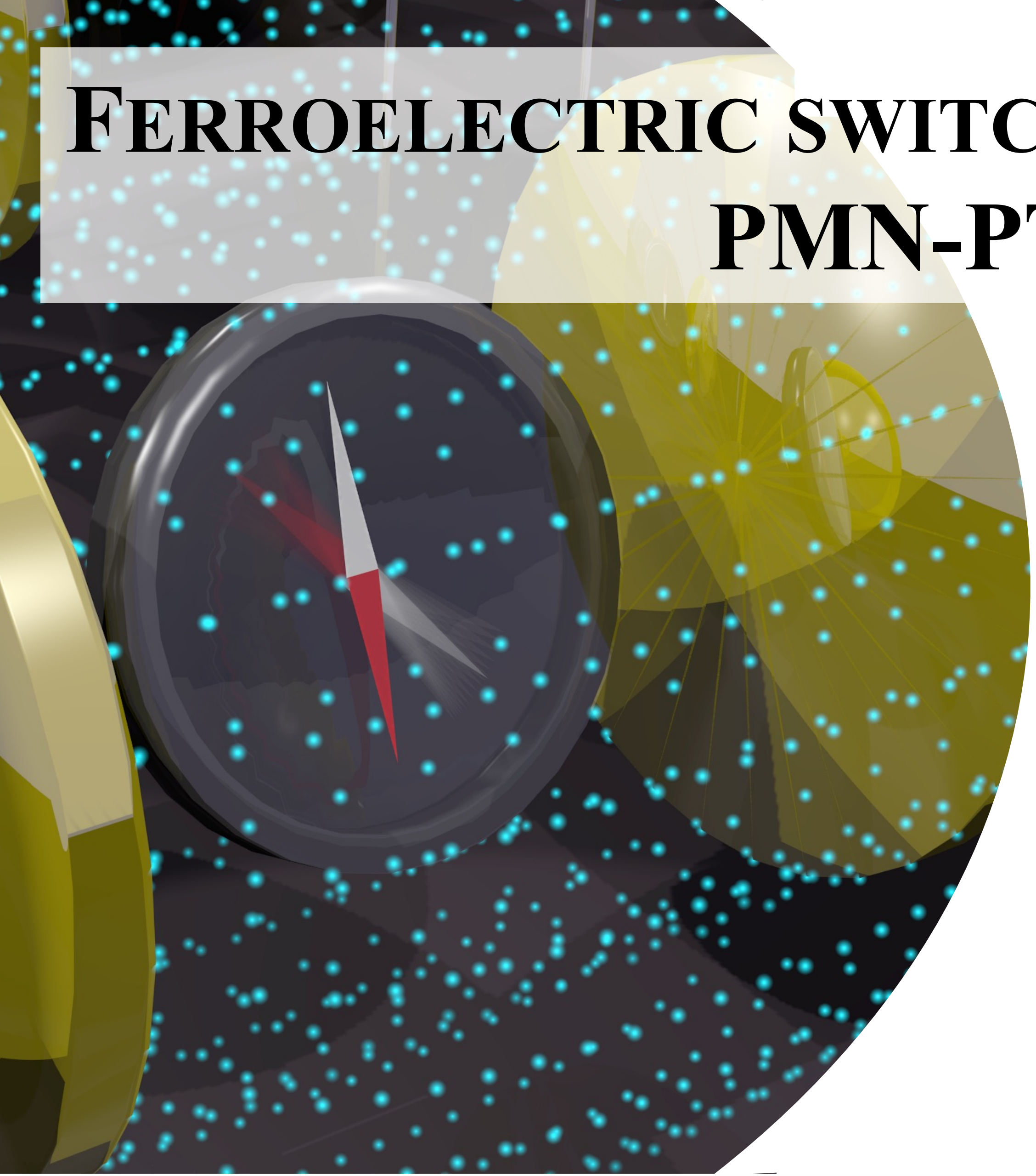

FERROELECTRIC SWITCHING KINETICS IN EPITAXIAL PMN-PT THIN FILMS

John Heron
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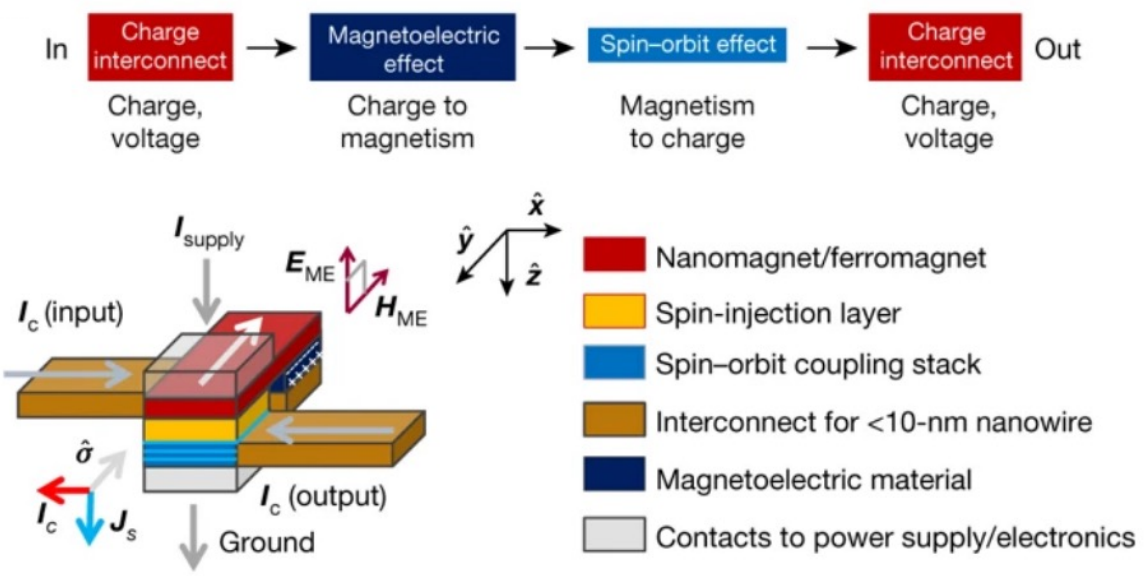
University of Michigan

Tony Chiang

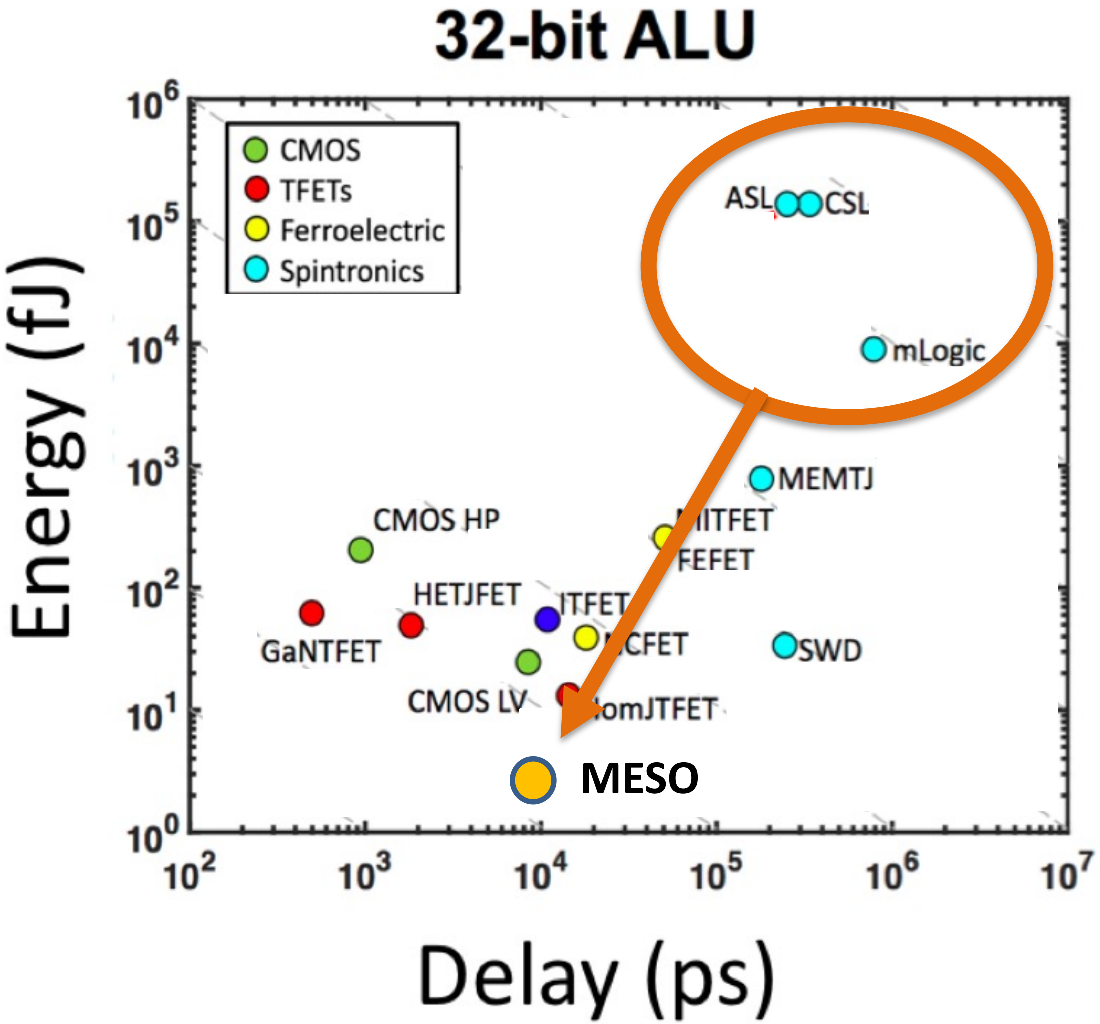
SRC
GRC

FERROELECTRONICS
Laboratory

Intel MESO



Targets: Sub 250 mV, Sub ns, 100 aJ per switch



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

Iraei, R.M., S. Dutta, S. Manipatruni, D.E. Nikonov, I.A. Young, J.T. Heron, and A. Naeemi. *(DRC), 2017 75th Annual.* 2017. IEEE.

