Magnetism at the Edge;
New phenomena at oxide interfaces

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J. M. D. Coey, Ariando, W. E. Pickett, MRS Bulletin, **38** 1040 (2013)

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Magnetism at the edge
Three short stories

J. M. D. Coey

Introduction - Magnetic thin films

1. MRG–The zero-moment half metal
2. Playing with the polar catastrophe
3. d^0 magnetism

www.tcd.ie/Physics/Magnetism

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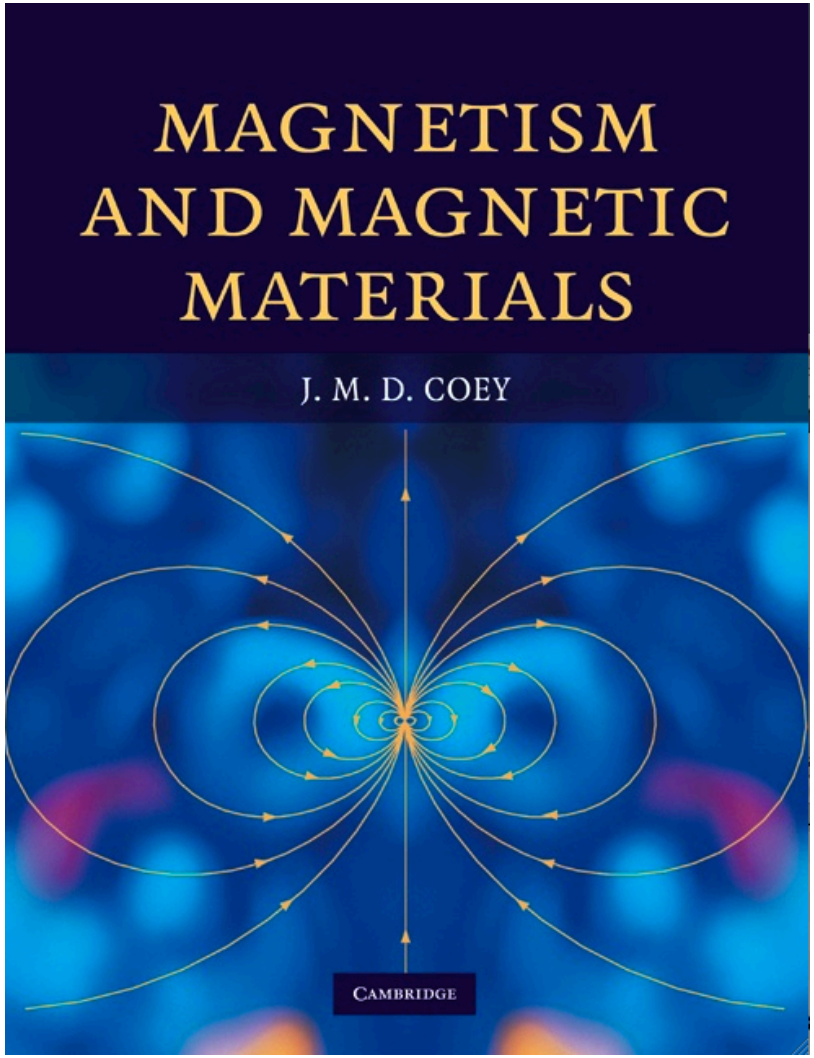
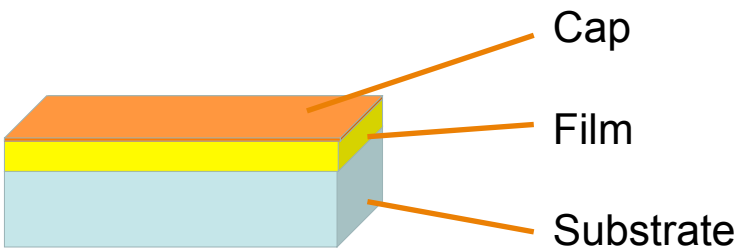


CUP 2010 Cost ~ €50

www.cambridge.org/9780521816144

Introduction - Magnetic thin films

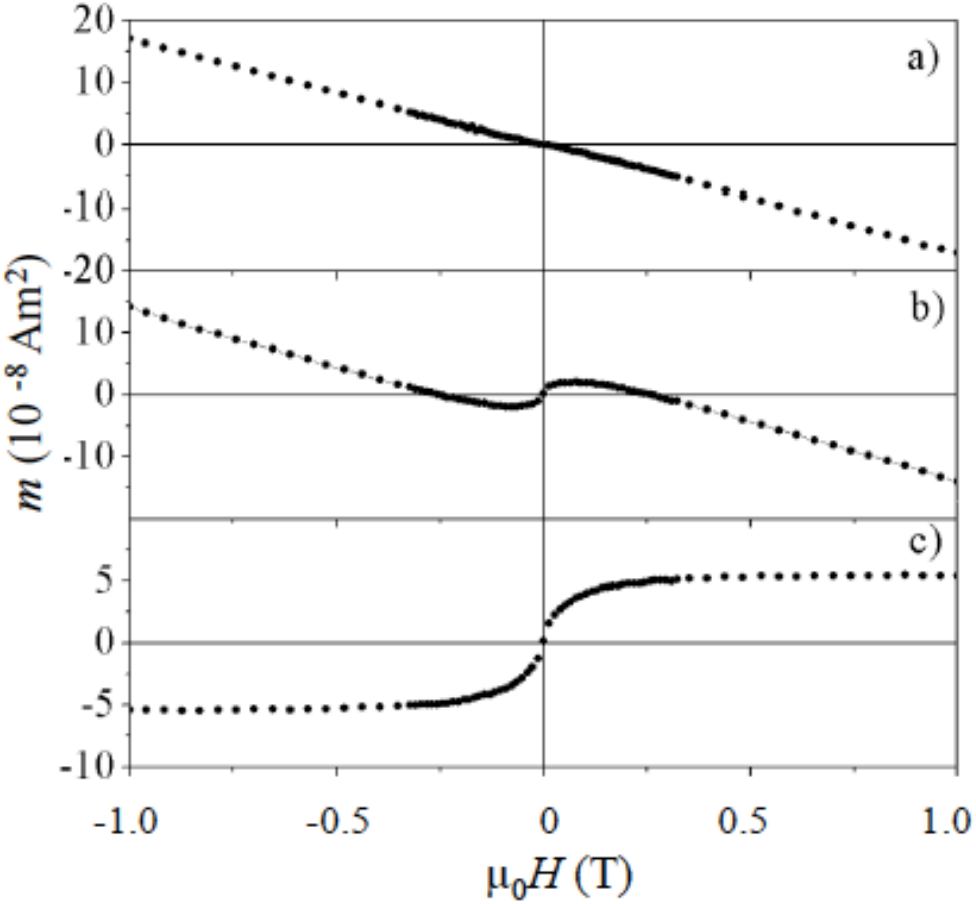
Magnetic thin films

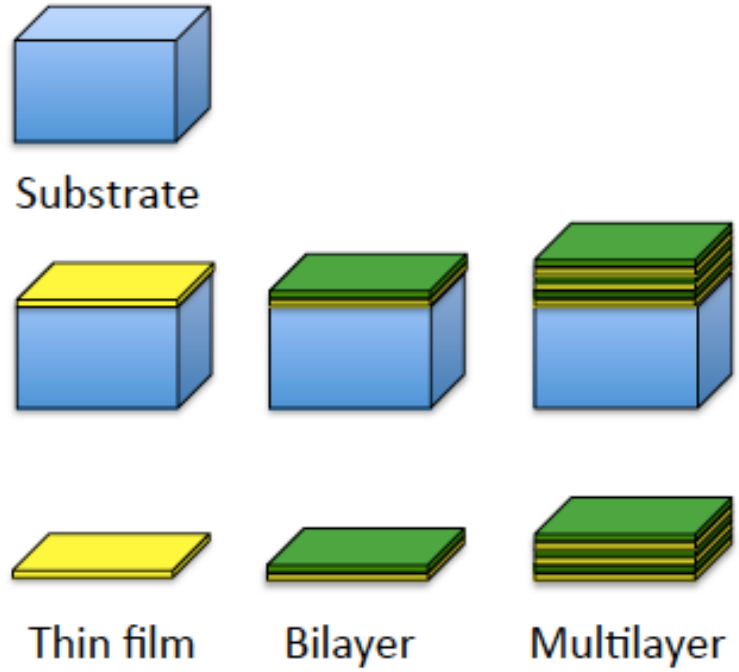


Achievable sensitivity with SQUID magnetometer	10^{-11} Am^2
Ferromagnetic monolayer 5 x 5 mm^2	~ 10^{-8} Am^2
Moment of oxide substrate 5x5x0.5 mm^2 in 1 MAm^{-1}	~ 10^{-8} Am^2

Table I. Magnetic susceptibility of insulating oxides. Units (SI) are 10^{-6}.

Al_2O_3	MgO	$SrTiO_3$	$LaAlO_3$	TiO_2	SiO_2	YSZ	$MgAl_2O_4$
–18	–11	–7	–18	4	–18	–8	–15





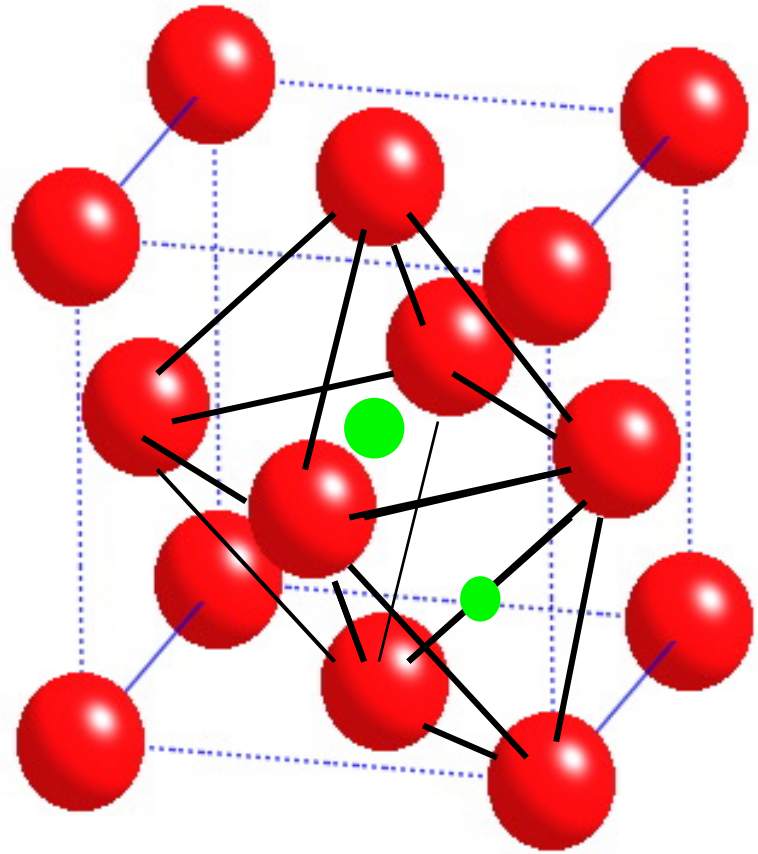
Assume $m_{\text{sample}} = m_{\text{sample on substrate}} - m_{\text{substrate}}$

This could be naïve

Substrates

Oxides are usually insulating.
Structures are based on dense-packed O^{2-} arrays, with cations in interstitial sites.

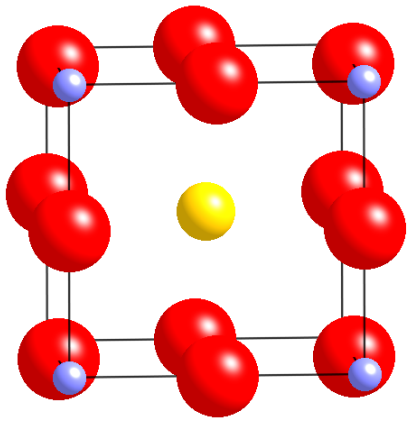
Substrate	*a, c* (pm)
Al_2O_3	477, 1304
MgO	420
$SrTiO_3$	391
$LaAlO_3$	379
TiO_2	459,296
SiO_2	490,539
YSZ	513
$MgAl_2O_4$	808



Scope for exerting biaxial strain, and growing otherwise unstable materials.

