



Strain-mediated magnetoelectric and magnetocaloric effects in oxide heterostructures

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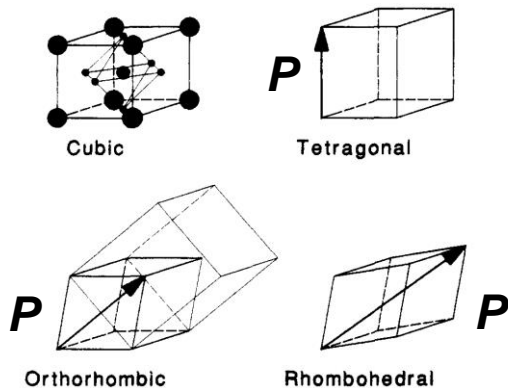
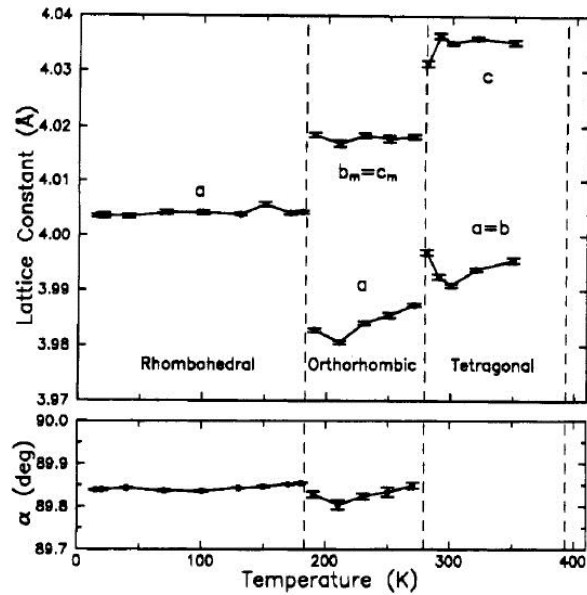
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Ferromagnetic films on BaTiO₃ substrates