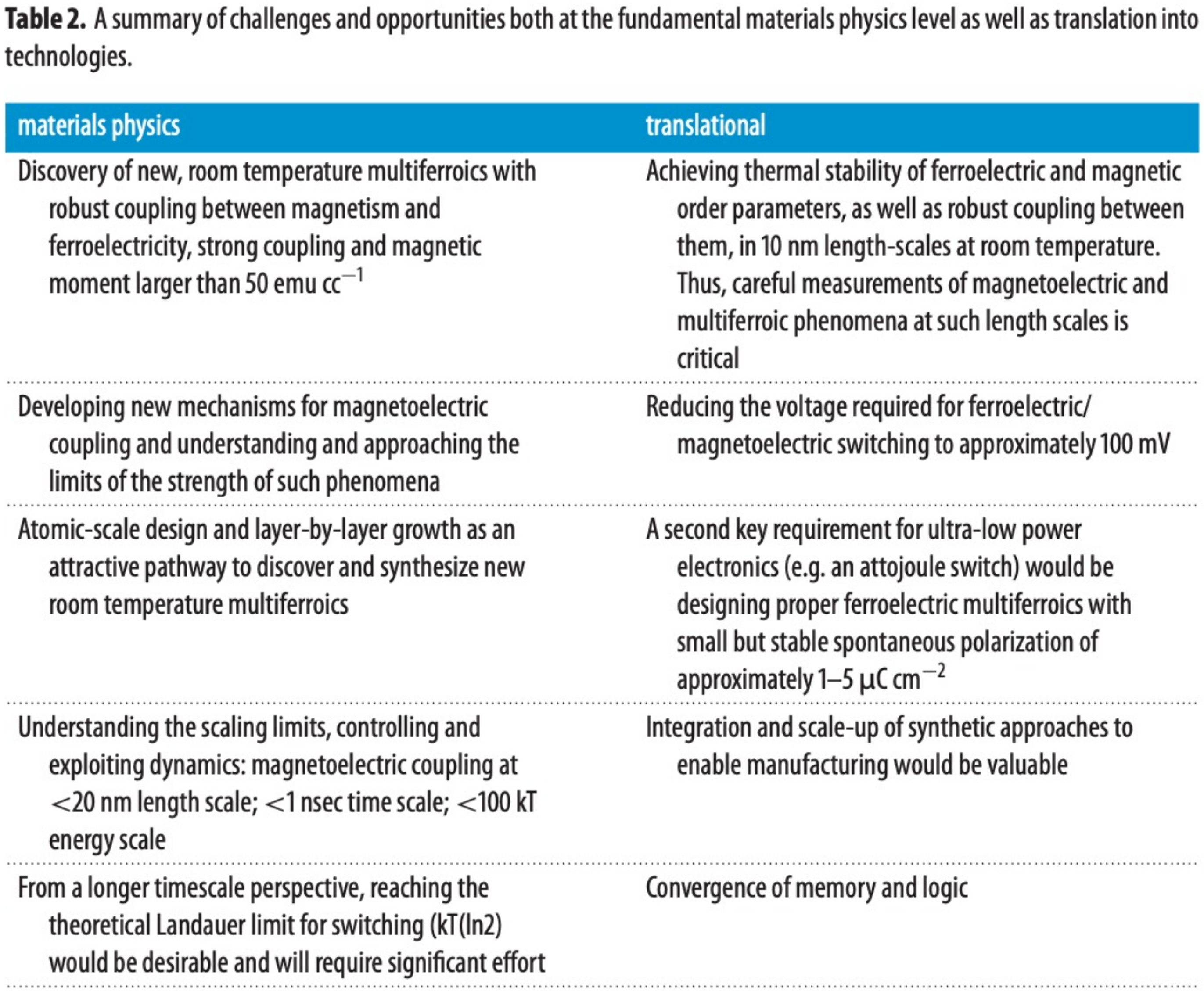


Table 2. A summary of challenges and opportunities both at the fundamental materials physics level as well as translation into technologies.

materials physics	translational
Discovery of new, room temperature multiferroics with robust coupling between magnetism and ferroelectricity, strong coupling and magnetic moment larger than 50 emu cc^{-1}	Achieving thermal stability of ferroelectric and magnetic order parameters, as well as robust coupling between them, in 10 nm length-scales at room temperature. Thus, careful measurements of magnetoelectric and multiferroic phenomena at such length scales is critical
Developing new mechanisms for magnetoelectric coupling and understanding and approaching the limits of the strength of such phenomena	Reducing the voltage required for ferroelectric/magnetoelectric switching to approximately 100 mV
Atomic-scale design and layer-by-layer growth as an attractive pathway to discover and synthesize new room temperature multiferroics	A second key requirement for ultra-low power electronics (e.g. an attojoule switch) would be designing proper ferroelectric multiferroics with small but stable spontaneous polarization of approximately 1–5 $\mu C\ cm^{-2}$
Understanding the scaling limits, controlling and exploiting dynamics: magnetoelectric coupling at <20 nm length scale; <1 nsec time scale; <100 kT energy scale	Integration and scale-up of synthetic approaches to enable manufacturing would be valuable
From a longer timescale perspective, reaching the theoretical Landauer limit for switching (kT(ln2) would be desirable and will require significant effort	Convergence of memory and logic

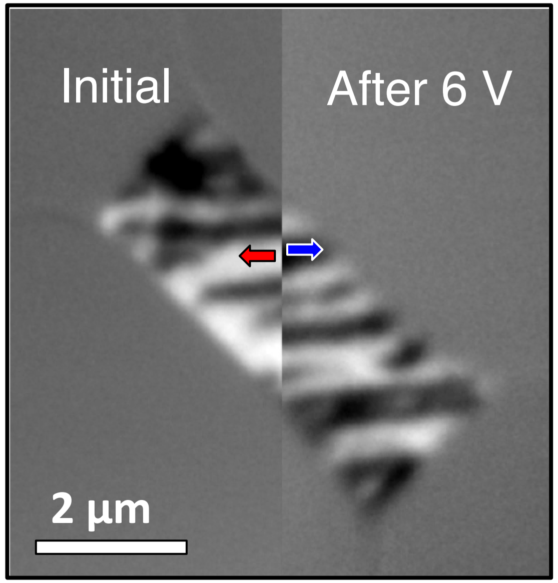
Main challenges

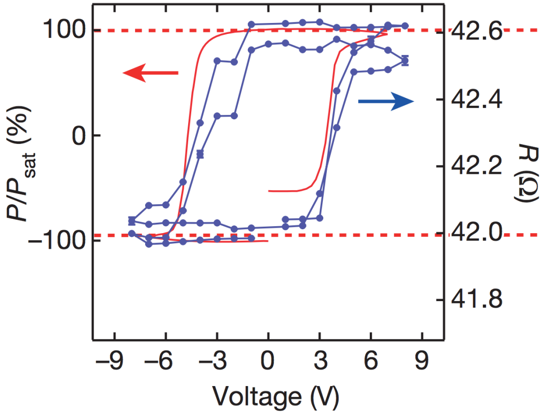
Larger magnetoelectric effect

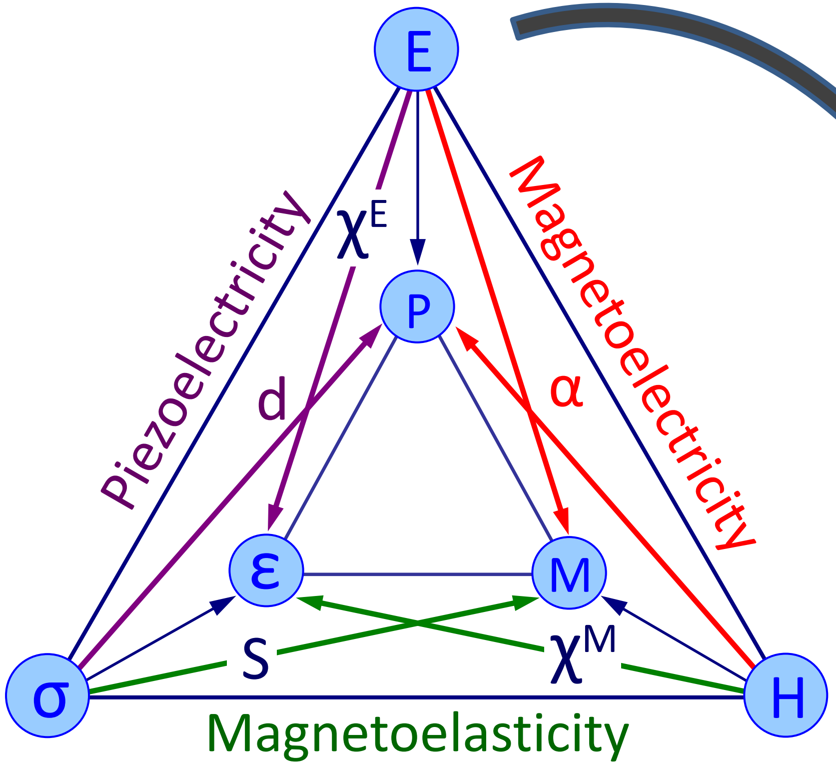
Lateral scaling (Below 10 nm)

