Strain-induced anomalous magnetoresistance effect in ultrathin manganite films and nanostructures

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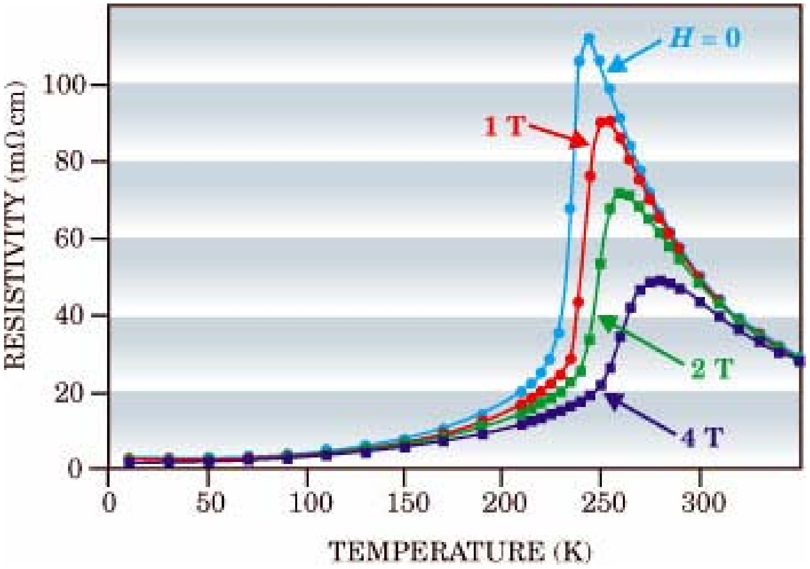
Outline

- **Introduction**
  - Basic electronic structure and properties of manganites
- **Strained ultrathin films and nanostructures**
- **Anomalous low field magnetoresistance**
  - Results
  - Discussion
- **Anomalous anisotropic magnetoresistance**
  - Results
  - Discussion

Introduction

Manganites: known for the colossal magnetoresistance effect (CMR). (Chabara *et al*., APL **63**, 1990 (1993); Helmolt *et al*., PRL **71**, 2331 (1993); S. Jin et al., Science 1994)

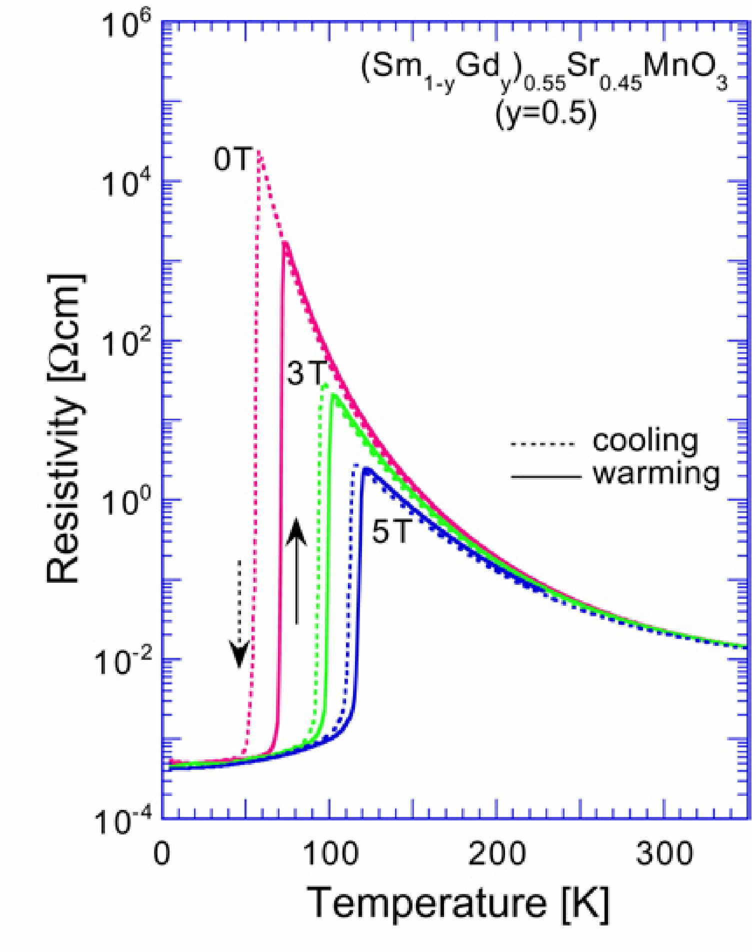
(La,Ca)MnO_3



- Metal-insulator transition: high T-insulator; low T-metal
- CMR occurs near ferromagnetic transition T_c as well as insulator to metal transition
- CMR occurs in high magnetic fields