$R_{oct} = (\sqrt{2}-1)r_O = 58$ pm

$R_{tet} = (\sqrt{(3/2)} - 1)r_O = 32$ pm



Perovskite structure
ABO_3

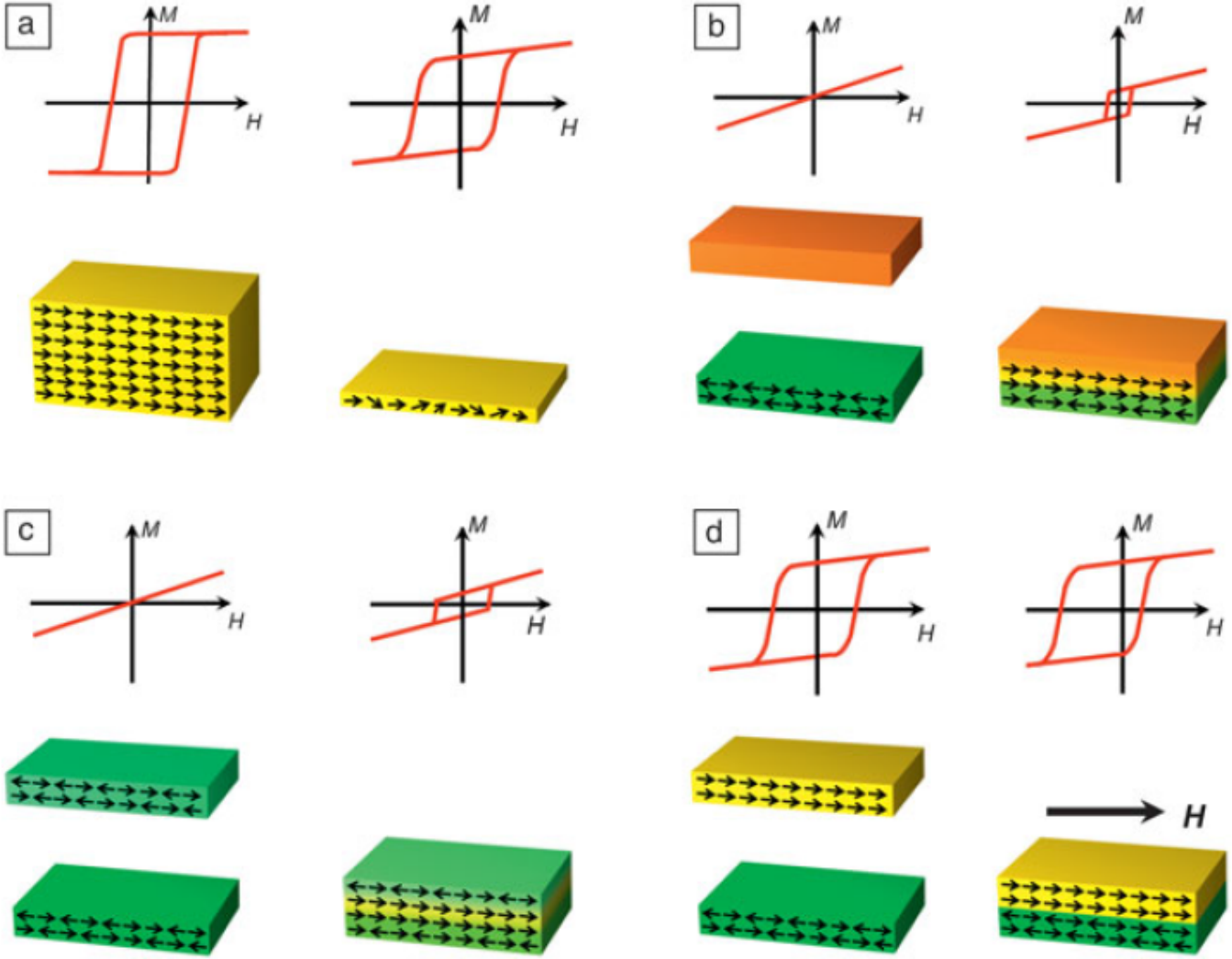


Figure 2. Schematic magnetic structures and hysteresis loops of thin films and heterostructures. (a) Change of magnetic order when the conducting bulk ferromagnet $La_{-0.7}Sr_{0.3}MnO_3$ is made into an ultrathin insulating film. (b) A bilayer of a Pauli paramagnet ($CaRuO_3$) and an insulating antiferromagnet ($CaMnO_3$) becomes ferromagnetic at the interface. (c) A bilayer of two antiferromagnets $LaMnO_3$ and $LaCrO_3$ becomes ferromagnetic at the interface. (d) Exchange coupling in a bilayer between a ferromagnet and an antiferromagnet produces a loop shift of the ferromagnet (exchange bias).

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TRINITY COLLEGE, DUBLIN

1. MRG - A zero-moment half metal

H. Kurt, K Rode, Y. C. Lau, N. Thiyanarajah, P. Stamenov, J. M. D. Coey

H Kurt et al PRL **112** 027201 (2014)

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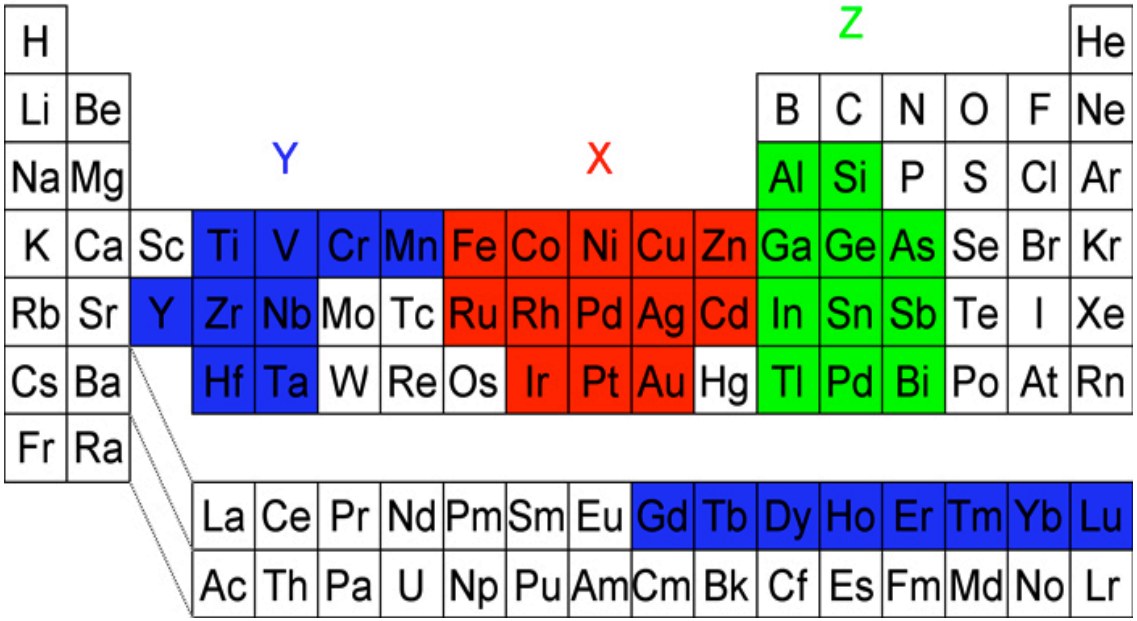
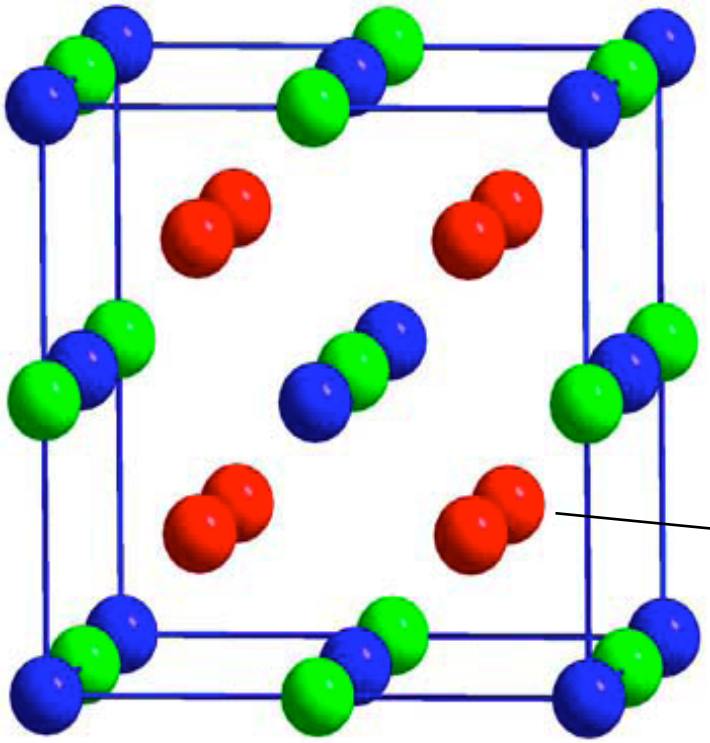
Heusler Alloys X_2YZ

Cubic $L2_1$ structure



$L2_1$ structure



Co_2MnSi $T_C = 985$ K

Co_2FeSi $T_C = 1120$ K

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$m = n_\uparrow - n_\downarrow$