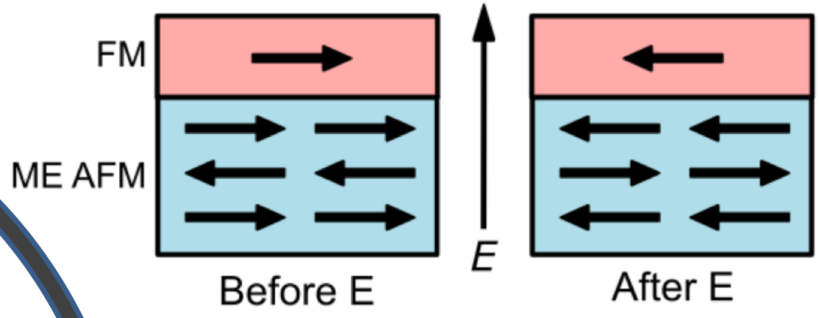
Faster switching times

The magnetoelectric effect









180° switching theoretically possible

Intrinsic magnetoelectrics are rare at room temperature

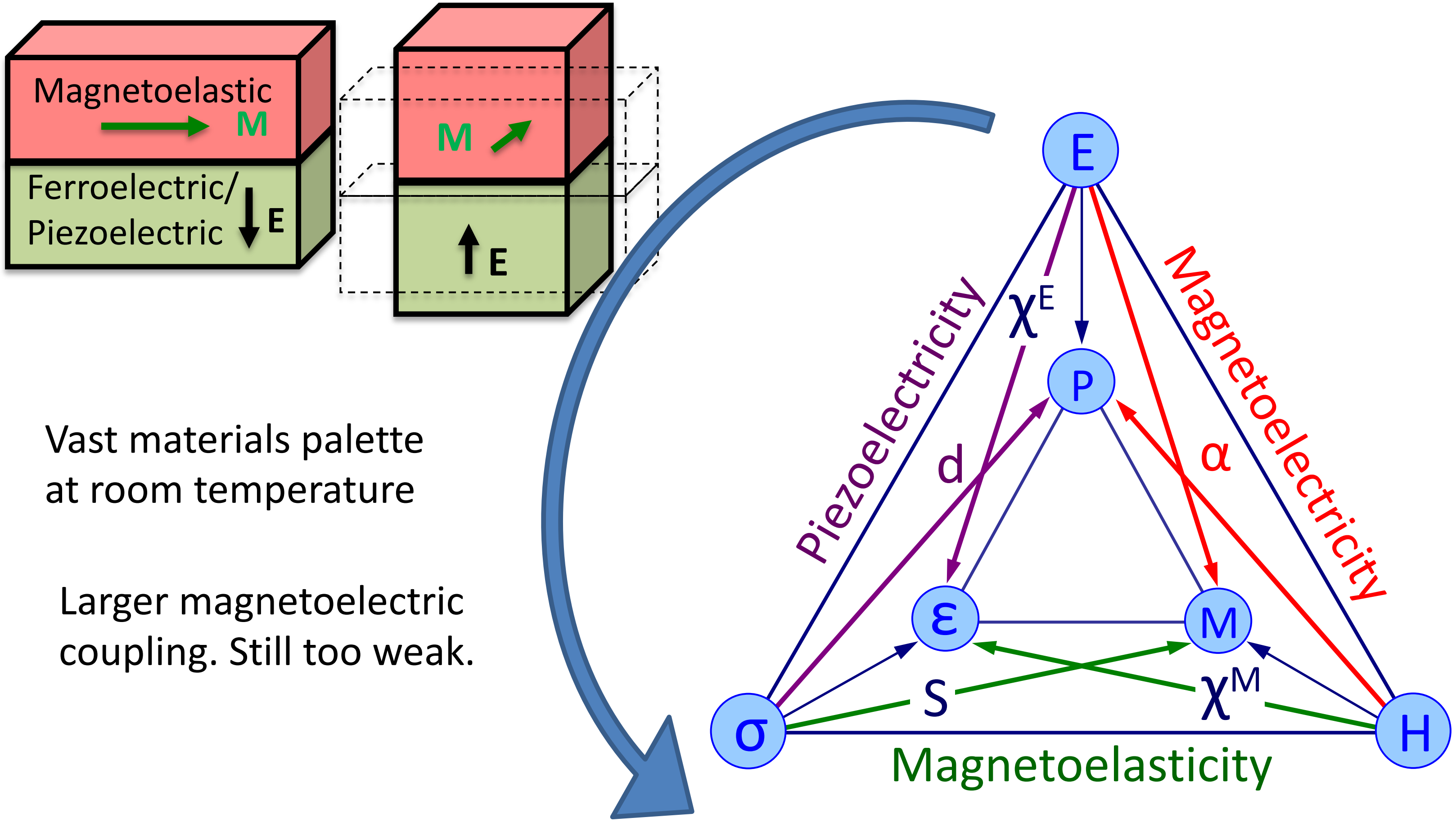
Magnetoelectric coupling is relatively weak

FERROELECTRONICS Laboratory

Heron, J. T. *et al.*. *Nature* **516**, 370–373 (2014)

Hill (Spaldin), *J. Phys. Chem. B 104*, 6694 (2001).
Fiebig, *J. Phys. D* 38, R123 (2005).
W. Eerenstein, N. D. Mathur and J. F. Scott, *Nature 442*, 759 (2006).

The magnetoelectric effect

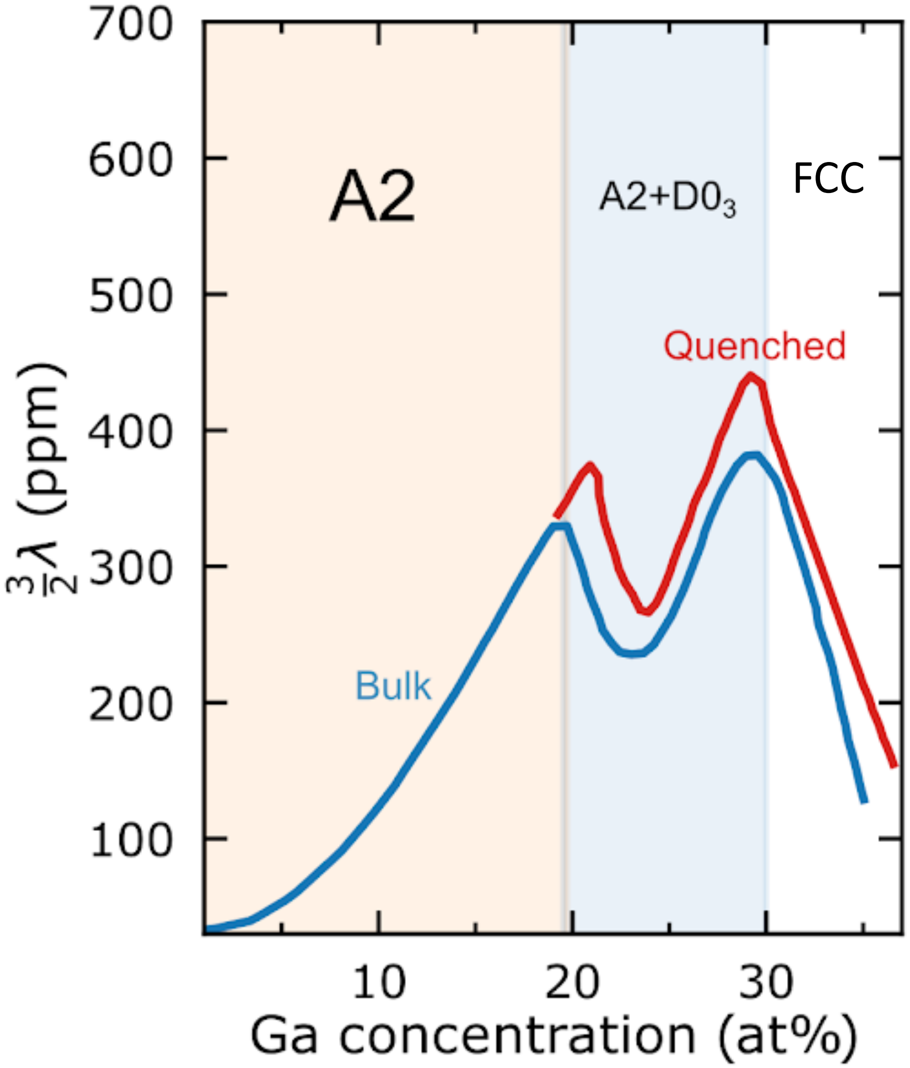


Vast materials palette
at room temperature

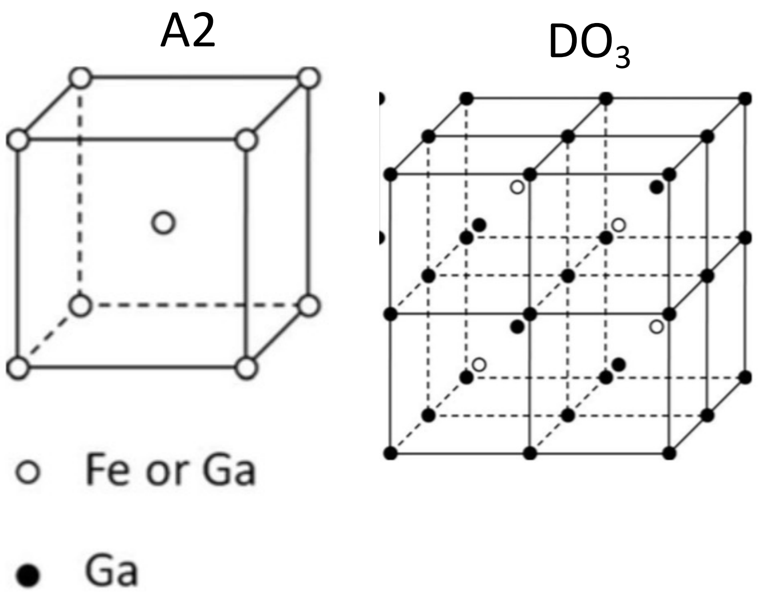
Larger magnetoelectric
coupling. Still too weak.

Hill (Spaldin), *J. Phys. Chem. B 104*, 6694 (2001).
Fiebig, *J. Phys. D* 38, R123 (2005).
W. Eerenstein, N. D. Mathur and J. F. Scott, *Nature 442*, 759 (2006).

