

Emergence of Ferrons and Ferronics

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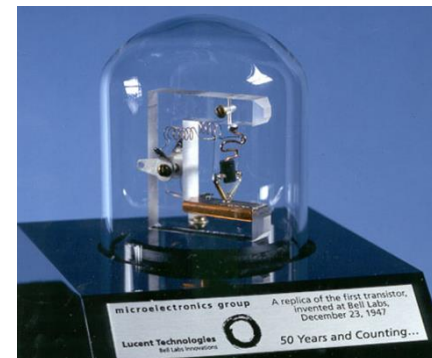


Thanks to collaborators: Gerrit Bauer, Ken-ichi Uchida,
Ryo Iguchi, Xianzhe Chen, ...

Research motivation

Conventional electronics

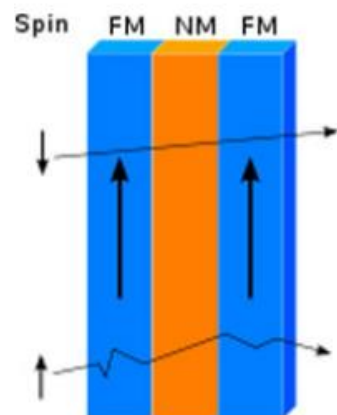
(carriers: electrons or holes)



first transistor (1947)



1956



2007

Giant magnetoresistance

Spintronics

(carriers: electrons, magnons)

electric charge

Various degrees of freedom in matter

spin
(magnetic dipole)

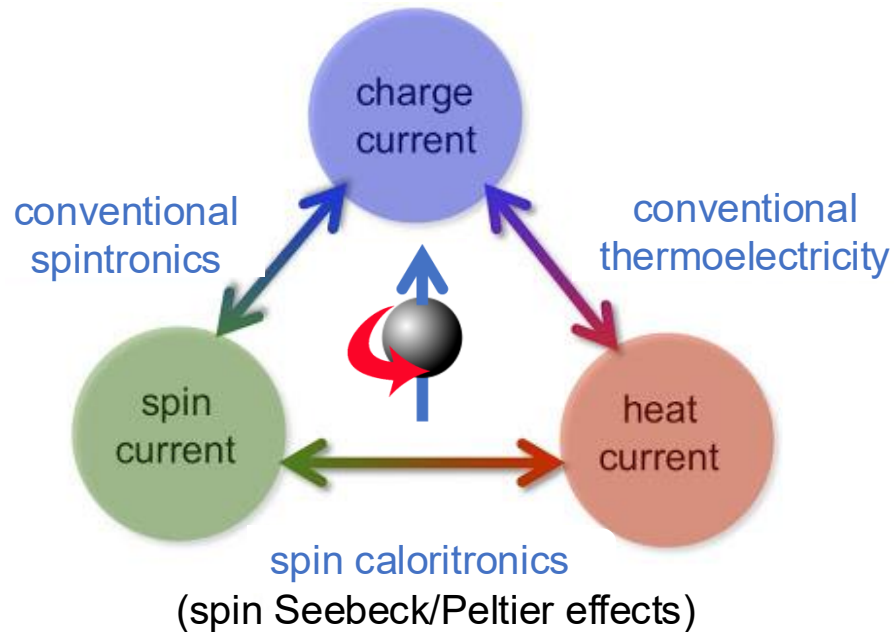
electric dipole

Electric-dipole degree of freedom is not actively exploited yet

carrier?

Spin vs. electric dipole

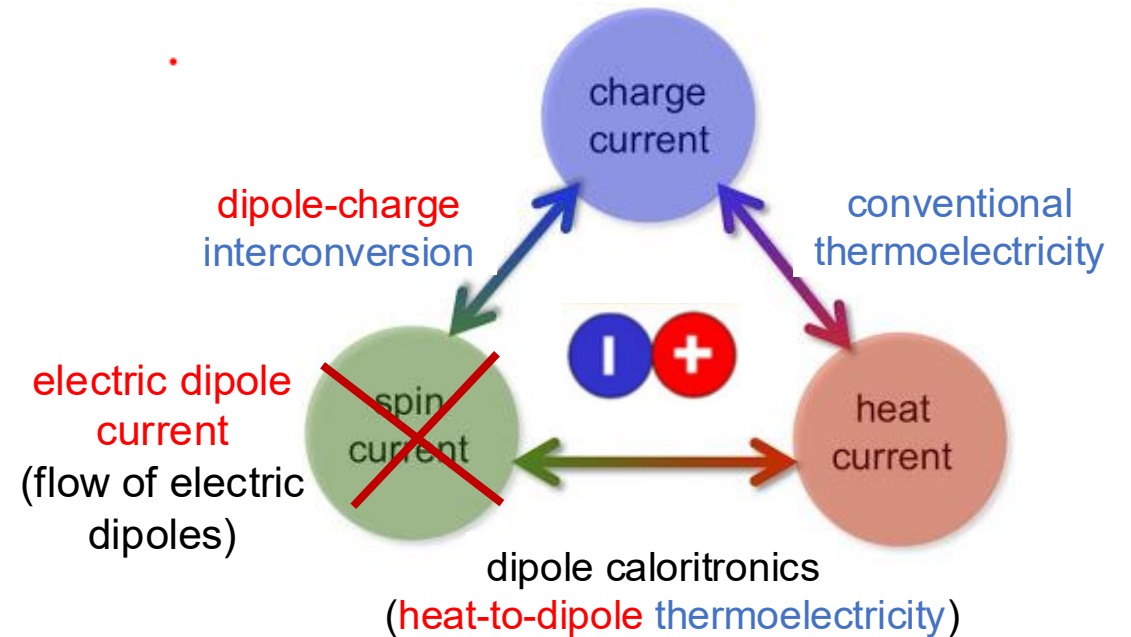
Magnetic materials (**spin**)



Spin carriers: electrons, magnons, ...

Material platforms: magnetic materials

Ferroelectric materials (**electric dipole**)

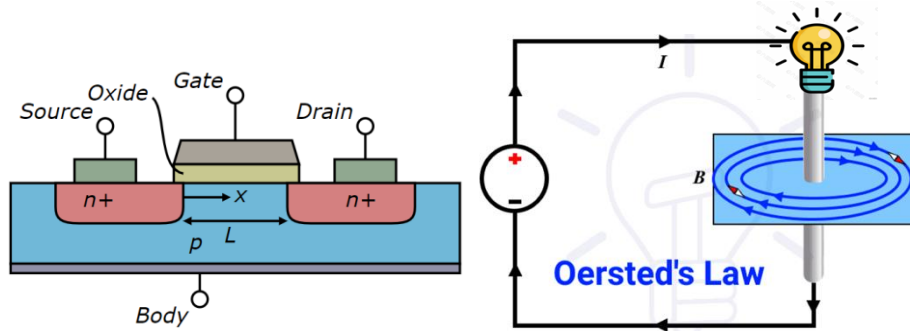


Dipole carriers: **ferrons**

Material platforms: ferroelectric materials

Charge vs. electric dipole current

Information and energy is transported by **electric (charge) current**

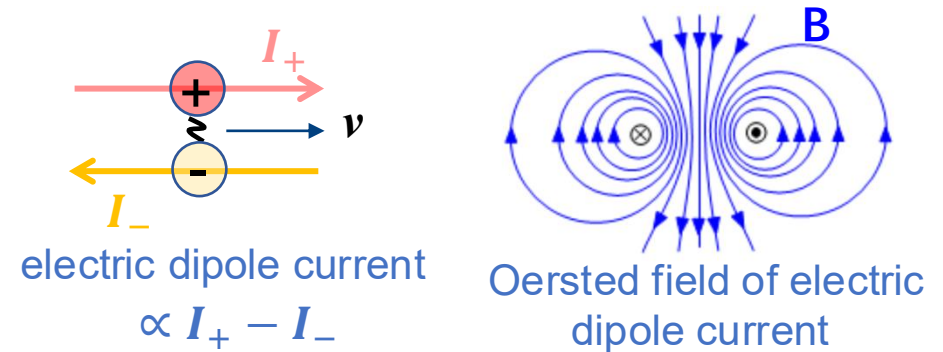


Carriers: electrons, holes

Issue: increased Joule heating as device sizes shrink

Material platforms: conductors (metals, semiconductors)

Information and energy is transported by **electric dipole current**



Carriers: ferrons ...

Advantage: available in *insulating* systems without the Joule heating loss

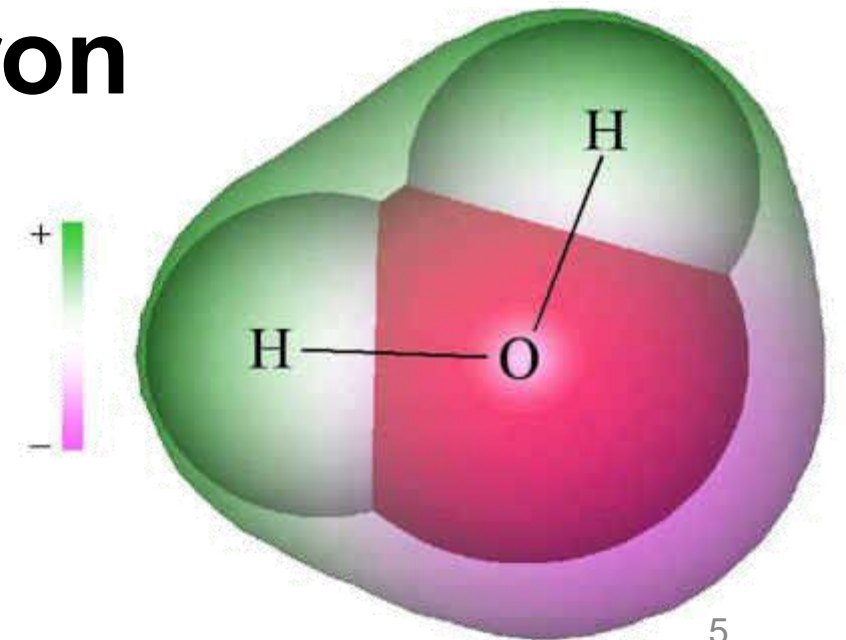
Material platforms: ferroelectrics,...

Electric dipole current is a real physical current that may function similar to conventional charge current!