$n_{tot} = n_\uparrow + n_\downarrow$

$m = n_{tot} - 2n_\downarrow$

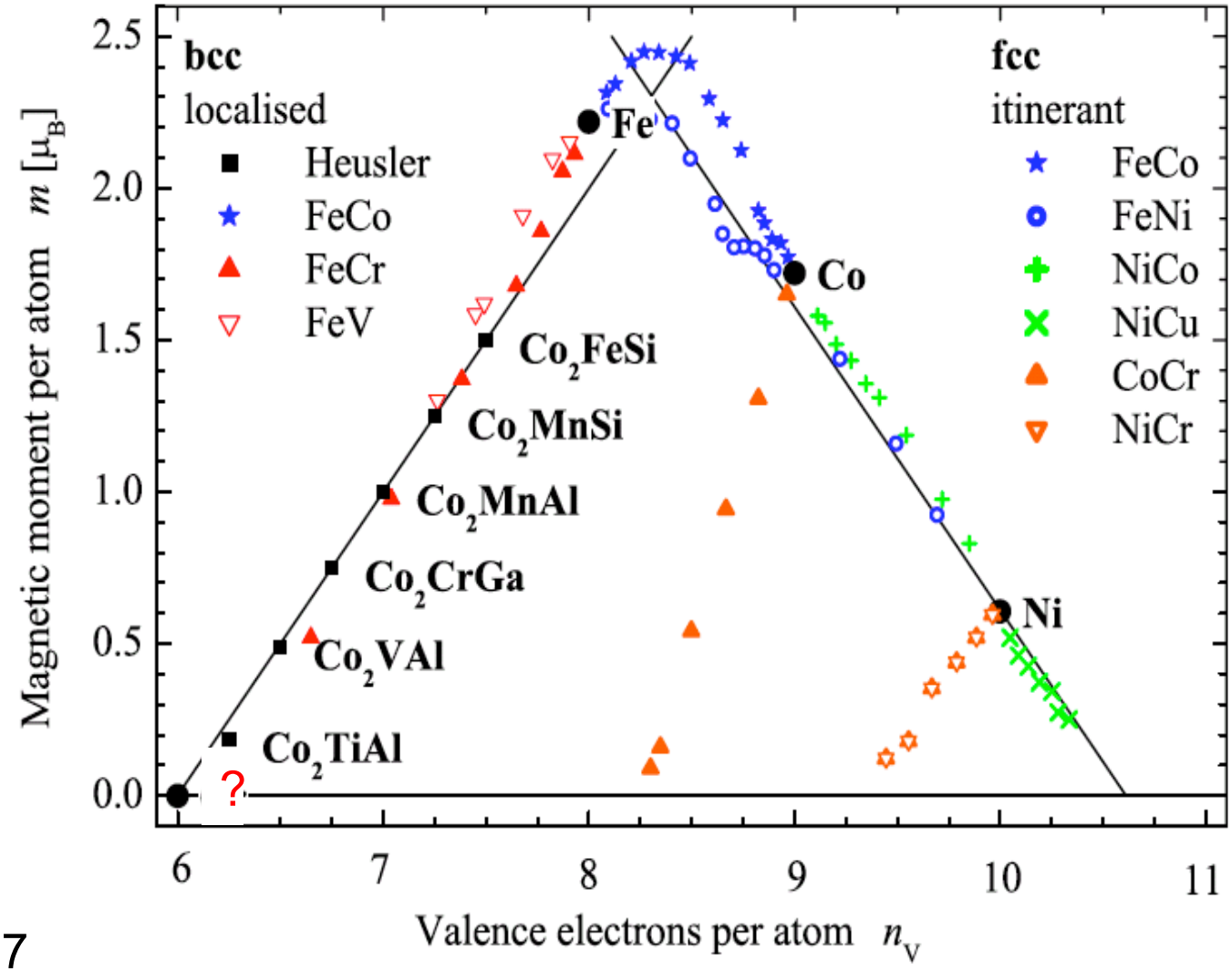
$n_\downarrow = 12$

$$m = n_{tot} - 24$$

$m = n_v - 2n_\downarrow$

or

$m = 2n_\uparrow - n_v$



e.g. Co_2CrAl

2 x 9 + 6 + 3 = 27

$m. = 3\mu_B$

N_v = 6 for Cr,7 for Mn, 8 for Fe, Ru, 9 for Co; 10 for Ni;3 for Al,Ga, 4 for Ge

H van Leuken and R A de Groot PRL **74** 1171(1995)

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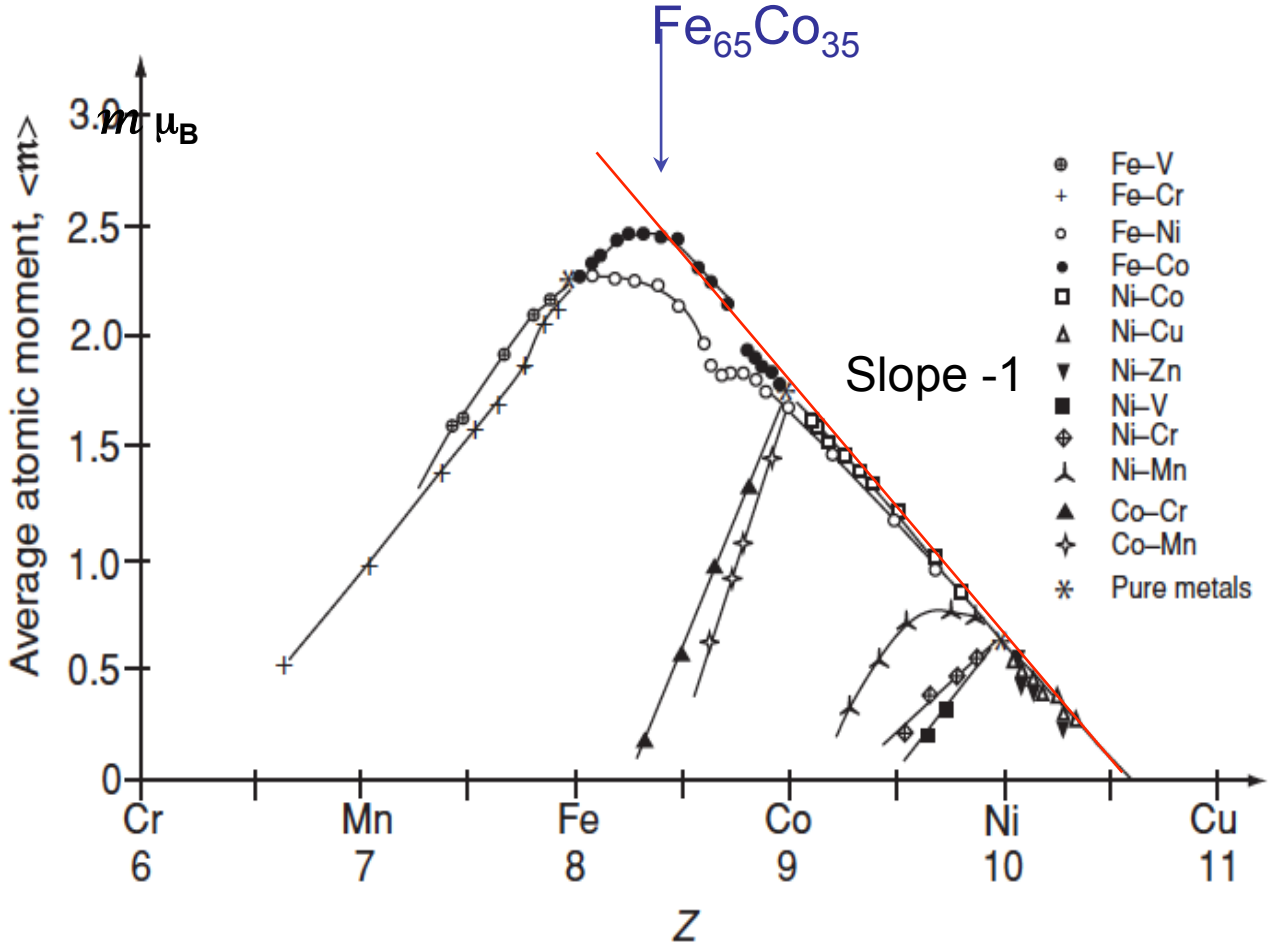
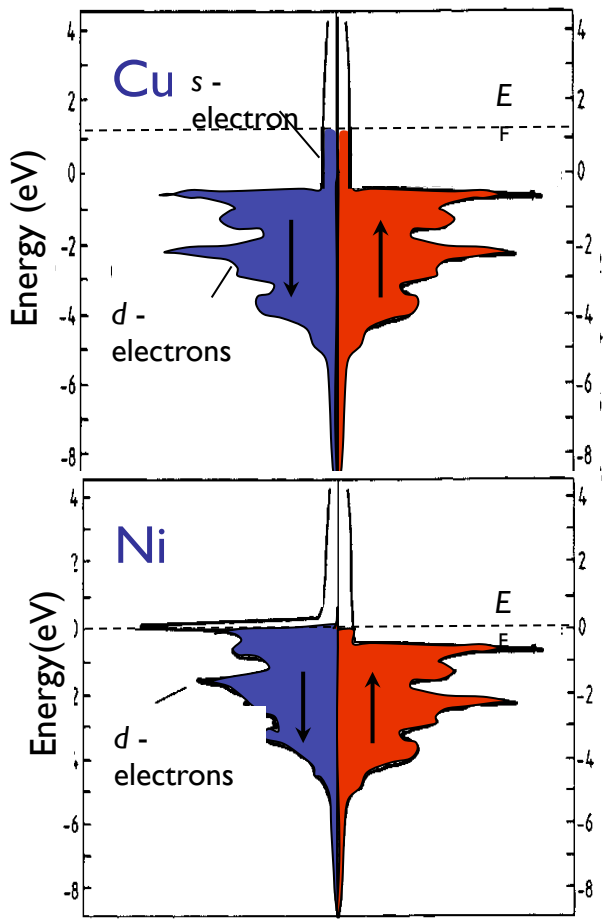
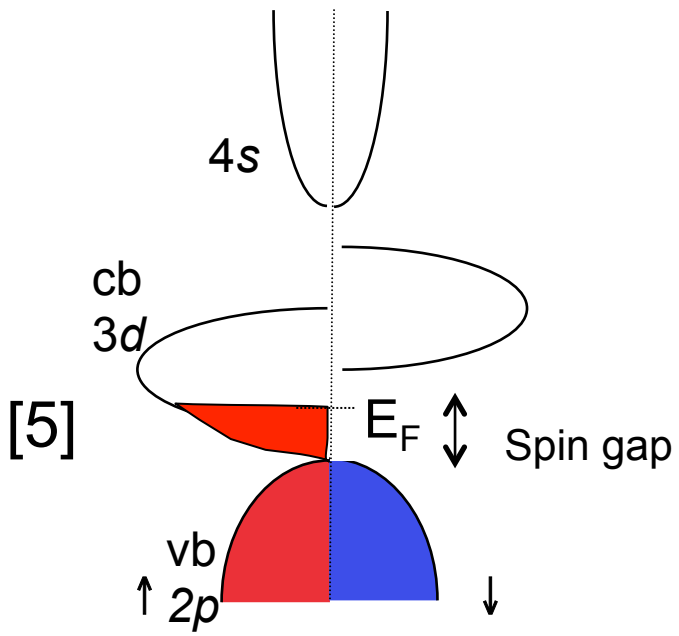
Slater-Pauling Curve