Magnetostriction in bulk FeGa alloys



$$\frac{B_1}{(c_{11}-c_{12})} = -1.5\lambda_{100}$$



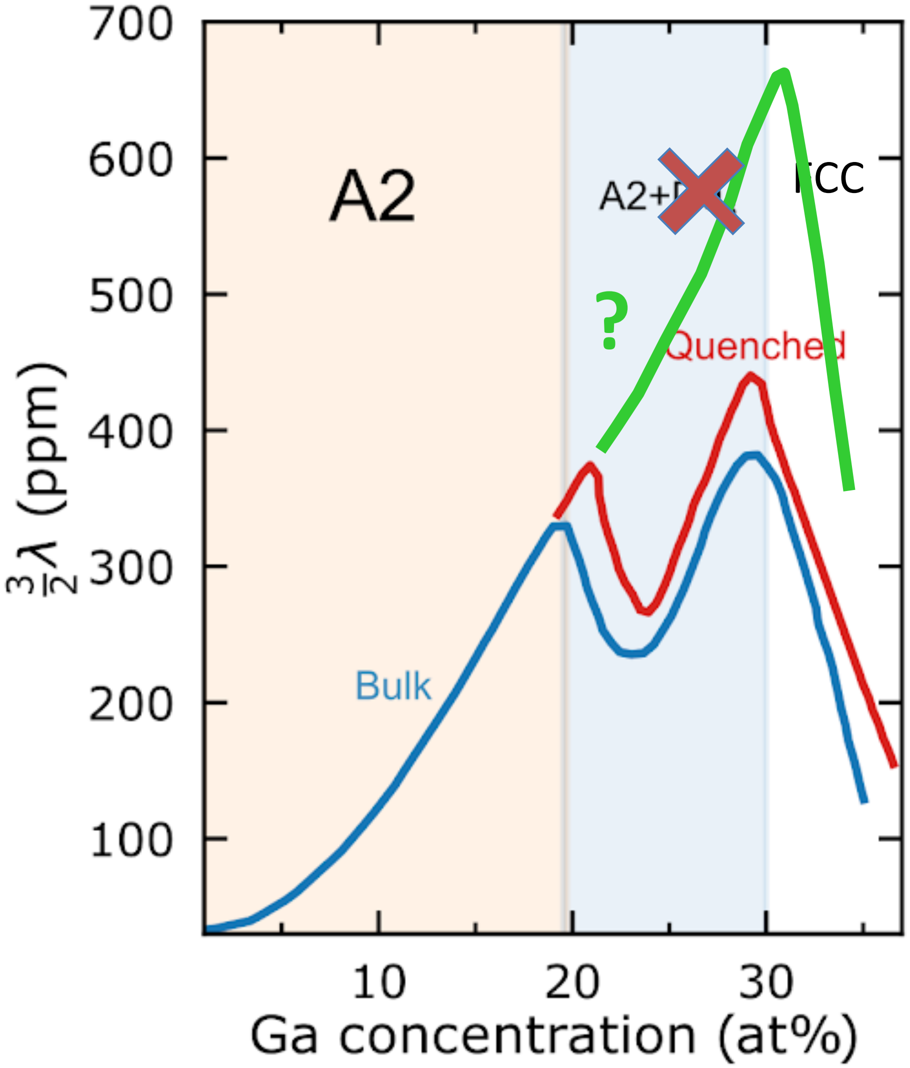
Reduction due to A2 into D0$_3$

D0$_3$ to FCC peak due to lattice softening

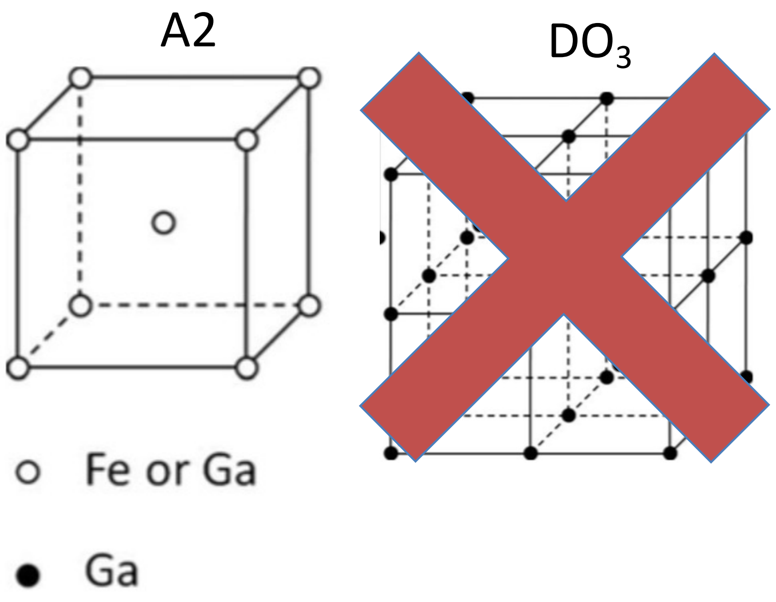
Quenching suppresses DO$_3$ formation

Y. Du et al., Phys. Rev. B 81, 054432 (2010)

Magnetostriction in bulk FeGa alloys



$$\frac{B_1}{(c_{11}-c_{12})} = -1.5\lambda_{100}$$



Reduction due to A2 into D0$_3$

D0$_3$ to FCC peak due to lattice softening

Quenching suppresses DO$_3$ formation

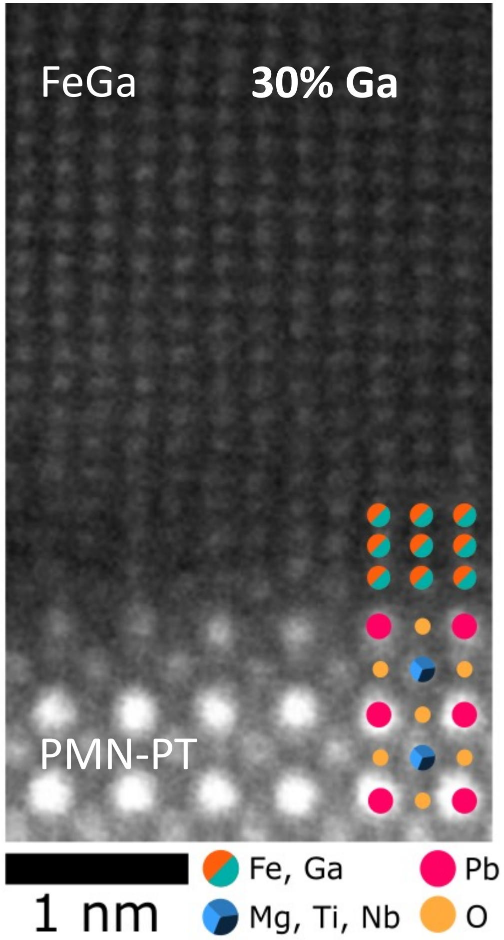
Low temperature thin film epitaxy?

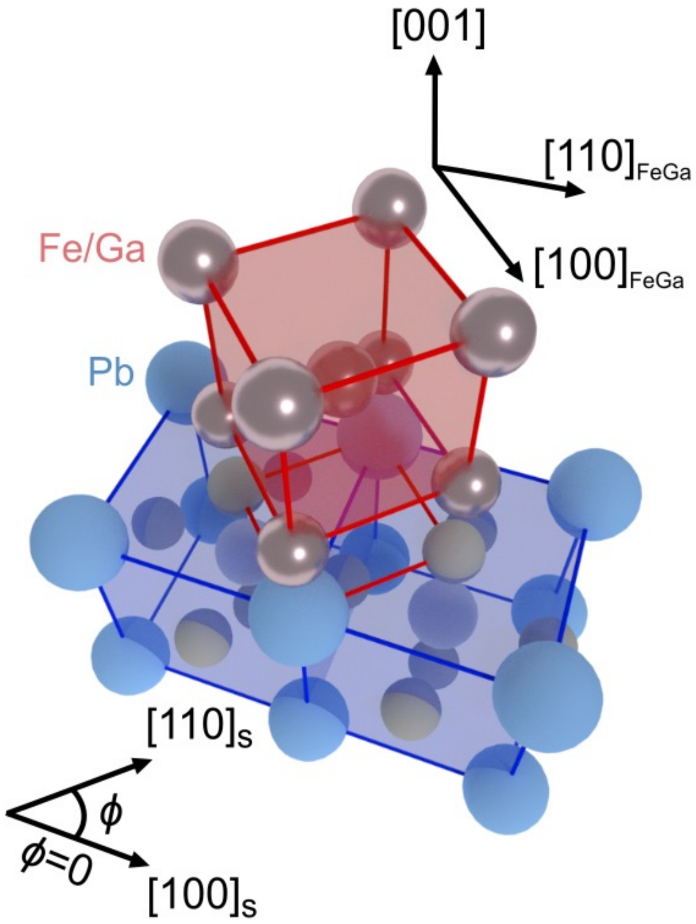
Y. Du et al., Phys. Rev. B 81, 054432 (2010)

