Multiferroic Energy Conversion in the Small ΔT Regime

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University of Minnesota

Workshop on Lower Grade Waste Heat Recovery
ARPA-E, December 13-14, 2016
San Francisco, USA

Outline

Introduction

- Key sources of low grade waste heat
- Multiferroic energy conversion
- Potential and challenges?

Our Approach

- Key idea
- Recent breakthroughs
- Innovation in thin film growth

Summary

Sources of Low Temperature Heat on Earth

- **Solar thermal** plants, **geothermal** sources
- **US Industry** consumes a terawatt, ~1/15 of all the power consumed on earth (DOE, 2008): 25-50% rejected as waste heat. 60% of this is “low grade” waste heat, rejected at < 232 °C

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- Computers: **US data centers** now consume 2.5 - 3% of the national energy budget
- Waste heat from **laptop** and **desktop computers**
- **Hand held electronic devices** (phones, video games)

Thin film devices: chip level integration

- The waste heat from **automobile exhaust systems**
- The waste heat from **air conditioning systems** and **power plants**
- Accumulated heat in **attics and roofs**

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The Goal: To develop solid state energy conversion technology based on Multiferroism through the innovation in computational design and materials synthesis.

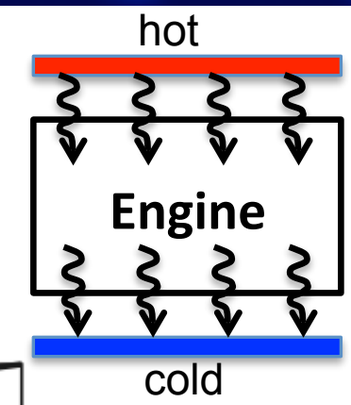
Existing Technologies....

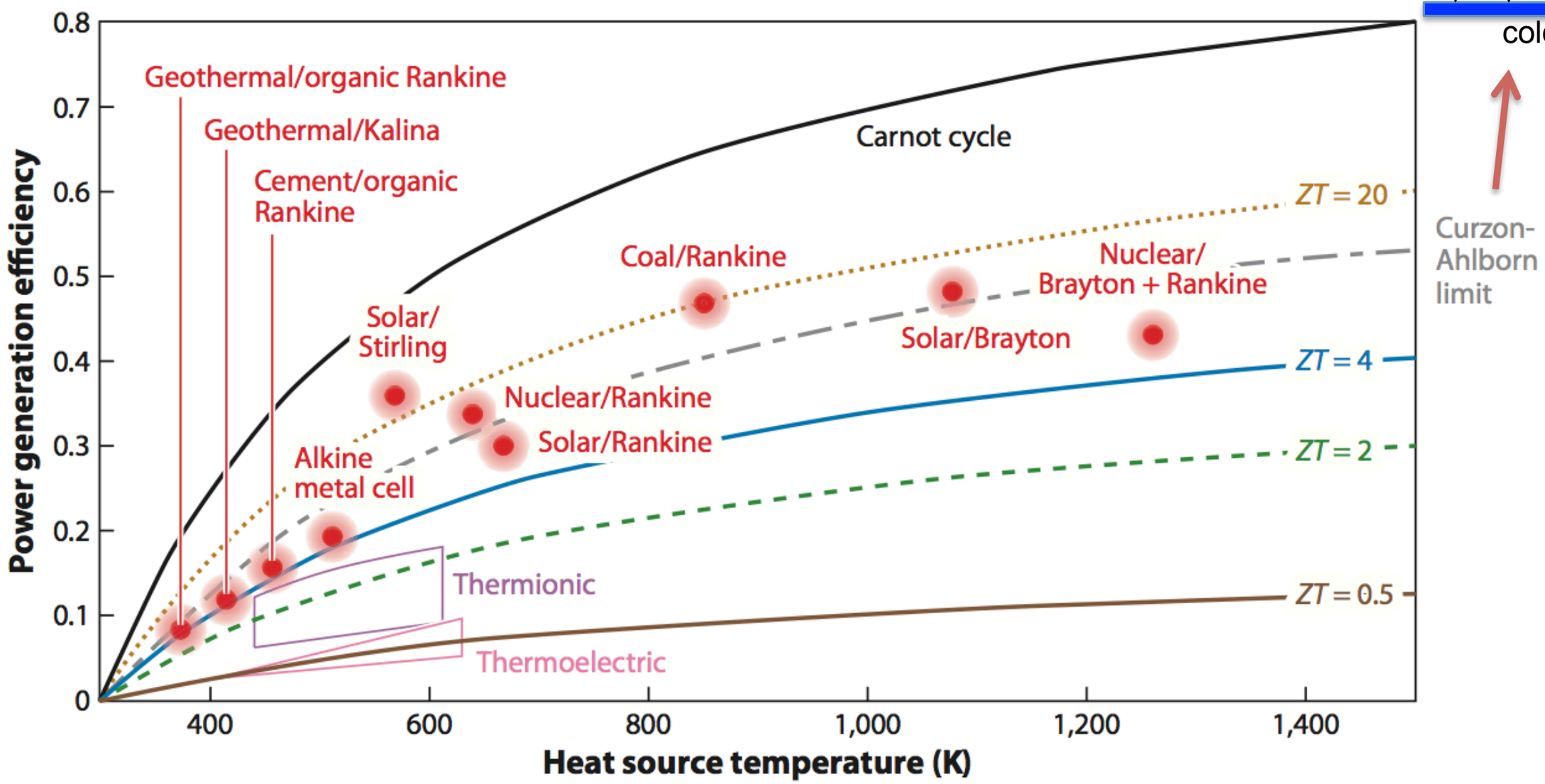
fixed at room temp.

$$eff \leq 1 - \frac{T^-}{T^+}$$

Measured Efficiency

Newton's law of cooling





(T^+)

$$ZT = \left(\frac{S^2\sigma}{\kappa}\right)T$$

A Shakouri, Ann Rev Mater Res, 2011

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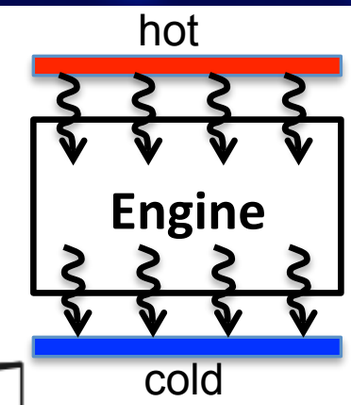

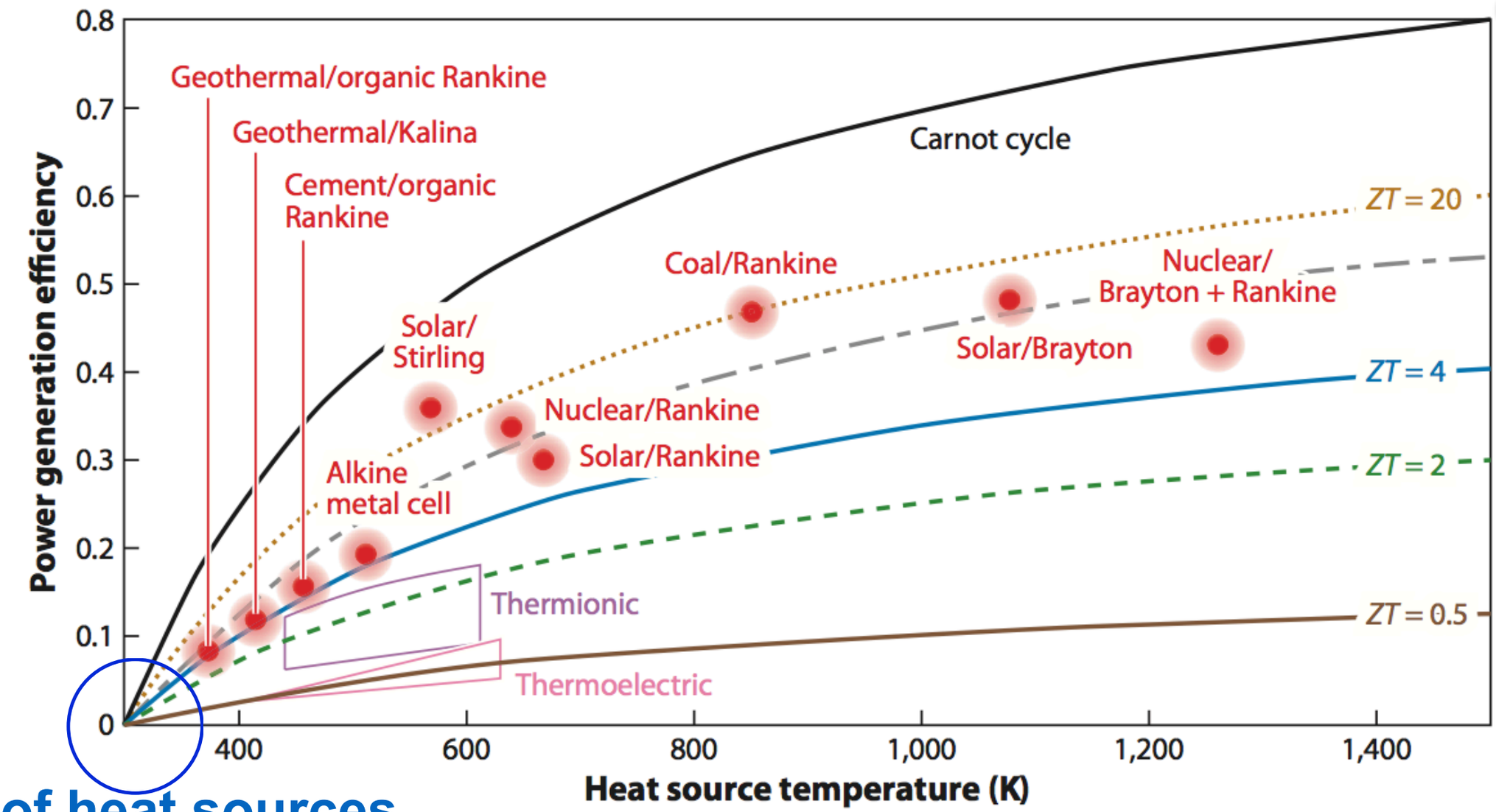

(T^+)

Lots of heat sources

no good method

Thermoelectric?

50+ years of work!