Broad applications of GMR effect

Reason for CMR

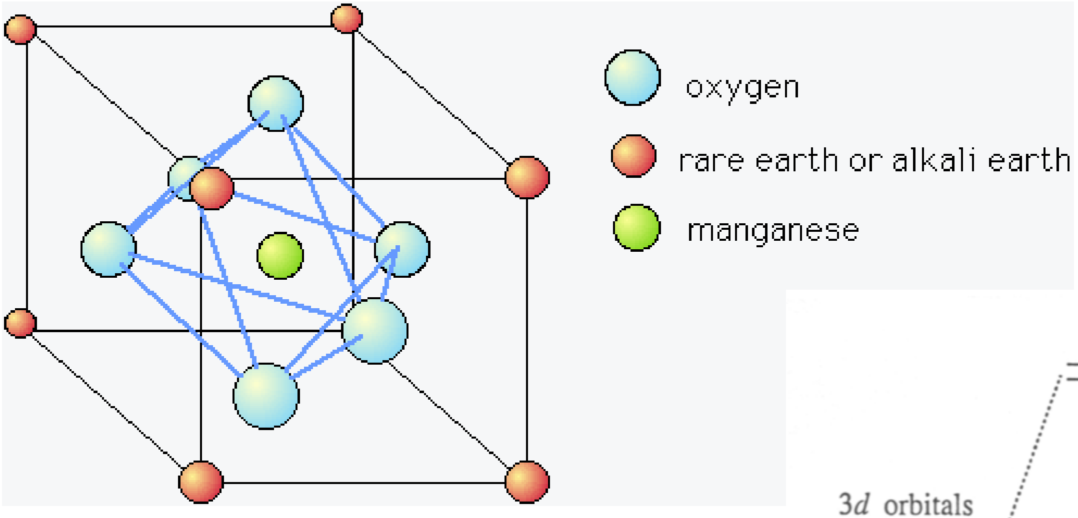


Y. Tokura

— Metal-insulator transition temperature is shifted by magnetic fields

Crystal and electronic structure

$La_{1-x}Ca_xMnO_3$

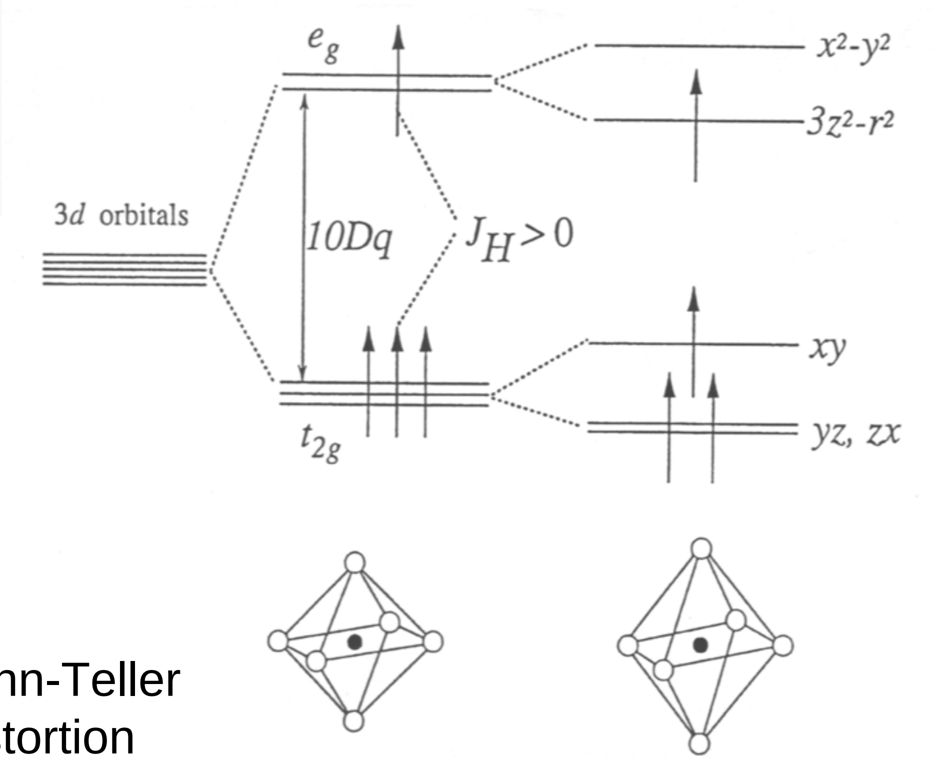


Undoped $LaMnO_3$

Mn^{3+} : has 4 d-electrons

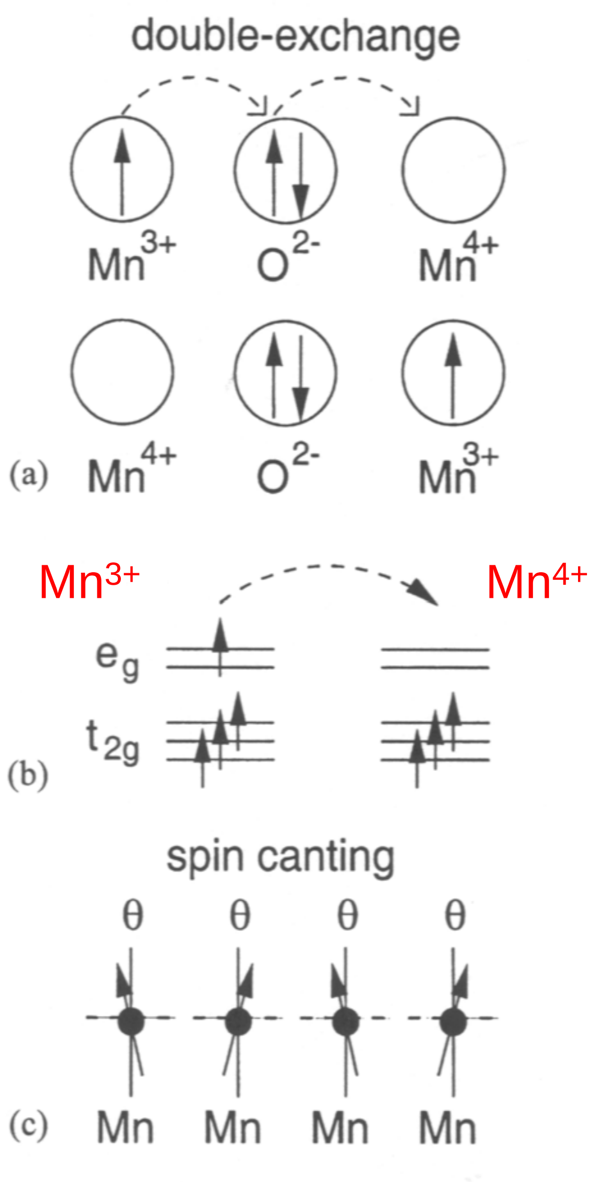
Hund's rule: spin alignment

Mn^{3+}- Mn^{3+}:
superexchange, AF



Jahn-Teller
distortion

Doping and double exchange



$La_{1-x}Ca_xMnO_3$

Doping creates Mn^{3+}/Mn^{4+} mixture

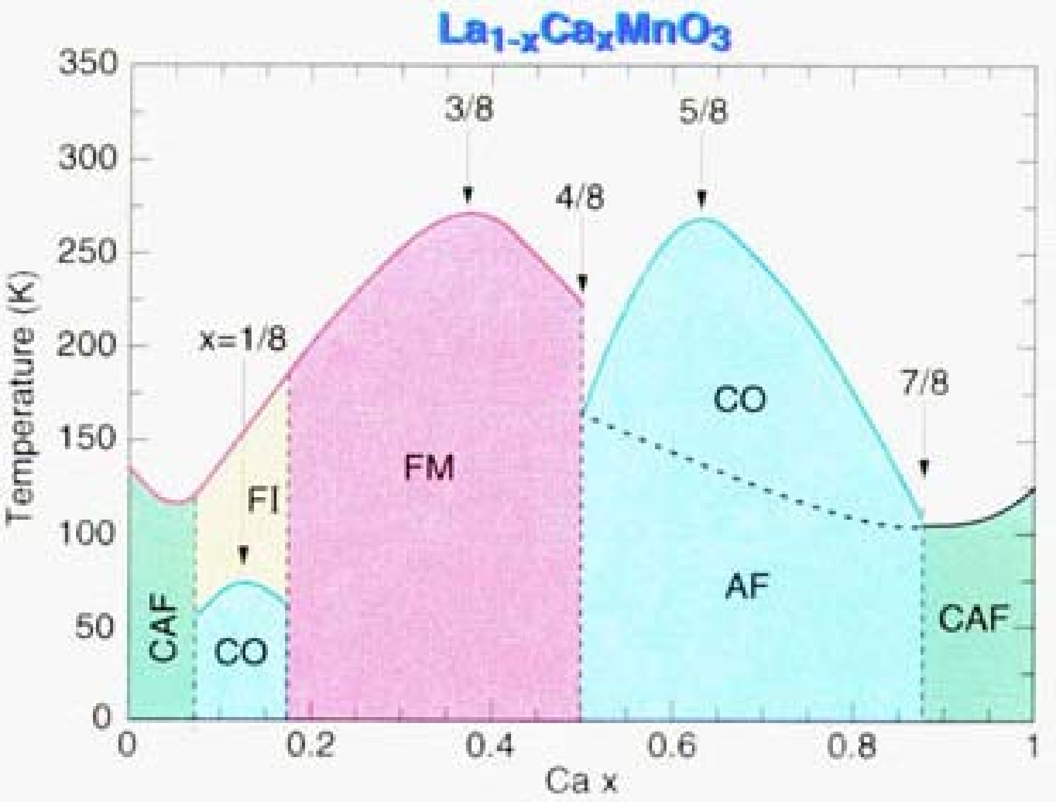
→ Double exchange interaction

charge transfer results in FM

- undoped, superexchange, AF insulator
- doped to certain level, double exchange dominates, FM metal

Effective Hopping $t \sim \cos(\theta/2)$

Phase diagram



S. Choeng, Rutgers

AF: antiferromagnetic (more than one form)

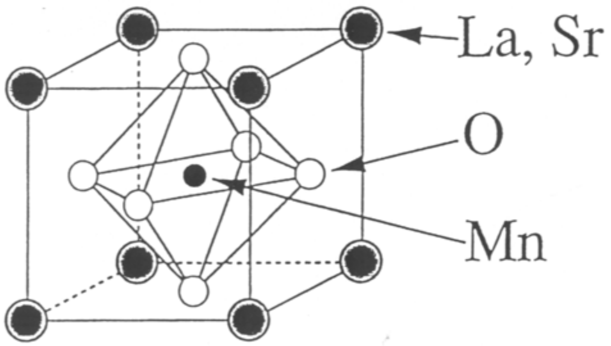
CAF: canted AF

FI: ferromagnetic insulator

FM: ferromagnetic metal

CO: charge ordering phase

Doping and electronic band structure



Two key parameters in the band structure (single electron band):

Band filling and band width

Doping element Sr, Ca, Ba, Pb…

⇒ carrier concentration

Doping elements La, Pr, Nd, Sm… ⇒ band width

Ionic radii of the dopant (tolerance factor)

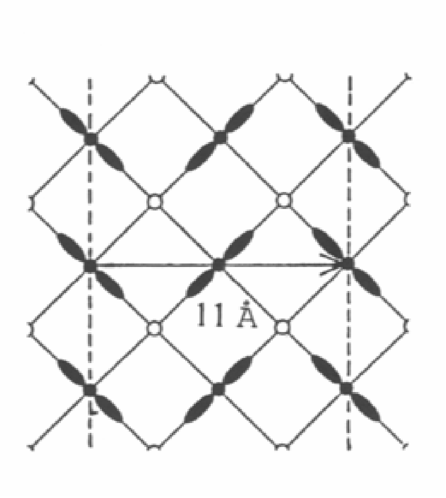
⇒lattice distortion from cubic and bond angle

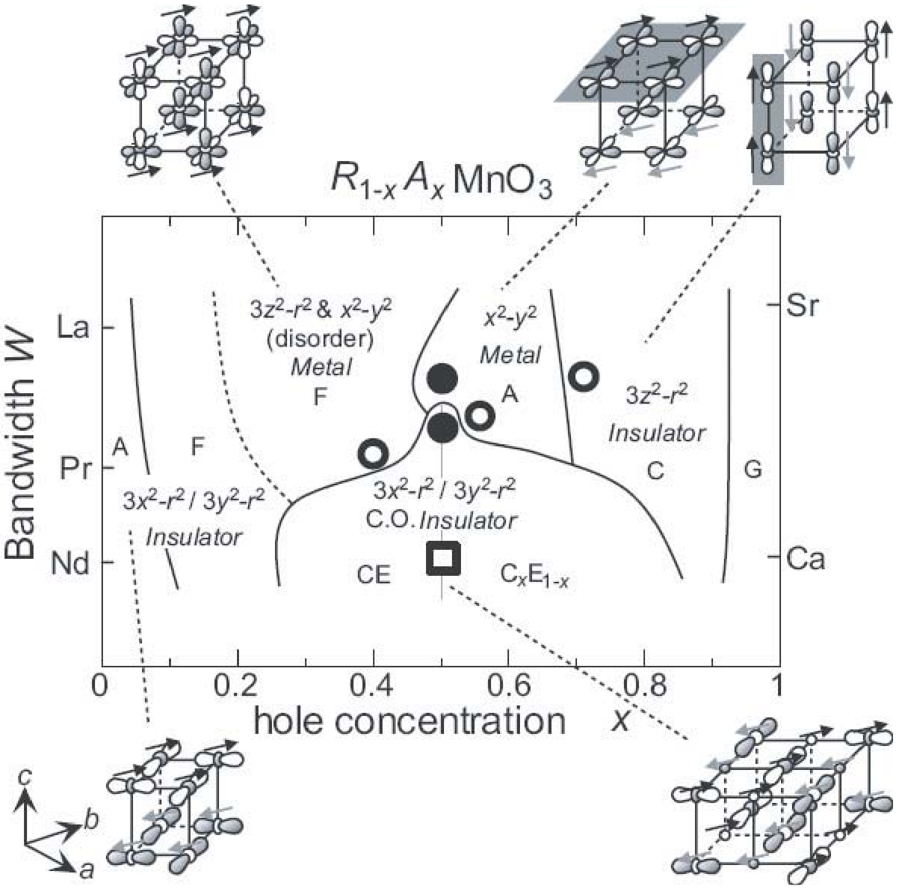
⇒ electronic band structure

Charge and Orbital ordering

- Collective Jahn-Teller effect
- Spin order
- Strong electron correlation: charge order
- Intersite exchange between e_g orbitals