OUTLINE

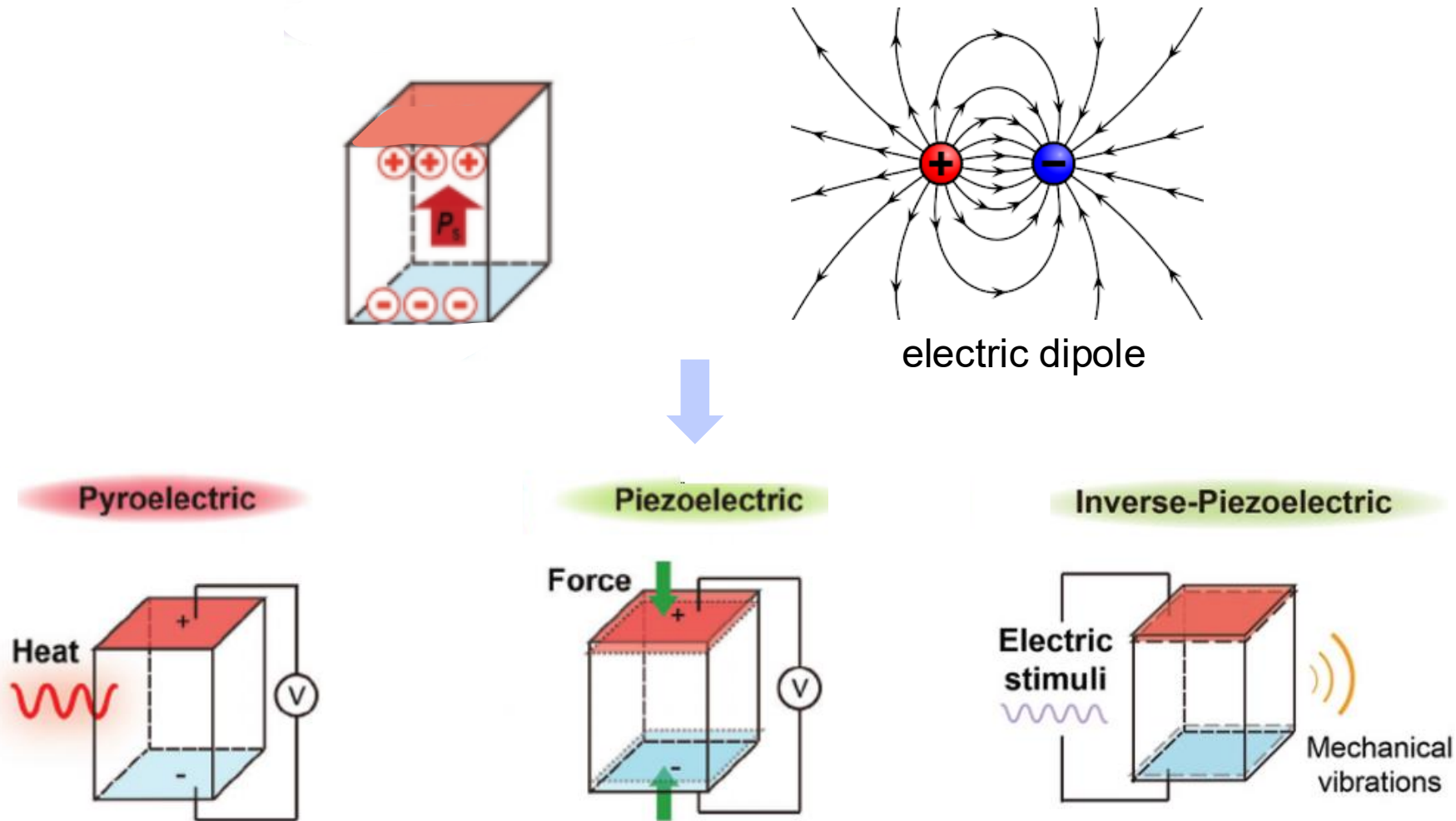
Emergence of ferrons and ferronics

- Introduction
- Ferrons and ferronics (“ferron electronics”)
- Beyond ferrons

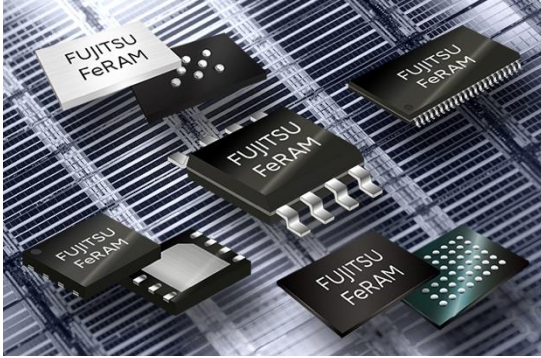


Ferroelectric materials

Ferroelectric material: spontaneous order of electric dipoles (or electric polarization)



Ferroelectric applications



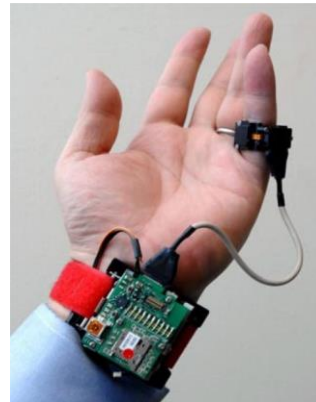
Non-volatile memory devices



Infrared sensors



Ultrasound imaging

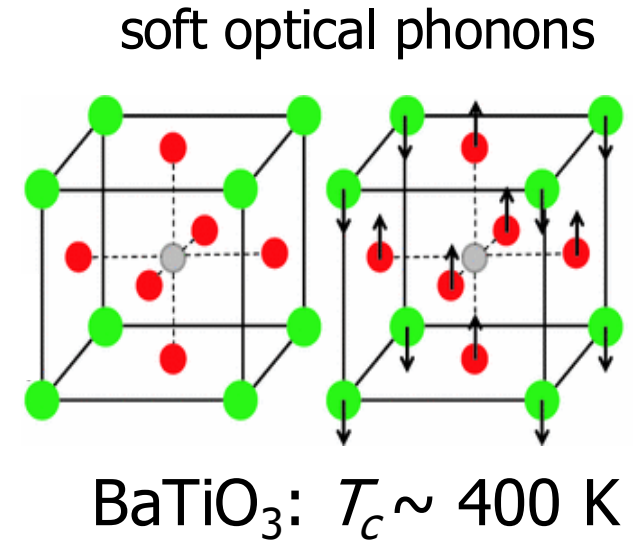
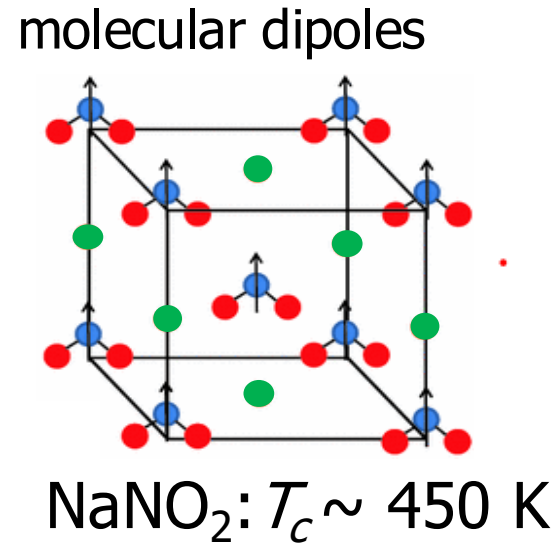
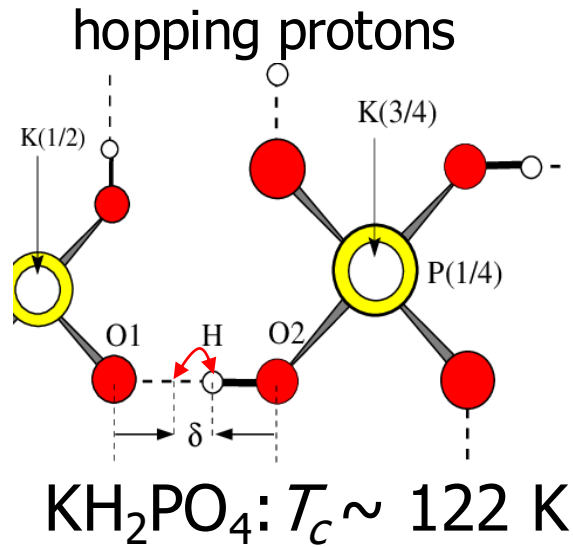


Blood pressure sensors

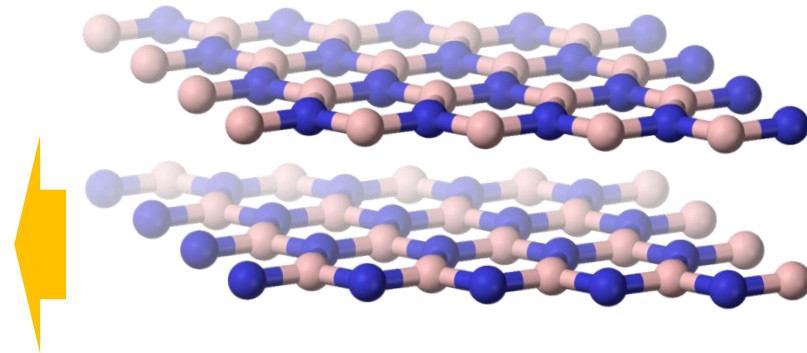


Piezoelectric generator

Ferroelectric materials of interest

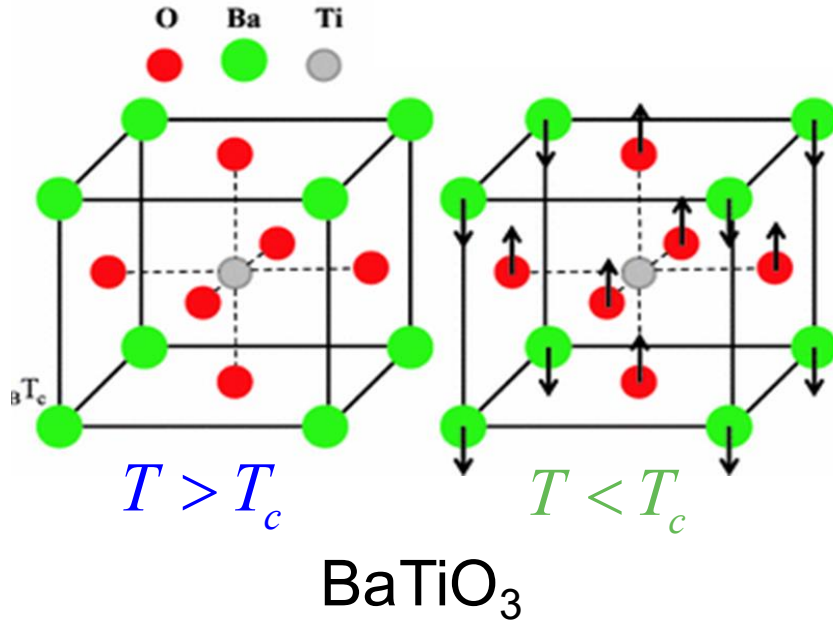


bilayer ferroelectrics
(Yasuda et al., 2020)