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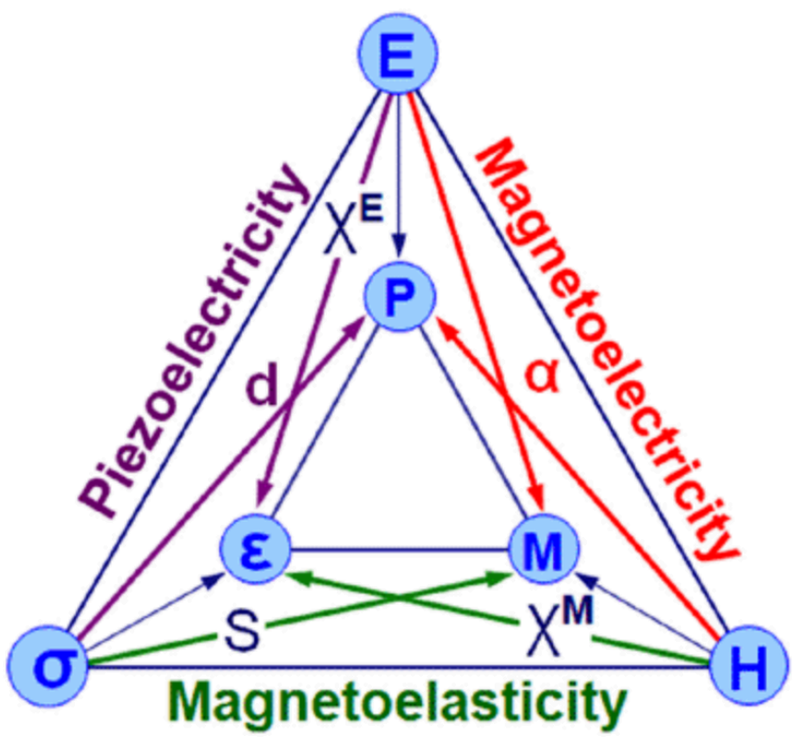
Multiferroic Energy Conversion

Coupling between different order parameters

Linear properties like
$\sigma = E\,\varepsilon + d\,P$



Of limited use for energy conversion

J. Phys: Cond. Matter. 20 (2008), 434220

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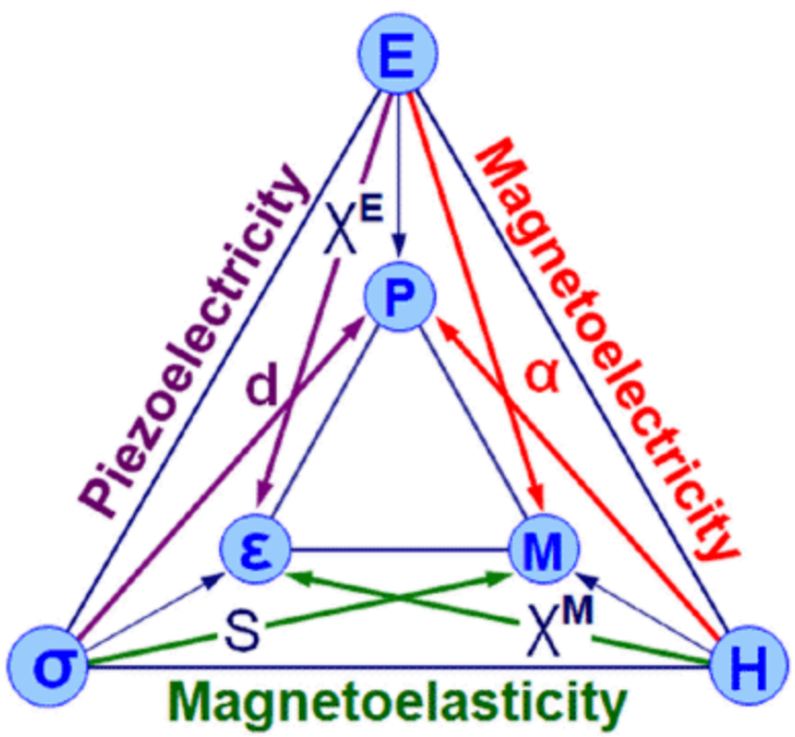

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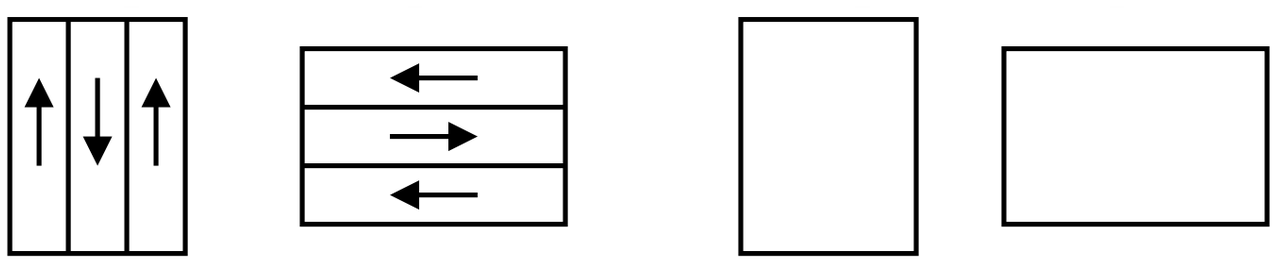
"Multiferroism" by Phase Transformation



polarization or magnetization

Heusler Handbook, (ed. C. Felser and A. Hirohata)
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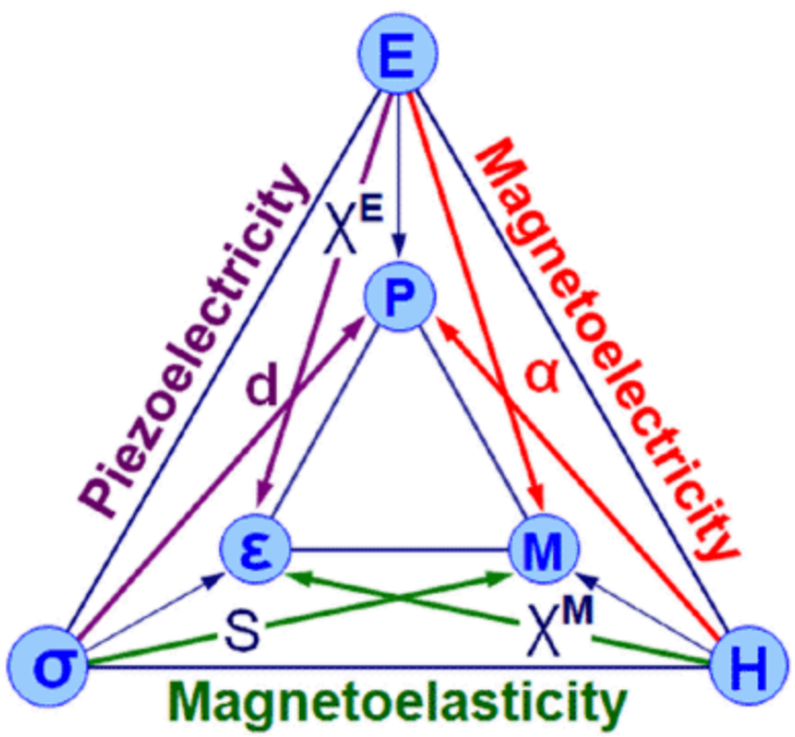

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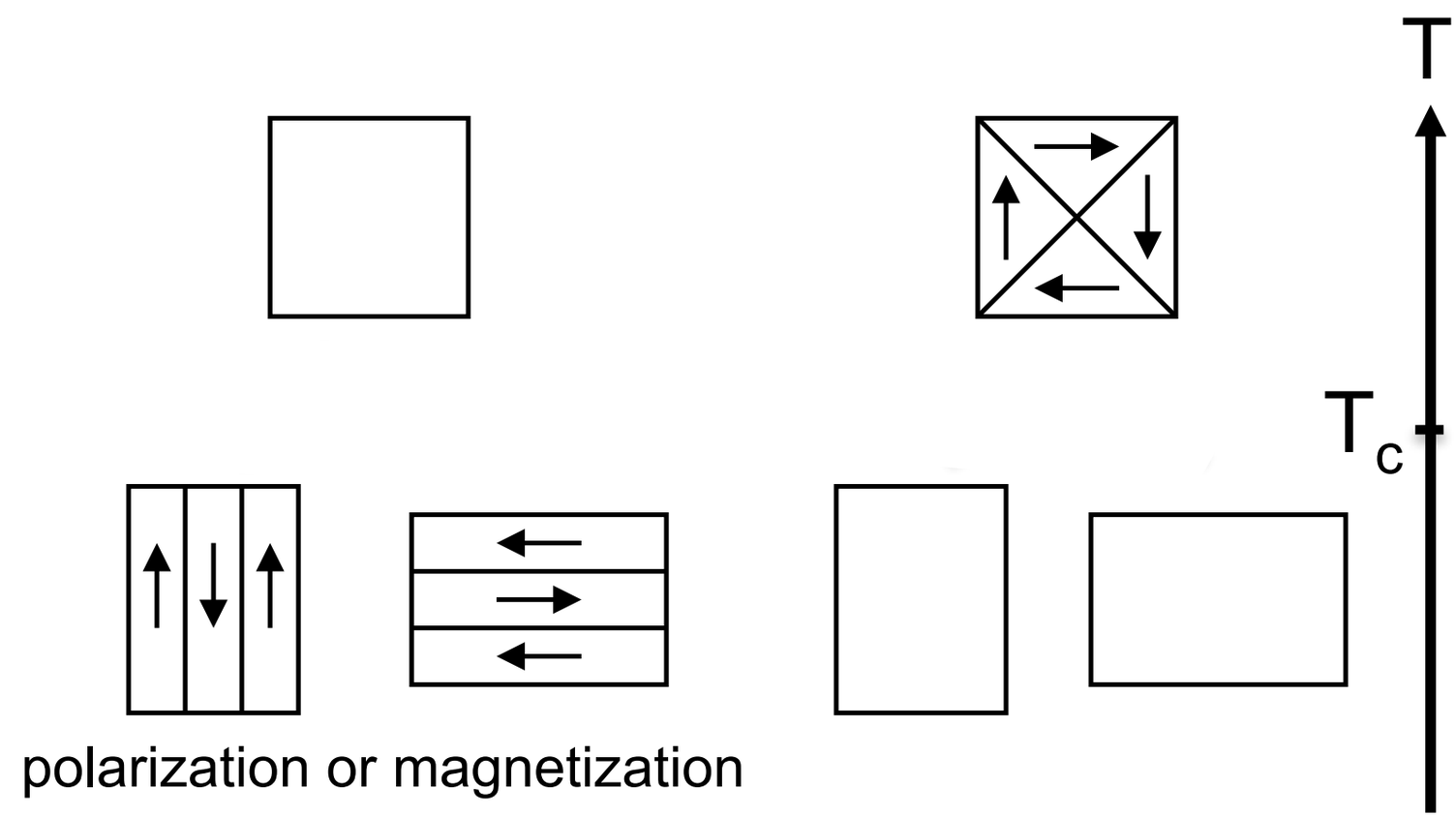