X=1/2





Y. Tokura

Competing interactions

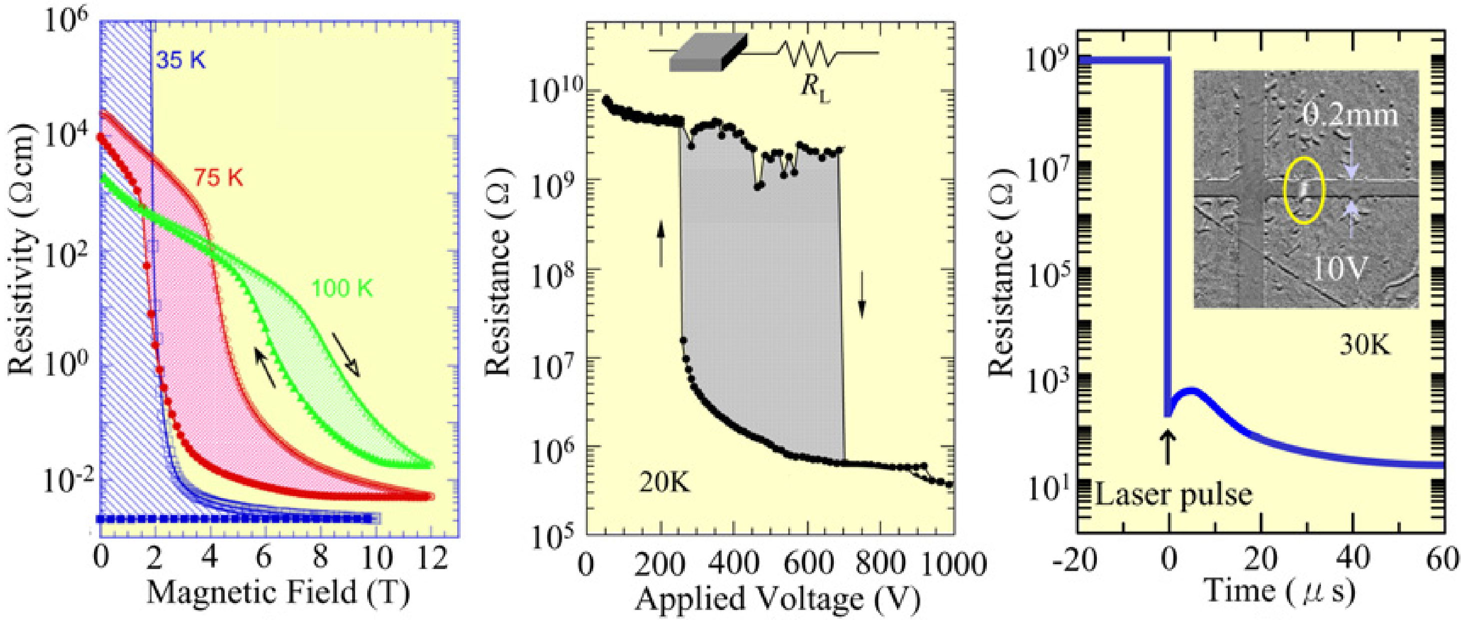
- superexchange, AF
- double exchange (superexchange), FM
- electron-electron interaction, charge order
- Jahn-Teller and intersite orbital interaction
- electron-lattice (mainly through Jahn-Teller phonon)

Lattice, spin, and charge degree of freedom are all strongly coupled.

Or one view: multicritical feature.

Strong coupling of lattice, spin, and charge

$Pr_{0.7}Ca_{0.3}MnO_3$



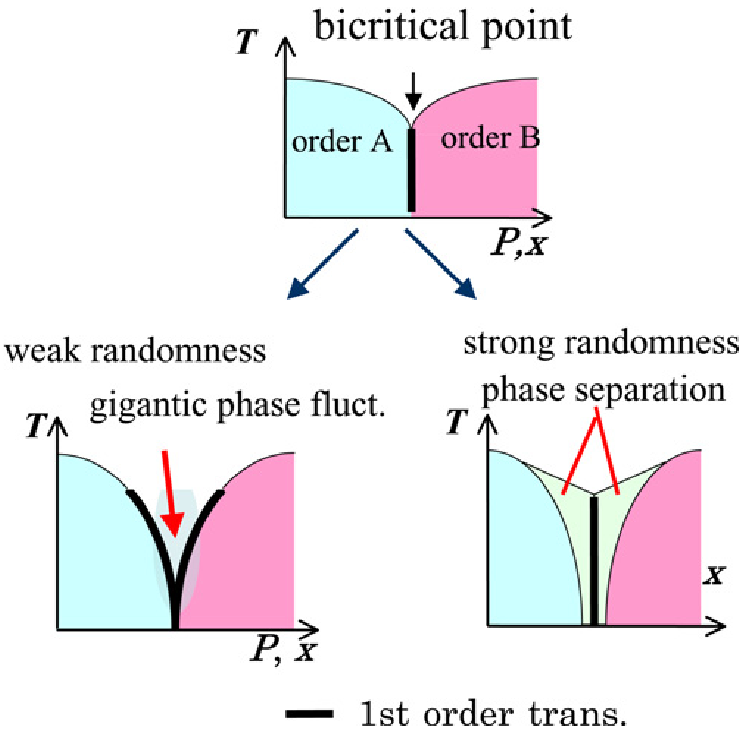
(a) (b) (c)

Long range and local ordering: phase separation scenario

- Doping of different elements on A site causes random distribution of ion of different radii: a form of disorder
- Complete ordered distribution of dopant: phase fluctuation

Result:

Electronic phase separation.



Our work

Introducing lattice distortion

Sample Structures

Sample: $Pr_{2/3}Sr_{1/3}MnO_3$ (LCMO, LSMO) film d ~50 - 150 Å

Lattice parameters: ~ 3.856 Å

Substrates:

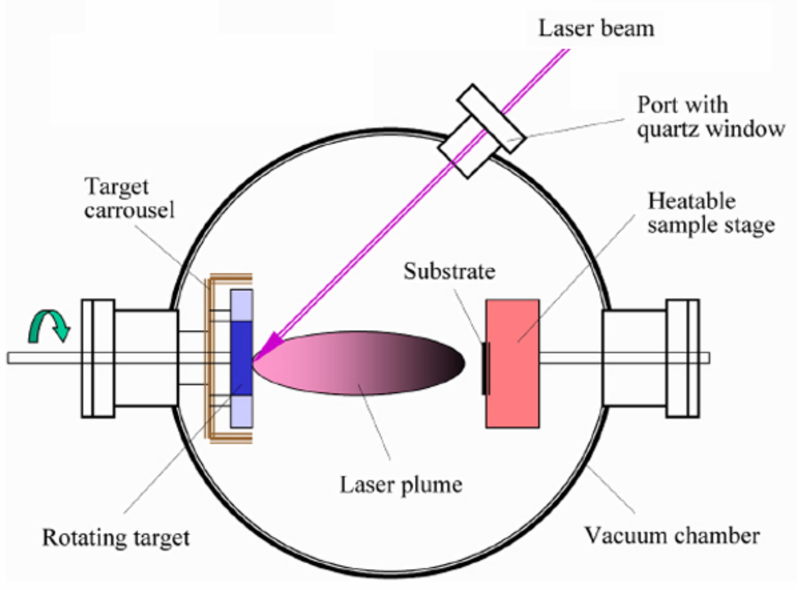
- $SrTiO_3$ (STO) (100), a=3.90 Å
- $NdGaO_3$ (NGO) (110), a~3.85 Å, b~3.86 Å
- $LaAlO_3$ (LAO) (100), a=3.79 Å