Bilayer h-BN
 $T_c \sim 1000 \text{ K}$

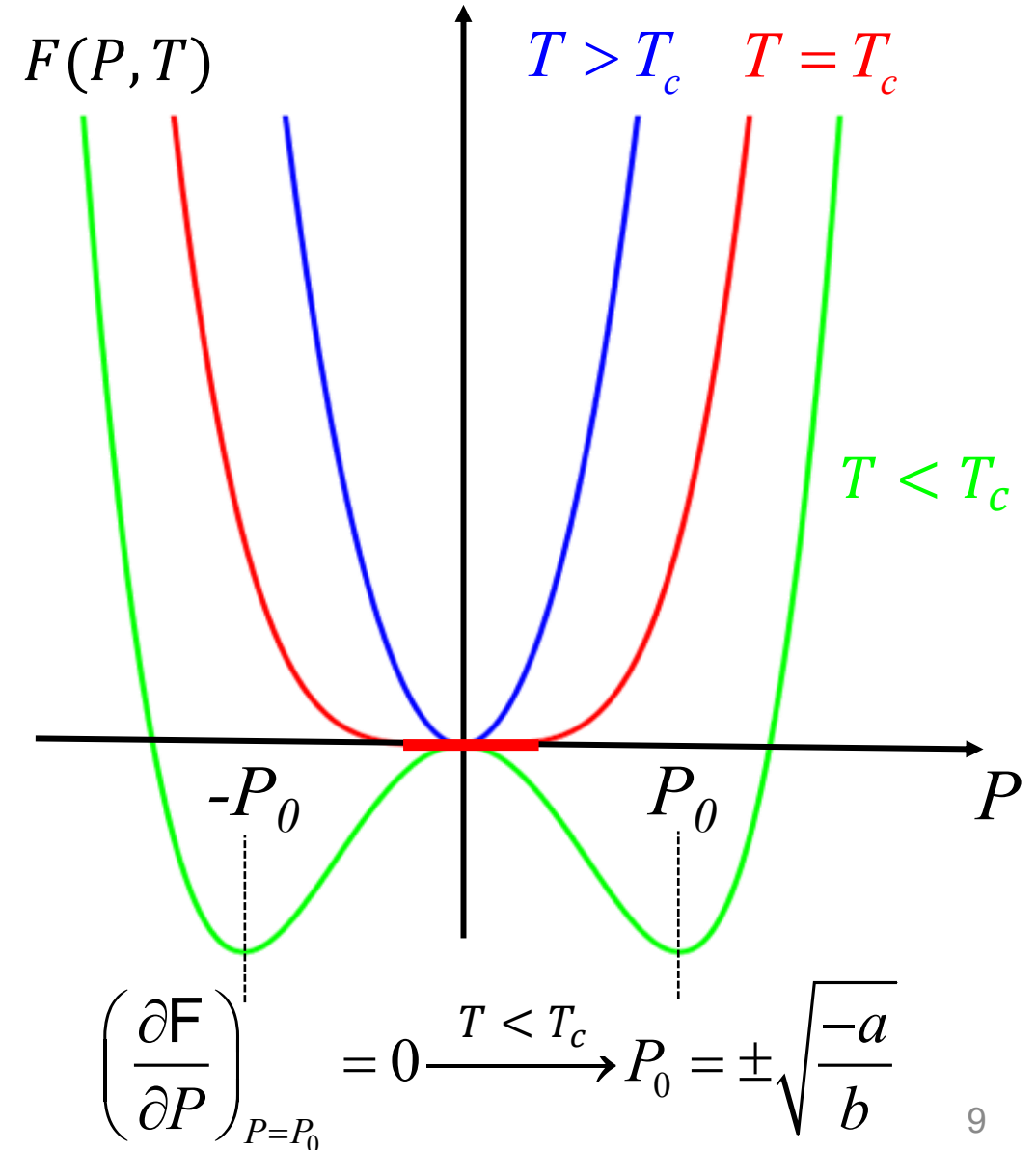
Landau-Ginzburg theory for ferroelectrics



Landau-Ginzburg free energy:

$$F(P, T) = \frac{G}{2} (\nabla P)^2 + \frac{a}{2} P^2 + \frac{b}{4} P^4$$

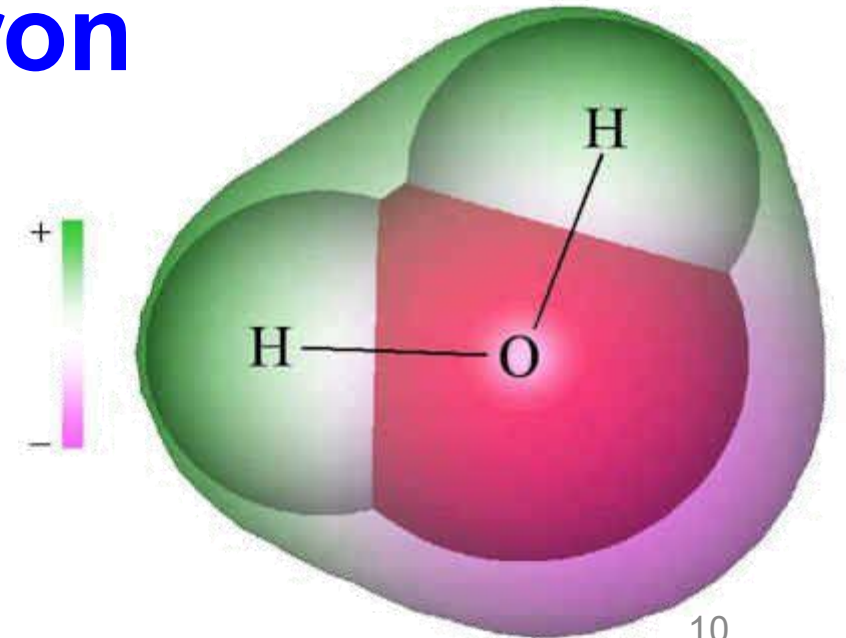
$$a = a_0 (T - T_c)$$



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- Beyond ferrons



Ferron excitations

Tang et al., *PRB* 106, L081105 (2022)

Landau-Khalatnikov-Tani (LKT) equation:

$$m_p \frac{\partial^2 P}{\partial t^2} + \gamma \frac{\partial P}{\partial t} = - \frac{\partial F}{\partial P}$$

inertia
damping

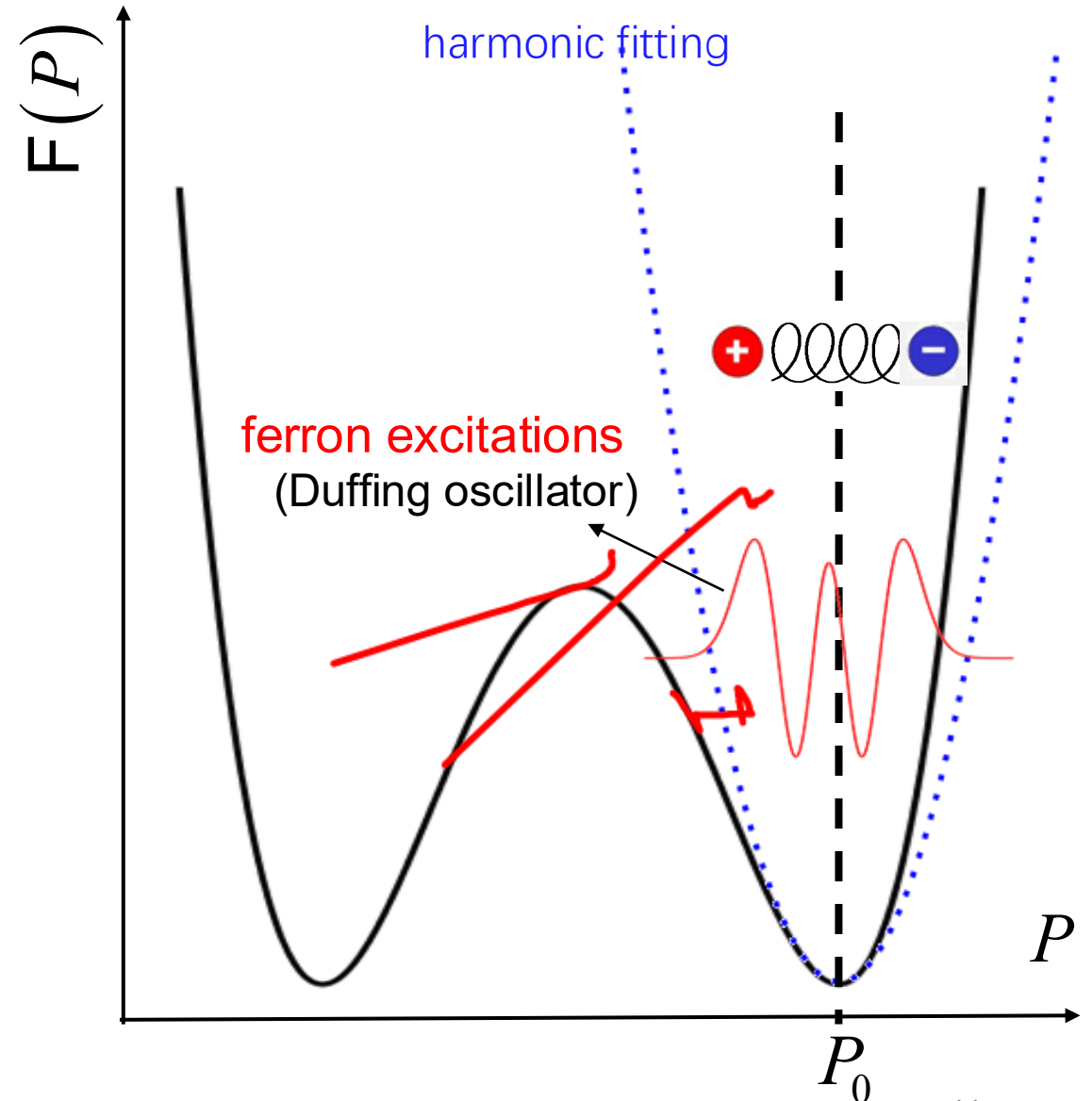
Free energy:

$$F = \frac{G}{2} (\nabla P)^2 + \frac{a}{2} P^2 + \frac{b}{4} P^4, \quad \frac{\partial F}{\partial P_0} = 0$$