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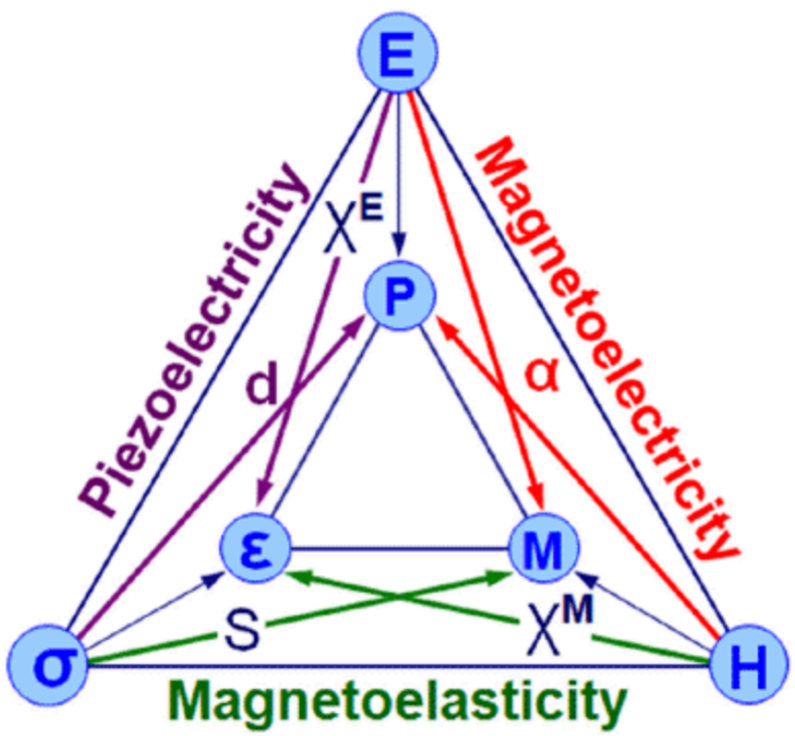

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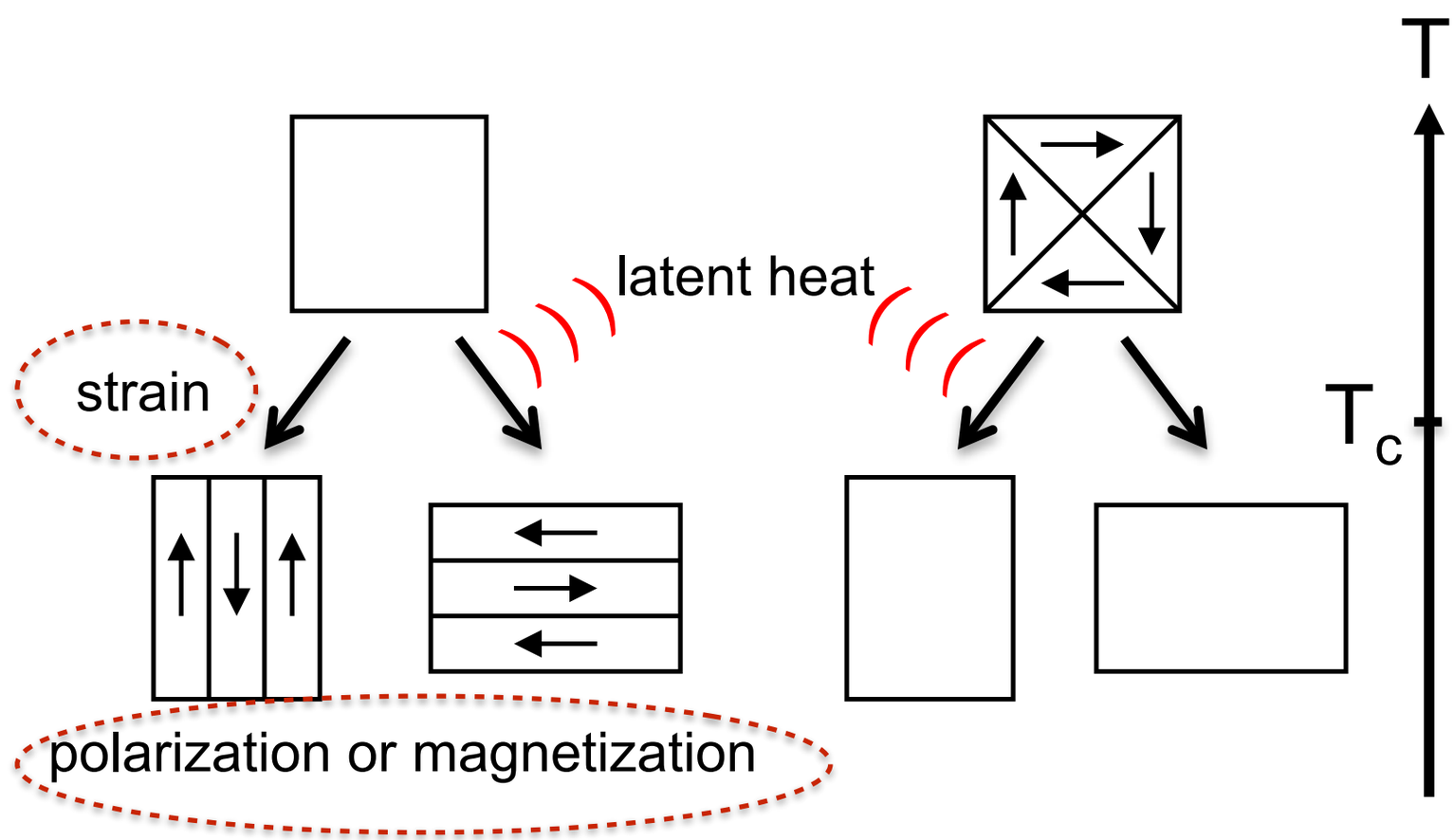

The key innovation for **high efficiency** and high power output is to use a first order phase transformation

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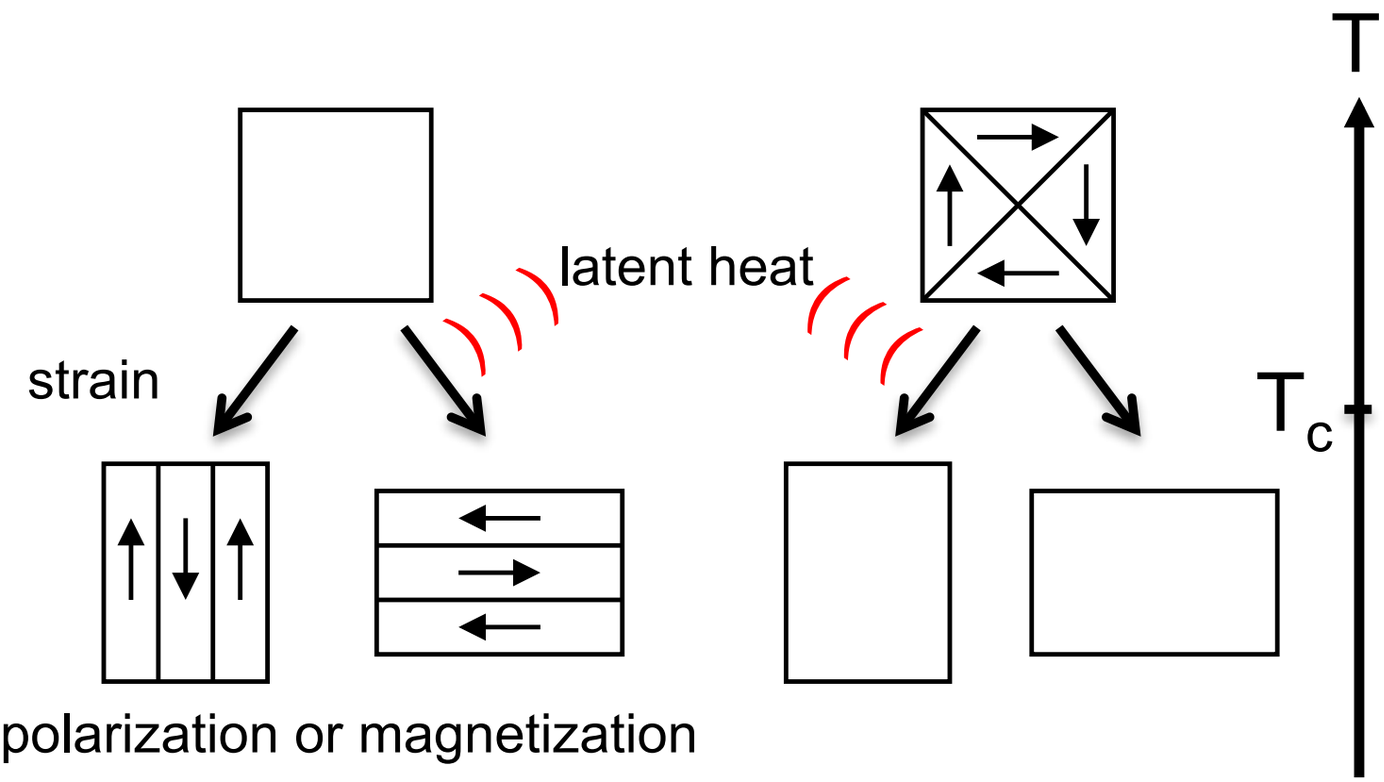

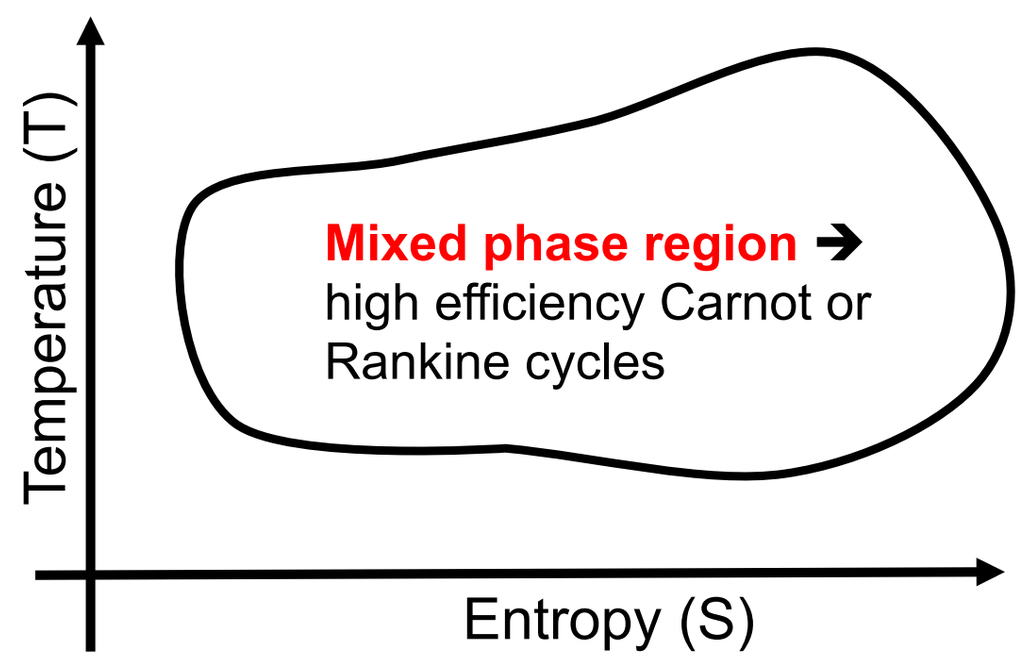

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First-order phase transformations with latent heat ensure large mixed phase region in T-S diagram to construct high efficiency Carnot and related cycle.