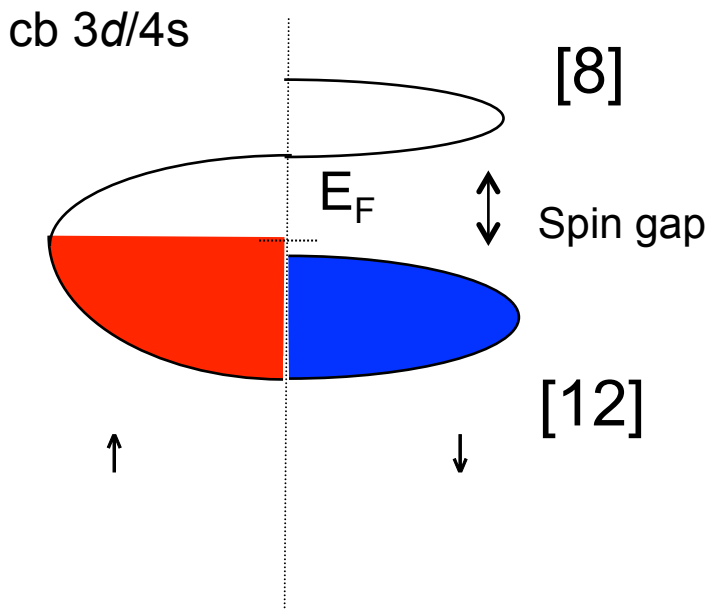




A half-metal



CrO_2



X_2YZ

$m = n_\uparrow - n_\downarrow$

$n_{tot} = n_\uparrow + n_\downarrow$

$m = n_{tot} - 2n_\downarrow$

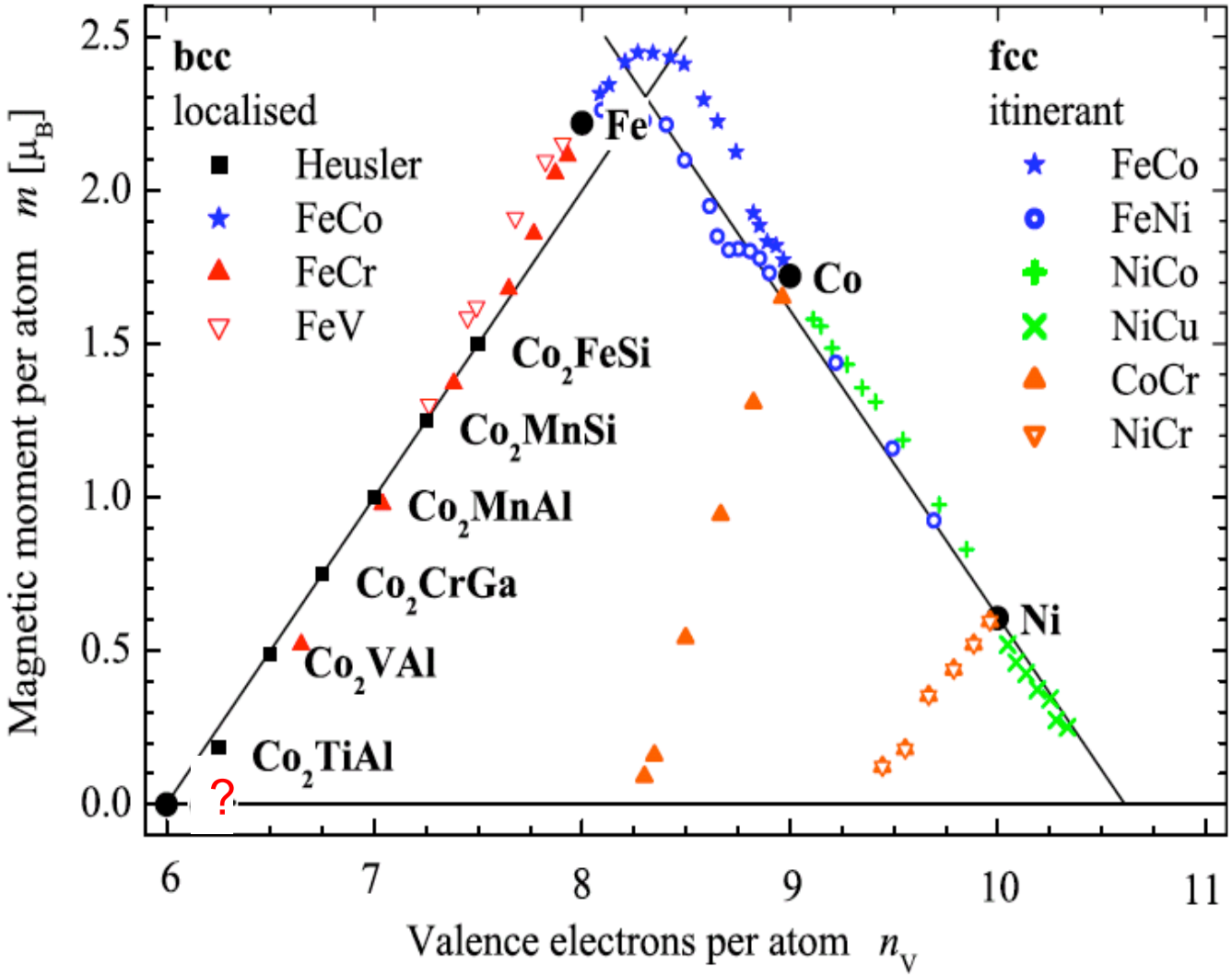
$n_\downarrow = 12$

$$m = n_{tot} - 24$$

$m = n_v - 2n_\downarrow$

or

$m = 2n_\uparrow - n_v$



e.g. Mn_3Ga

3 x 7 + 3 = 24

$m. = 0\ \mu_B$

N_v = 7 for Mn, 3 for Ga

H van Leuken and R A de Groot PRL **74** 1171(1995)

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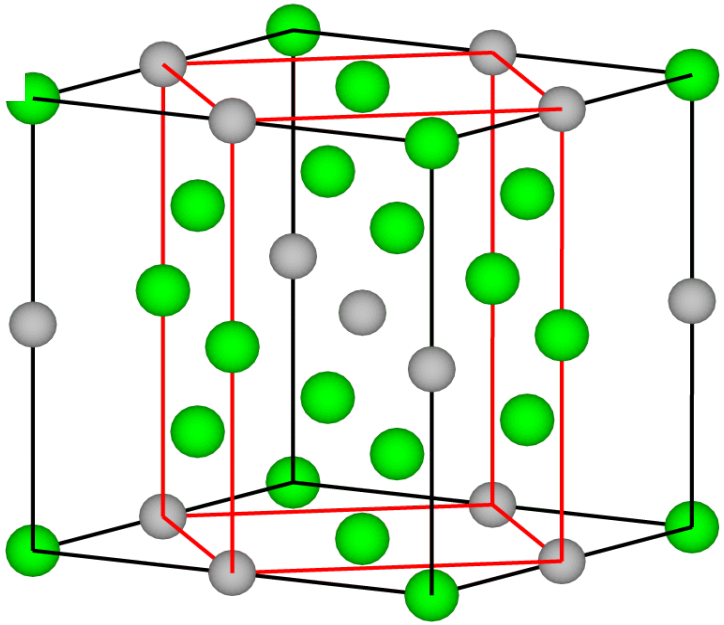
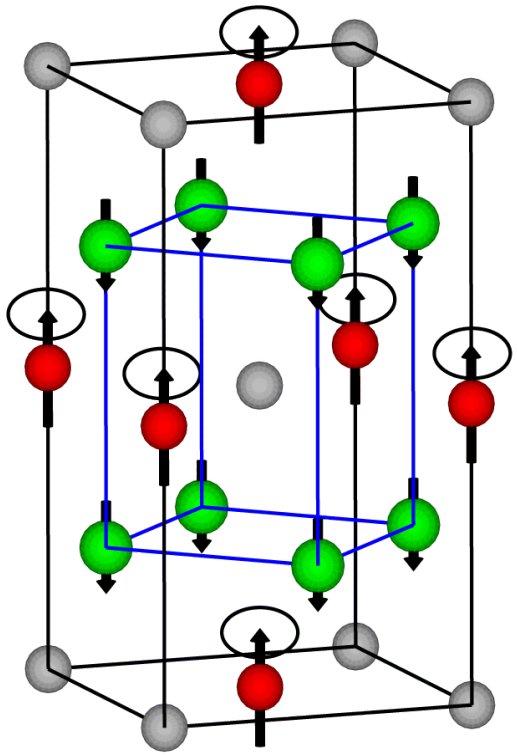
Mn_3Ga

Cubic $D0_3$ X_2YZ Heusler; X = Y



Ordered bcc

Tetragonal $D0_{22}$



m = 1.1 μ_b/fu

Ordered fct

c-axis extension ≈ 20%

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$Mn_{3-x}Ga$ thin film growth

In-plane lattice spacings (Angstroms) for various substrates and seed layers

InAs †	4.28	AlAs †	4.00
V*	4.28	Pt	3.92
MgO	4.21	$SrTiO_3$	3.90
Cr*	4.11	Pd	3.89
Au	4.08	Ru	3.82
Al	4.05	Si †	3.84
GaAs †	4.00	Cu	3.61

$*a_0\sqrt{2}$ † $a_0/\sqrt{2}$ Mn_3Ga ($D0_{22}$) a = 3.92 Å;

Mn_3Ga (D03) $a_0/\sqrt{2}$ = 4.22 Å

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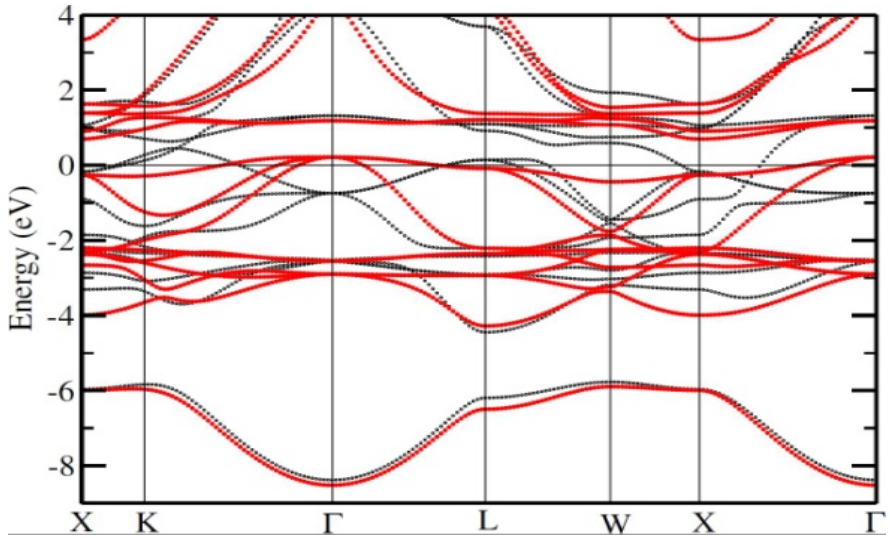
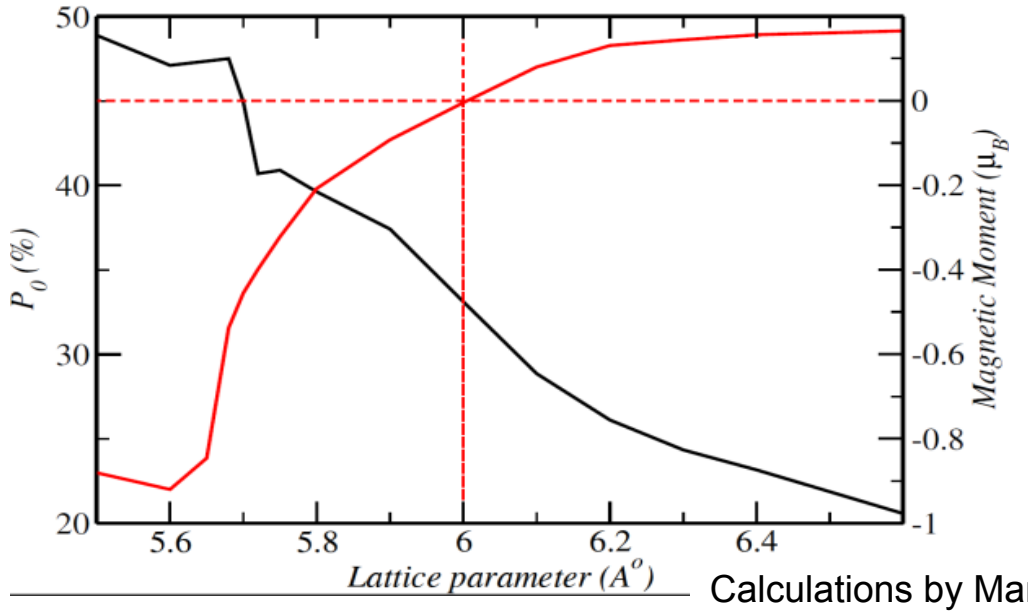
Electronic structure of cubic Mn_2Ga films