Ferron dipole and frequency:

$$d_q = - \frac{3\hbar b P_0}{m_p (a + 3b P_0^2)} \frac{1}{\omega_q}$$

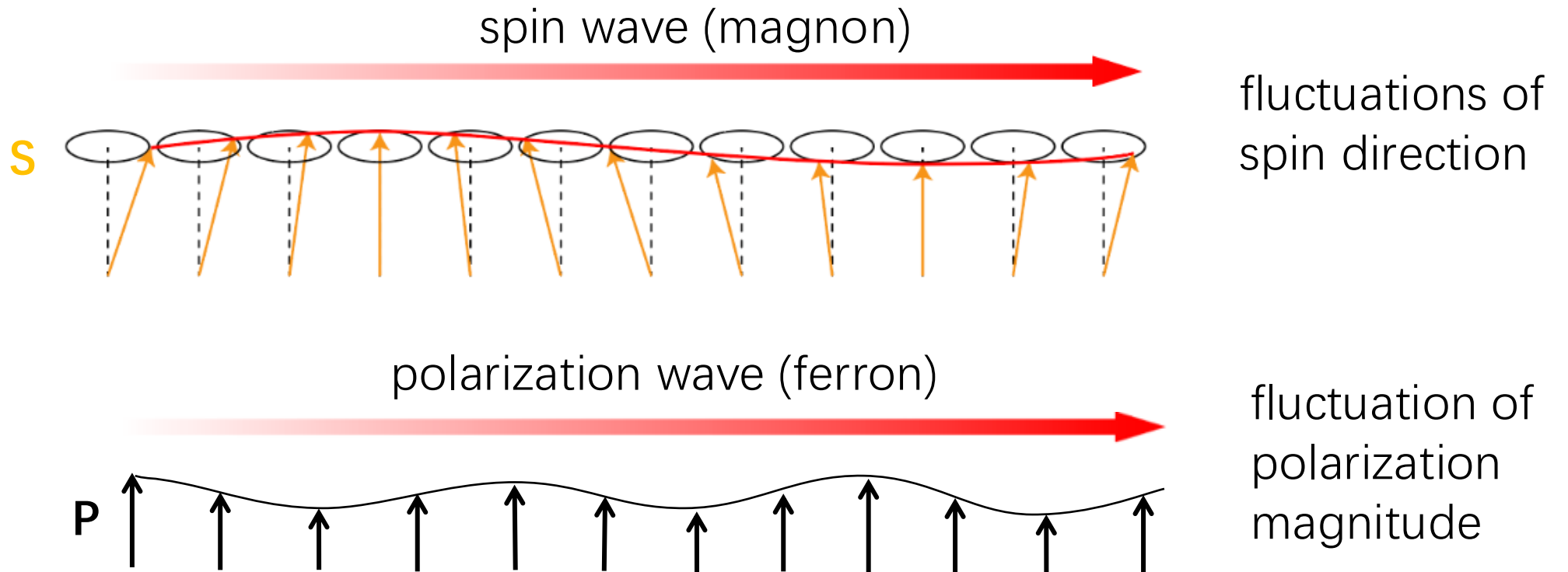
$$\omega_q = \sqrt{(a + 3b P_0^2 + G q^2) / m_p}$$



Magnons vs. ferrons

Magnon: a quasiparticle excitation in magnet that carries a magnetic dipole (spin)

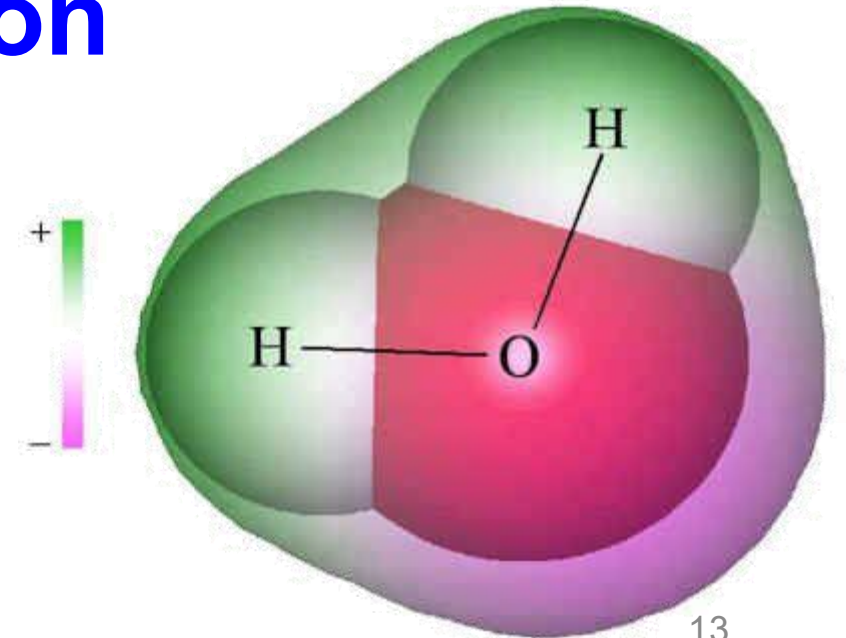
Ferron: a quasiparticle excitation in ferroelectric that carries an electric dipole



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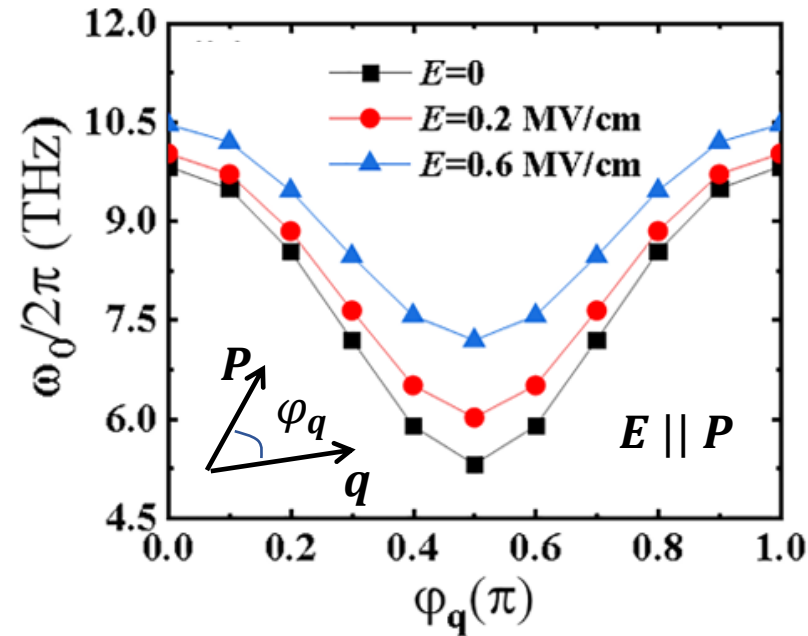
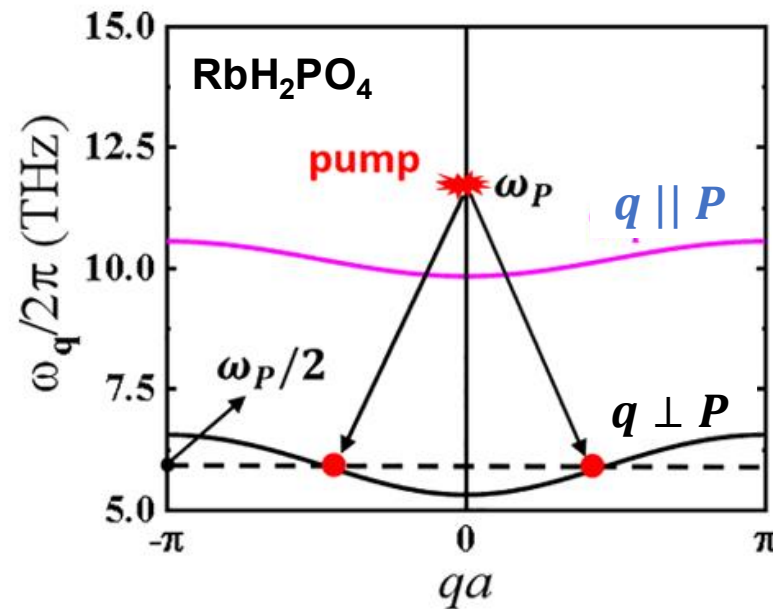


A. Ferron Stark effect

Tang et al., *PRB* **109**, L060301 (2024)

Stark interaction: $\mathcal{K} = \mathcal{K}_0 - \mathbf{P} \cdot \mathbf{E}$ and $\mathcal{K}\psi_i = \varepsilon_i\psi_i$

Ferron dipole: $\Rightarrow d_q = -\frac{\partial \hbar\omega_q}{\partial E}$ (Hellmann-Feynman theorem)



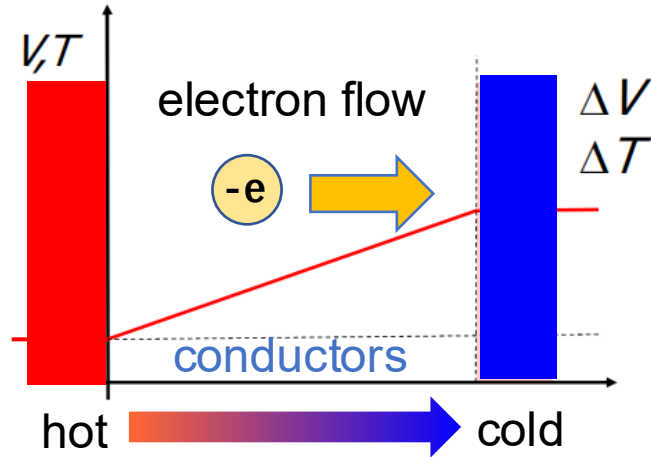
A frequency shift of ~ 10 GHz is caused by a moderate electric field $\sim 10^6$ V/m!