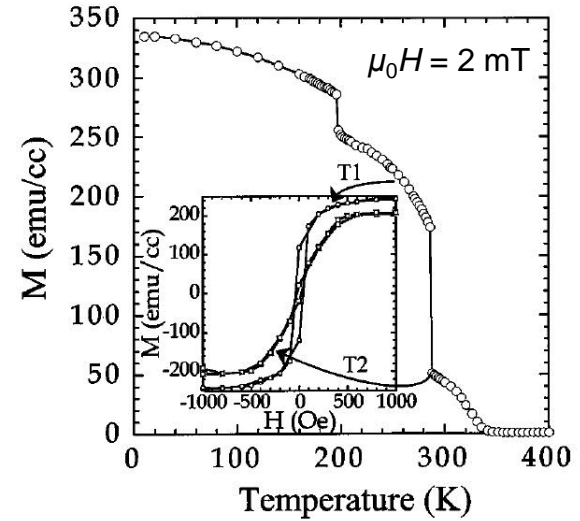
Structural transitions BTO



G. H. Kwei *et al.*, *J. Phys. Chem.* **97**, 2368 (1993)

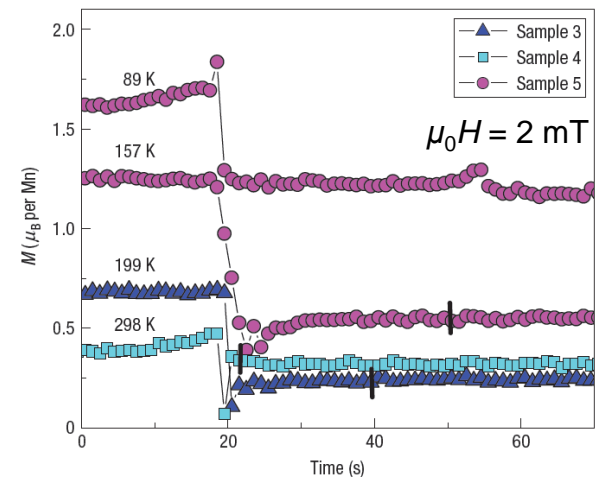
Magnetic changes LSMO/BTO

T-driven



M. K. Lee *et al.* *Appl. Phys. Lett.* **77**, 3547 (2000)

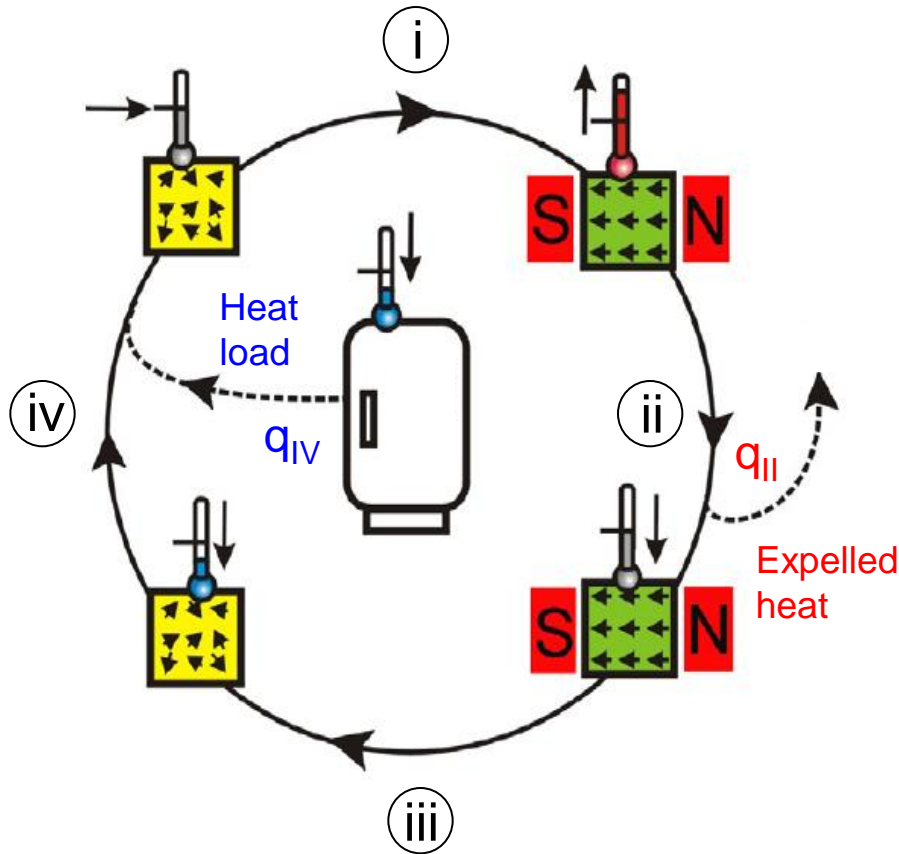
E-driven



W. Eerenstein *et al.* *Nature Materials* **6**, 348 (2007)

Magnetocaloric effect

Coupling between magnetic and thermal properties



MCE magnitudes:

$$\Delta S = \mu_0 \int_0^H \left(\frac{\partial M}{\partial T} \right)_{H'} dH'$$

$$\Delta T = -\frac{T}{C} \Delta S$$

Large at phase transitions

1st order

Giant magnetocaloric materials

Material	T_t (K)	$\Delta S/\mu_0\Delta H$ (J K ⁻¹ kg ⁻¹ T ⁻¹)	Reference
Gd ₅ Si ₂ Ge ₂	276	-3.8	Pecharsky <i>et al.</i> PRL 78 , 4494 (1997)
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MnAs	318	-6.4	Wada <i>et al.</i> APL 79 , 3302 (2001)
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CoMnSi _{0.95} Ge _{0.05}	215	1.8	Sandeman <i>et al.</i> PRB 74 , 224436 (2006)
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LCMO	259	-0.87	Zhang <i>et al.</i> APL 69 , 3596 (1996)

