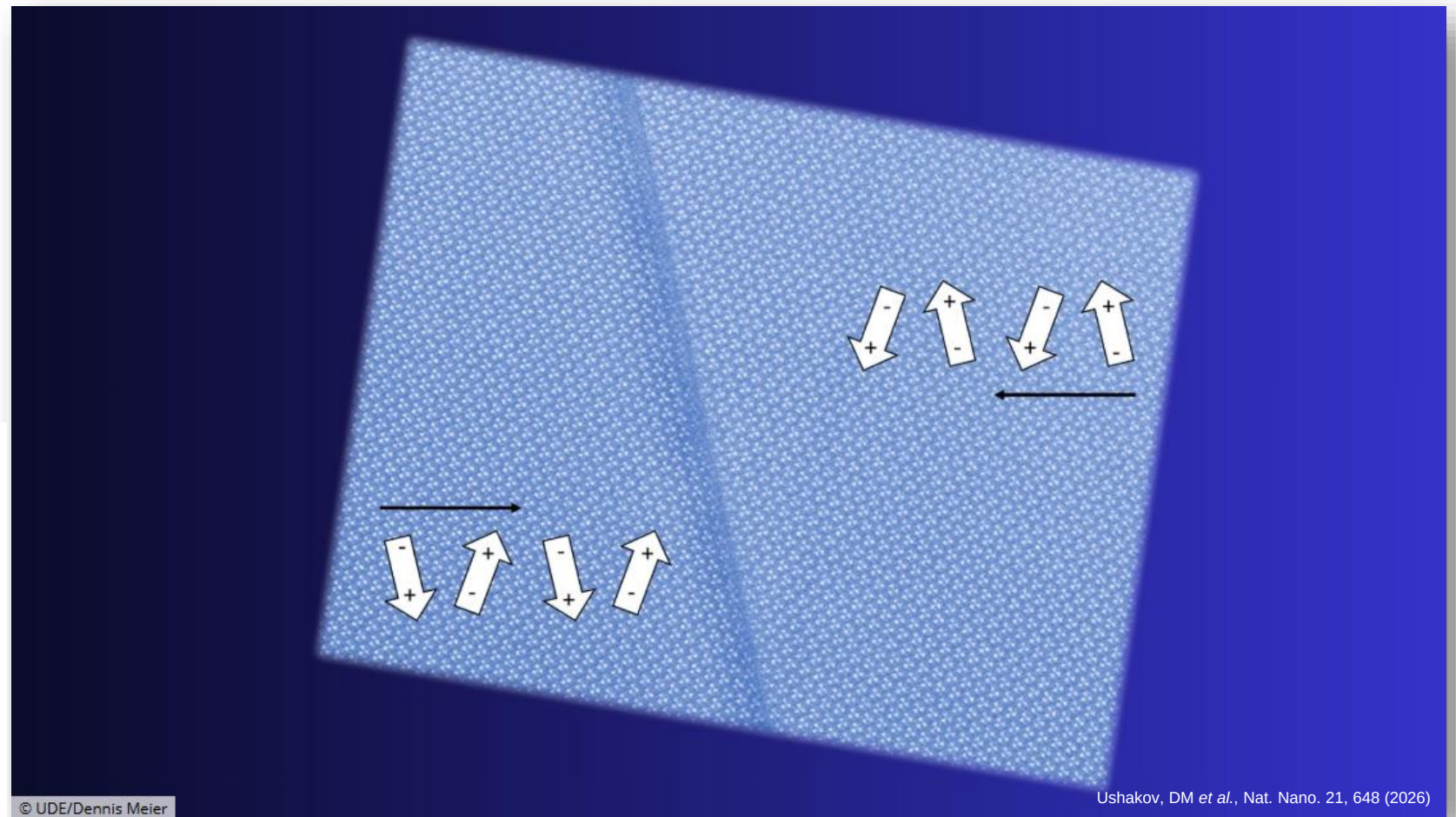
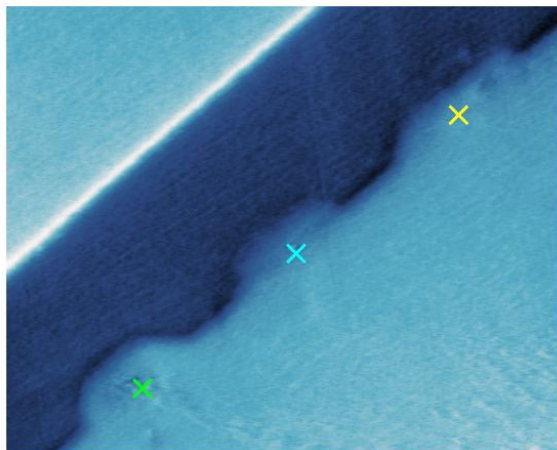
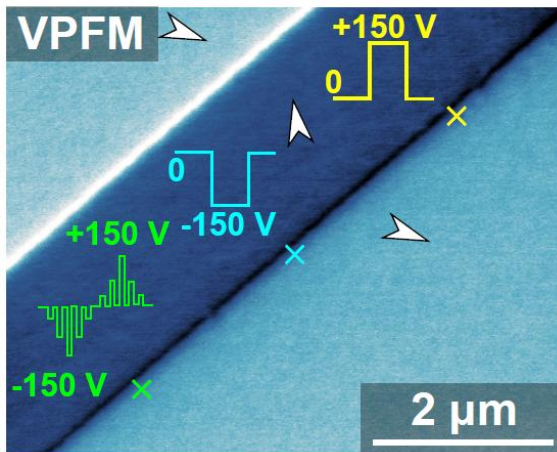
Atomic structure of hybrid antiferroelectric-ferroelectric walls