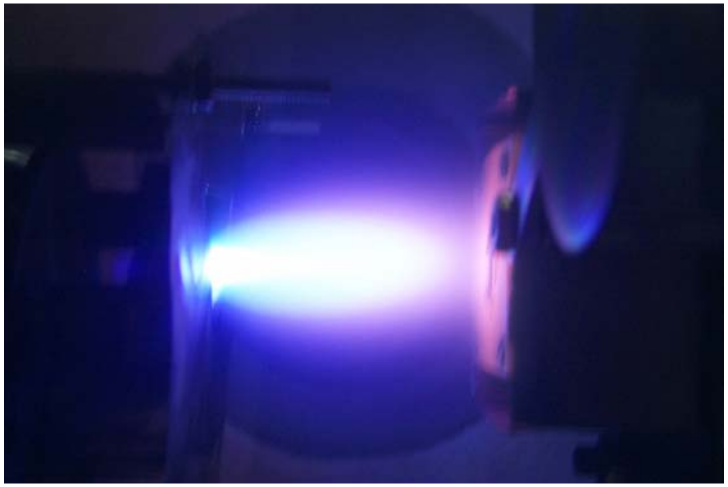
-2.0% <-0.3% 1.0%

Mismatch

Film Preparation

- ***Method:*** pulsed laser deposition (PLD), max E ~1J/pulse, 20ns



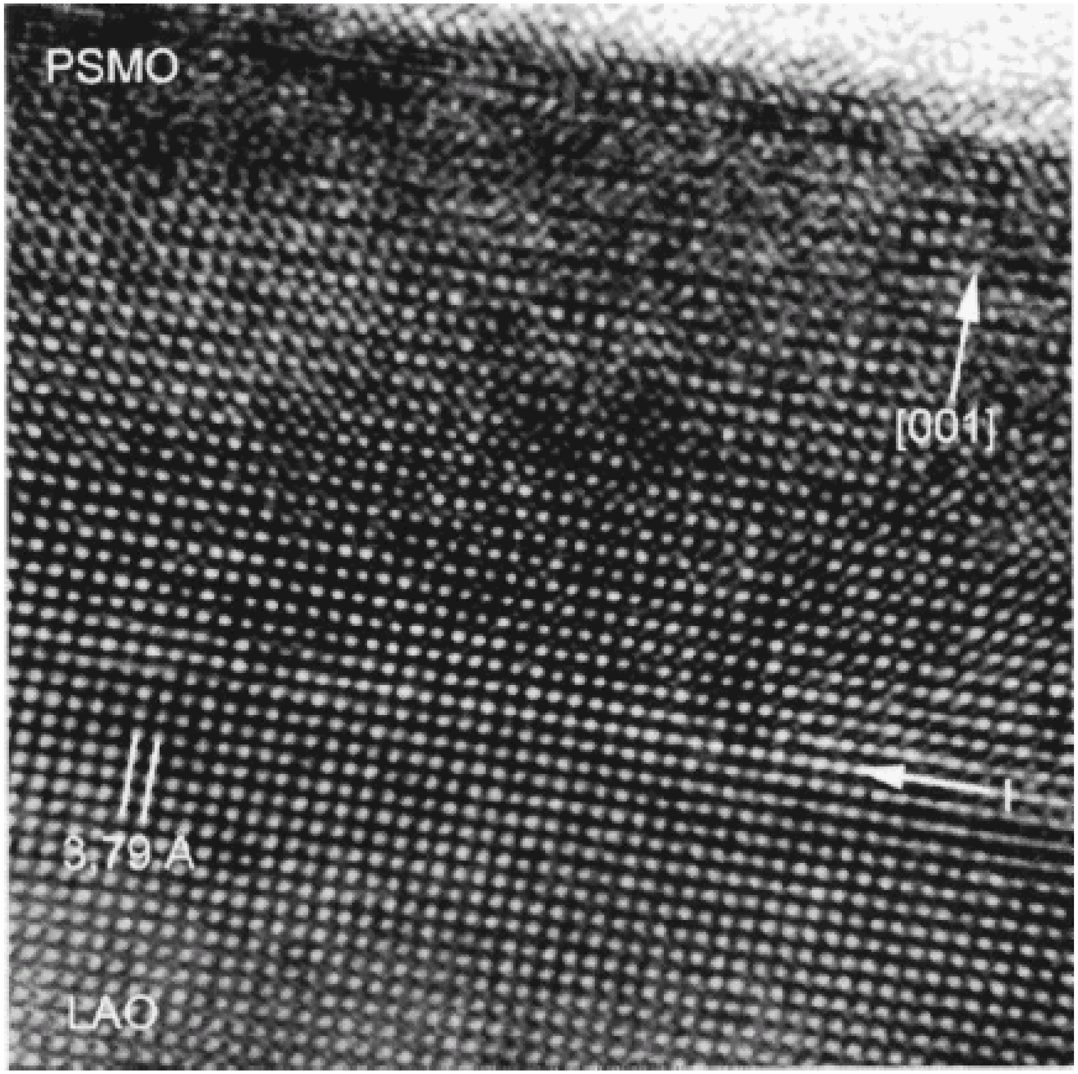


Structures

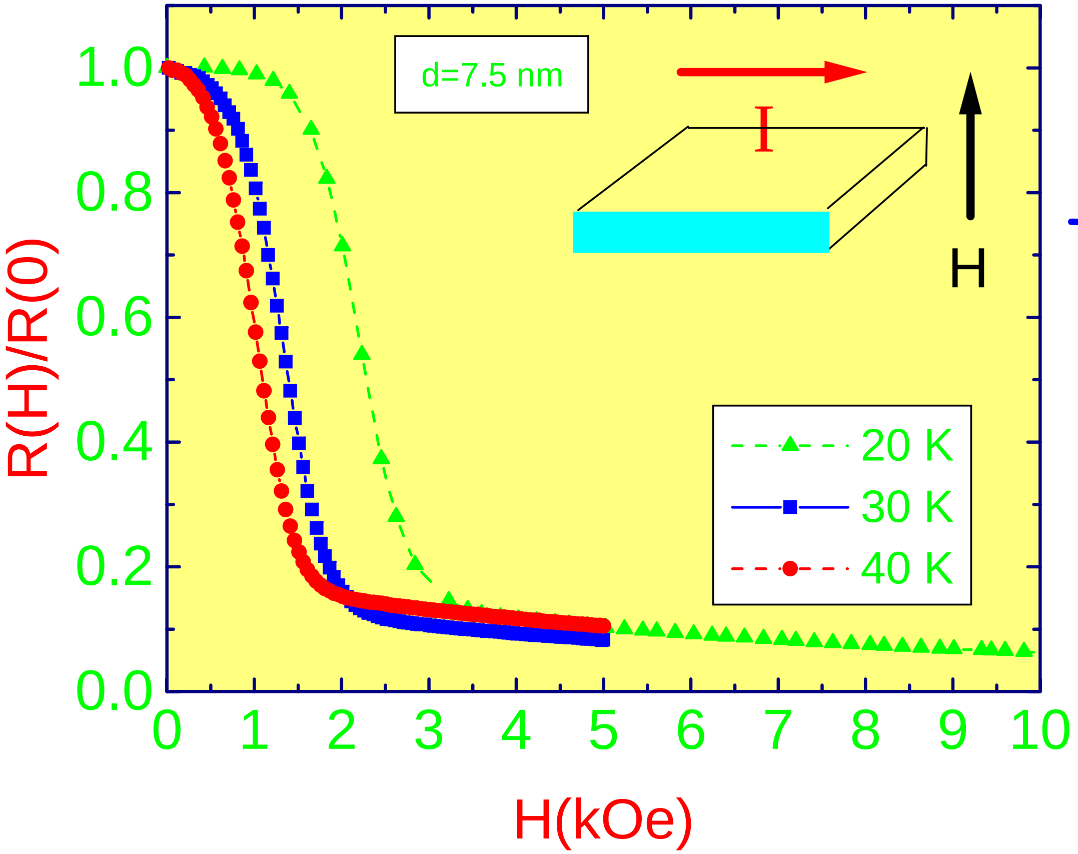
Thin films are coherently strained up to ~ 40 nm on $SrTiO_3$ substrate.

And up to ~ 150 nm on LAO substrate.