Few materials, suffer hysteresis

LCMO/BTO

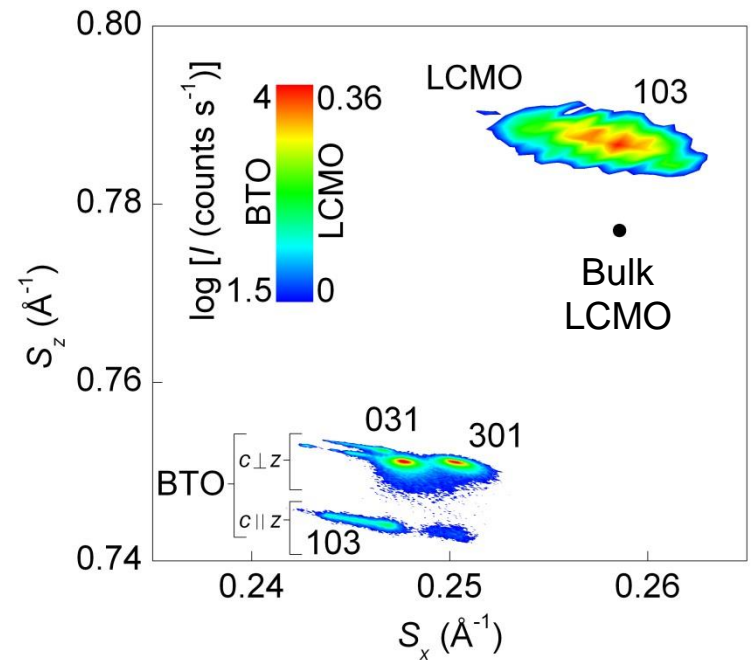
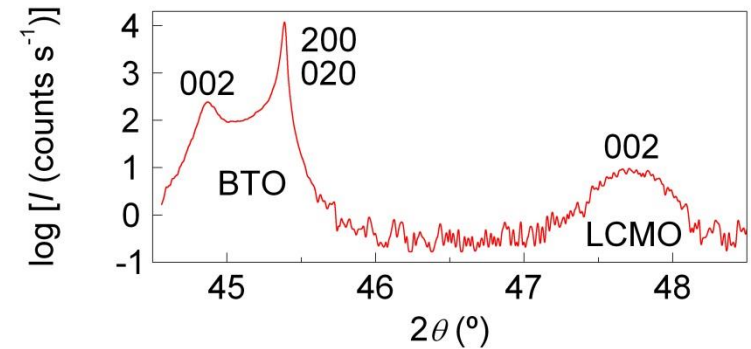
Samples grown by PLD



34 nm $\text{La}_{0.7}\text{Ca}_{0.3}\text{MnO}_3$

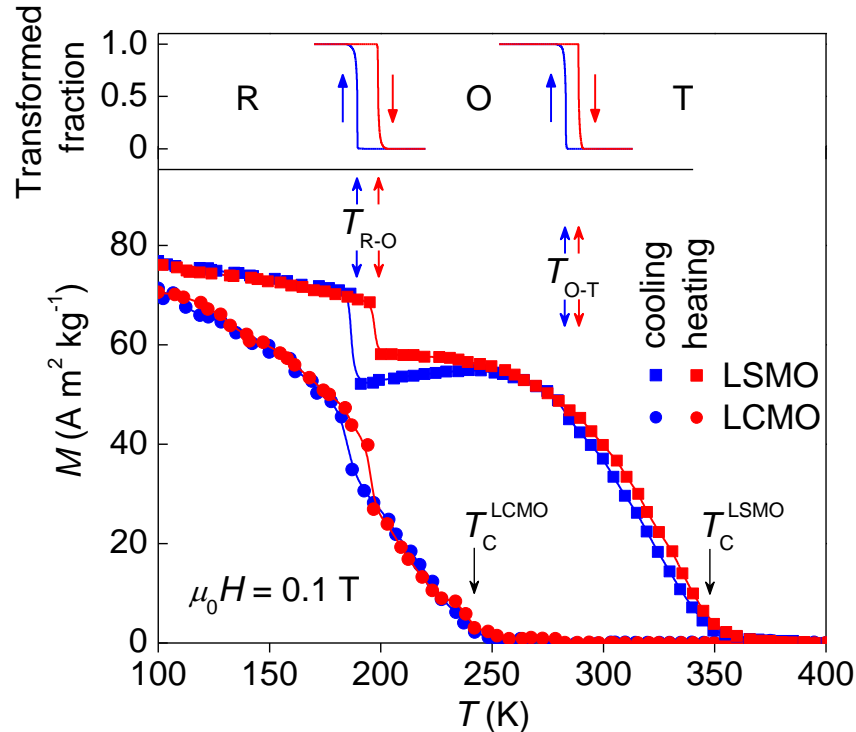
0.5 mm BaTiO_3 (001)