$\Rightarrow d_q \sim 1 e$
angstrom

B. Novel thermoelectricity by ferrons

Tang et al., *PRL* 128, 047601 (2022)

Conventional thermoelectricity



heat-to-charge current convention

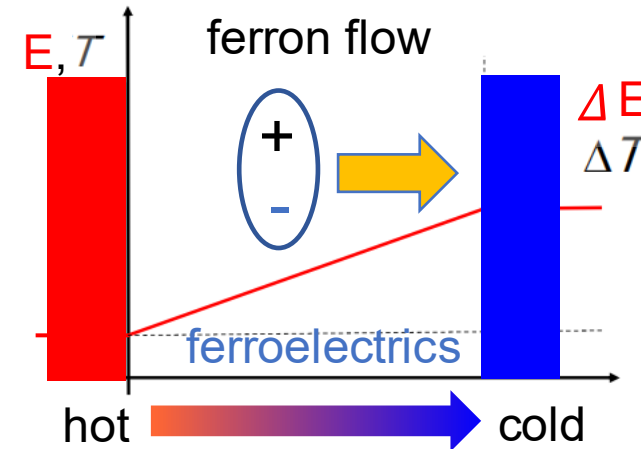
Ohm's Law:

$$\begin{pmatrix} J_c \\ J_q \end{pmatrix} = -G \begin{pmatrix} 1 & S \\ \Pi & KT/G \end{pmatrix} \begin{pmatrix} \Delta V \\ \Delta T \end{pmatrix}$$

Labels in the diagram:

- charge current** (points to J_c)
- charge conductance** (points to G)
- Peltier coefficient** (points to Π)
- Seebeck coefficient** (points to S)
- heat conductance** (points to KT/G)

Novel thermoelectricity by ferron



heat-to-dipole current convention

Ohm's-like Law:

$$\begin{pmatrix} J_D \\ J_q \end{pmatrix} = -G \begin{pmatrix} 1 & S \\ \Pi & KT/G \end{pmatrix} \begin{pmatrix} \Delta E \\ \Delta T \end{pmatrix}$$

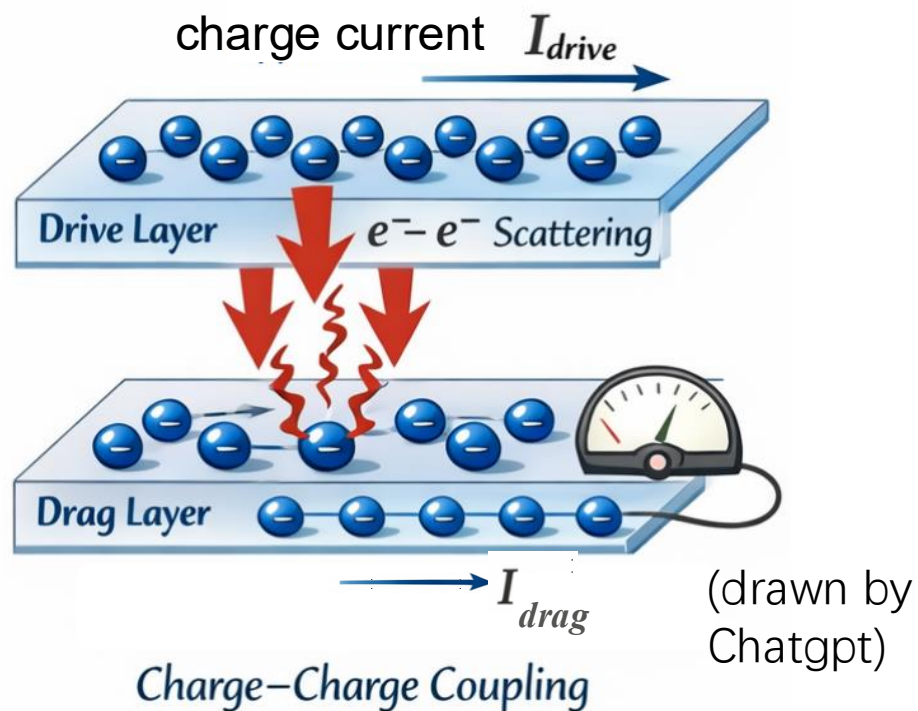
Labels in the diagram:

- electric dipole current** (points to J_D)
- dipole conductance** (points to G)
- dipole Peltier coefficient** (points to Π)
- dipole Seebeck coefficient** (points to S)

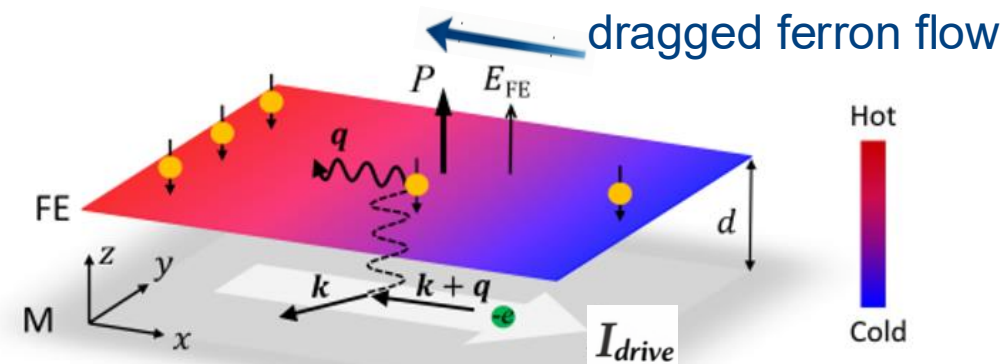
C. Nonlocal ferron drag

Tang et al., *PRB* **107**, L121406 (2023)

Coulomb Drag (电荷拖拽)



L. I. Pogrebinskii, Sov. Phys. Semicond. **11**, 372 (1977)



FE: 2D ferroelectric layer
M: metallic layer (graphene)

Interlayer dipole-charge Coulomb coupling:

$$\mathcal{H}_{int} = - \int \mathbf{E}_{el}(\mathbf{r}) \cdot \mathbf{P}(\mathbf{r}) d\mathbf{r},$$

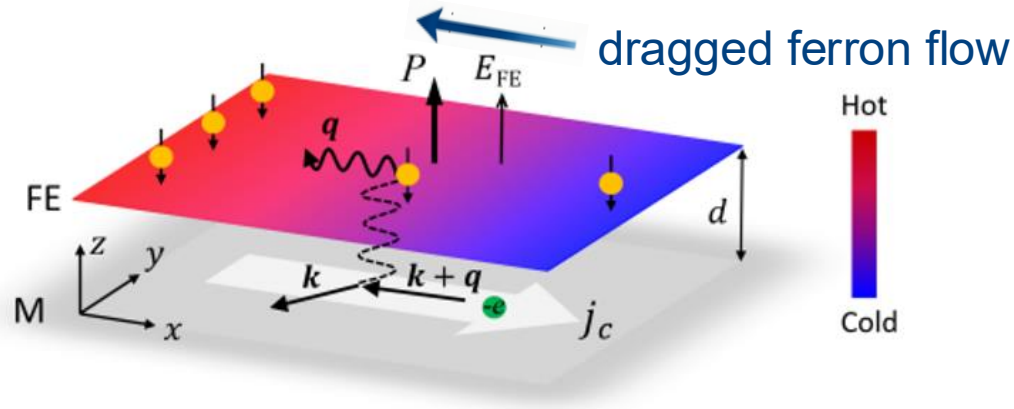
$$\mathbf{E}_{el}(\mathbf{r}) = - \frac{e}{4\pi\epsilon_r\epsilon_0} \int d\mathbf{r}' \frac{n(\mathbf{r}')}{|\mathbf{r} - \mathbf{r}'|^3} (\mathbf{r} - \mathbf{r}')$$

$$\Rightarrow \mathcal{H}_{int} = \sum_{\mathbf{k}\mathbf{q}\nu\nu'} V_{\mathbf{k}\mathbf{q}}(\nu', \nu) \hat{c}_{(\mathbf{k}+\mathbf{q})\nu'}^\dagger \hat{c}_{\mathbf{k}\nu} \hat{a}_{\mathbf{q}} + \text{H.c.},$$

A ferron flow is dragged in the ferroelectric layer by an applied charge current in the metallic layer and vice versa!