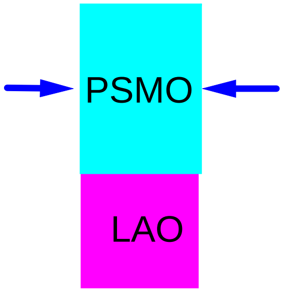
Cross section view



Low-field MR as a function of field



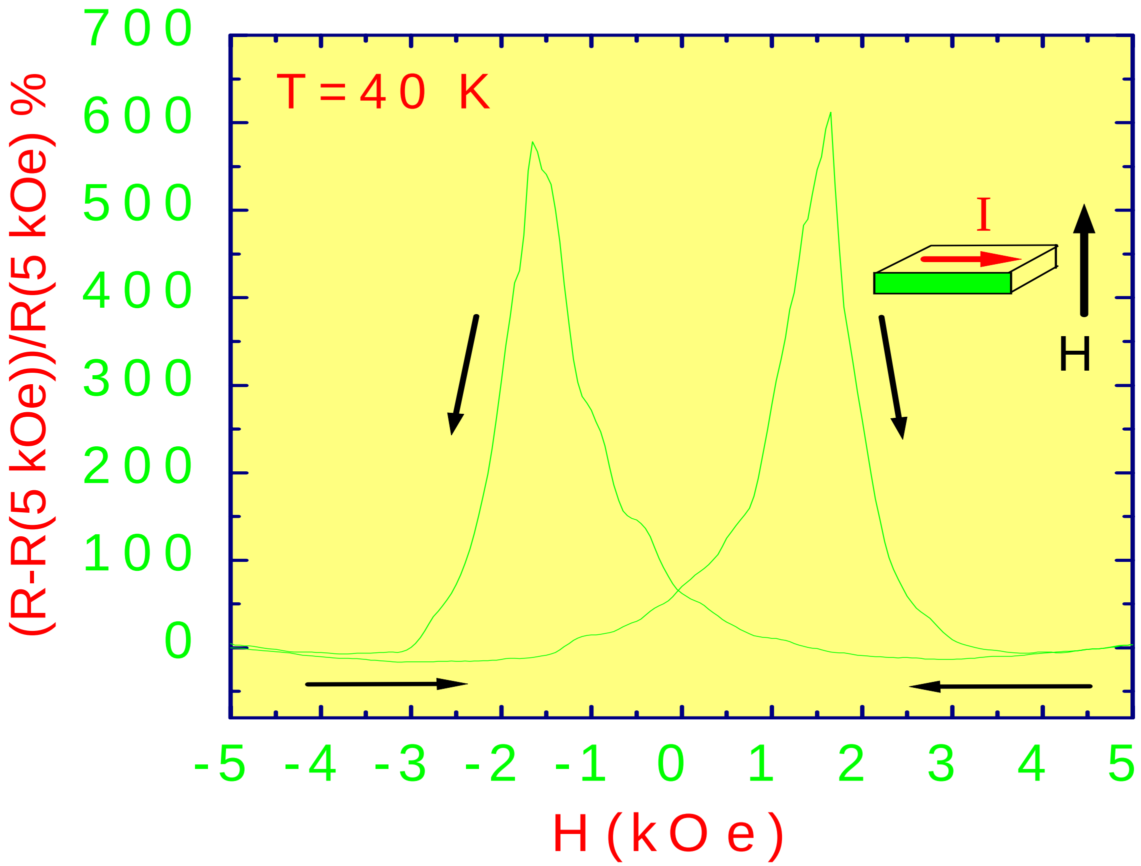
Compressive Strain



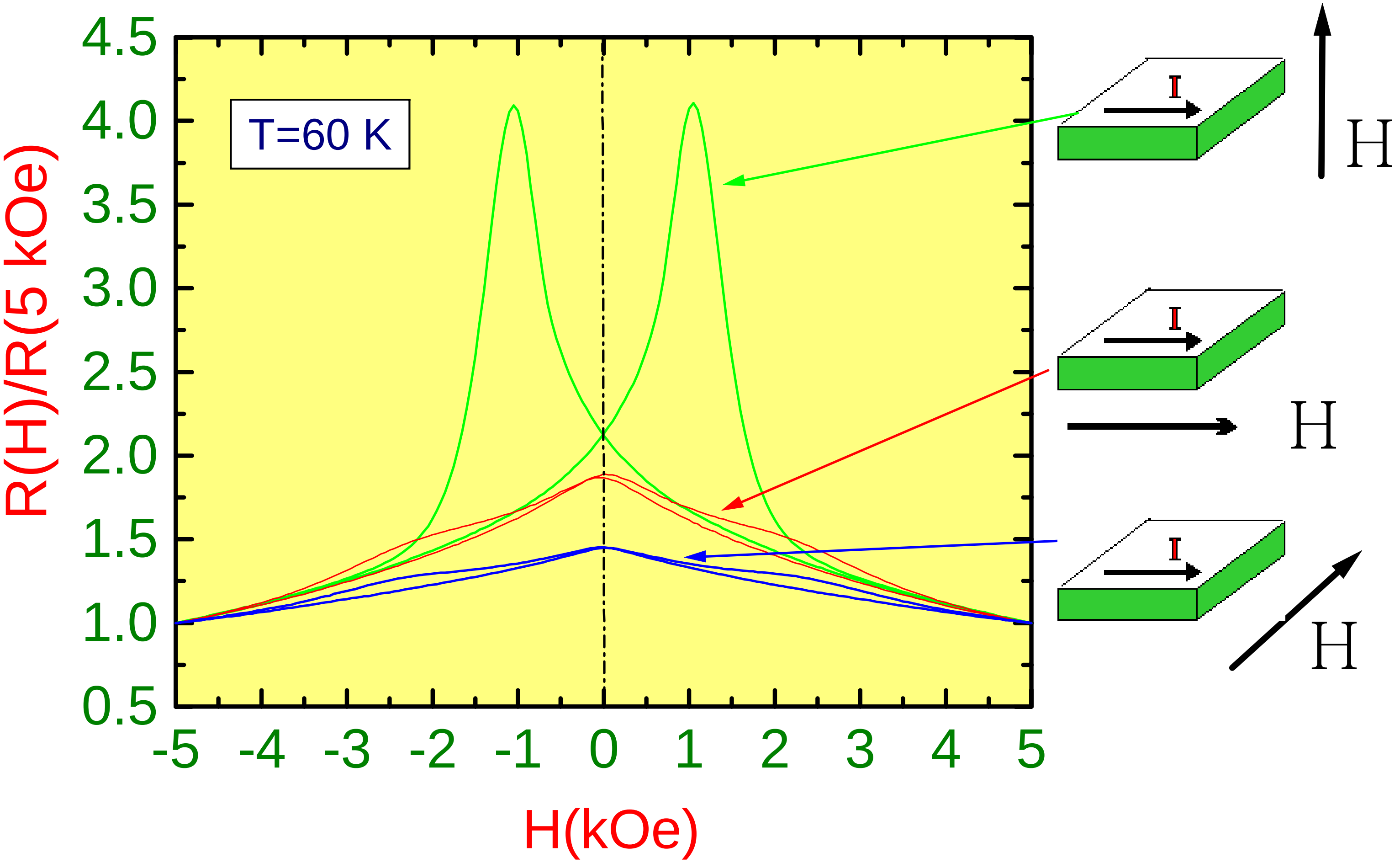
R_0/R_H~12
(H=2.5 kOe)

MR > 1000 % (comparing largest GMR ~ 150 % in metallic multilayers)