XRD

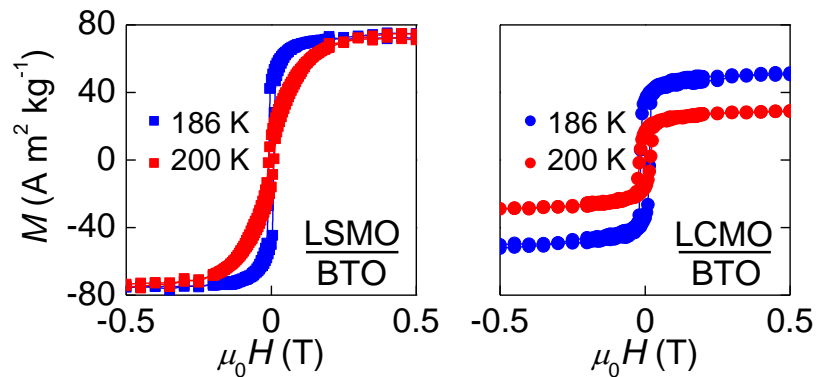


Macroscopic magnetic properties

$M(T)$



$M(H)$

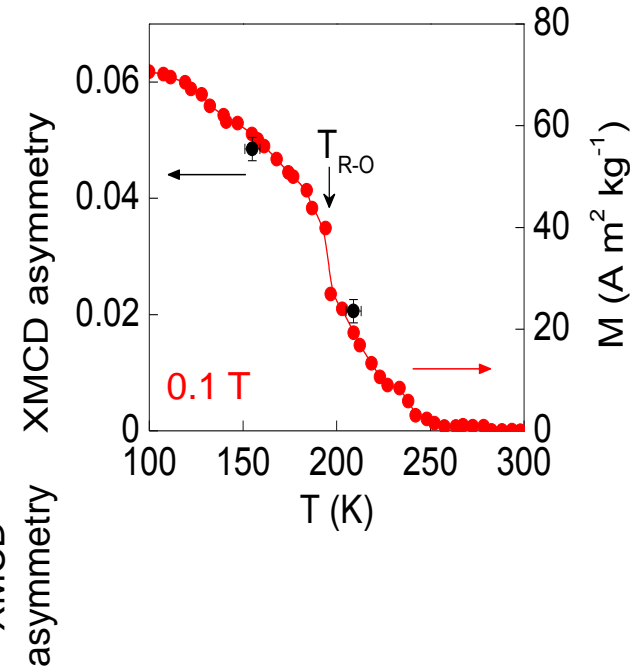
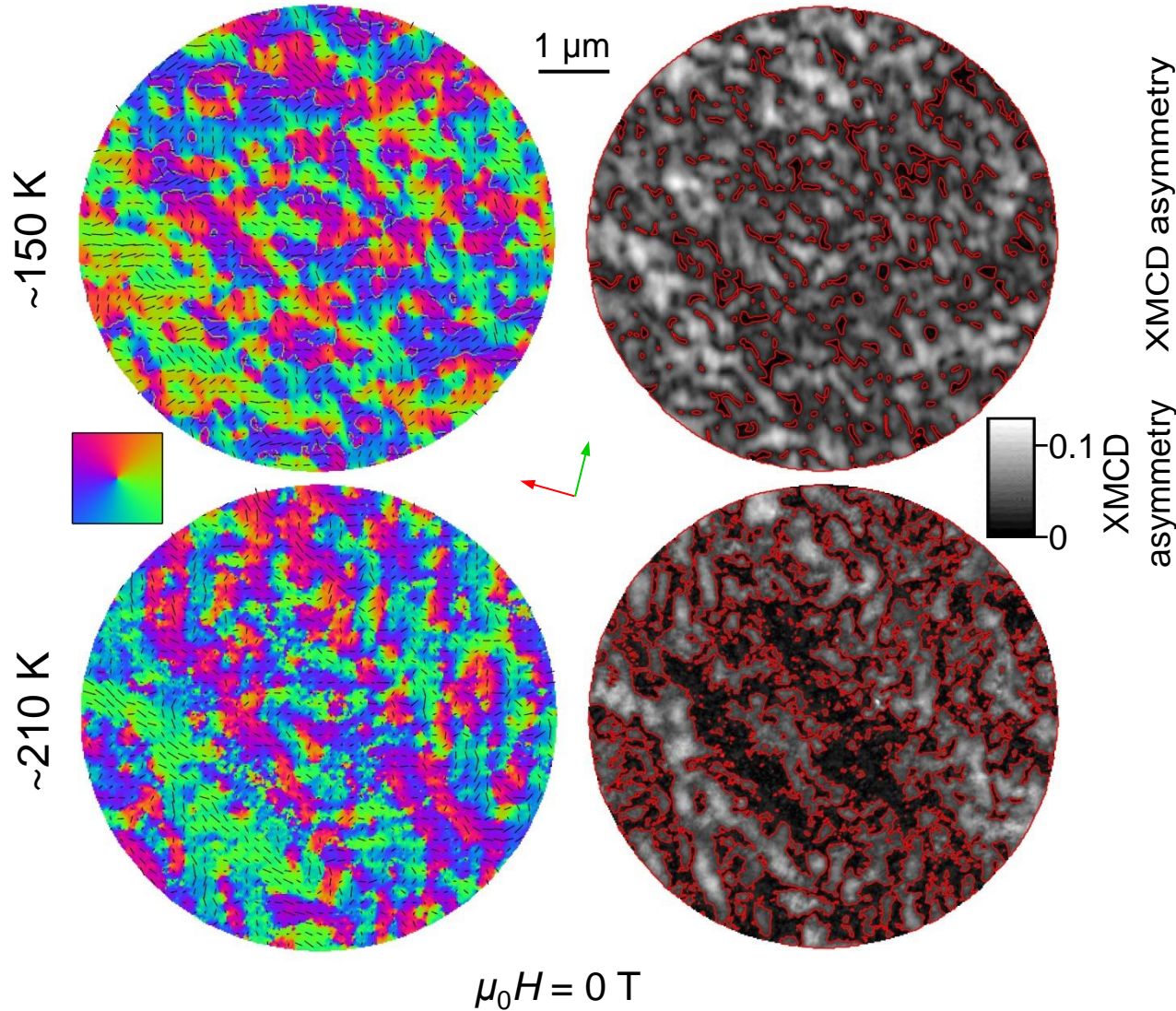