Note the spin gap 0.2 eV above E_F

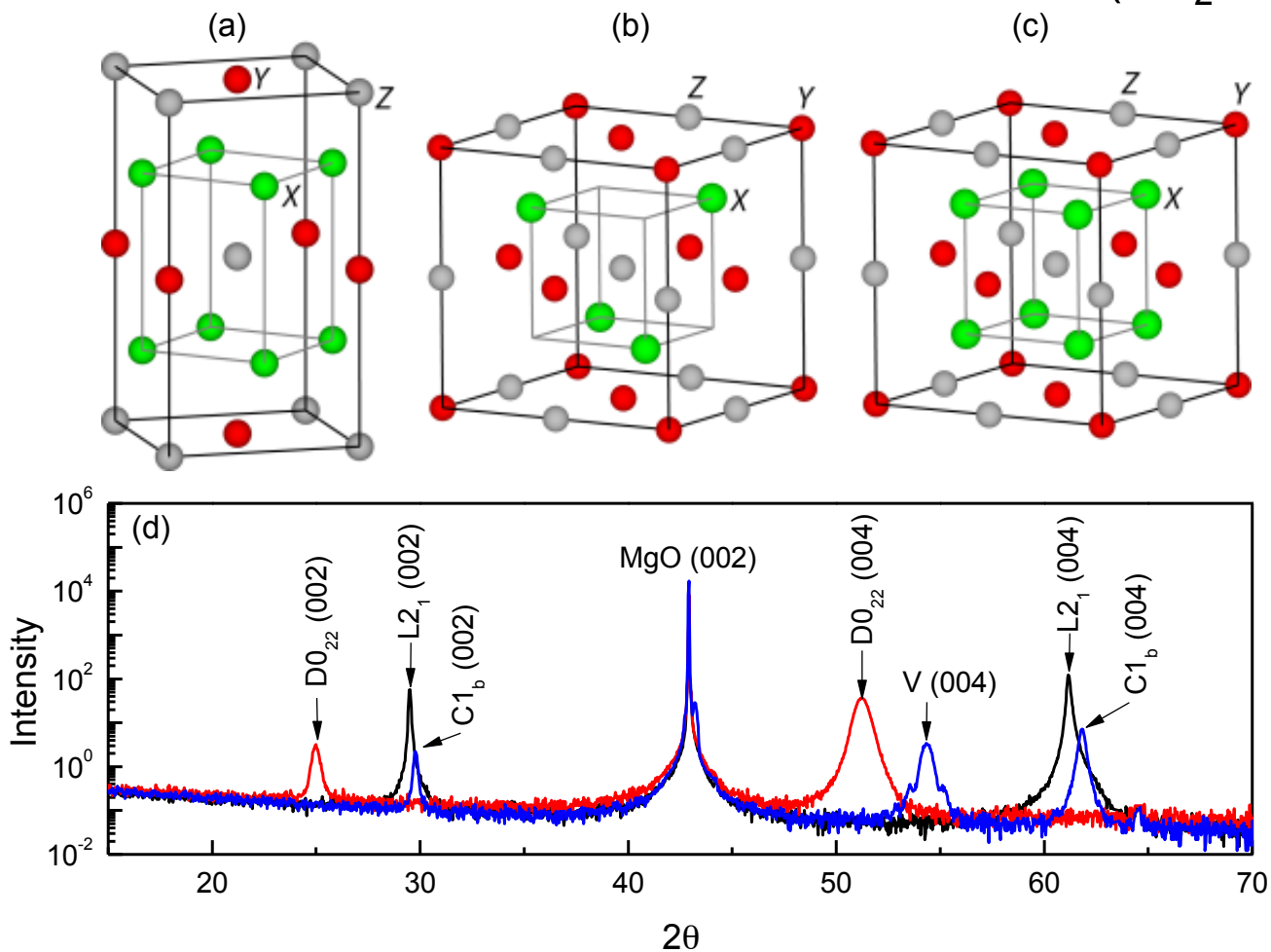
Type/Magnetic configuration	**Ferromagnetic**	**Antiferromagnetic**
Type I, MnGaMn or MnMnGa	842	0
Type II, GaMnMn	187	68



Calculations by Mario Zic, Stefano Sanvito

Growth of *cubic* Mn_3Ga and Mn_2Ga films

$m(Mn_3Ga) = 0.5\mu_B/fu$
$m(Mn_2Ga) = (-)1.6\mu_B/fu$
$m(Mn_2RuGa) = 0.6\mu_B/fu$



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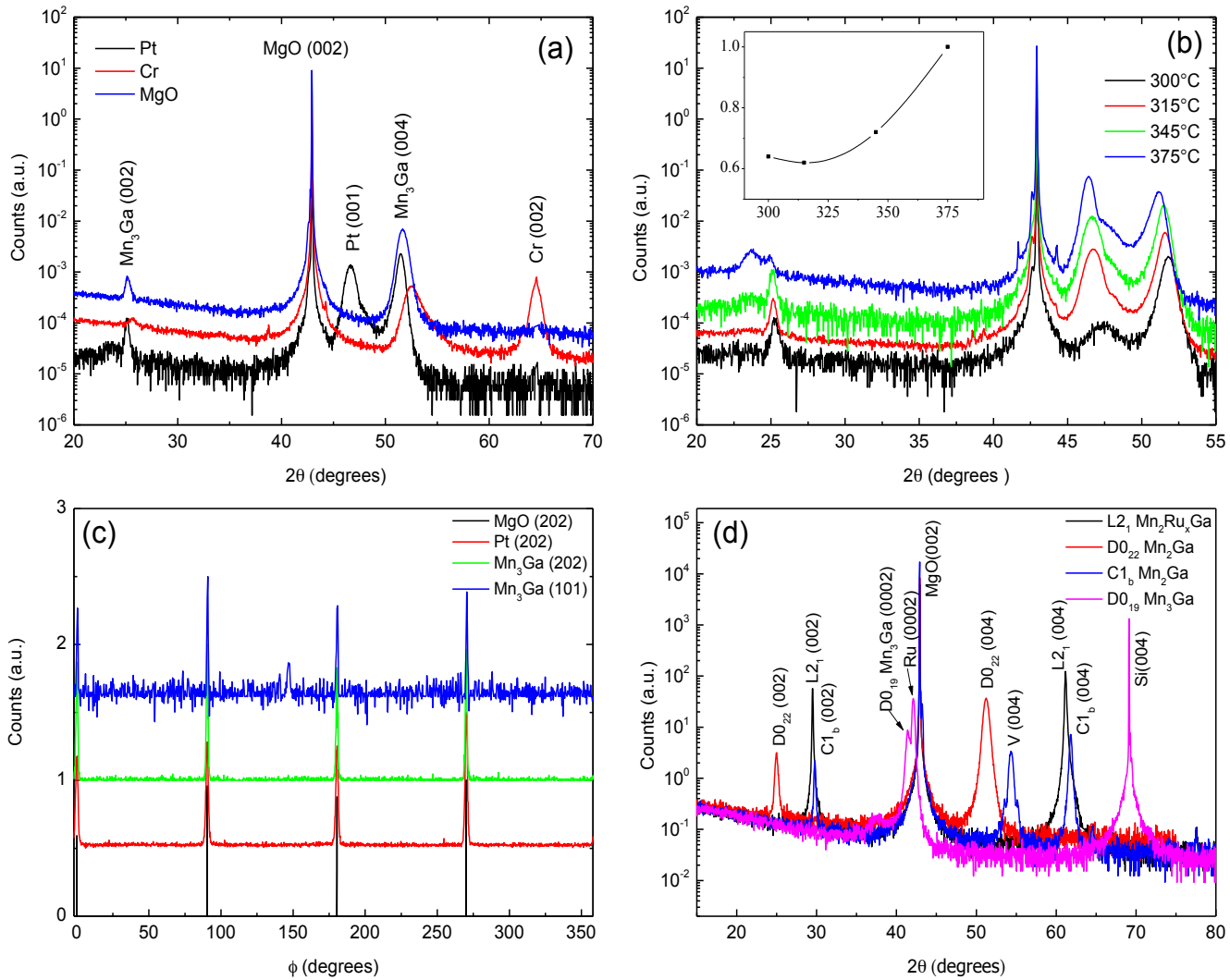
Mn_2Ru_xGa films; Cubic with biaxial strain



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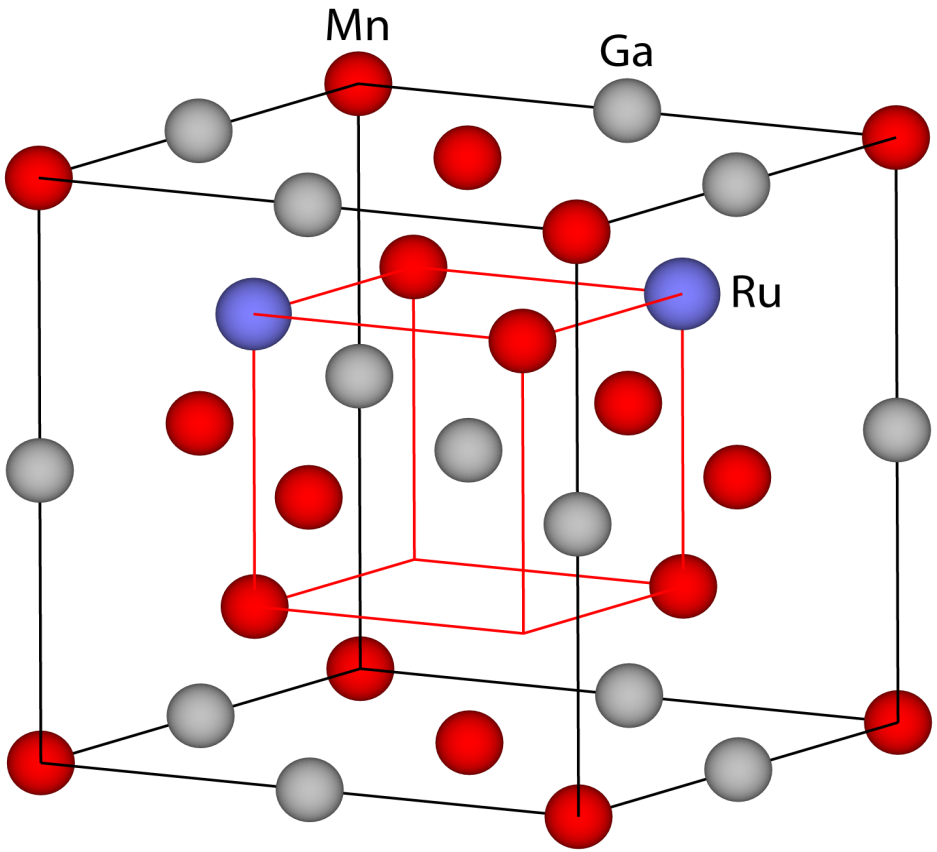
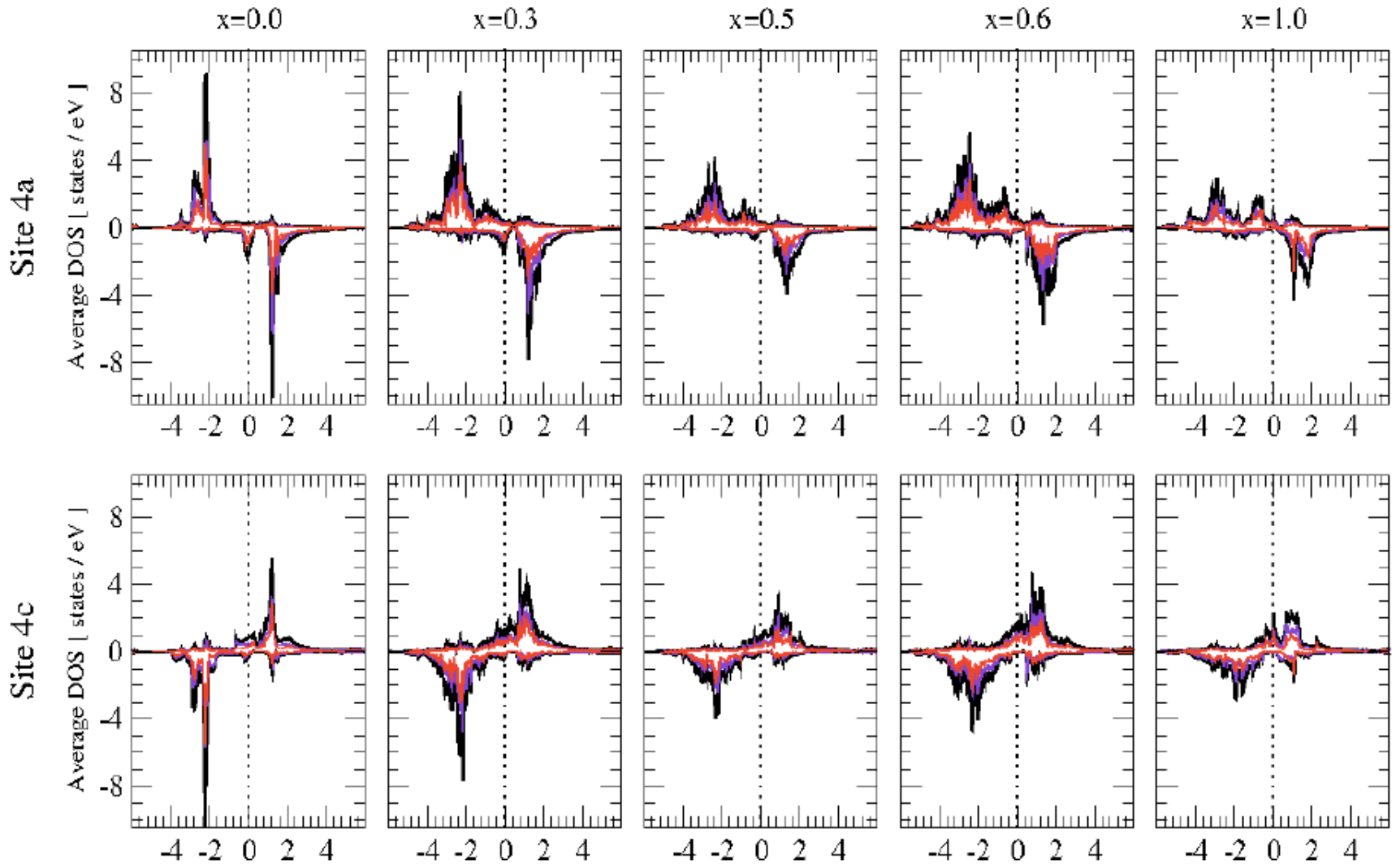


Atomic structure of cubic $Mn_2Ru_{0.5}Ga$ MRG n_v = 18

Ruthenium occupies half of the 4*d* sites and there are no Ru-Ga nearest neighbours.