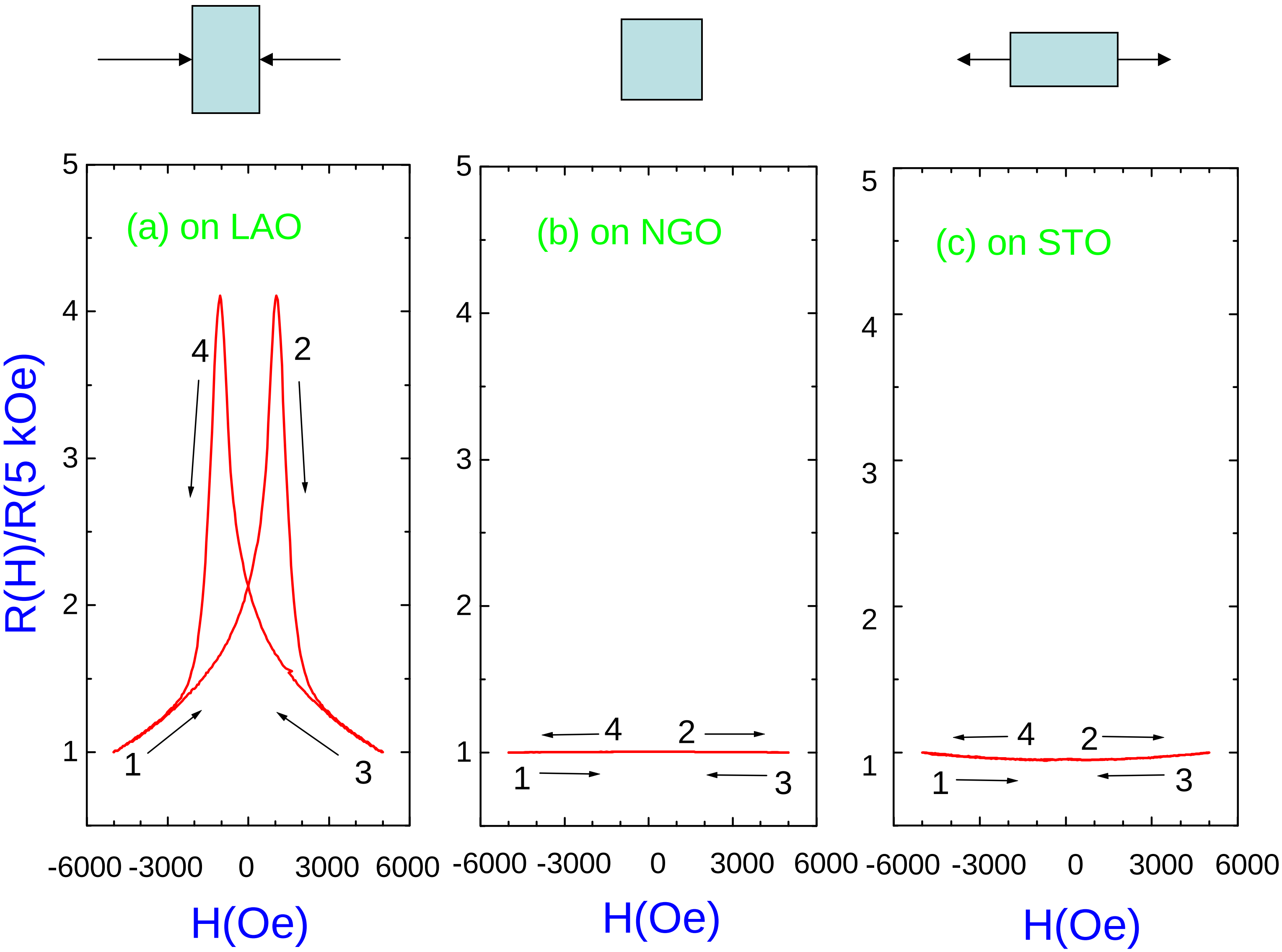
Low-field MR hysteresis



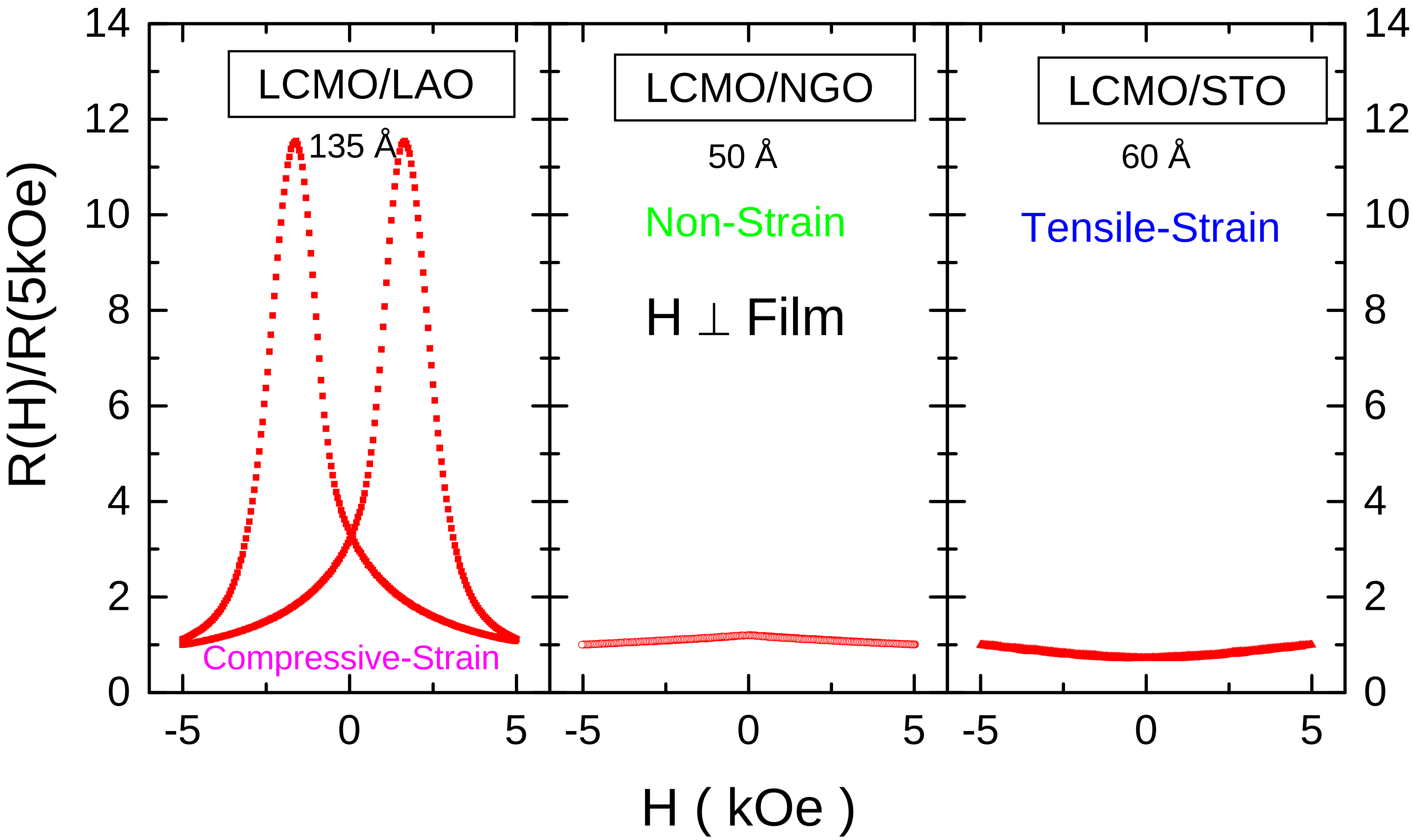
Anisotropic low-field MR of ultrathin PSMO/LAO film



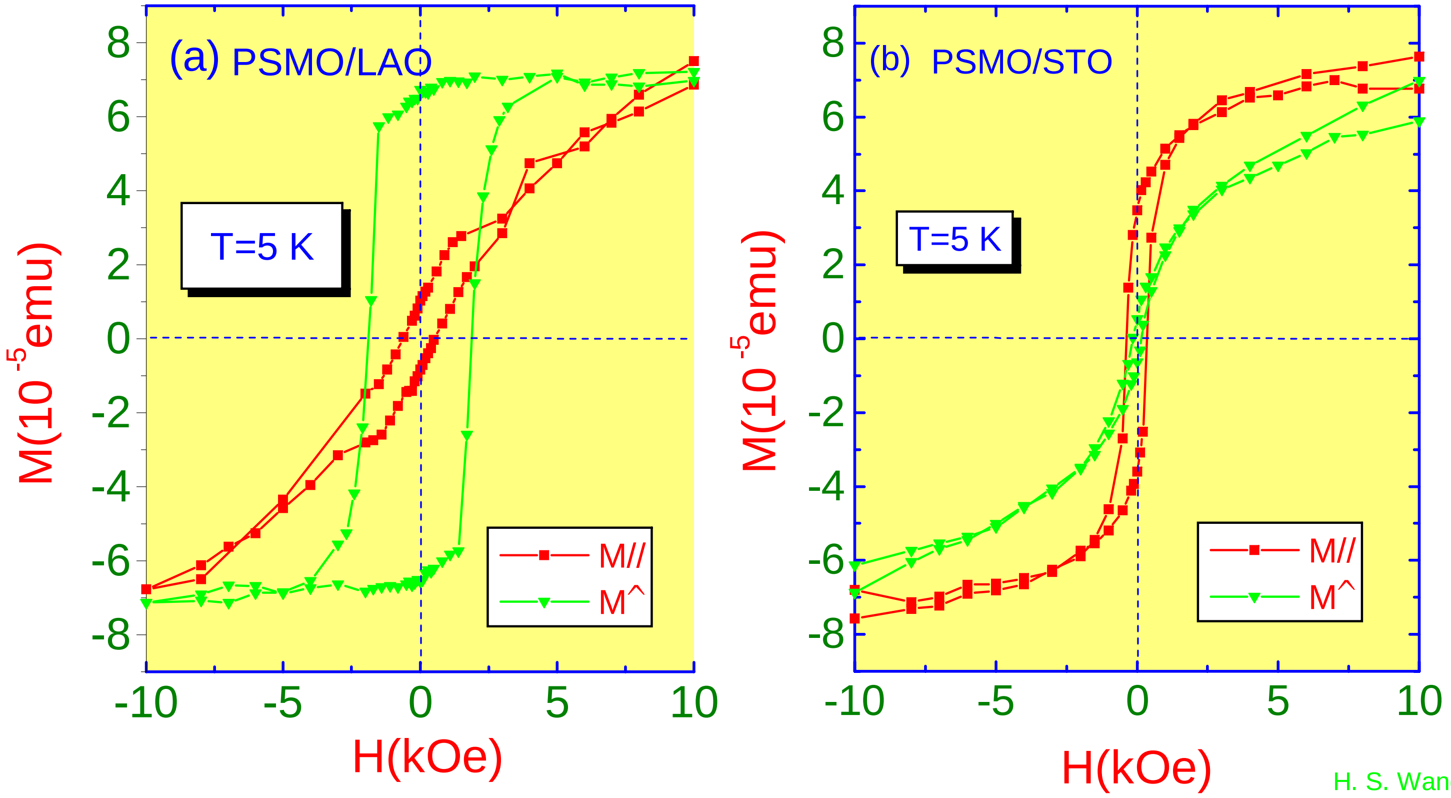
Comparison for different strains



Strain Effect on LFMR



Magnetization curves of ultrathin PSMO films



H. S. Wang, Qi LI,
K. Liu, and C. L. Chien,
Appl. Phys. Lett. 74,
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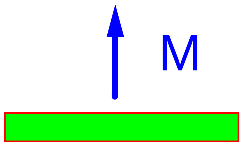
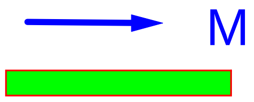
X. W. Wu, M. S. Rzchowski,
H. S. Wang, and Qi Li,
Phys. Rev. B, in press