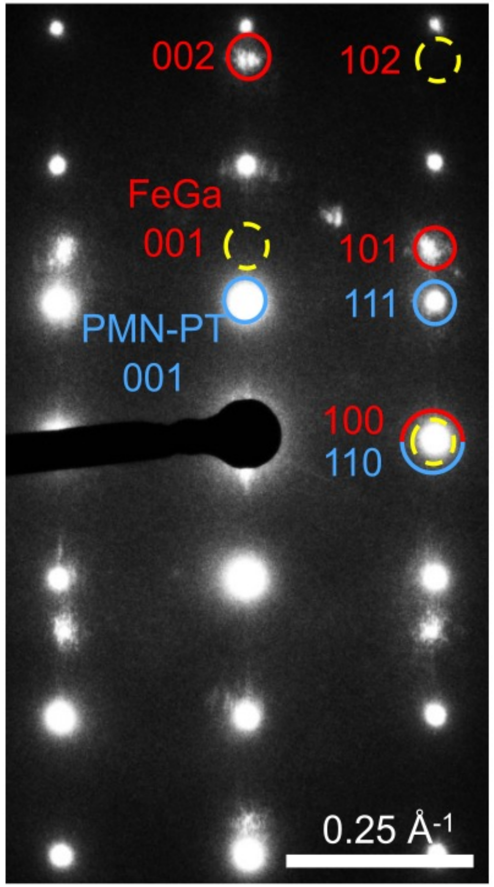
Stable A2 FeGa with above 19% Ga

Growth at 180 °C

No 001 reflection from $D0_3$ phase

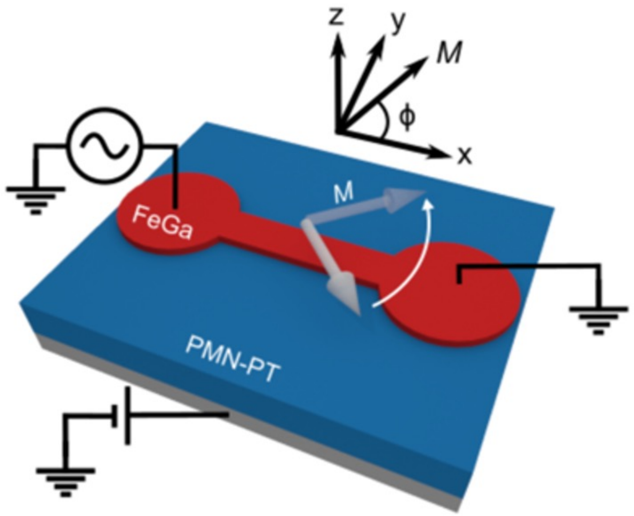






P. Meisenheimer *et al.*, Nature Commun. **12,** 2757 (2021)

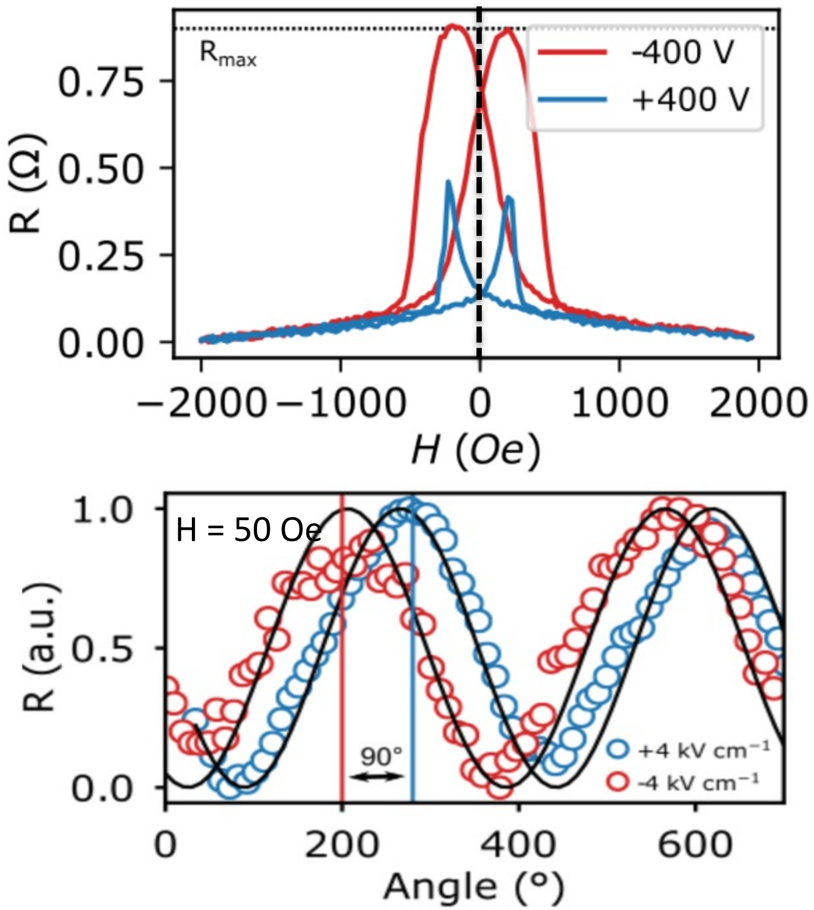
Reversible magnetization switching at room temperature

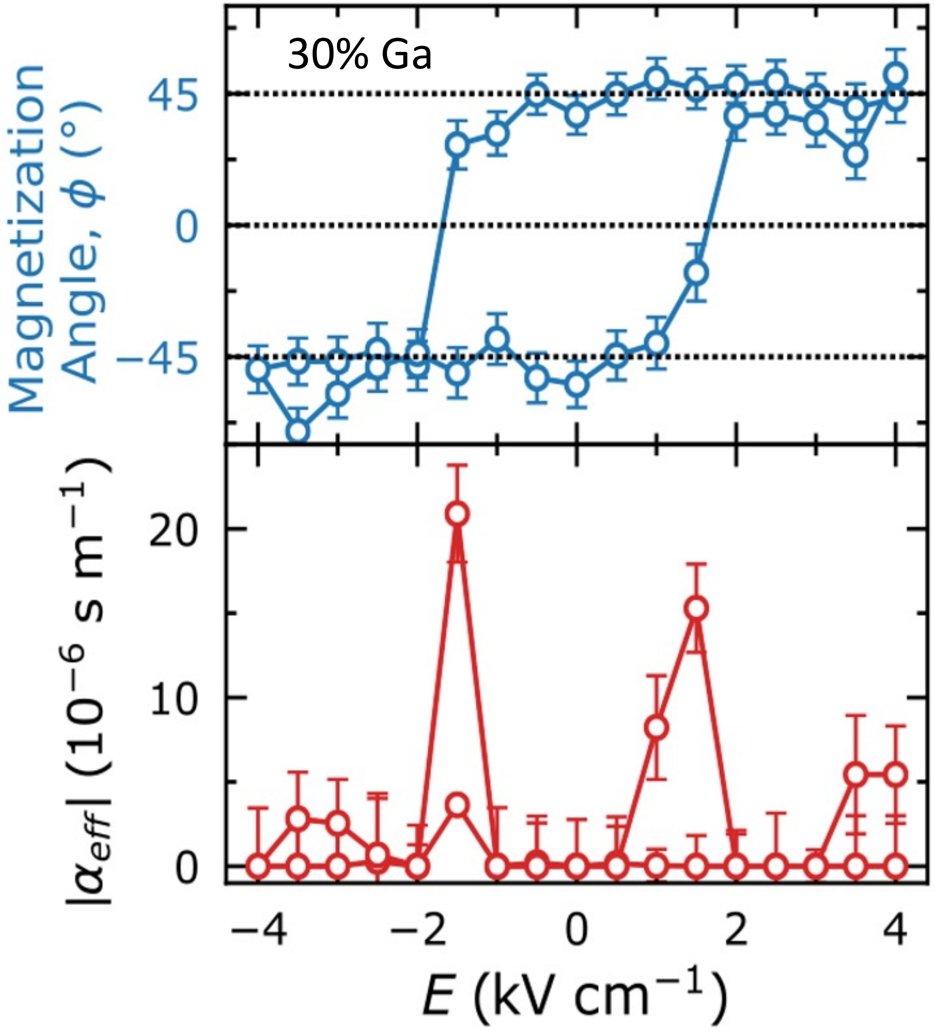


10 μm × 50 μm bar
PMN-PT substrate

$$\rho(\varphi) = \rho_\perp + (\rho_\parallel - \rho_\perp)\cos^2\varphi$$

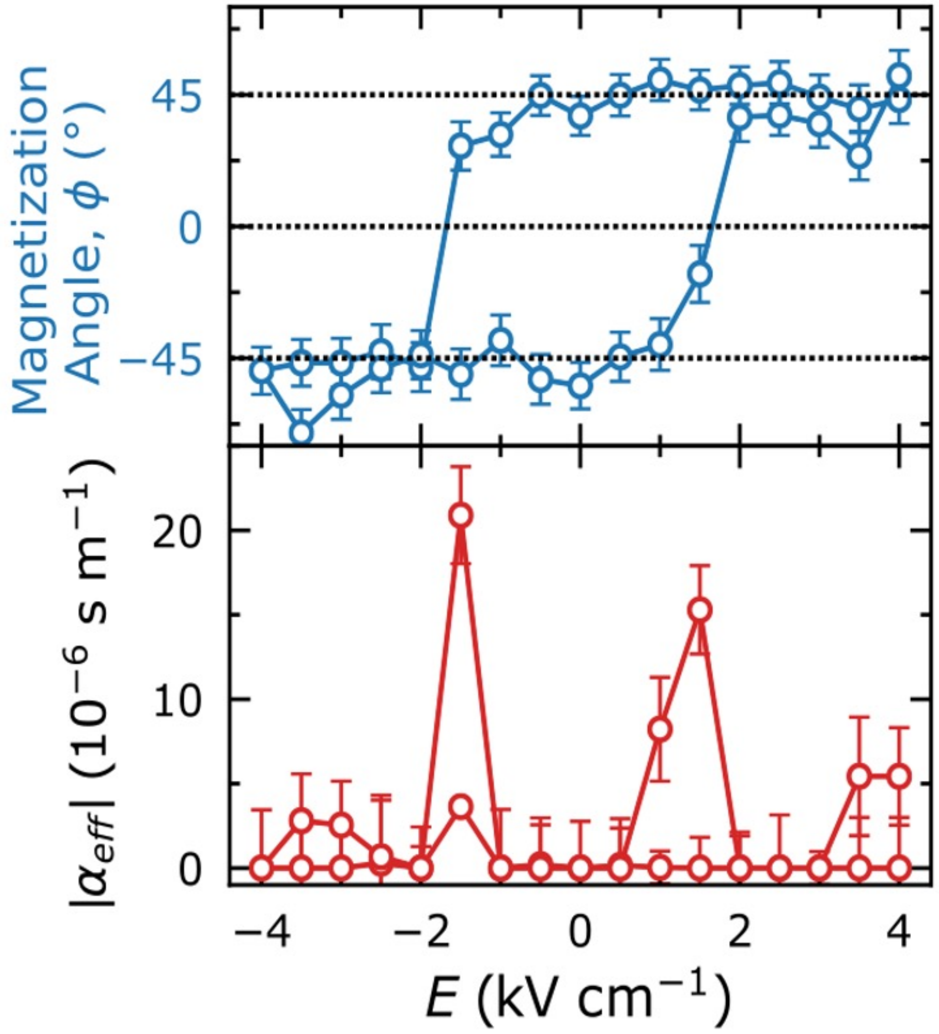
$$|\alpha_{eff}| = \mu_0 \left|\frac{dM}{dE}\right| = \mu_0 M_S \left|\frac{d\,cos\phi}{dE}\right|$$