Calculations by Mario Zic, Stefano Sanvito

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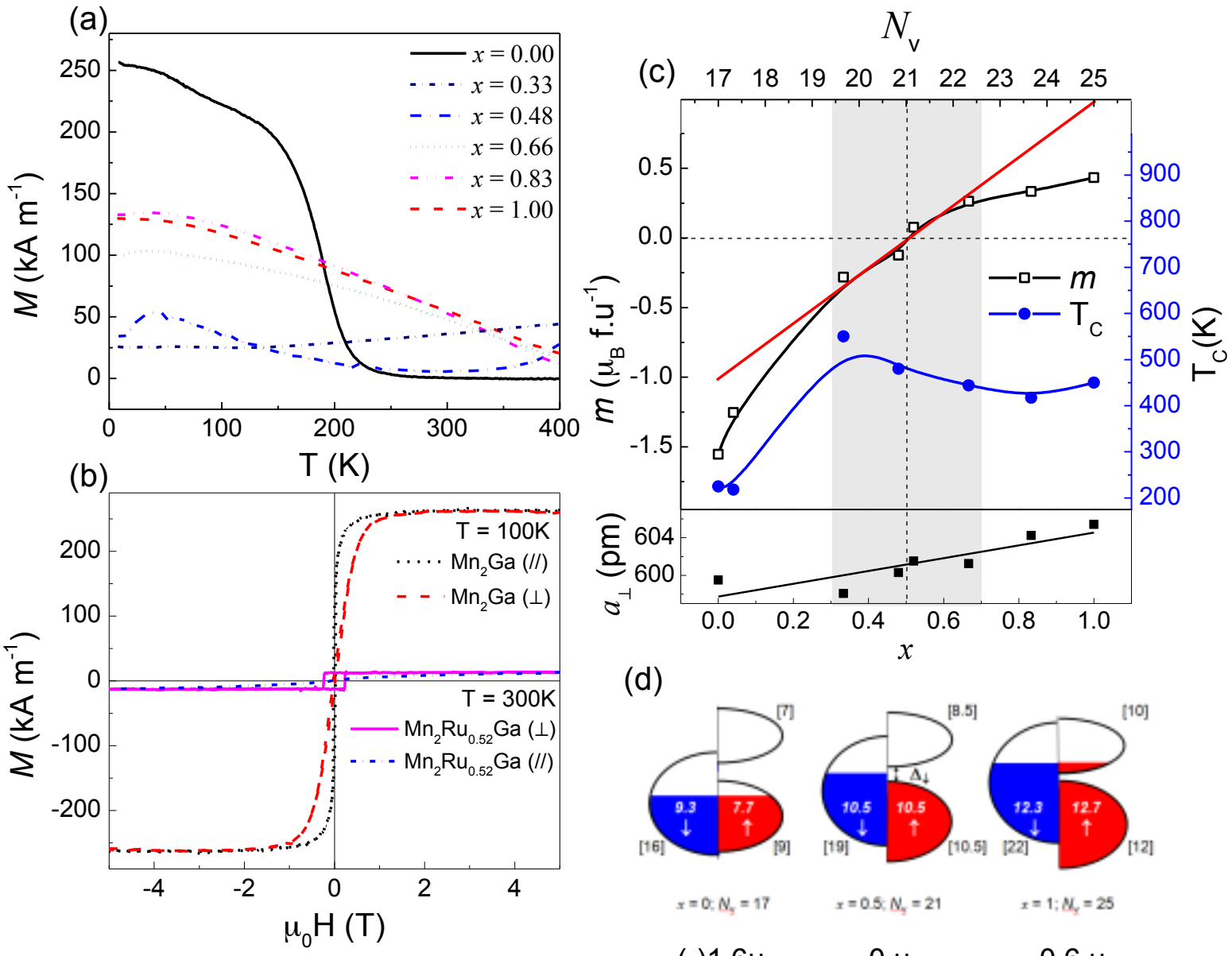

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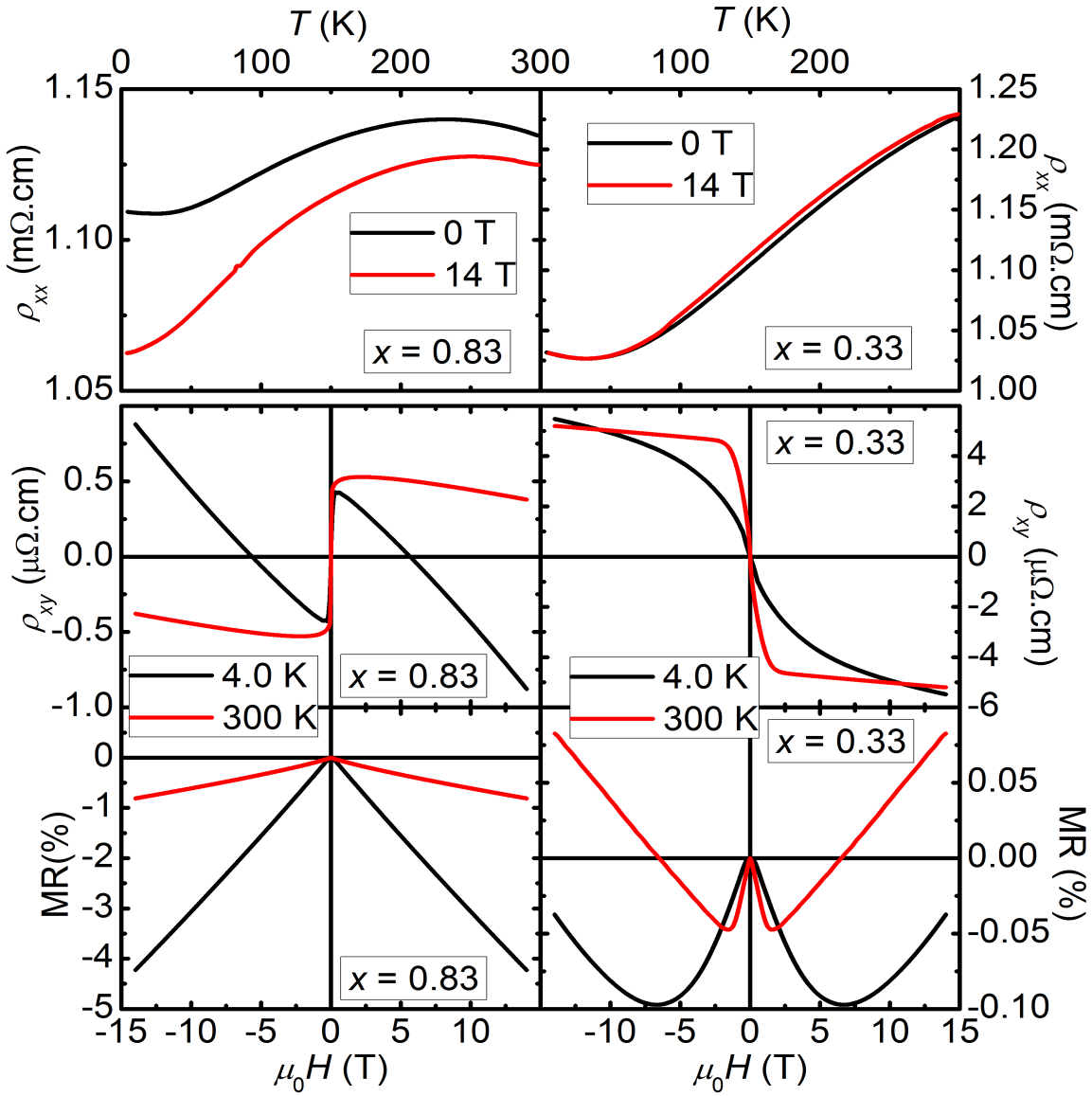
H Kurt et al PRL **112** 027201 (2014)

Magnetotransport properties of cubic Mn_2Ru_xGa films



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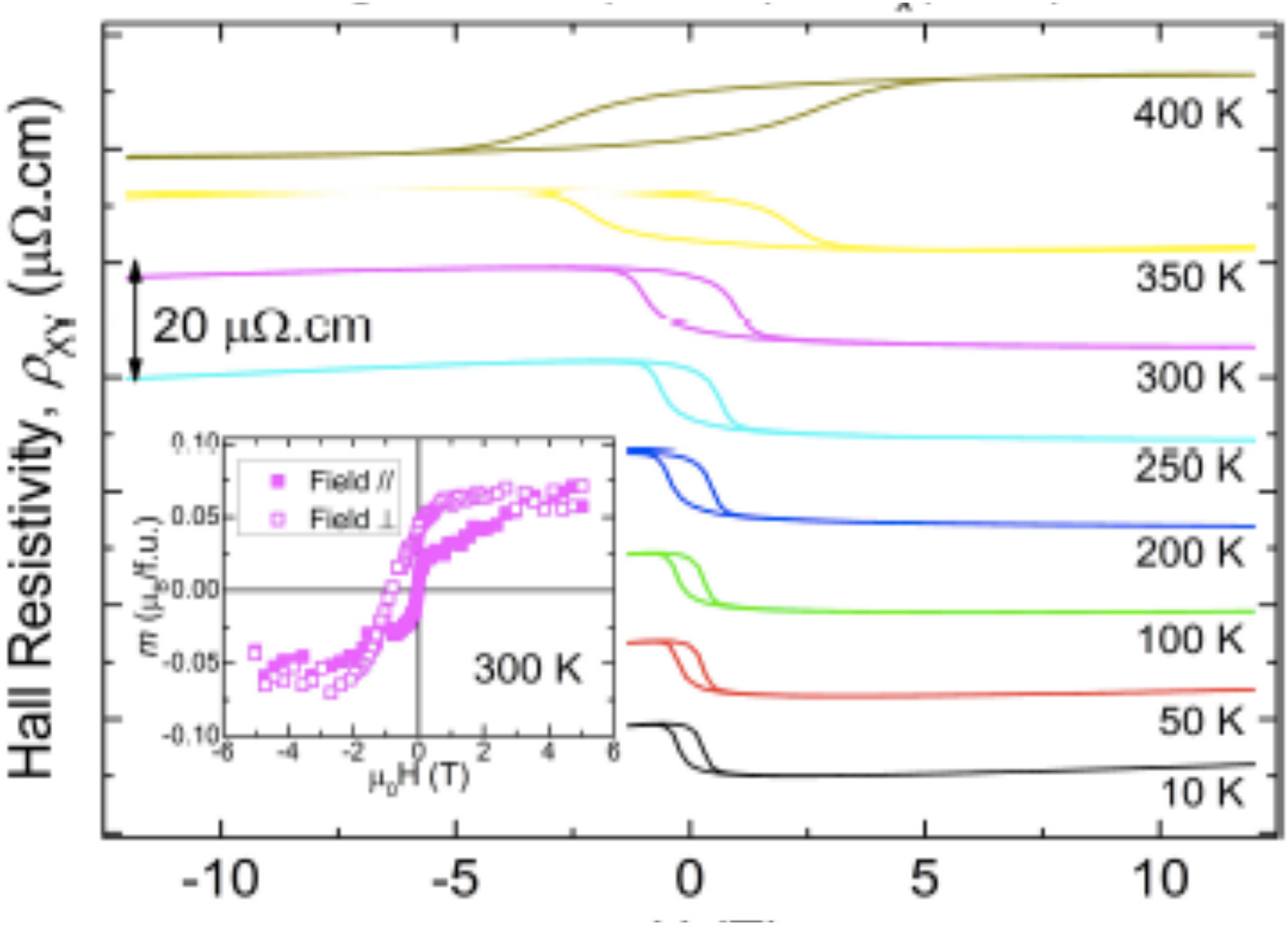