C. Nonlocal ferron drag

Tang et al., *PRB* **107**, L121406 (2023)



FE: 2D ferroelectric layer
M: metallic layer (graphene)

Interlayer dipole-charge Coulomb coupling:

$$\mathcal{H}_{\text{int}} = - \int \mathbf{E}_{\text{el}}(\mathbf{r}) \cdot \mathbf{P}(\mathbf{r}) d\mathbf{r},$$

$$\mathbf{E}_{\text{el}}(\mathbf{r}) = - \frac{e}{4\pi\epsilon_r\epsilon_0} \int d\mathbf{r}' \frac{n(\mathbf{r}')}{|\mathbf{r} - \mathbf{r}'|^3} (\mathbf{r} - \mathbf{r}')$$

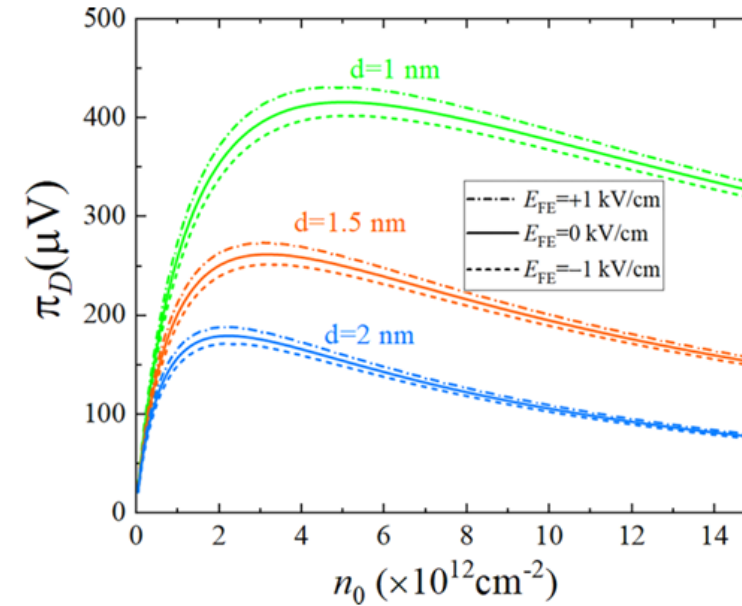
$$\Rightarrow \mathcal{H}_{\text{int}} = \sum_{\mathbf{k}\mathbf{q}\nu\nu'} V_{\mathbf{k}\mathbf{q}}(\nu', \nu) \hat{c}_{(\mathbf{k}+\mathbf{q})\nu'}^\dagger \hat{c}_{\mathbf{k}\nu} \hat{a}_{\mathbf{q}} + \text{H.c.},$$



Ferron-drag Peltier coefficient:

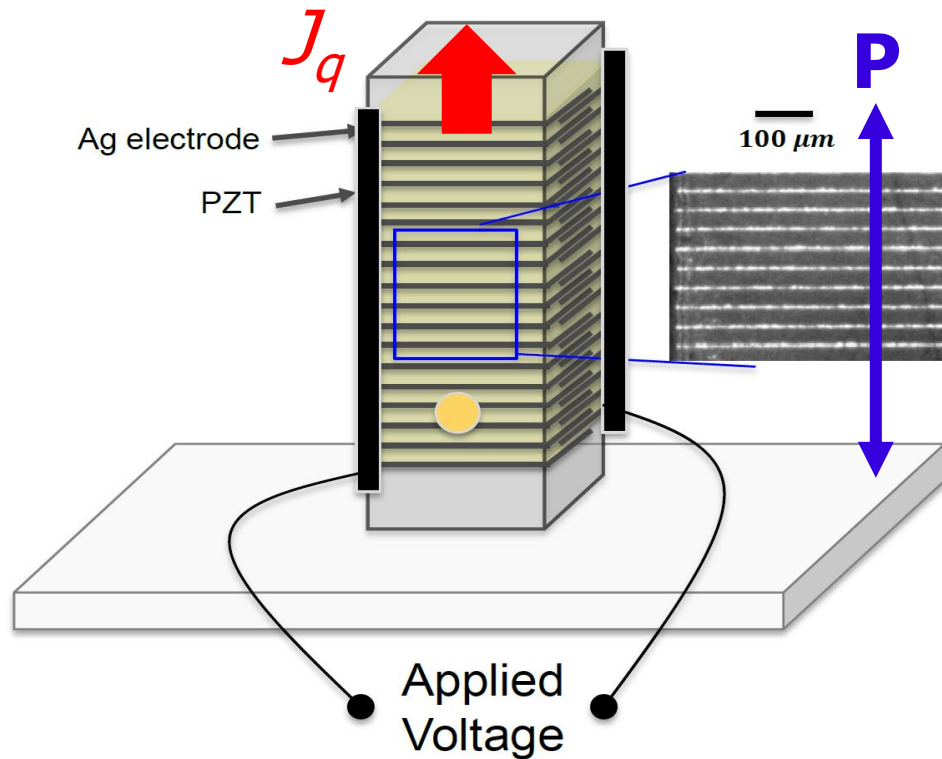
$$\pi_D \simeq \frac{e\tau_f g \hbar^3 D_F^2}{32\delta m_p^2 \epsilon_0^2 n_0 k_F k_B T} \int_0^{2k_F} \frac{\cos^2(\theta/2) q^2 dq}{\sqrt{1 - (q/2k_F)^2}}$$

$$\times \frac{e^{-2dq}}{(1 + q_{\text{TF}}/q)^2} \text{csch}^2\left(\frac{\hbar\omega_q}{2k_B T}\right).$$



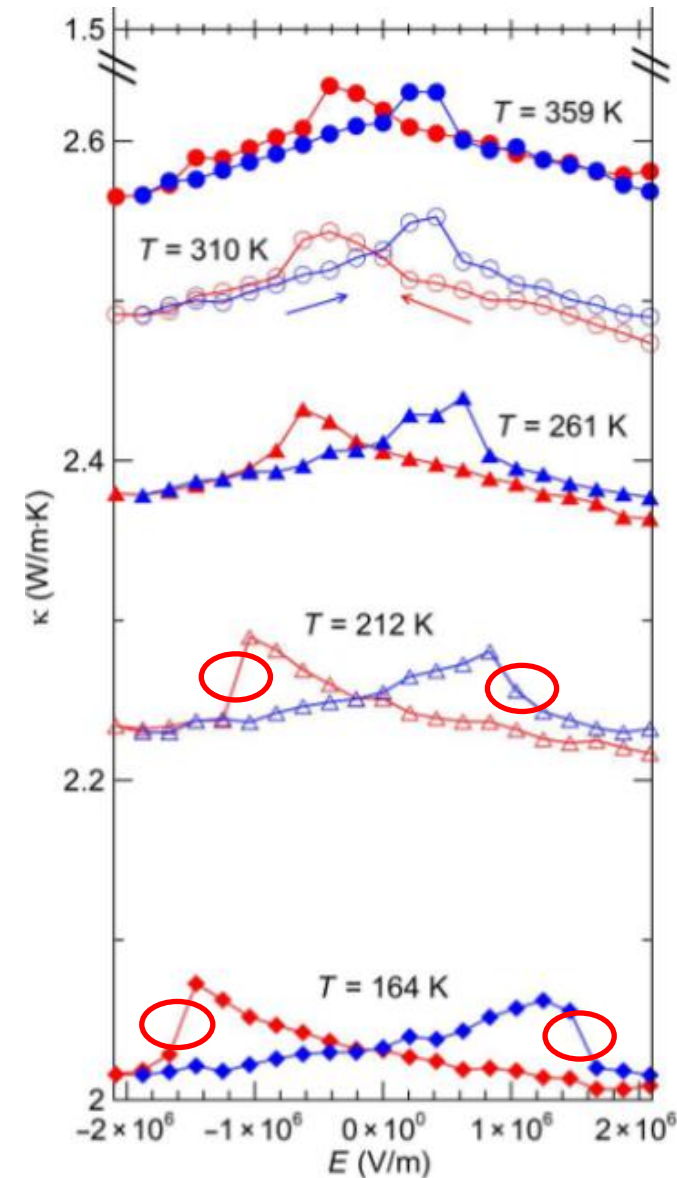
n_0 : electron density
in the metallic layer

Experiment A: Electric-field-tunable thermal conductivity by ferrons



B. Wooten et al., *Sci. Adv.* **9**, eadd7194 (2023)

Ferron is evidenced by a nontrivial decrease in thermal conductivity at high electric fields due to suppressed ferron excitations



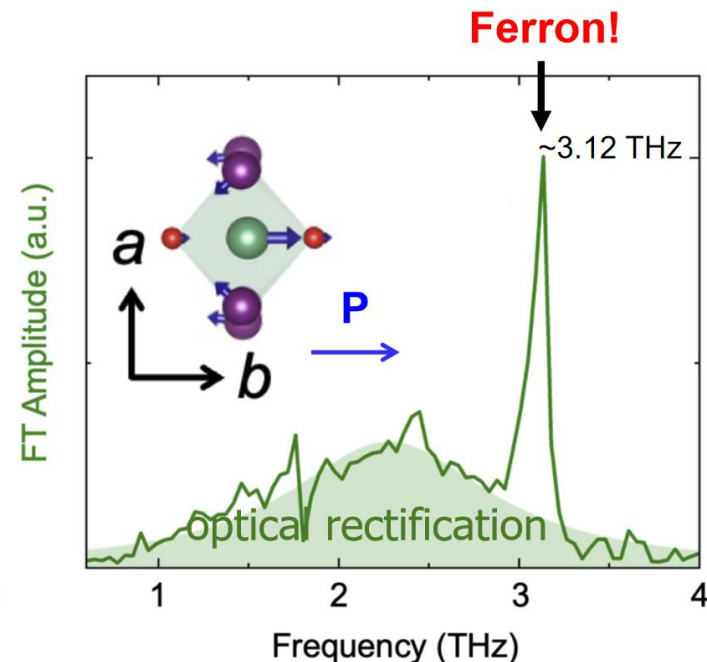
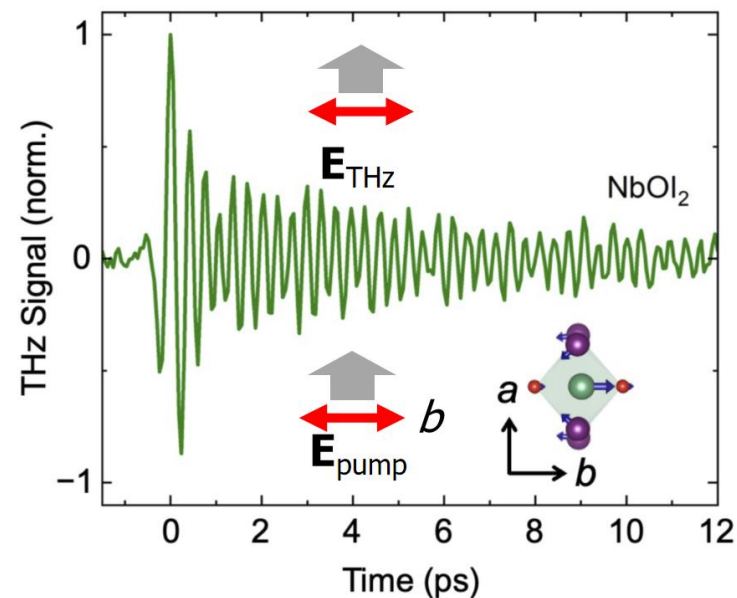
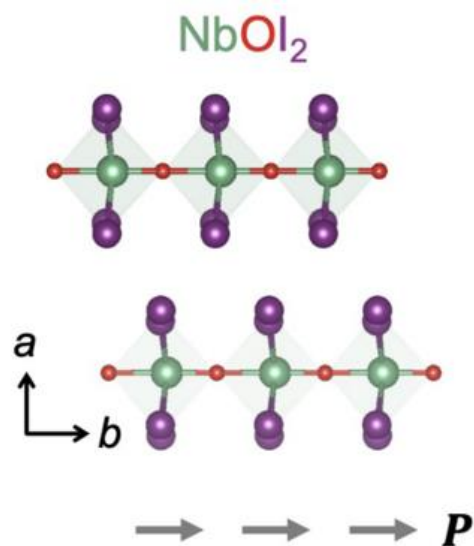
Experiment B: THz emission by coherent ferrons