LSMO
Anisotropy change

LCMO
Entropy change

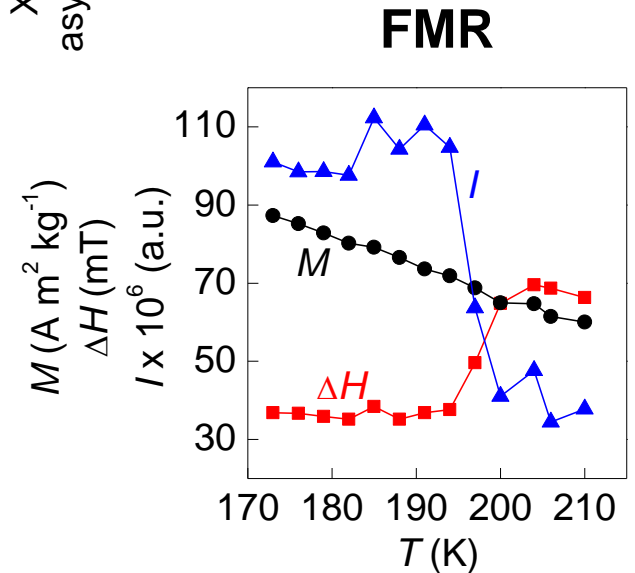
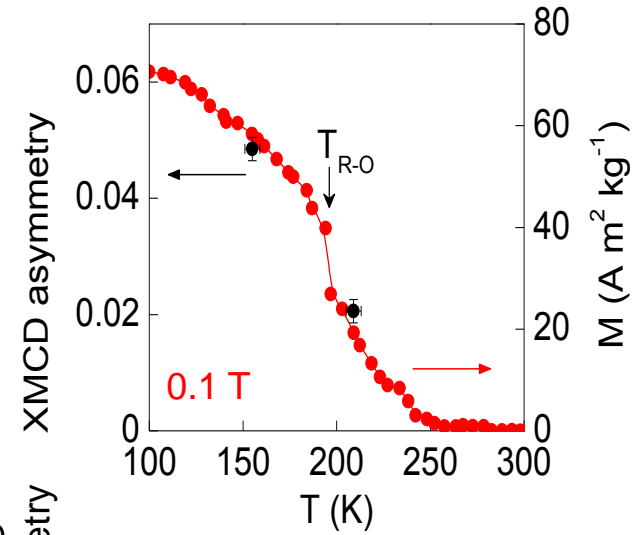
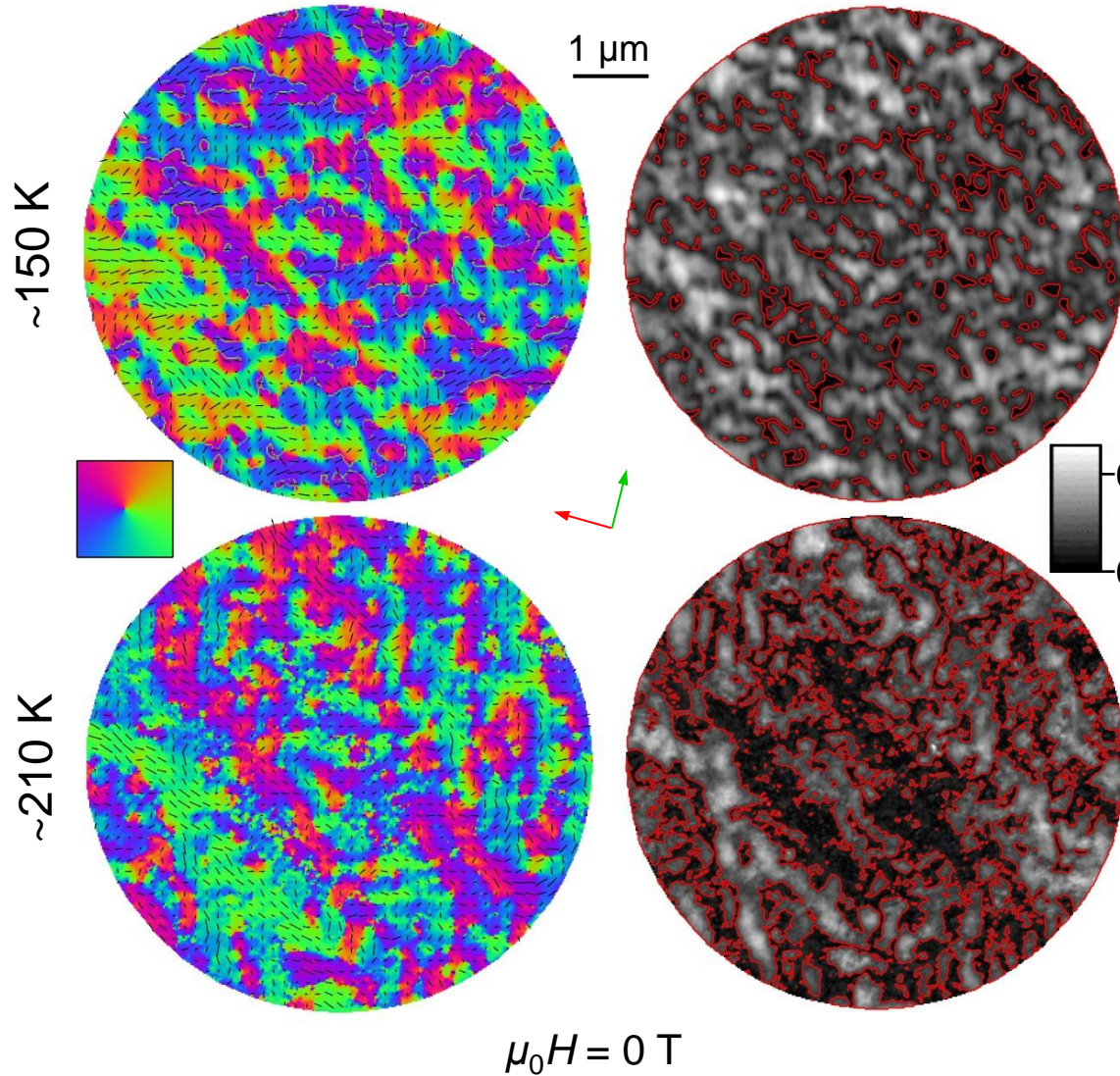
Temperature-Driven Phase Interconversion