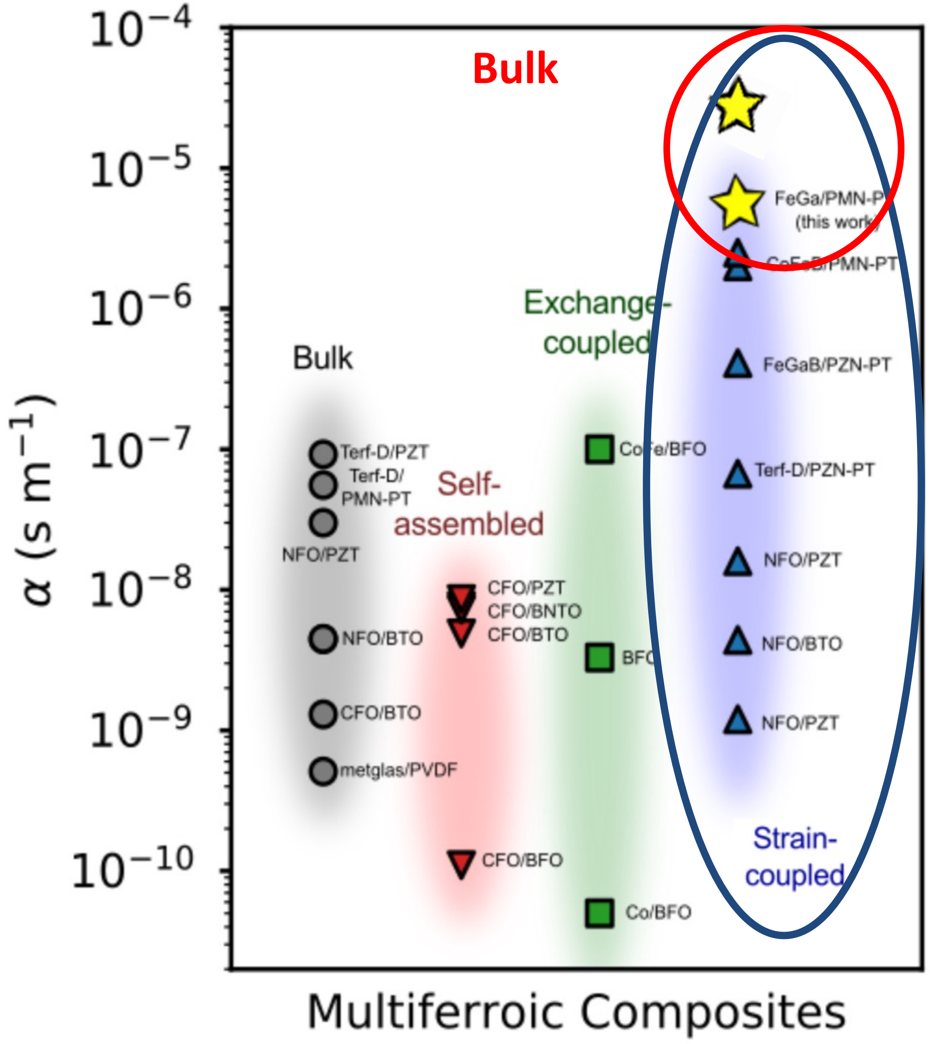




P. Meisenheimer *et al.*, Nature Commun. **12,** 2757 (2021)

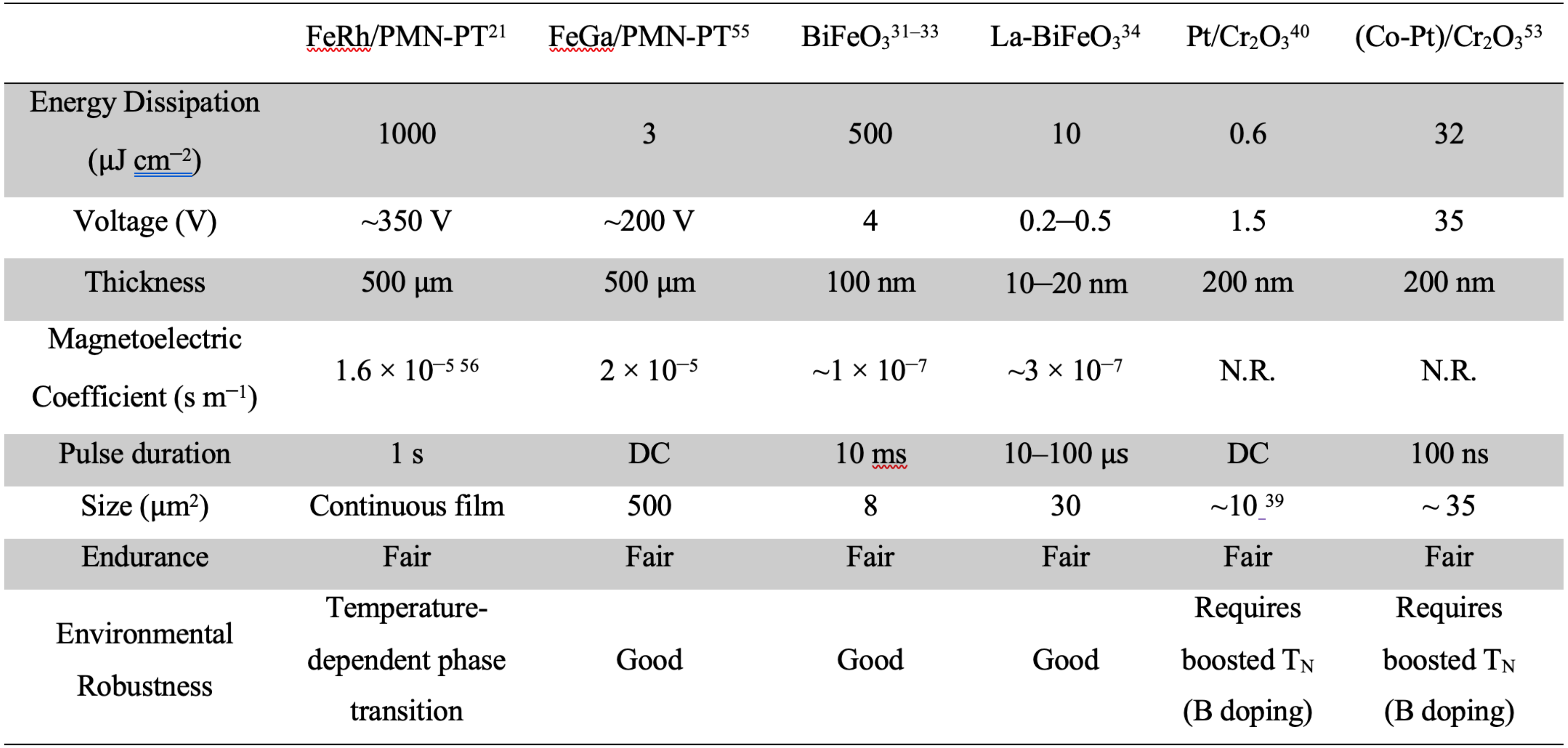
Magnetoelectric coefficient





Perspective

Table I. Converse magnetoelectric switching metrics



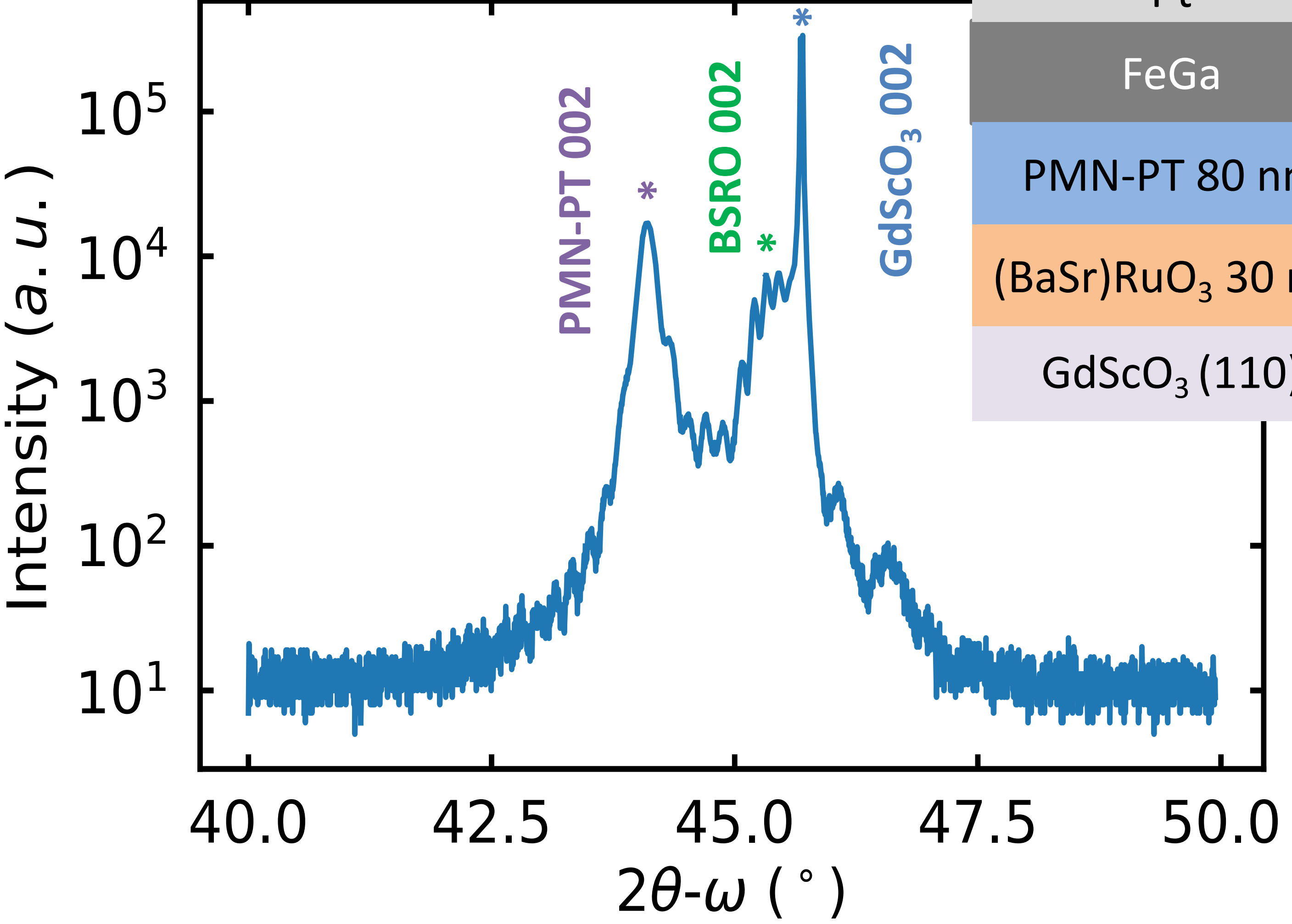
	FeRh/PMN-PT[21]	FeGa/PMN-PT[55]	$BiFeO_3$[31–33]	La-$BiFeO_3$[34]	Pt/Cr_2O_3[40]	(Co-Pt)/Cr_2O_3[53]
Energy Dissipation (μJ cm^{-2})	1000	3	500	10	0.6	32
Voltage (V)	~350 V	~200 V	4	0.2–0.5	1.5	35
Thickness	500 μm	500 μm	100 nm	10–20 nm	200 nm	200 nm
Magnetoelectric Coefficient (s m^{-1})	1.6×10^{-5} [56]	2×10^{-5}	$\sim 1 \times 10^{-7}$	$\sim 3 \times 10^{-7}$	N.R.	N.R.
Pulse duration	1 s	DC	10 ms	10–100 μs	DC	100 ns
Size (μm^2)	Continuous film	500	8	30	~10[39]	~ 35
Endurance	Fair	Fair	Fair	Fair	Fair	Fair
Environmental Robustness	Temperature-dependent phase transition	Good	Good	Good	Requires boosted T_N (B doping)	Requires boosted T_N (B doping)