Article | Published: 04 May 2026

Observation of coherent ferron emission and propagation

[Jeongheon Choe](#), [Taketo Handa](#) , [Chun-Ying Huang](#), [André Koch Liston](#), [Jordan Cox](#), [Jonathan Stensberg](#), [Yongseok Hong](#), [Daniel G. Chica](#), [Ding Xu](#), [Fuyang Tay](#), [Samra Husremovic](#), [Vinicius da Silveira Lanza Avelar](#), [Eric A. Arsenault](#), [Zhuquan Zhang](#), [James McIver](#), [Dmitri N. Basov](#), [Milan Delor](#) , [Xavier Roy](#)  & [X.-Y. Zhu](#) 

[Nature Materials](#) (2026) | [Cite this article](#)



Another experiment on ferron THz emission

Electric-field Control of Giant Ferronics

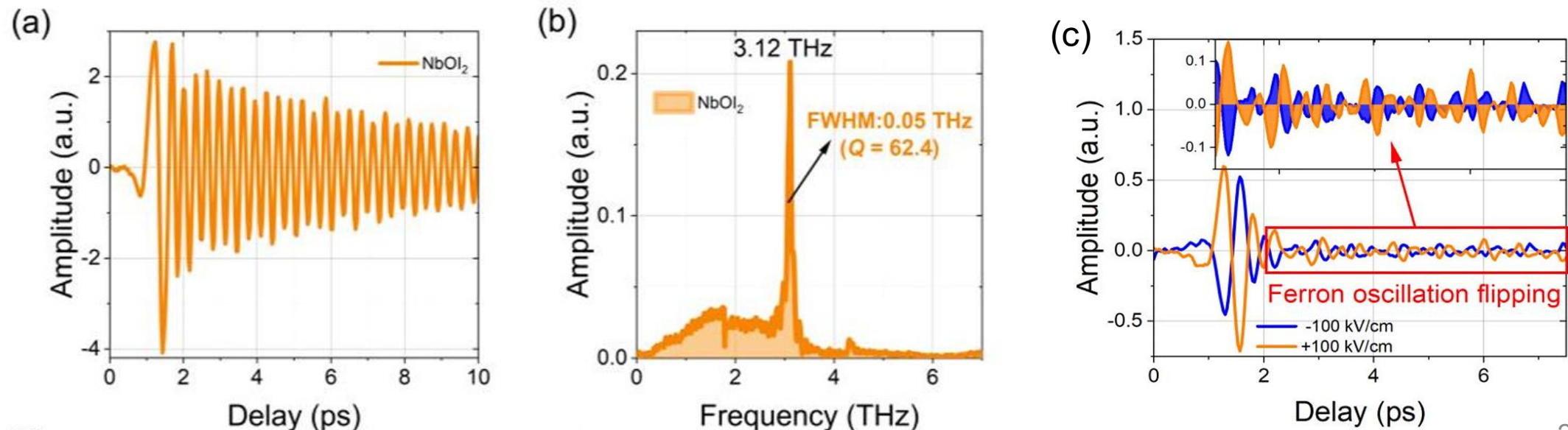
[arXiv:2509.06057](https://arxiv.org/abs/2509.06057)

Baolong Zhang^{1,2†}, Ruihuan Duan^{3†}, Sobhan Subhra Mishra^{1,2}, Sambhu Jana^{1,2}, Jonghyeon

Kim⁴, Thomas Tan Caiwei^{1,2}, Yi Ji Tan^{1,2}, Wenhao Wang^{1,2}, Pang Teng Chen Ietro^{1,2},

Zheng Liu^{3*}, Ranjan Singh^{5*}

3. Nanyang Technological University, Singapore & 5. University of Notre Dame, USA



Experiment C: Ferron-mediated nonlocal transport

Observation of ferron transport in ferroelectrics

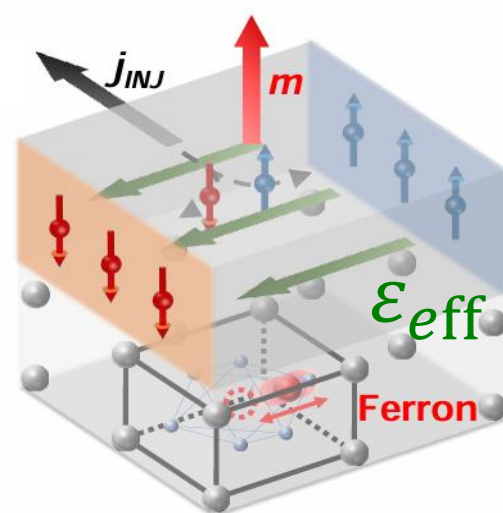
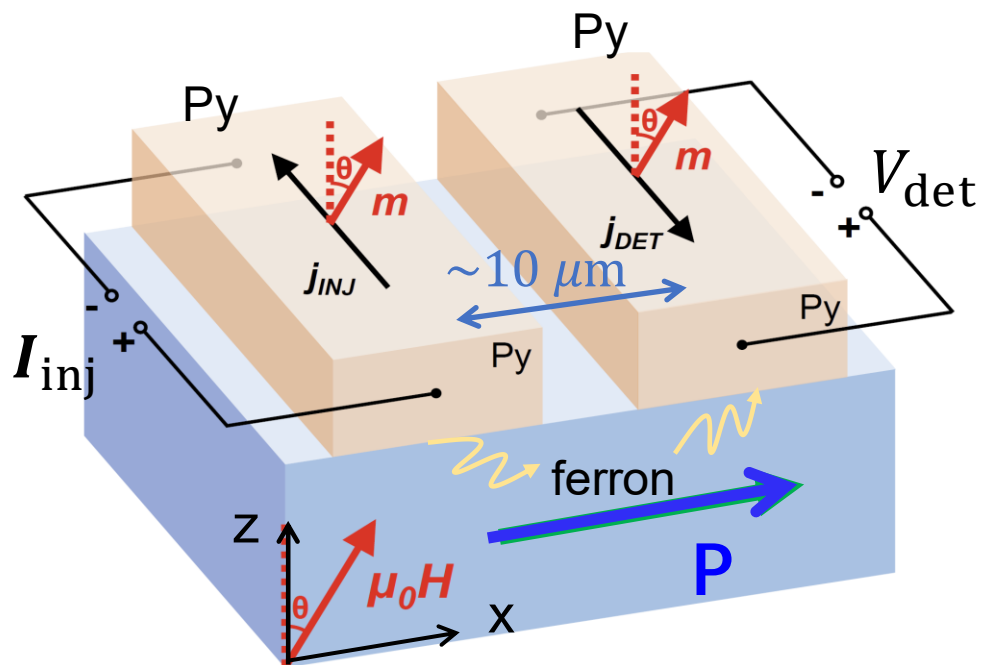
[arXiv:2505.24419](https://arxiv.org/abs/2505.24419)

Kaiwen Shen^{1†}, Ping Tang^{2†}, Xianzhe Chen^{1*}, Yifan Gao¹, Yuanfei Fan³, Zejing Guo⁴, Yingfen Wei¹, Hao Jiang¹, Xumeng Zhang¹, Ming Wang¹, Pan He⁴, Wu Shi⁴, Jiahao Han², Yizheng Wu³, Jian Shen^{3,4}, Qi Liu¹, Gerrit E.W. Bauer^{2,5,6}, and Ming Liu¹

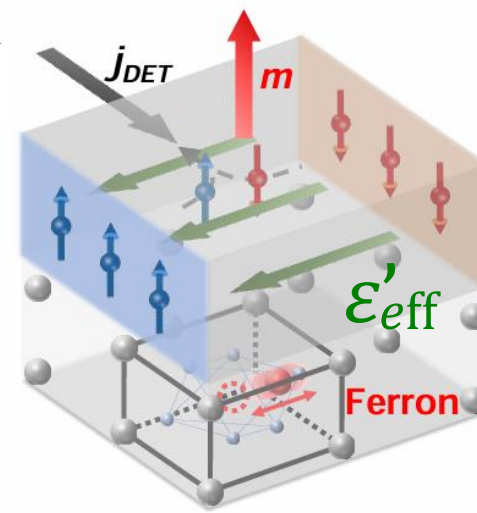
Fudan University, Shanghai, China

Ferron-mediated nonlocal transport signal (theory) :

$$V_{\text{det}} \sim C_1 m_z^2 I_{\text{inj}} + C_2 m_z P_x I_{\text{inj}}^3 + \dots$$