LCMO/BTO PEEM-XMCD



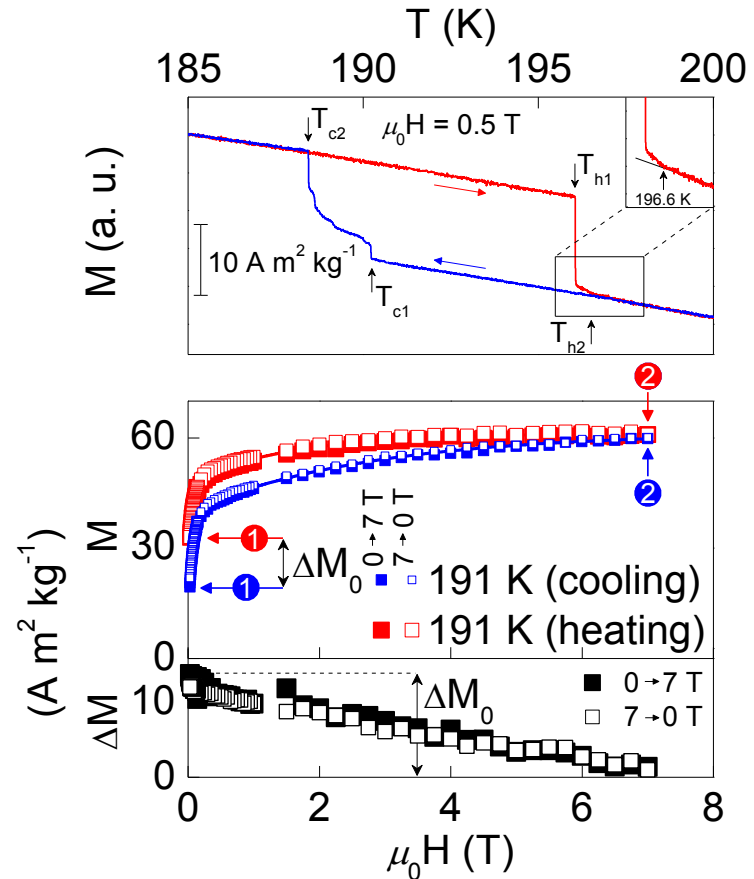
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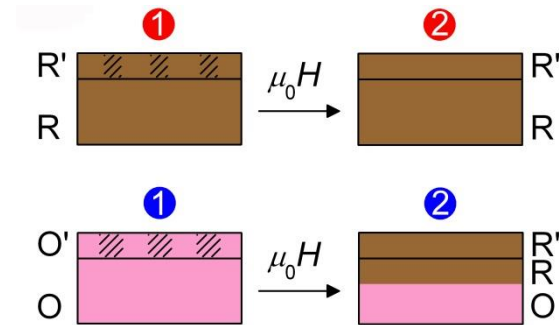
Magnetic-Field-Driven Phase Interconversion

Detail of transition in $M(T)$



Drive transition directly
Reversible

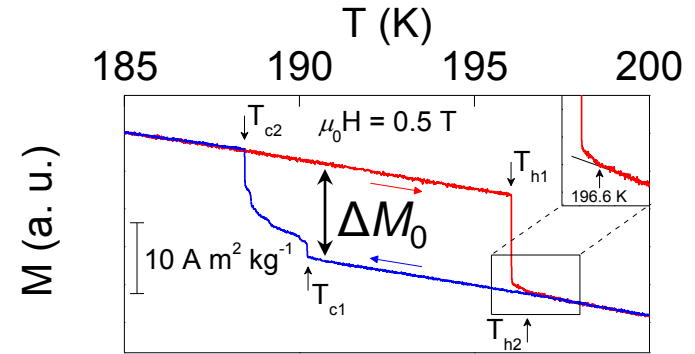
Schematics



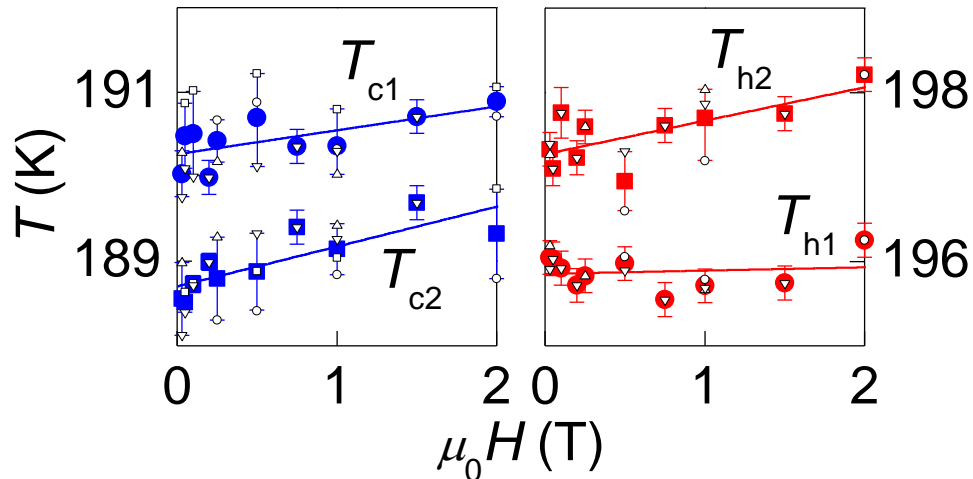
Feedback

Quantifying the MC effect (1)