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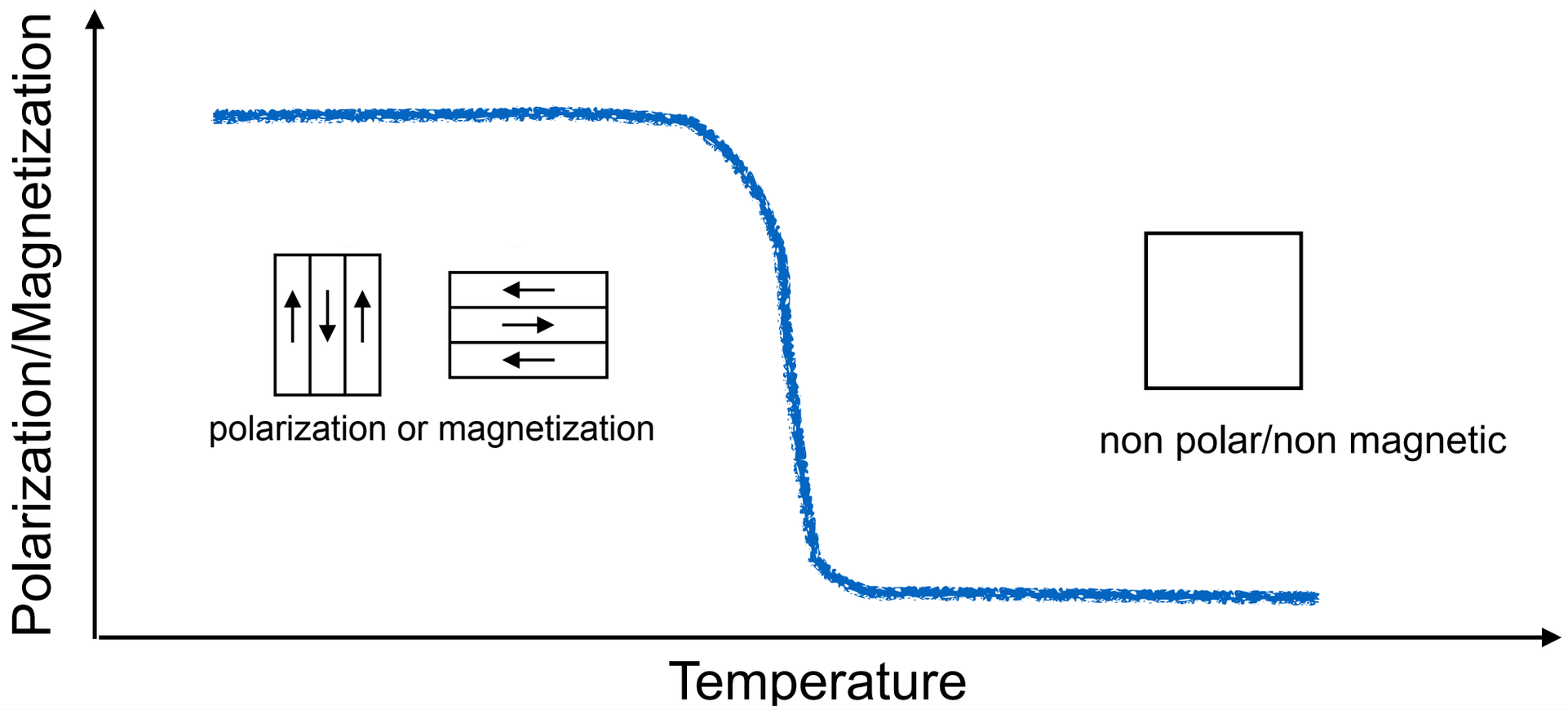
Key Idea

“Multiferroism” by Phase Transformation



Thermo-Magnetic case

$$\frac{dB}{dt} \propto \frac{dM}{dt} \propto \text{current}$$

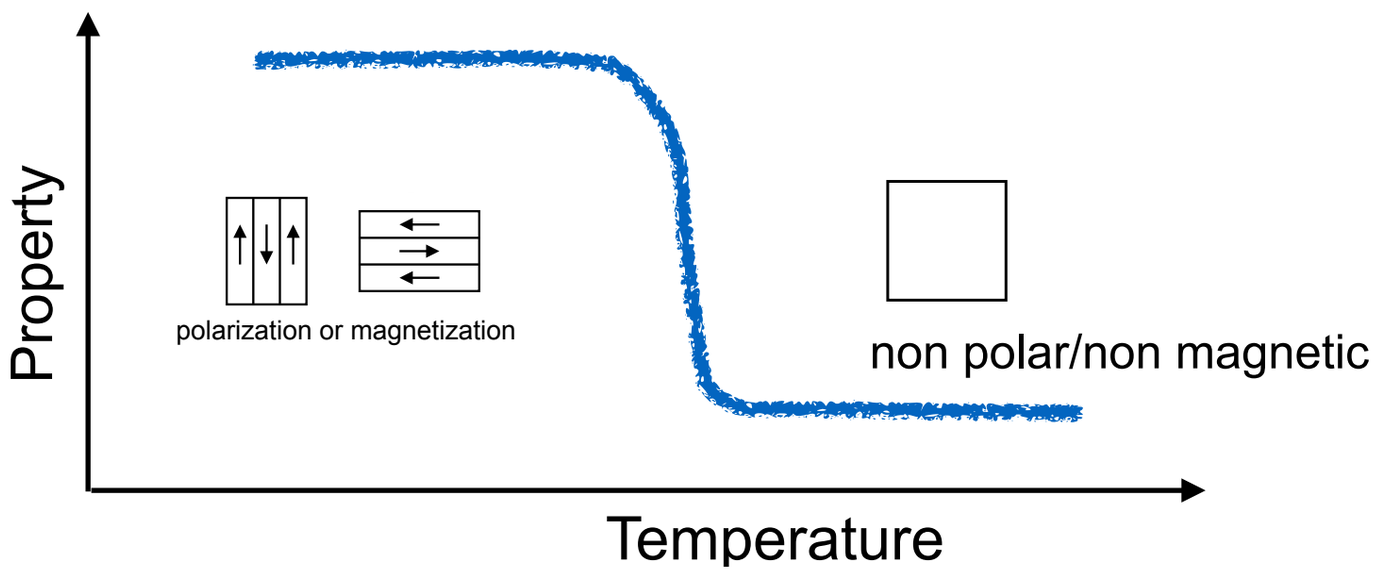
(Faraday’s law of induction)

Ferroelectric case

capacitance $\propto \epsilon \propto$ charge stored

Key Idea

Potential and Challenges

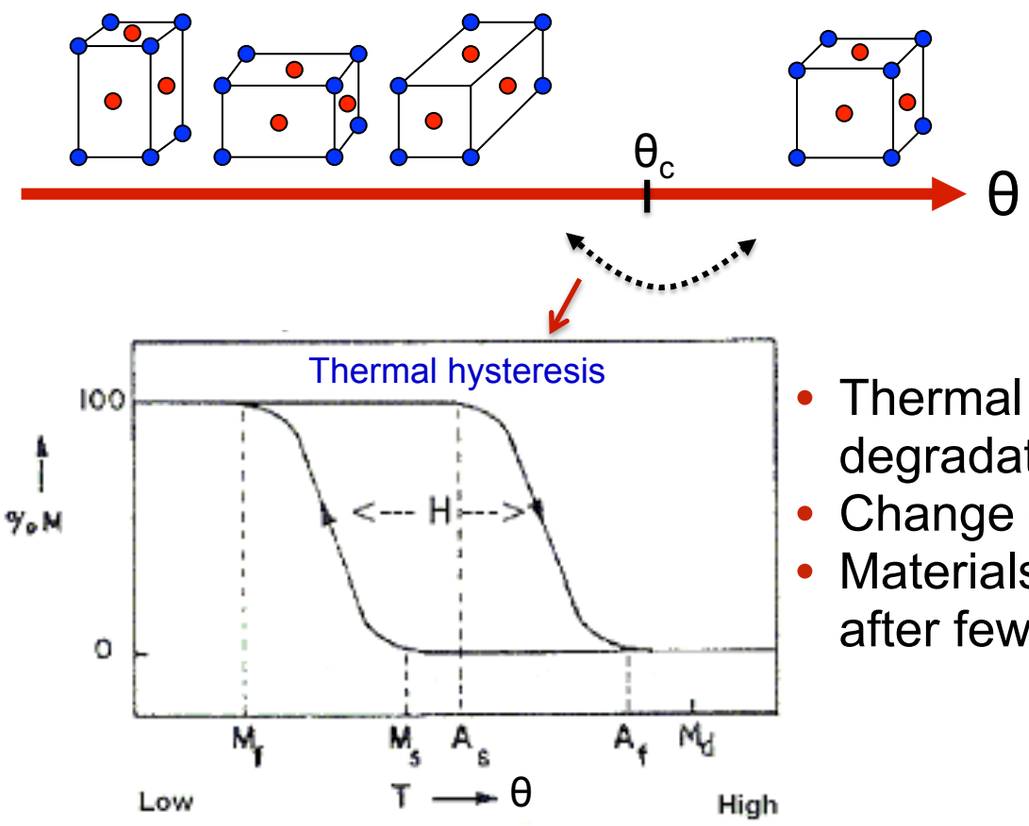


- ✓ New Idea for direct heat-to-electrical energy conversion using electromagnetic properties
- ✓ Adapted to energy conversion at small temperature difference, ~10-100 ºC
- ✓ Highly tunable (transformation temperature and ranges)

- Materials Issues
  - Reversibility of phase transformation
  - Chip level integration - requires thin films architecture
  - Scalability
- Device reliability
- Efficiency and cost