electrical ferron
injection

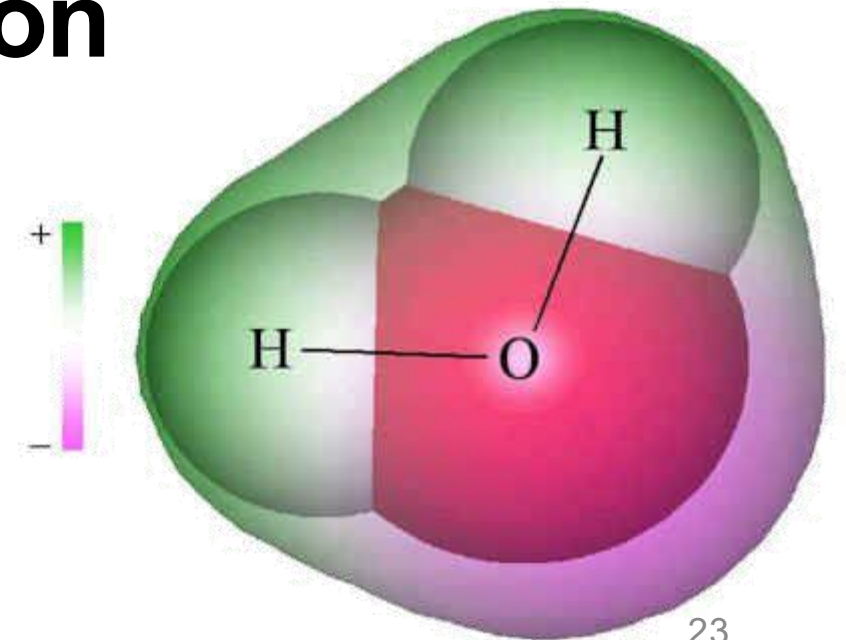


electrical ferron
detection

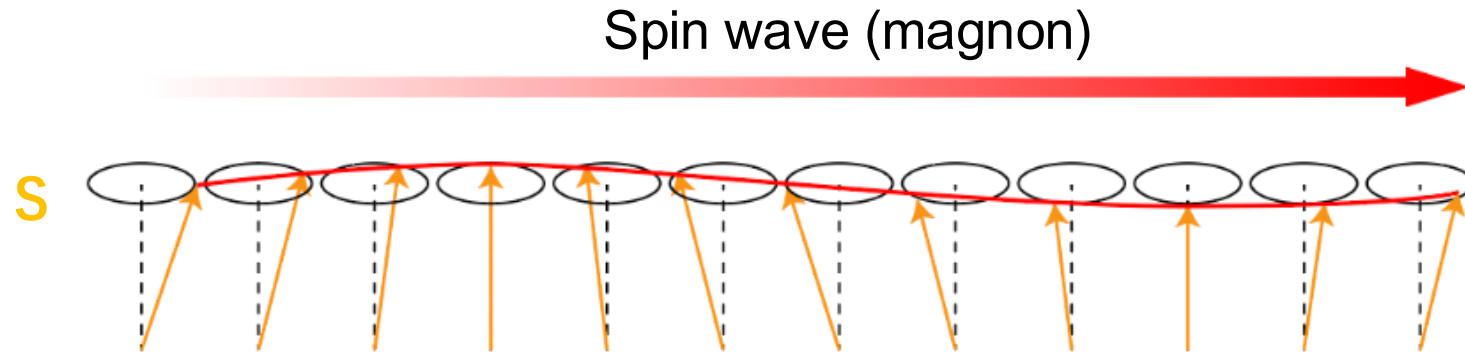
OUTLINE

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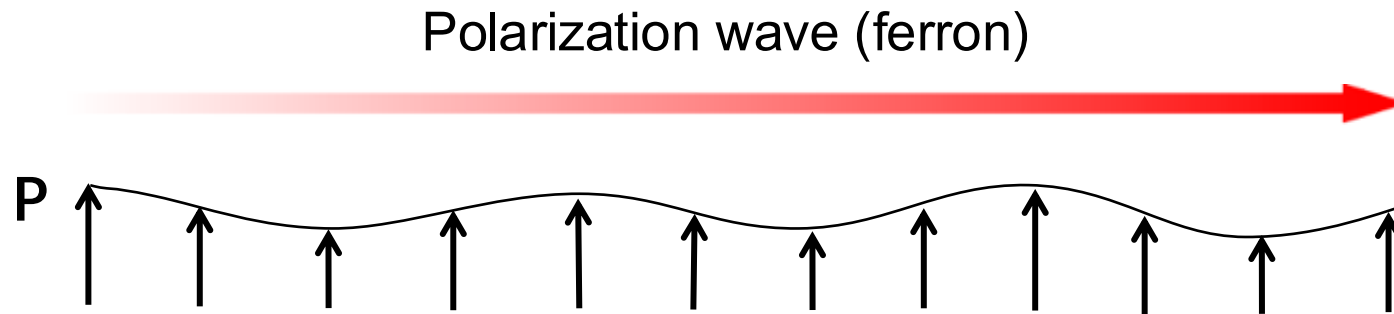
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Magnon vs. ferron



Goldstone-type
mode
(dynamics of
magnetization
direction)



Higgs-type mode
(dynamics of
polarization **magnitude**)

“Multiferrons” — precession dynamics of polarization

PHYSICAL REVIEW LETTERS **136**, 176702 (2026)

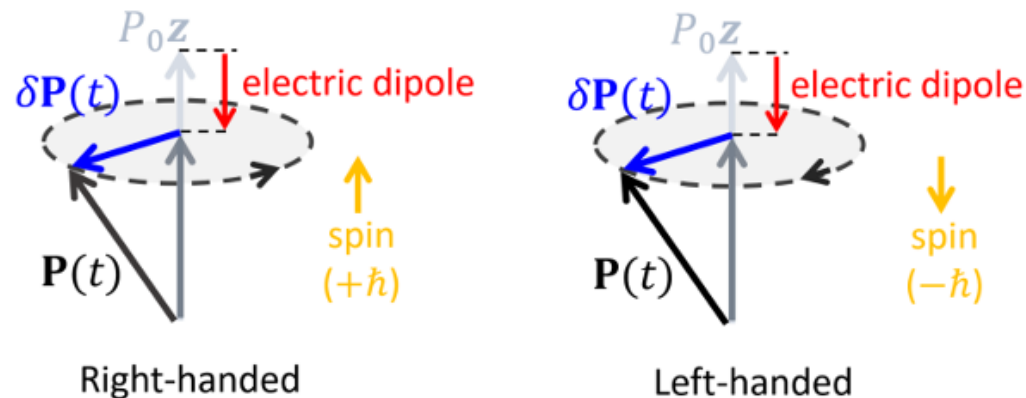
Multiferroic-like Quasiparticles in Ferroelectrics

Ping Tang^{1,*} and Gerrit E. W. Bauer²

¹*Institute for Materials Research, Tohoku University, 2-1-1 Katahira, Sendai 980-8577, Japan*

²*WPI-AIMR and CSIS, Tohoku University, 2-1-1 Katahira, Sendai 980-8577, Japan*

 (Received 5 November 2025; accepted 14 April 2026; published 1 May 2026)



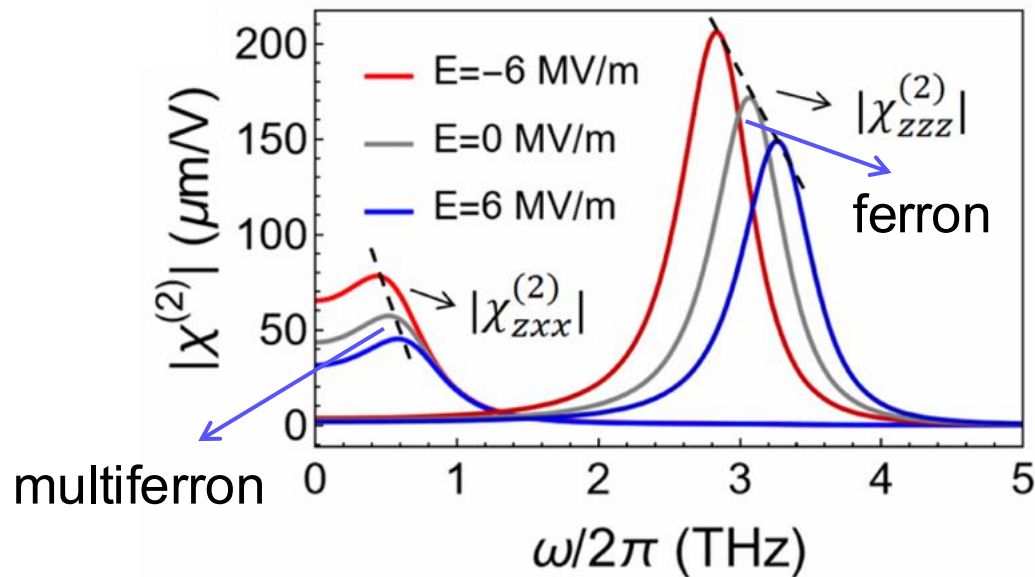
$$\mathbf{M} \sim \mathbf{P} \times \frac{\partial \mathbf{P}}{\partial t}$$

“Multiferron”: a quasiparticle that carries **both** static magnetic and electric dipoles

Second-harmonic generation by multiferron and ferons

Second-harmonic response:

$$p_i(2\omega) = \epsilon_0 \sum_{j,l} \chi_{ijl}^{(2)}(-2\omega; \omega, \omega) \mathcal{E}_j \mathcal{E}_l$$



	$\Delta/2\pi$ (THz)	d (eÅ)	$\mu_M(\mu_B)$	$\alpha_{\text{EdH}}(\hbar/\text{T})$
Multiferrons	0.74	-0.34	6.6×10^{-3}	1.2×10^{-5}
Ferrons	3.1	-1.44 ^a		

BiTiO3

Both multiferron and feron lead to resonantly enhanced electric-field-tunable SHG in the THZ regime

Lattice Excitations with Finite Polarization and Magnetization

Mike Pols^{1,*}, Carl P. Romao^{2,†} and Dominik M. Juraschek^{1,§}

¹*Department of Applied Physics and Science Education, Eindhoven University of Technology, 5612 AP Eindhoven, Netherlands*

²*Department of Materials, Faculty of Nuclear Sciences and Physical Engineering, Czech Technical University in Prague, Prague 120 00, Czech Republic*



(Received 5 November 2025; accepted 30 March 2026; published 22 April 2026)

Ferrons are a type of quasiparticle corresponding to elementary excitations of the ferroelectric order. Analogously to how magnons modulate and transport magnetization, ferrons modulate and transport electric polarization. Here, we introduce *multiferrons* as elementary excitations with both electric and magnetic character. Multiferrons lead to a tilt and elliptical precession of the polarization and at the same time create a magnetization through the mechanism of dynamical multiferroicity. Using first-principles calculations for LiNbO_3 , we show that the electric polarization of multiferrons is perpendicular to the equilibrium ferroelectric polarization, whereas the magnetization is parallel to it. Our calculations further demonstrate that multiferrons carry net electric and magnetic quadrupole and octupole moments, which we term multipolons. These multipolons could couple to internal multipolar degrees of freedom, for example in altermagnets, or to external probes such as neutrons, leading to potentially experimentally observable phenomena following coherent or thermal excitation of multiferrons.

DOI: [10.1103/2sj3-33ky](https://doi.org/10.1103/2sj3-33ky)

Thanks for your attention!