The two sublattices have different temperature dependence

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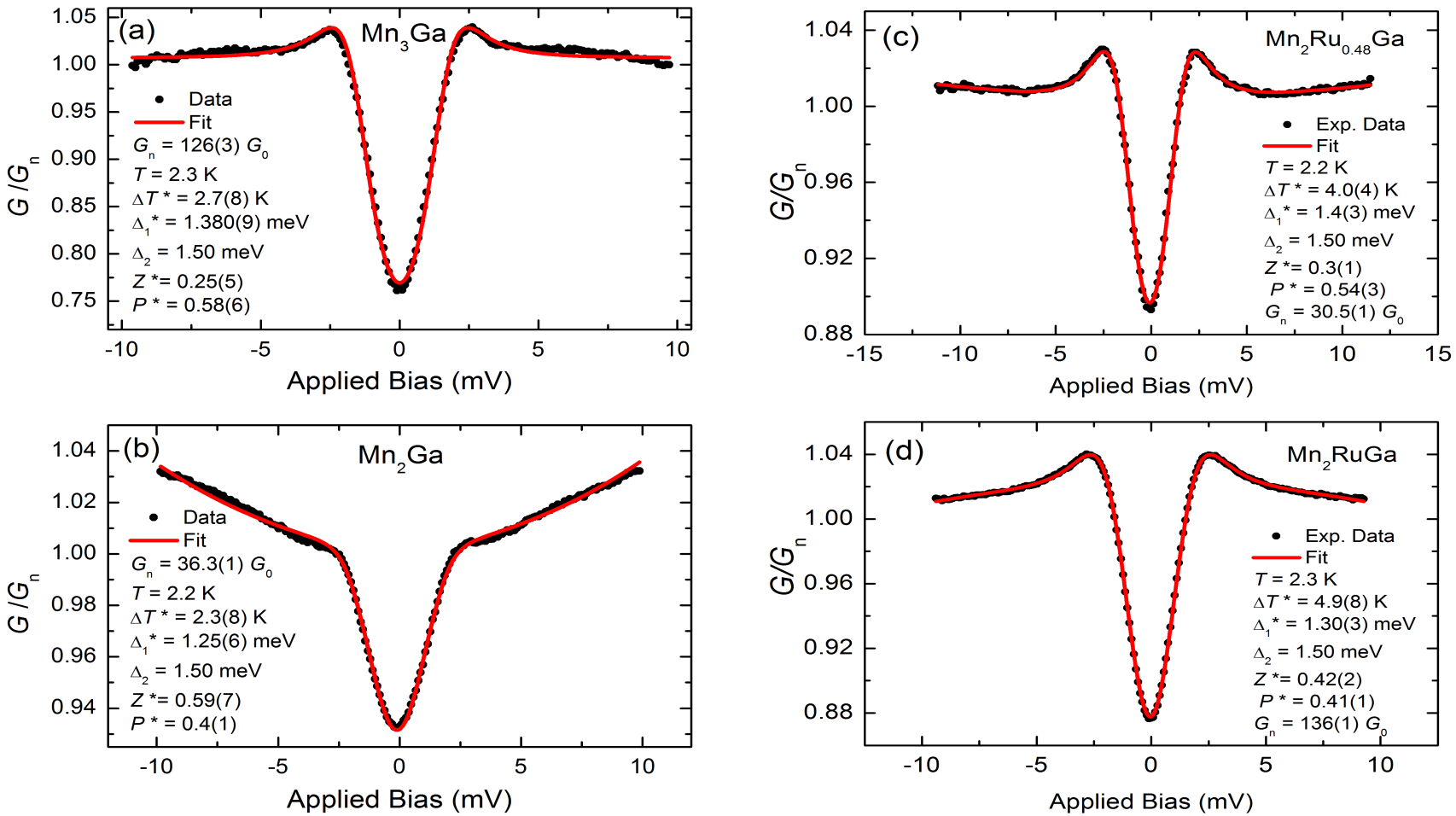

PCAR Summary

Film stack	Spin Polarization (%)	Resistivity (μΩcm)	Magnetization (kA m^{-1})
Pt/Mn_3Ga [62]	58	160	110
MgO/Mn_2Ga [61]	40	120	470
$SrTiO_3/Mn_3Ge$ [69]	46	-	73
MgO/Mn_2RuGa [72]	41	280	74
$MgO/Mn_2Ru_{0.48}Ga$ [72]	54	221	21

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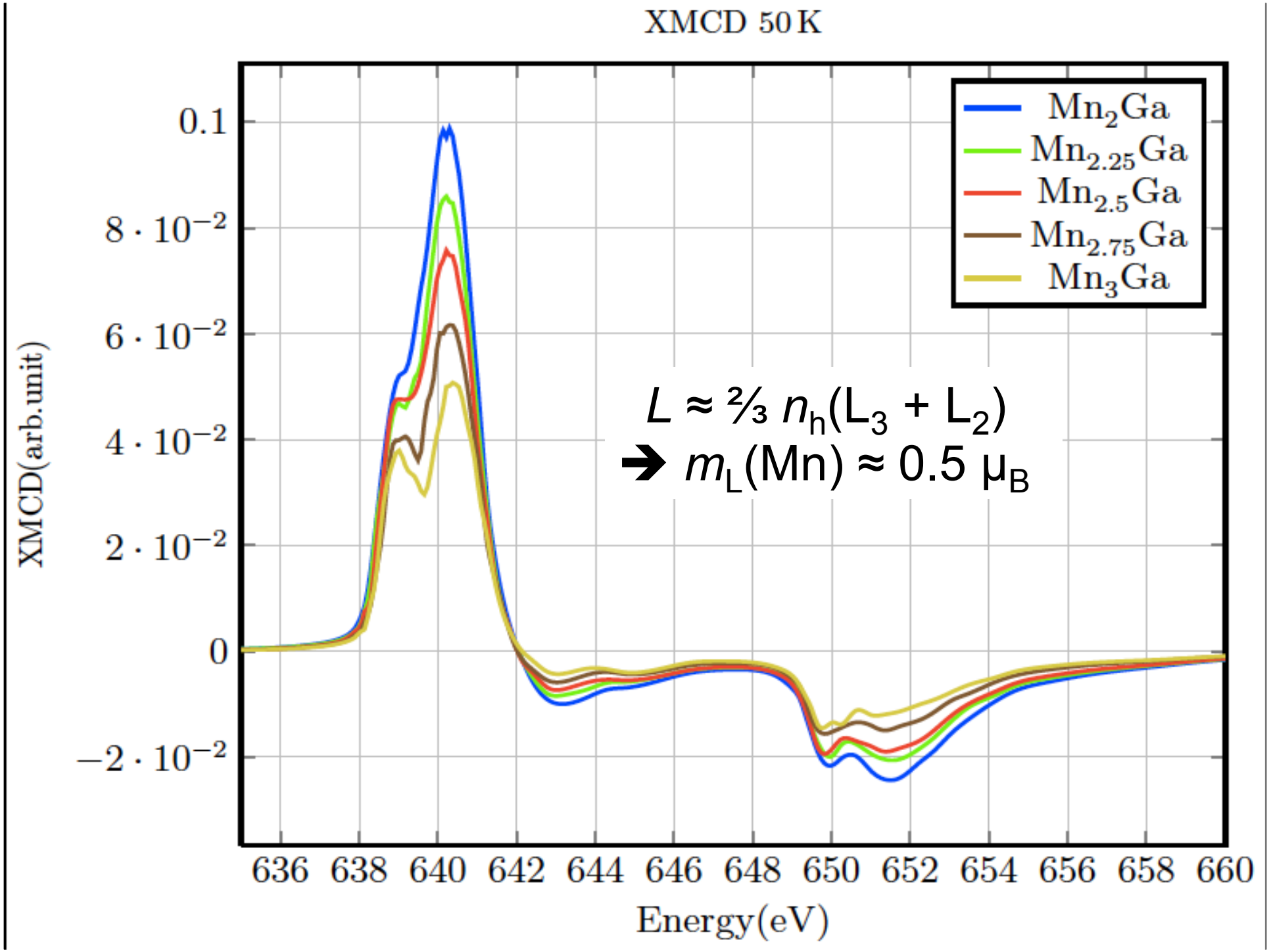
Summary

- Cubic $Mn_2Ru_{-.5}Ga$ is the first example of the long-sought zero-moment half metal. It has 21 valence electrons
- Biaxially strained cubic films grow on MgO 001 at 350 °C
- They have perpendicular anisotropy (K_u ~ 30 kJm^{-3}) and huge coercivity.
- Curie temperature is ~ 200 °C
- Fermi-level spin polarization at room temperature is ≈ 60%
- The material creates no stray field, and it is immune to external field
- MRG may serve as the pinned layer in ultra-thin stacks with no SAF (read heads), but MTJs have to be built.
- It could serve as the storage layer in memory, but STT switching needs to be demonstrated.


XMCD 50 K
Mn2Ga
Mn2.25Ga
Mn2.5Ga
Mn2.75Ga
Mn3Ga
0.1
8 · 10−2
6 · 10−2
4 · 10−2
2 · 10−2
0
−2 · 10−2
XMCD(arb.unit)
636 638 640 642 644 646 648 650 652 654 656 658 660
Energy(eV)
L ≈ ⅔ nh(L3 + L2)
➔ mL(Mn) ≈ 0.5 μB

2. Playing with the polar catastrophe

X. R Wang, W. M. Lv, Ariando, T. Venkatesan, H Hilgenkamp, J. M. D. Coey

H R Wang et al to be published

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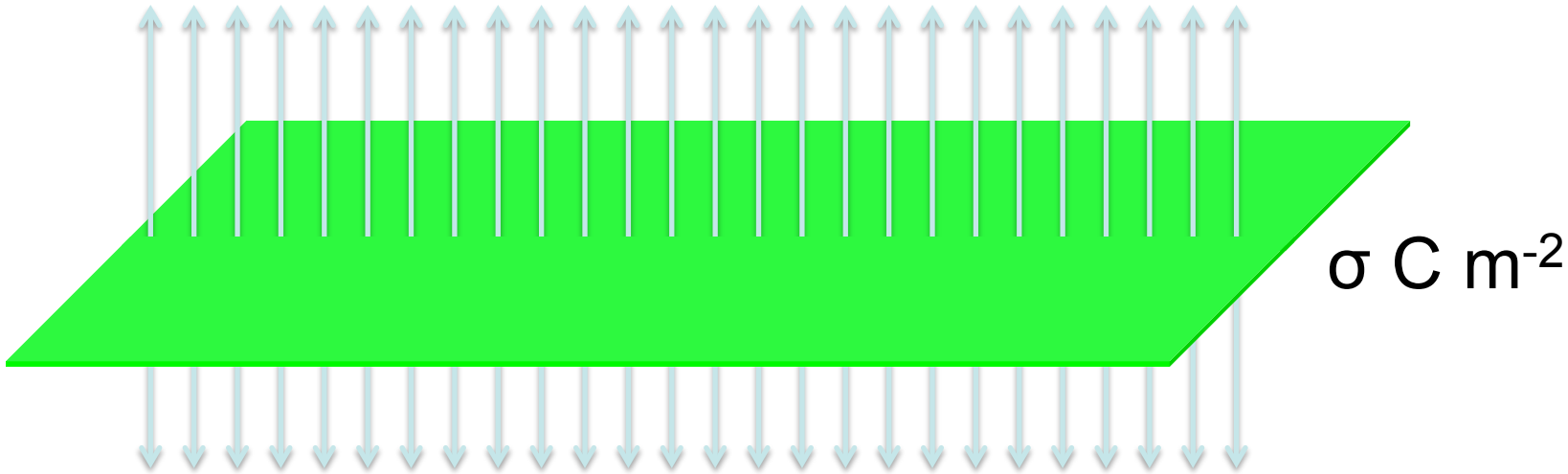
single charged sheet