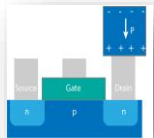
Ushakov, DM et al., Nat. Nano. 21, 648 (2026)

Canted antiferroelectricity and new degrees of freedom

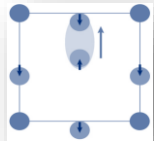
Electric-field poling



Ferroic electric and magnetic order - from fundamentals to novel nanoscale phenomena



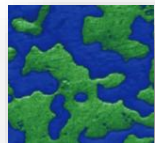
Beyond classical systems



Fundamentals



Improper Ferroelectrics



Hyperferroelectrics



Antiferroelectrics

nature reviews materials The evolution of multiferroics

Manfred Fiebig , Thomas Lottermoser, Dennis Meier & Morgan Trassin

Nature Reviews Materials **1**, Article number: 16046 (2016)

nature reviews physics

Domain-wall engineering and topological defects in ferroelectric and ferroelastic materials

G. F. Nataf , M. Guennou, J. M. Gregg, D. Meier, J. Hlinka, E. K. H. Salje & J. Kreisel

Nature Reviews Physics **2**, 634–648 (2020)

nature reviews materials

Ferroelectric domain walls for nanotechnology

Dennis Meier  & Sverre M. Selbach 

Nature Reviews Materials **7**, 157–173 (2022)

nature reviews physics

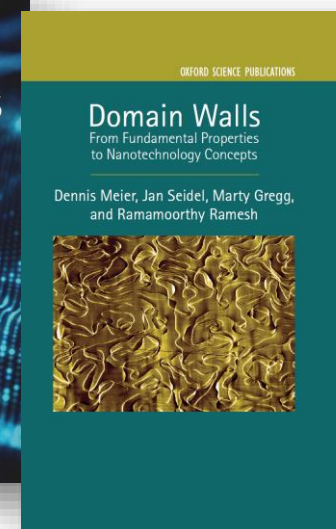
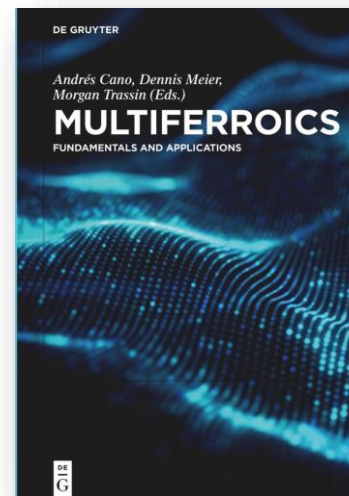
<https://doi.org/10.1038/s42254-024-00729-w>

Perspective

 Check for updates

Topological magnetic and ferroelectric systems for reservoir computing

Karin Everschor-Sitte ¹, Atreya Majumdar ¹, Katharina Wolk ² & Dennis Meier ^{2,3}



nature materials

A modern perspective on antiferroelectrics

Gustau Catalan , Alexei Gruverman , Jorge Íñiguez-González , Dennis Meier  & Morgan Trassin 

Nature Materials **25**, 557–565 (2026) | [Cite this article](#)

EMA's actions:

Flagship Conference: Overseeing of JEMS

Awards: Young Scientist, Dominique Givord Award

Foster community actions: STF, magnetometry, industry

Young scientists: European School (ESM), networking

Communication: Website, newsletter, social media, calendar of events, job market

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