Easy Axis



Compressive strain

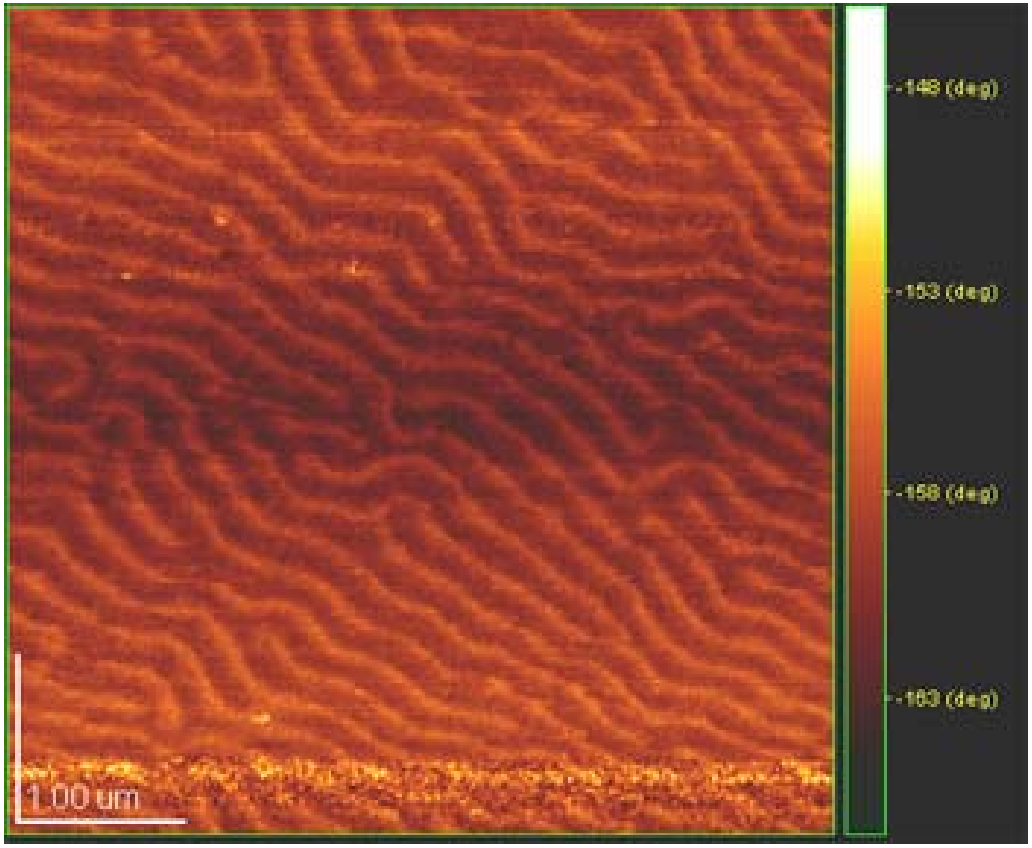


Tensile strain

Strain induced anisotropy dominates.

MFM domain image

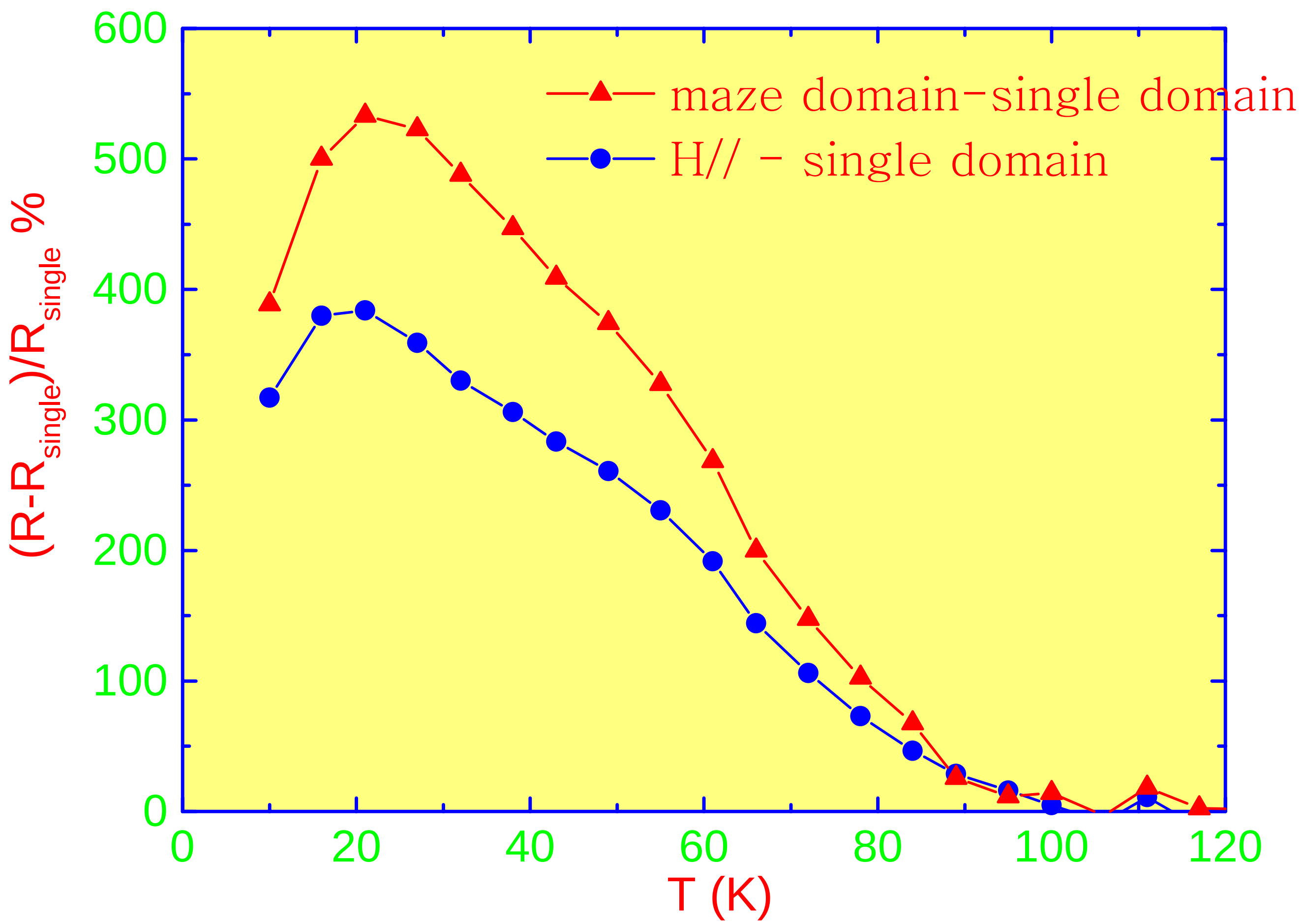
LSMO/LAO 1500 Å, ZFC, 5 μ x 5 μ scan:



Domain width decreases with thickness.

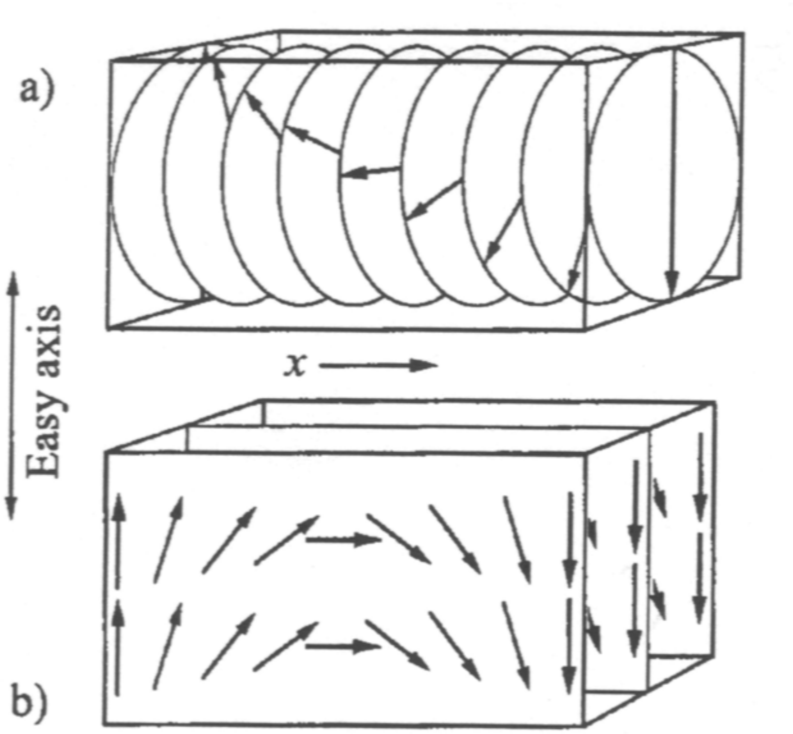
Domain stripes can be aligned with an in-plan field.

Temperature Dependence of the Domain Wall Resistance



Discussion

Bloch or Neel wall



- It is known theoretically and experimentally, magnetic domain wall resistance is normally negligible (Cabrera and Falicov,1974)

- Only when Fermi wavelength (scattering length) is larger than the wall width, spin reflection (resistance) can occur.

This is not possible for manganites since mean free path is ~ A

Conventional ferromagnet

- Largest reported in Co film with stripe domain, DWR ~8% (Viret, PRL, 2001)
- Theory based on majority and minority channel mixing+impurity scattering (Zhang and Levy 1997)

This model cannot be applied directly to manganites as double exchange prohibits mixing. Our DWR is too large to be explained.