Enabling Scientific Breakthroughs

Methods for exceptionally reversible phase transformation



- Thermal degradation
- Change of T_c
- Materials failure after few cycles

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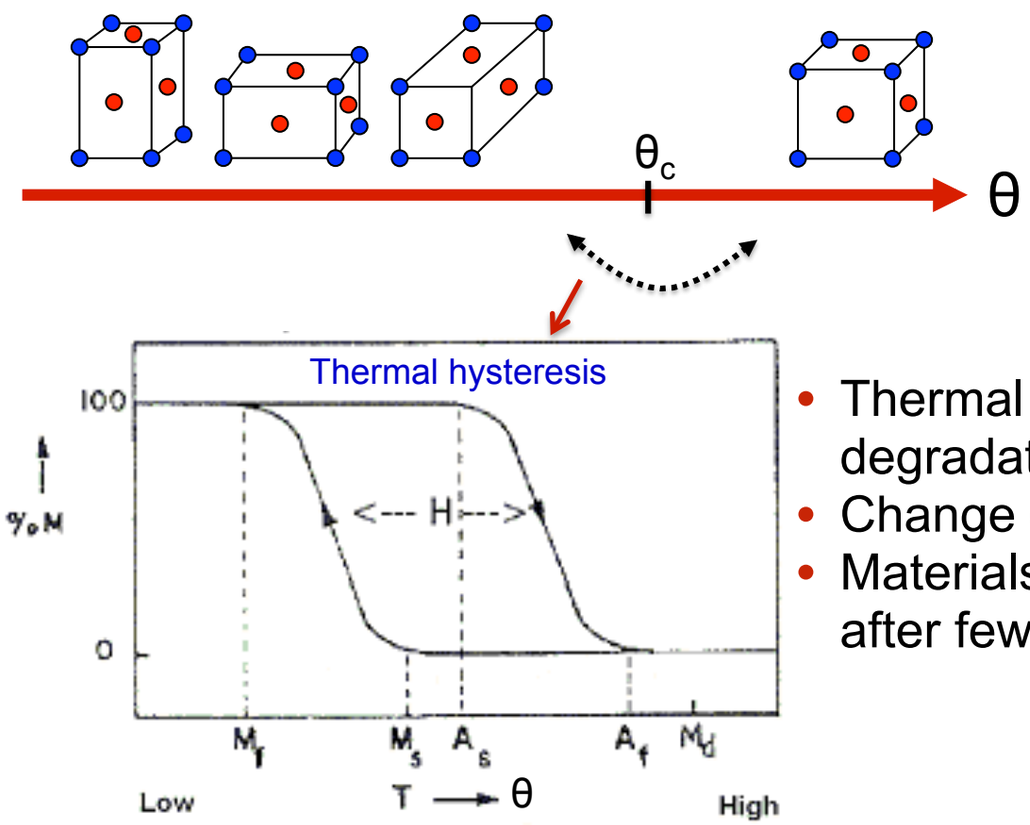

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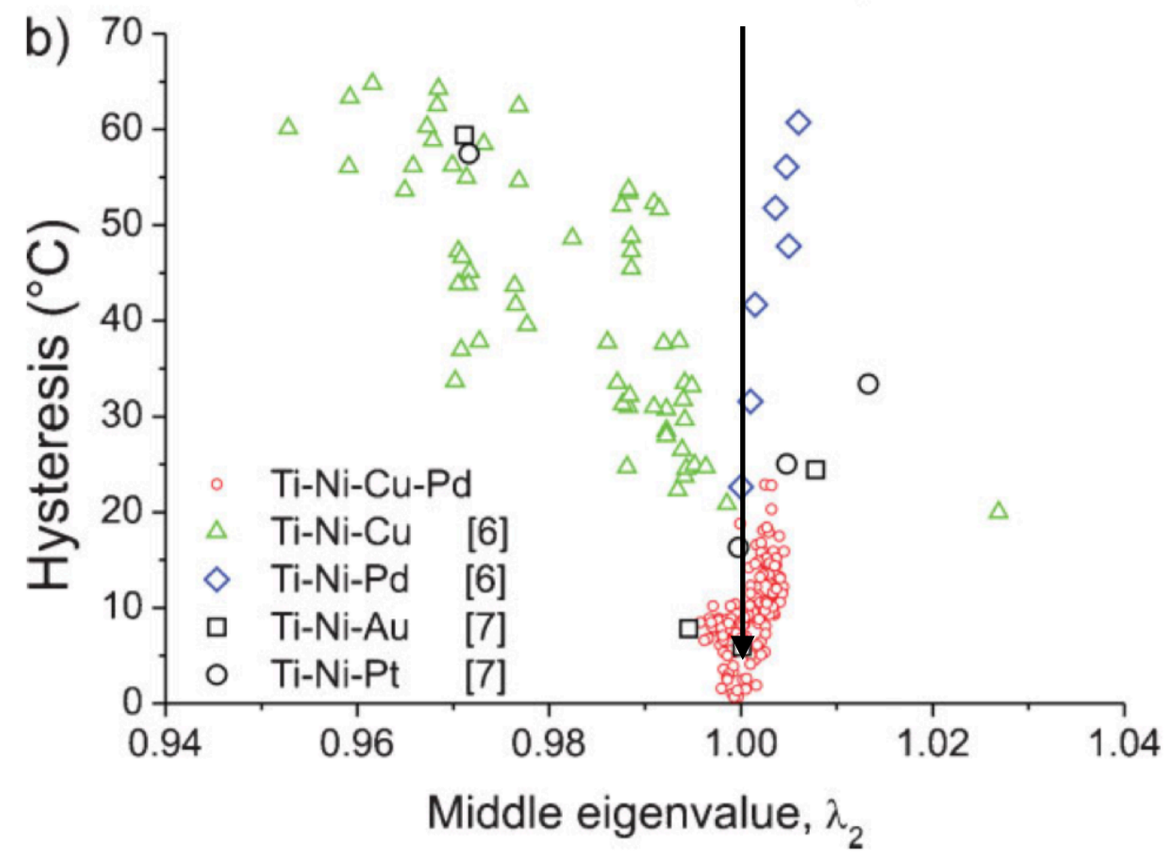
As $\lambda_2 = 1$, H —> 0
controlled by tuning lattice parameter



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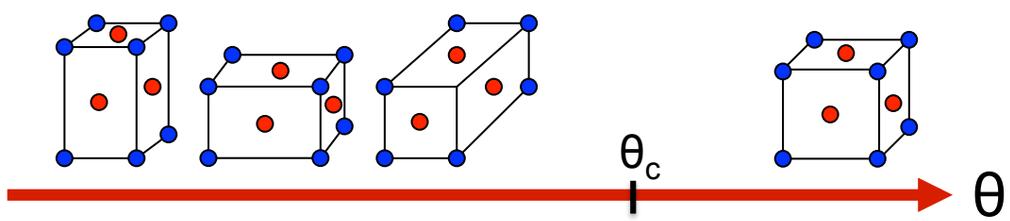

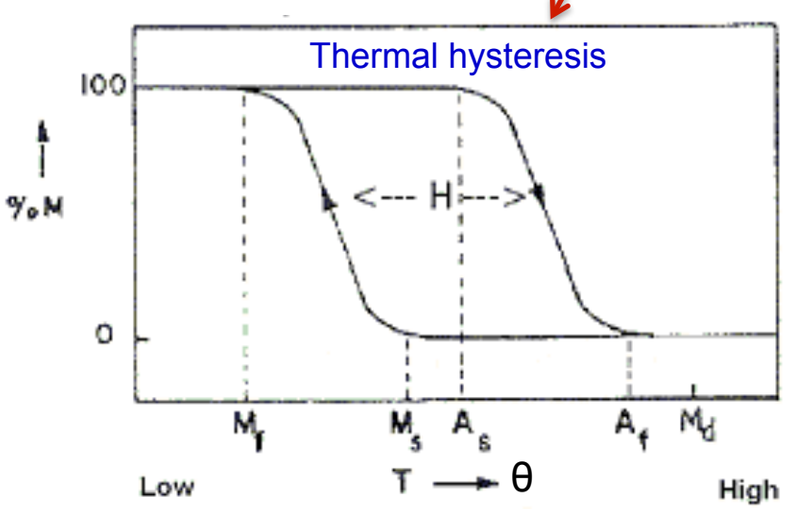

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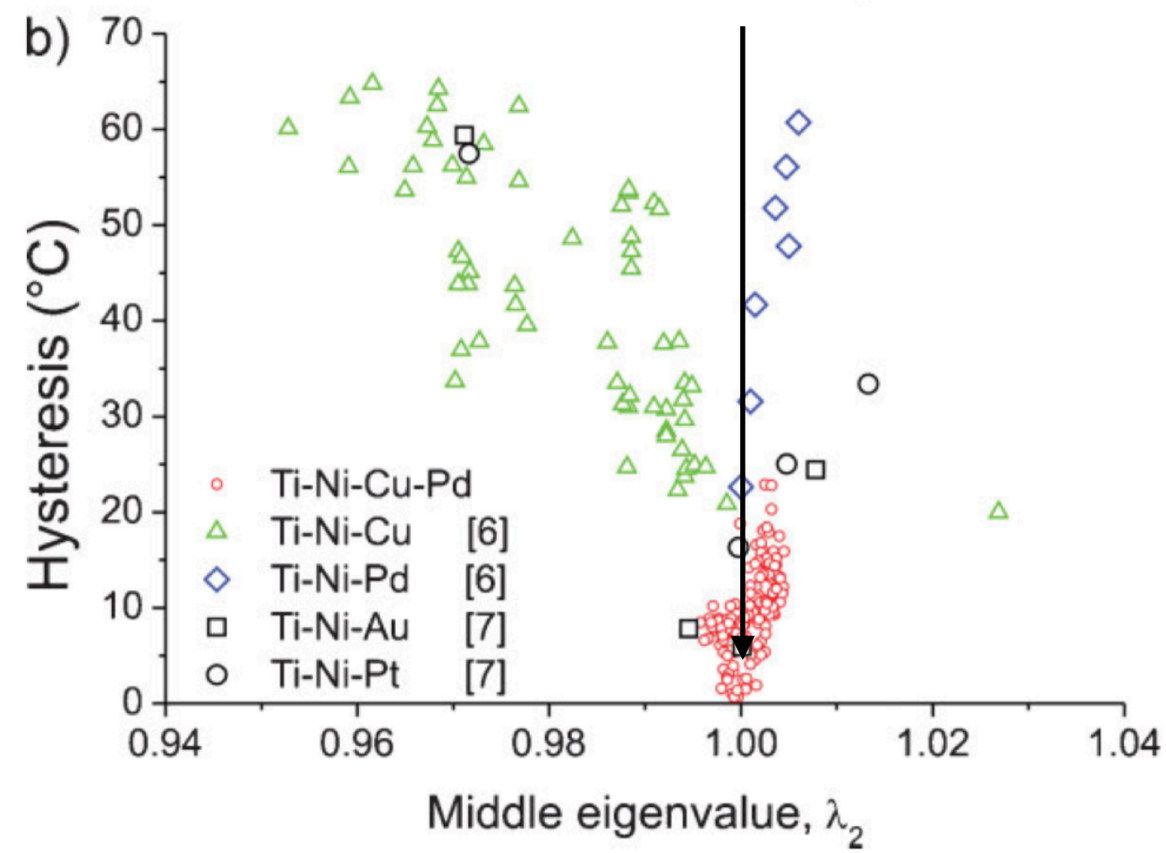