Energy dissipation 2.9 μ J cm^{-2}

Magnetic device: 45 × 45 nm^2**, switching energy dissipation is ~80 aJ,**

J. Heron and T. Chiang *MRS Bulletin* (2021)

From 500 μm thick PMN-PT substrate to 10’s nm thick film



Pt

FeGa

PMN-PT 80 nm

$(BaSr)RuO_3$ 30 nm

$GdScO_3$ (110)

FeGa: a = 2.9 A

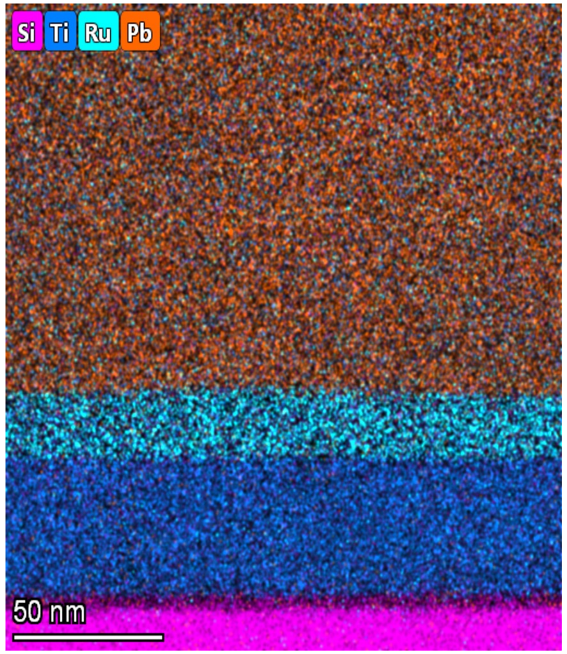
PMN-PT: a = 4.02 A

BSRO: a = 3.97 A

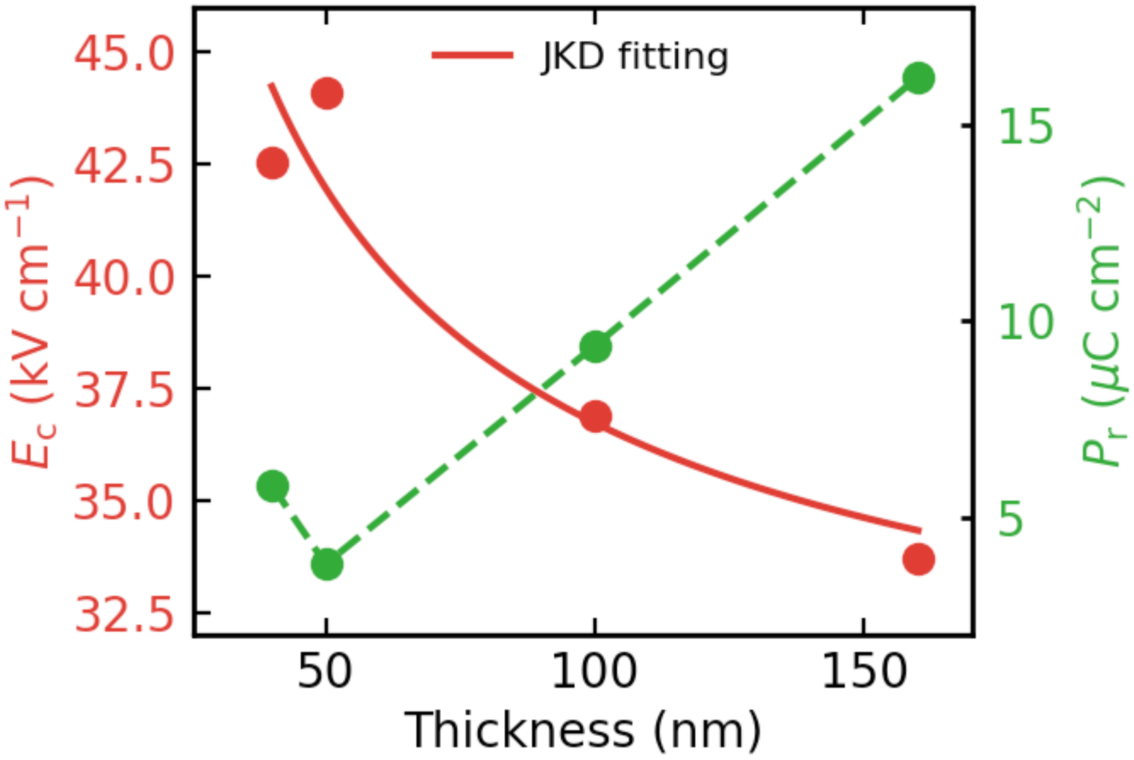
$GdScO_3$: a =3.97 A

PLD grown: 600 C

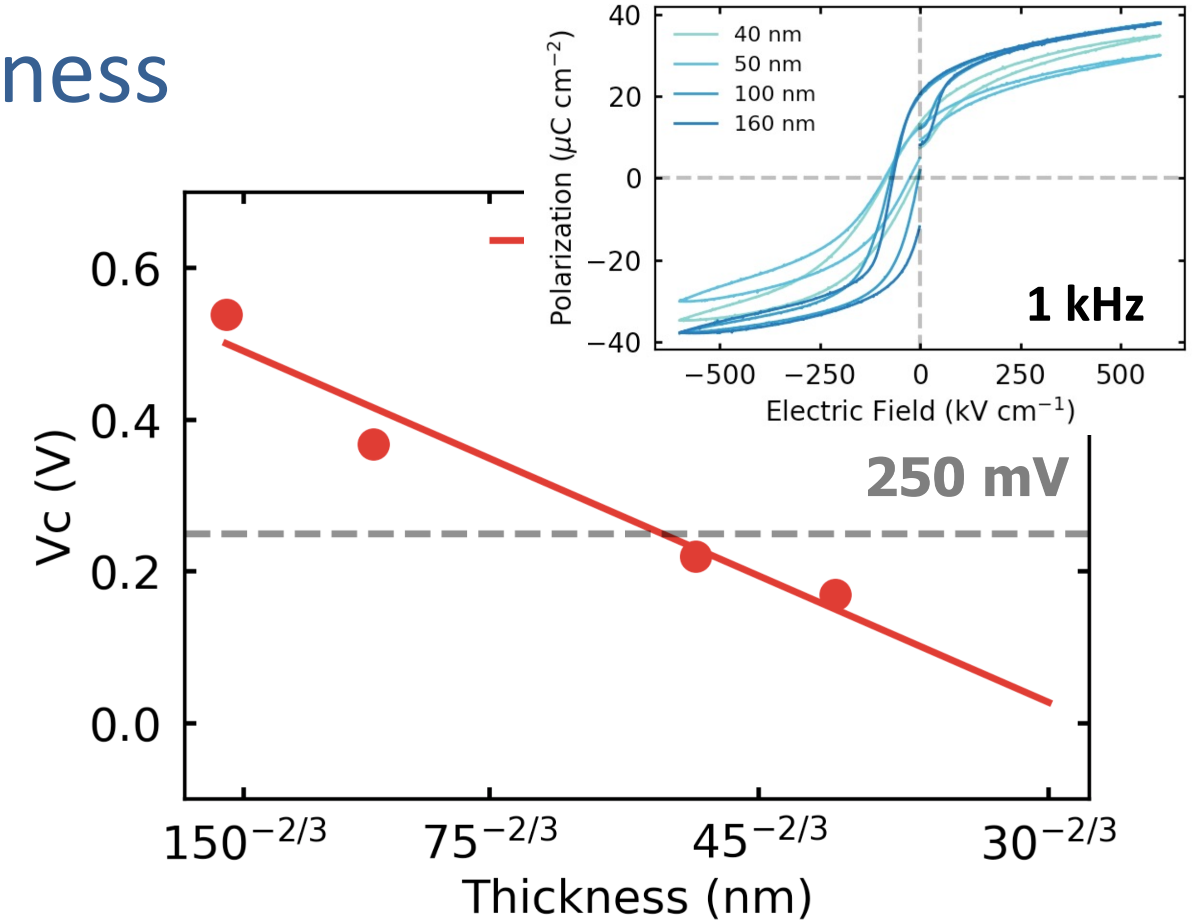
Silicon compatible



Switching performance vs thickness

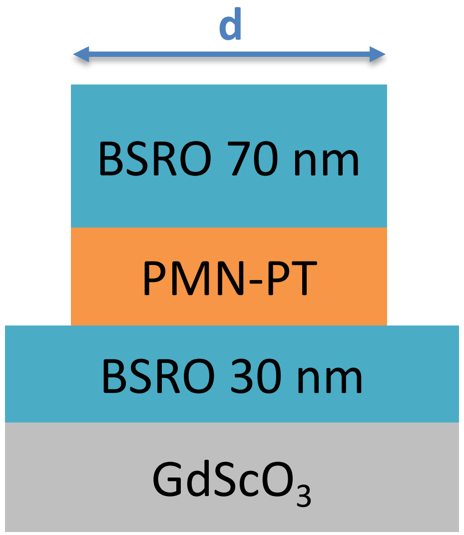


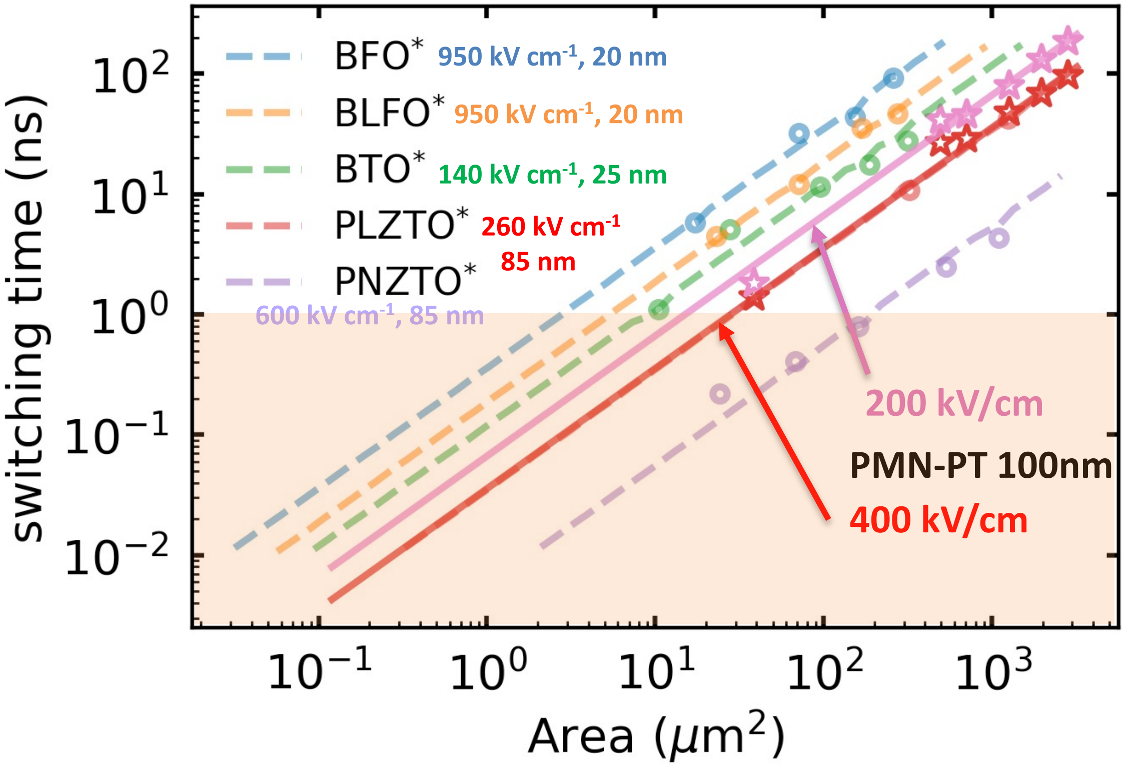
Janovec–Kay–Dunn (JKD) law:
$E_c \propto d^{-2/3}$



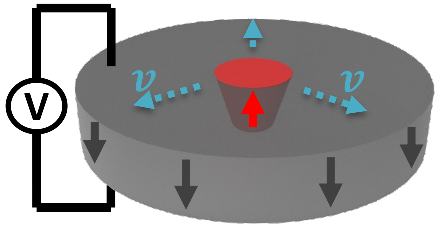
Sub-250 mV Switching at 55 nm

Switching speed near 1 ns with lateral scaling

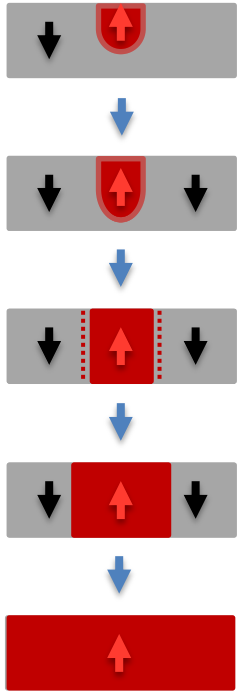




$$v \propto \exp\left(-\frac{E_a}{E}\right)$$



Thin film ferroelectrics



Switching still growth dominated at 3 micron diameter
Out performed BFO and BTO

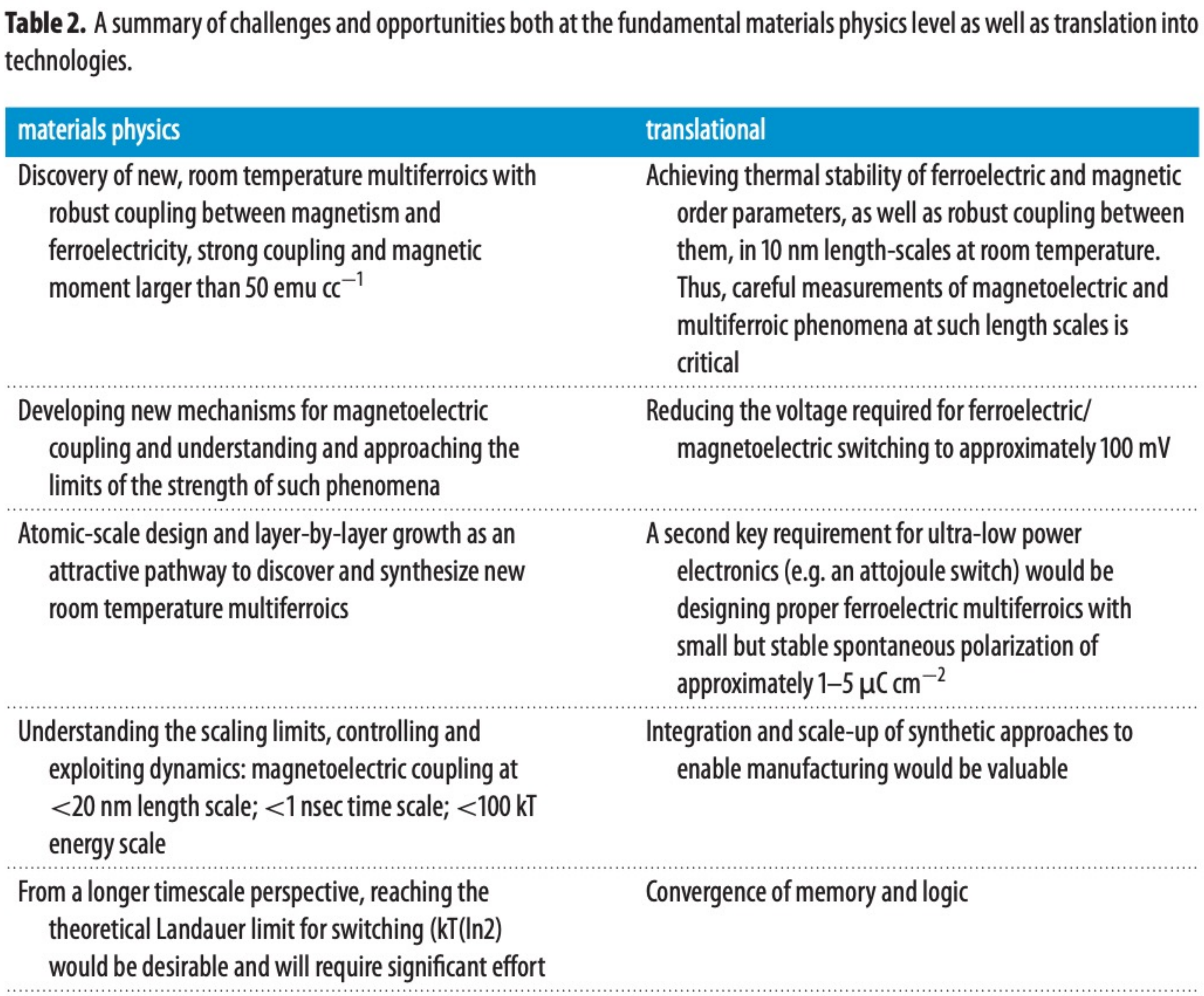


Table 2. A summary of challenges and opportunities both at the fundamental materials physics level as well as translation into technologies.

materials physics	translational
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Developing new mechanisms for magnetoelectric coupling and understanding and approaching the limits of the strength of such phenomena	Reducing the voltage required for ferroelectric/magnetoelectric switching to approximately 100 mV
Atomic-scale design and layer-by-layer growth as an attractive pathway to discover and synthesize new room temperature multiferroics	A second key requirement for ultra-low power electronics (e.g. an attojoule switch) would be designing proper ferroelectric multiferroics with small but stable spontaneous polarization of approximately 1–5 $\mu C\ cm^{-2}$
Understanding the scaling limits, controlling and exploiting dynamics: magnetoelectric coupling at $<$20 nm length scale; $<$1 nsec time scale; $<$100 kT energy scale	Integration and scale-up of synthetic approaches to enable manufacturing would be valuable
From a longer timescale perspective, reaching the theoretical Landauer limit for switching (kT(ln2) would be desirable and will require significant effort	Convergence of memory and logic

Main challenges/potential for collaboration

Larger magnetoelectric effect

Lateral scaling (to 10 nm)

Fast measurements

Wafer scaling – large scale fabrication

Prototyping