Double exchange model

- Anisotropy energy k ~ 1.5 mev/nm^2, exchange constant J ~ 2.5 mev

$\Rightarrow$ Domain wall width ~ 8 nm (20 atoms)

$R_{DW}/R \sim 1/\cos(\theta/2) \sim 1.003$, DWR ~ 0.3 % (P. Littlewood et al., JAP, 1999)

Cannot explain the result

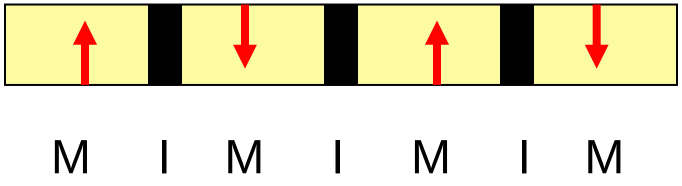
Possible explanation

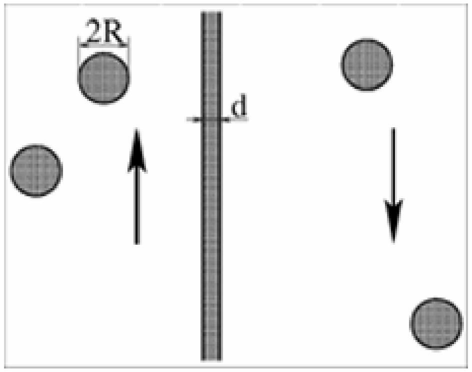
Mathur and Littlewood (2001): phase separation in strained samples (self organized structures).

D. Golosov (PRB 67, 064404 (2003) calculated domain wall in double exchange system, suggested 3 types of domain walls, Block, abrupt, and stripe walls, and our sample may have stripe wall.

Stripe wall: domains are separated by an AF insulating phase (charge ordering phase)

Effectively self organized phase

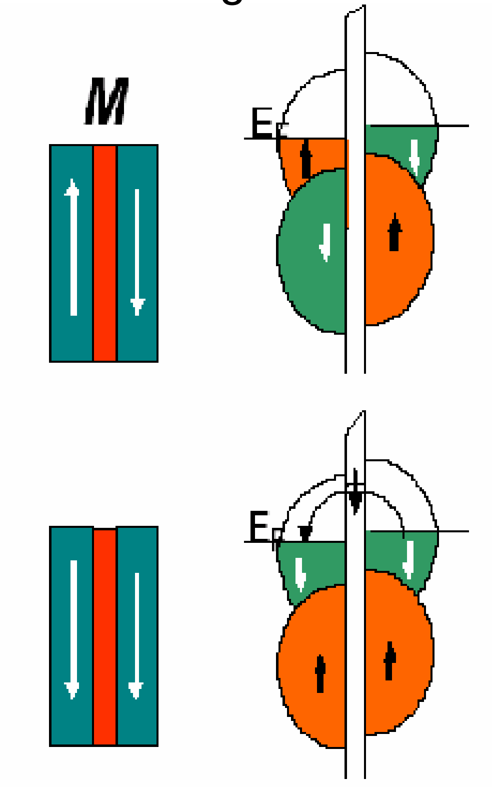




Reason for large DWMR:

- Spin polarized tunneling across the stripe walls
- or melting of charge ordering phase when the domains are aligned

tunneling



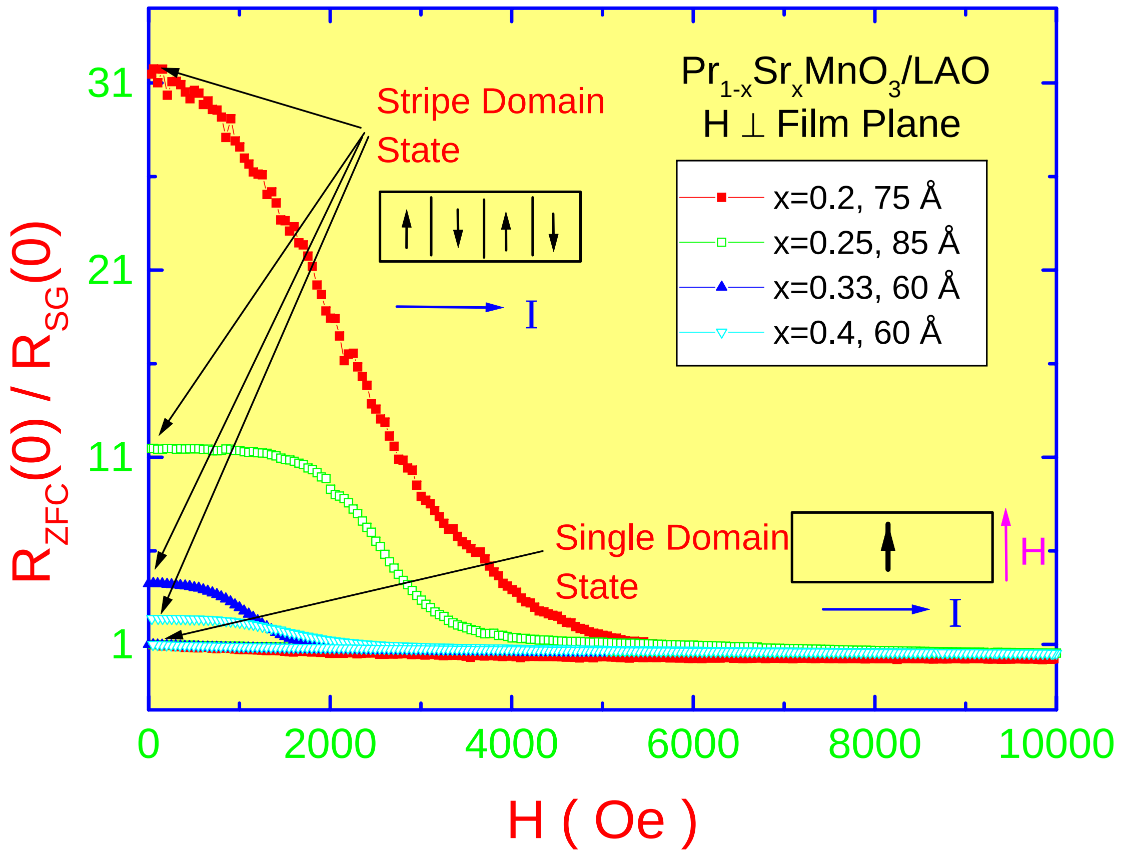
Spin Polarization

$$P = \frac{n_\uparrow - n_\downarrow}{n_\uparrow + n_\downarrow}$$

Manganites are half metal *p* ~ 1

Therefore largest TMR is expected.

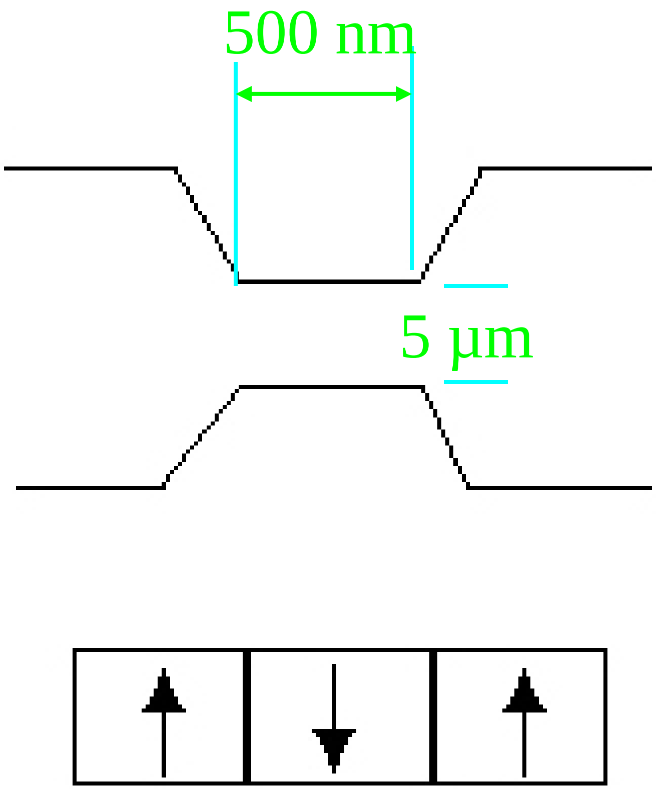
DWR for different doping



Large DWR is observed in compressive strained PSMO thin films, and the DWMR is larger for smaller Sr doping x. For x=0.2, DWMR~3000% !

Nano-bridges

- To understand the observed large LFMR and DWR, measurements across a small number of domain walls are necessary.
- Sharp switching of MR may be obtained in small size sample which contains a few domains.



Discussion

- Manganite nanostructures maintain the LFMR and DWR properties, but show nonlinear I-V behaviors;
- Nonlinear I-V curves can be fitted very well by Simmons tunneling model;
- There are internal phase separation in the sample as well as at the domain walls;
- The reduced tunneling barrier height in the magnetic field may indicate the melting of the AFM phase at the domain wall in the sample.

Anisotropic magnetoresistance

- Tool to probe intrinsic anisotropic energy
- To study spin-orbital coupling
- Used in sensors

In manganite single crystals, AMR (crystalline) is negligible.

Summary

- Large low field magnetoresistance in compressively strained ultrathin films and nanostructures with unconventional domain walls (possibly stripe walls).
- Very large anisotropic magnetoresistance associated with Jahn-Teller type lattice distortion.
- Small change in lattice can result in dramatic changes in magnetic and transport properties.