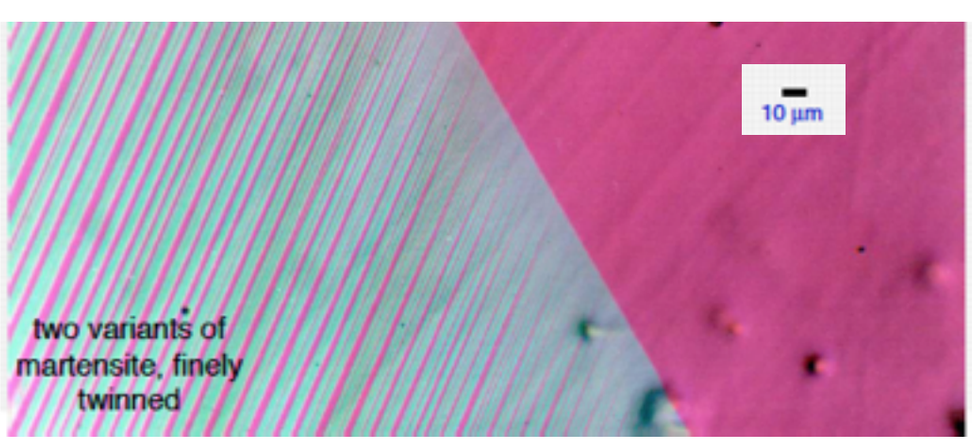

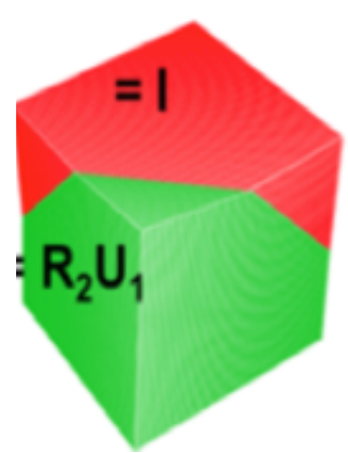

- Unstressed crystallographic planes between phases that remain undistorted during phase transformation "compatible parallelism"
- Confirmed both theoretically and experimentally.

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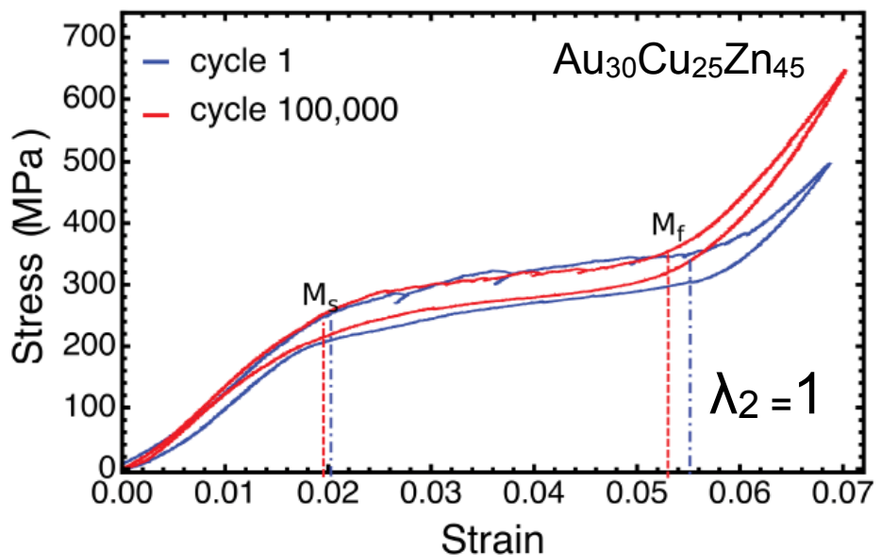
Enabling Scientific Breakthroughs

Examples: Materials Systems



NanoLetters, to appear (2016),
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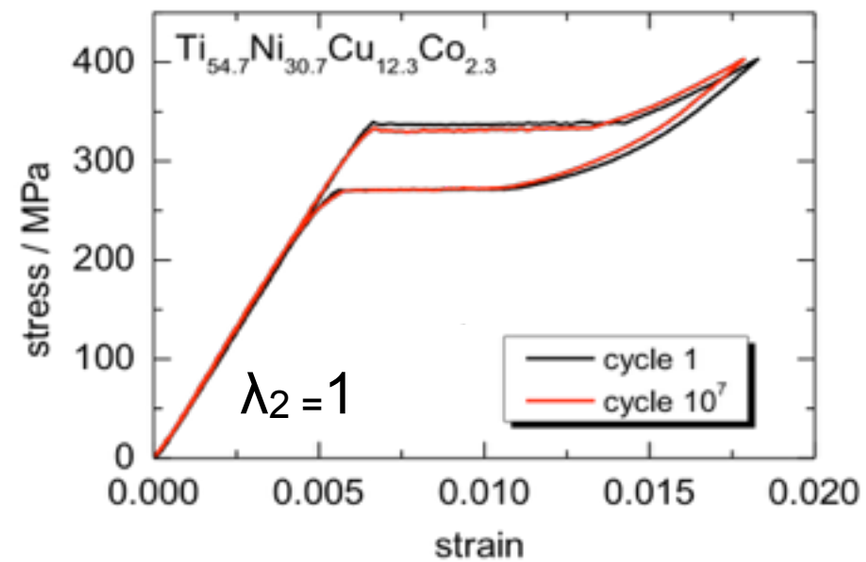

Science, 348, 1004 (2015)

New alloys tuned to satisfy $\lambda_2 = 1$

Cyclic stress induced phase transformation at very demanding conditions

Enabling Scientific Breakthroughs

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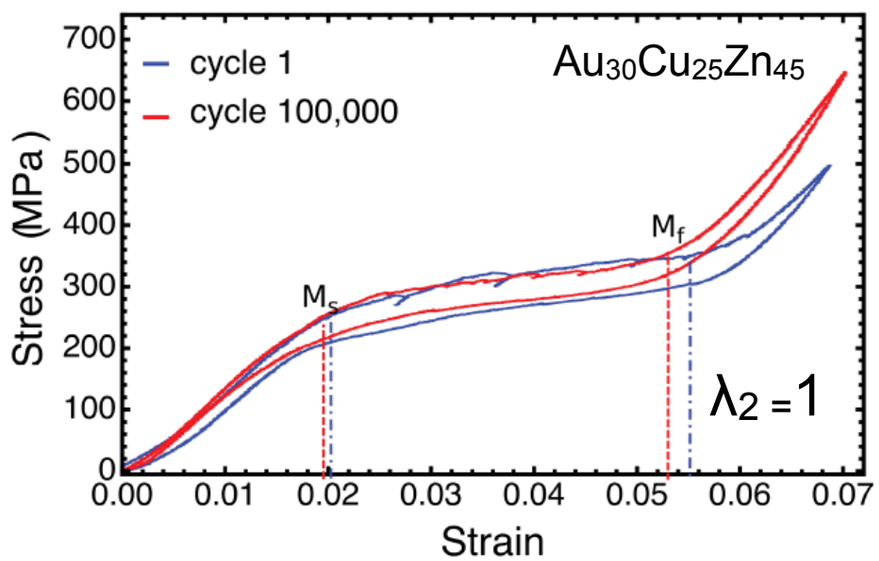

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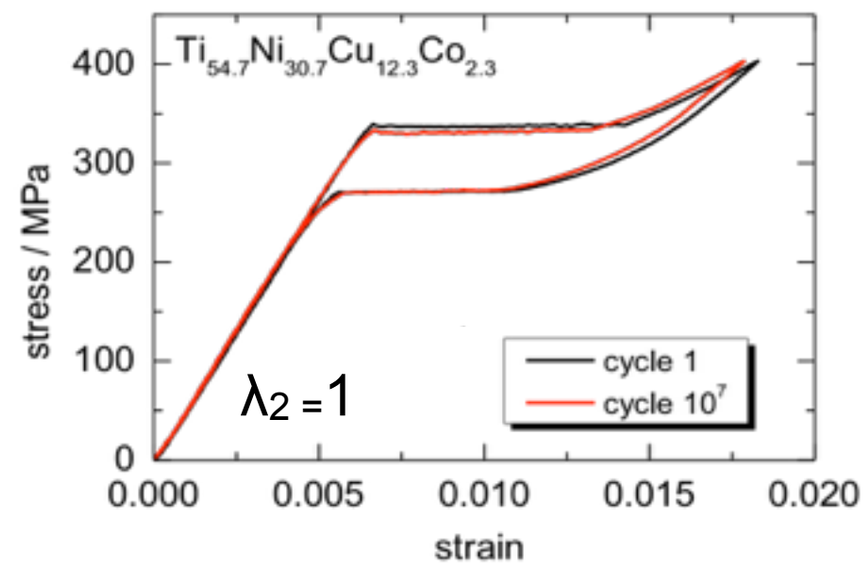