Detail of transition in $M(T)$

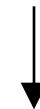


Clausius-Clapeyron:
$$\frac{dT_0}{\mu_0 dH} = -\frac{\Delta M_0}{\Delta S}$$



$$\Delta M_0 \sim 13.5 \text{ A m}^2 \text{ kg}^{-1}$$

$$\frac{dT_0}{\mu_0 dH} \sim 0.4 \text{ K T}^{-1}$$



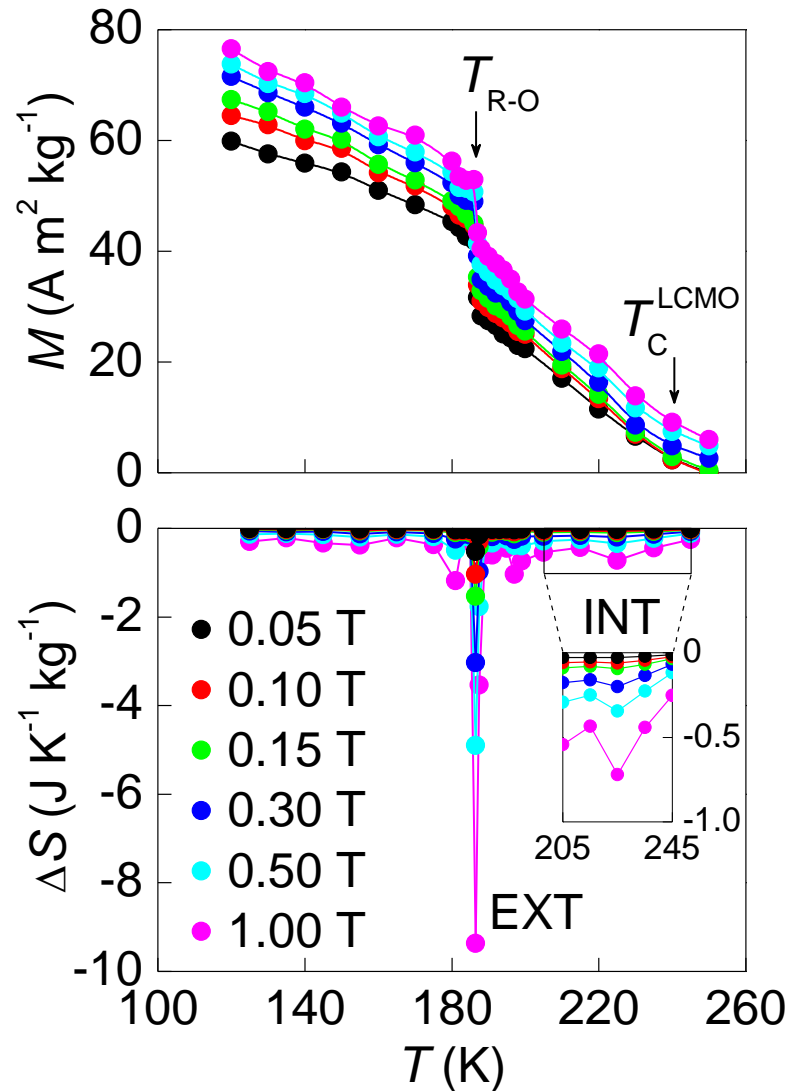
$$\Delta S/\mu_0 \Delta H \sim -9 \text{ J K}^{-1} \text{ kg}^{-1} \text{ T}^{-1}$$

Quantifying the MC effect (2)

$$\Delta S = \mu_0 \int_0^H \left(\frac{\partial M}{\partial T} \right)_{H'} dH'$$

INT $\sim -0.7 \text{ J K}^{-1} \text{ kg}^{-1} \text{ T}^{-1}$

EXT $\sim -9 \text{ J K}^{-1} \text{ kg}^{-1} \text{ T}^{-1}$



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LCMO/BTO	186	-9	Extrinsic

Strain-mediated magnetoelectric and magnetocaloric effects in oxide heterostructures

BTO strain creates extrinsic magnetic transitions

LSMO/BTO: T and E control of magnetic anisotropy
sharp and persistent ME effects

LCMO/BTO: T and H control of phase interconversion
giant and reversible MC effects

Other geometries: nanocomposites, core-shell particles

(68 nm-thick bilayer $\Delta S/\mu_0\Delta H \sim -4.7 \text{ J K}^{-1} \text{ kg}^{-1} \text{ T}^{-1}$)

$$\Delta S^{\text{BTO}}_{\text{O} \rightarrow \text{R}} \sim -1.6 \text{ J K}^{-1} \text{ kg}^{-1}$$