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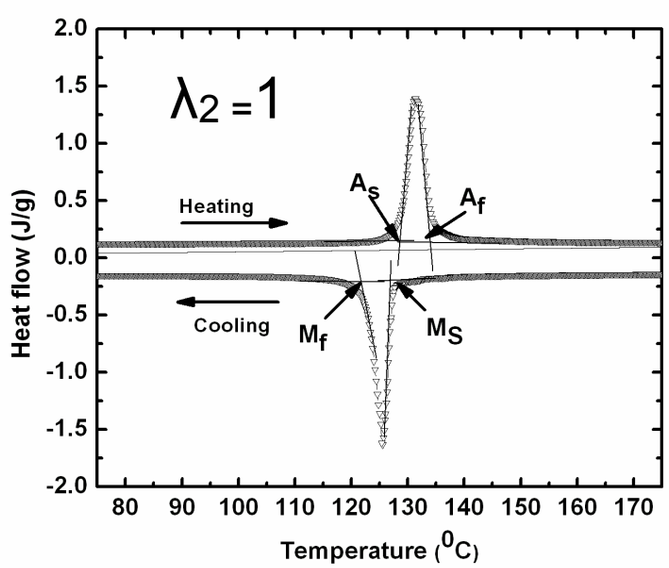
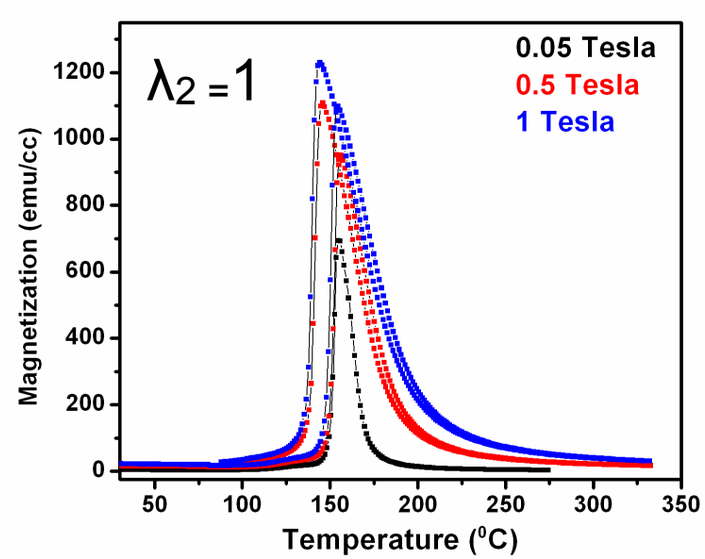
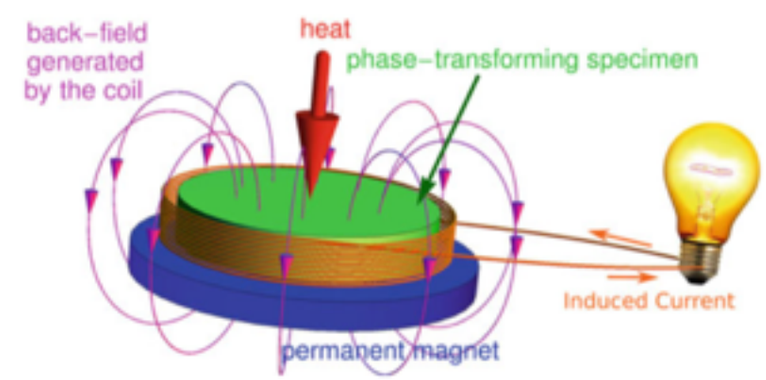
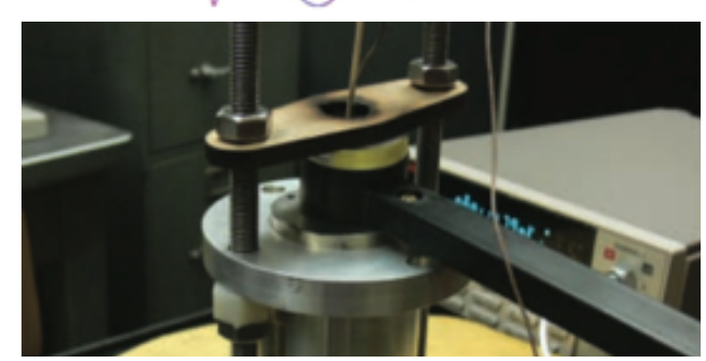
Example: $Ni_{45}Co_5Mn_{40}Sn_{10}$









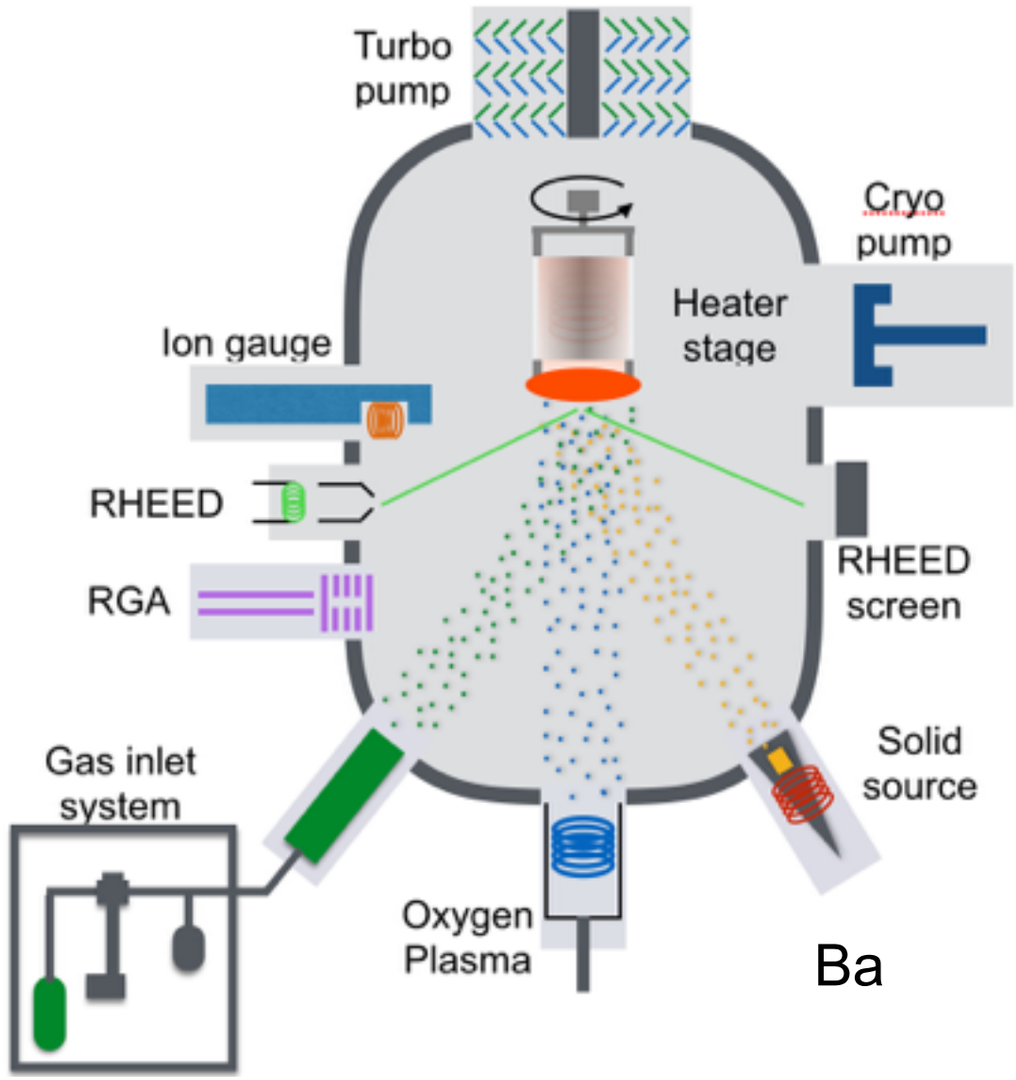
Phys. Rev. B 85 (2012), 134450 Appl. Phys. Lett. 97 (2010), 014101 Phys. Rev. B 91 (2015), 21421 Handbook of Heusler Alloys, ed. A. Hirohata and C. Felser

Our Approach

Confidential..

Innovation in Growth of Ferroelectric Oxides

Combinatorial Hybrid Molecular Beam Epitaxy



Ti tetraisopropoxide (TTIP)

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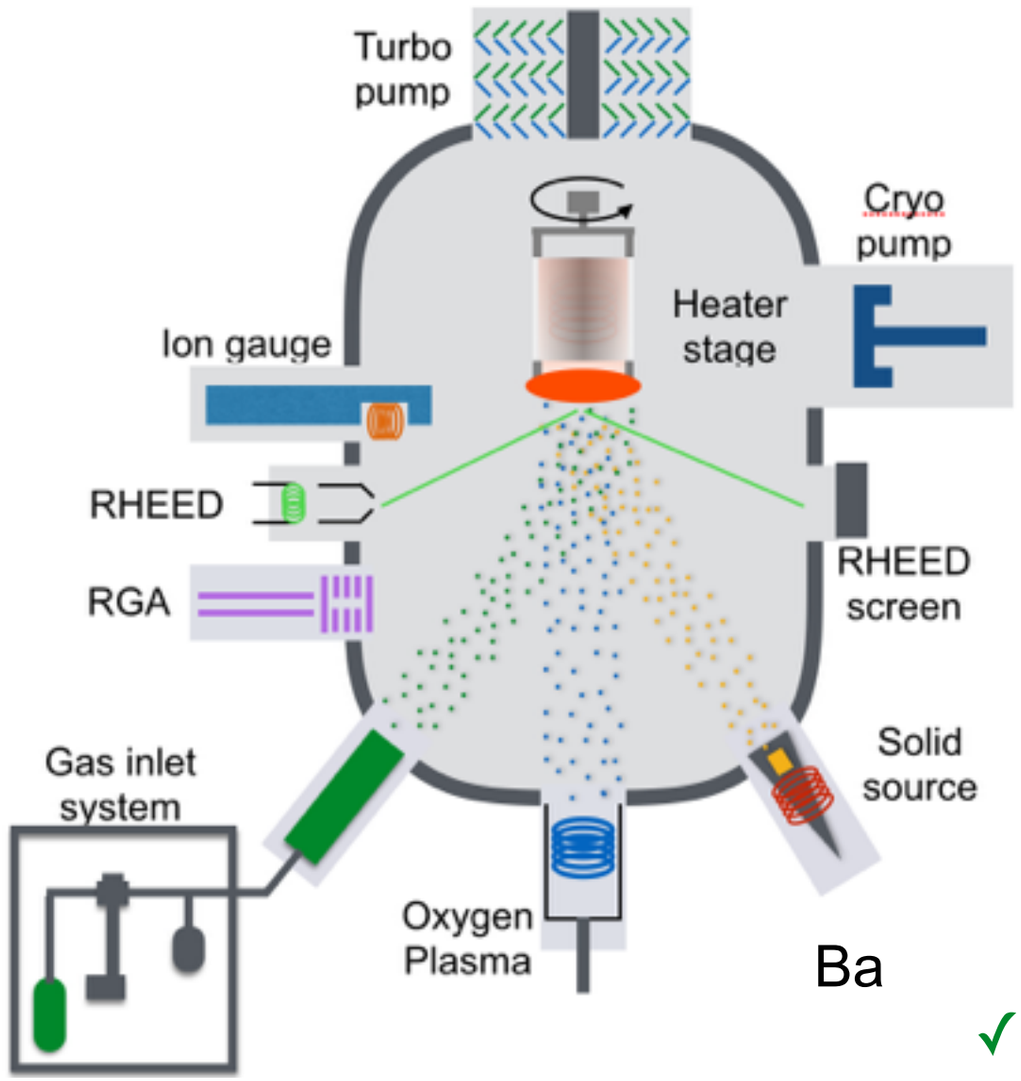

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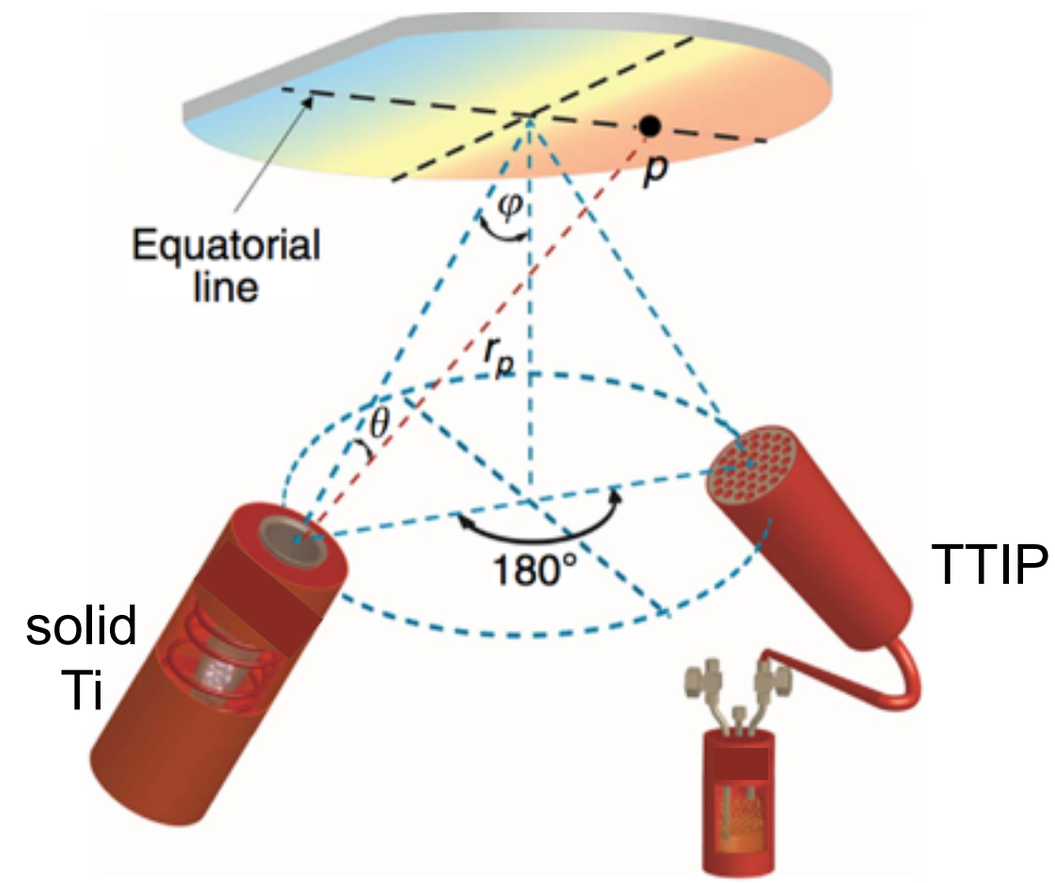

- ✓ Exceptional control over composition
- ✓ Combinatorial synthesis
- ✓ Using in-situ electron diffraction to calibrate composition

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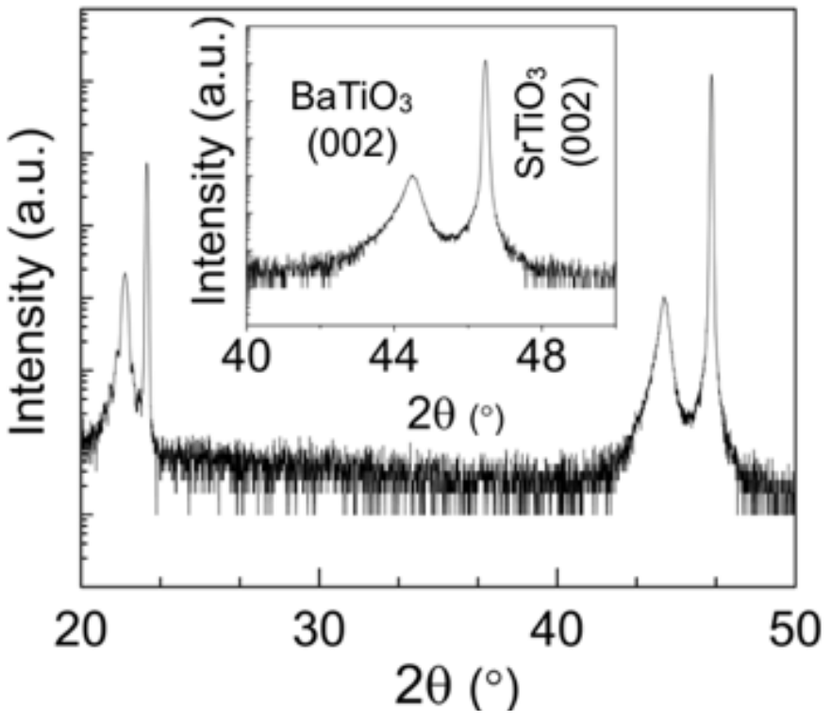

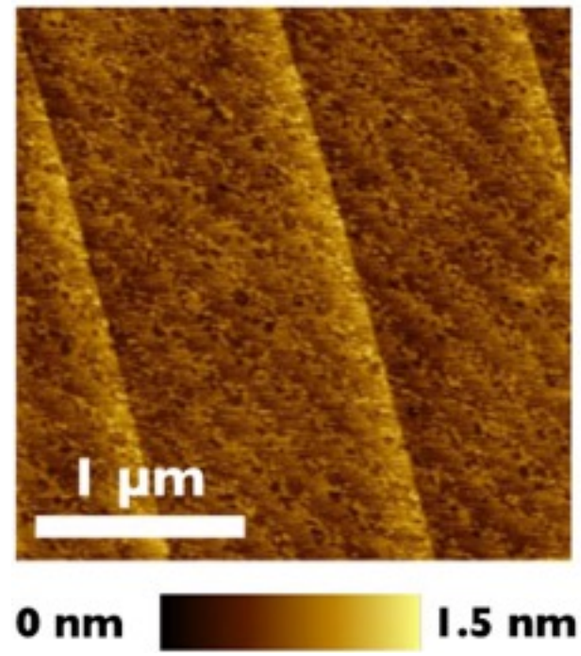

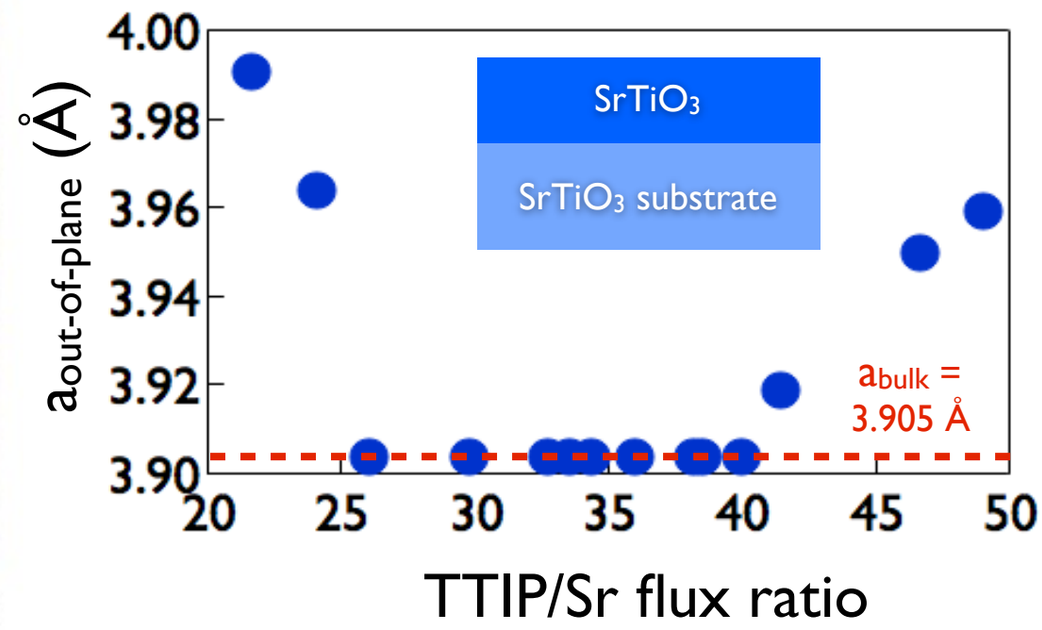

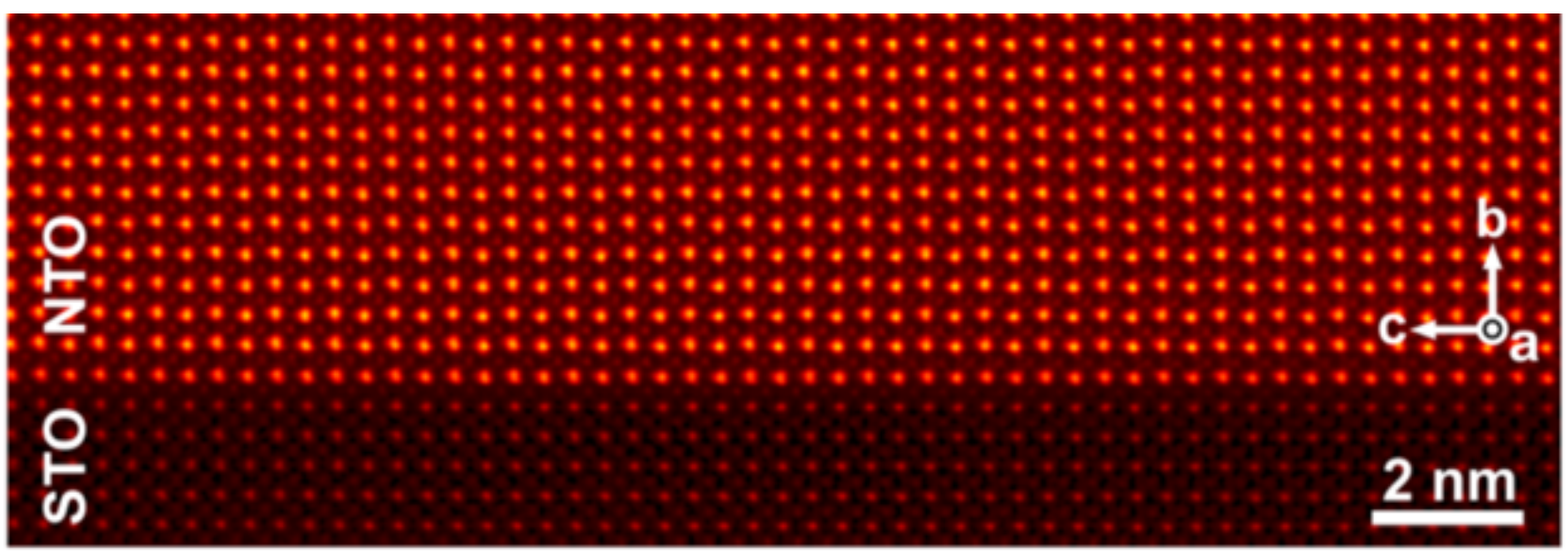

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Phys. Rev. Lett. 117, 106803 (2016).

- ✓ Growth of high quality epitaxial films using hybrid MBE
- ✓ Excellent structural quality and interface control

Thank you

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