Gauss law: $\int \boldsymbol{E}.\mathrm{d}\boldsymbol{A} = q/\varepsilon_0$ $\varepsilon_0 = 8.854\ 10^{-12}\ \mathrm{C\ V^{-1} m^{-1}}$

$\boldsymbol{E} = \sigma/2\varepsilon_0$ Taking $\sigma = 1\ \mathrm{C\ m^{-2}}$

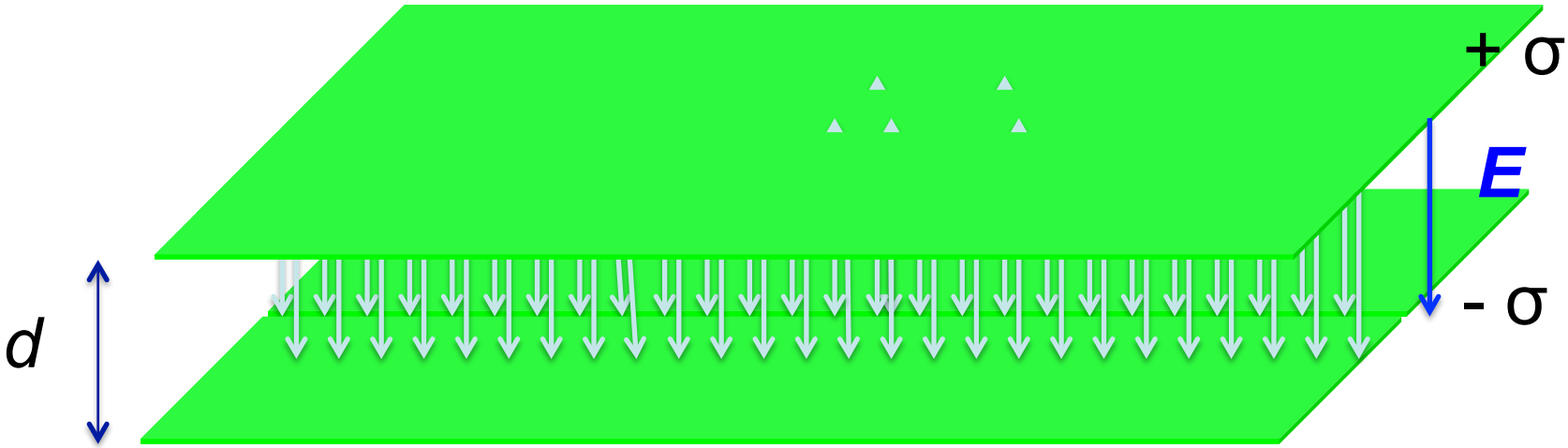
$\boldsymbol{E} = 57\ 10^9\ \mathrm{V\ m^{-1}}$

Energy density $\frac{1}{2}\varepsilon_0 E^2 = \sigma^2/8\varepsilon_0 = 14\ 10^9\ \mathrm{J\ m^{-3}}$

➔ ∞!

22 eV per unit cell! ($a_0 = 0.39$ nm)

double sheet



$\boldsymbol{E} = \sigma/\varepsilon_0$ Taking $\sigma = 1$ C m $^{-2}$

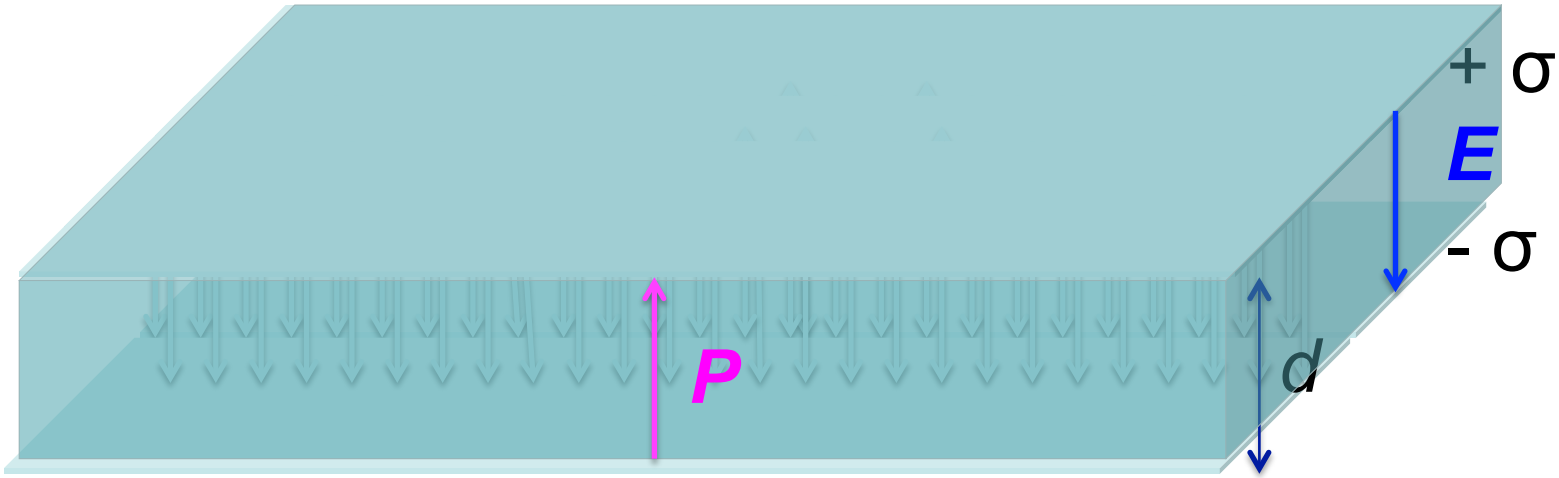
$\boldsymbol{E} = 113\ 10^9$ V m^{-1}

Areal energy density $(d/2)\varepsilon_0 E^2 = d\sigma^2/2\varepsilon_0$.

$= 22$ J m^{-2} if $d = a_0$

~ 20 eV/a_0^2

ferroelectric slab



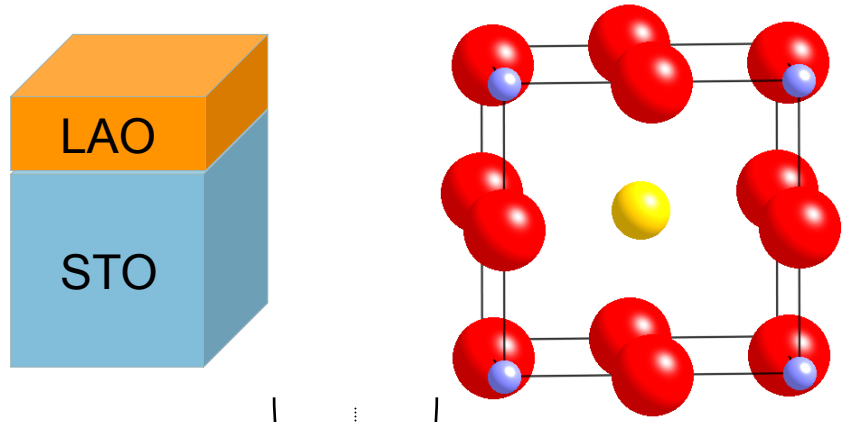
$\boldsymbol{E} = \sigma/\varepsilon_0$ $\qquad$ $\boldsymbol{P} = -\,\varepsilon_0\boldsymbol{E} = 1\ \mathrm{C\ m^{-2}}$

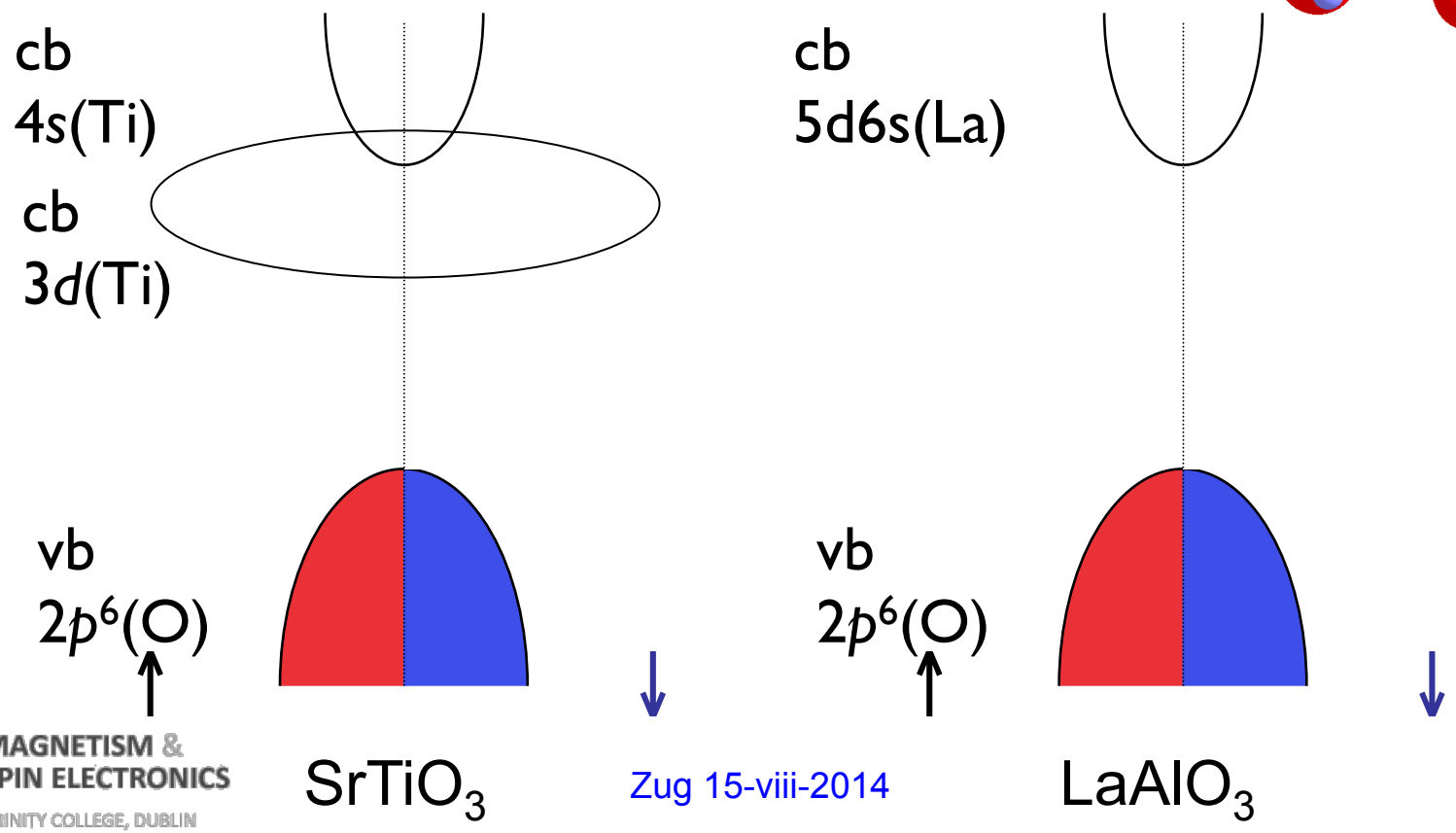
$\boldsymbol{E} = -\nabla V$ $\qquad$ $\boldsymbol{E} = 113\ 10^9\ \mathrm{V\ m^{-1}}$

The huge potential difference is neutralized by charges attracted to the free surfaces.

Perovskite interfaces

	E_g (eV)	a_0 (pm)	ε
$SrTiO_3$	3.2	391	300
$LaAlO_3$	5.6	379	24





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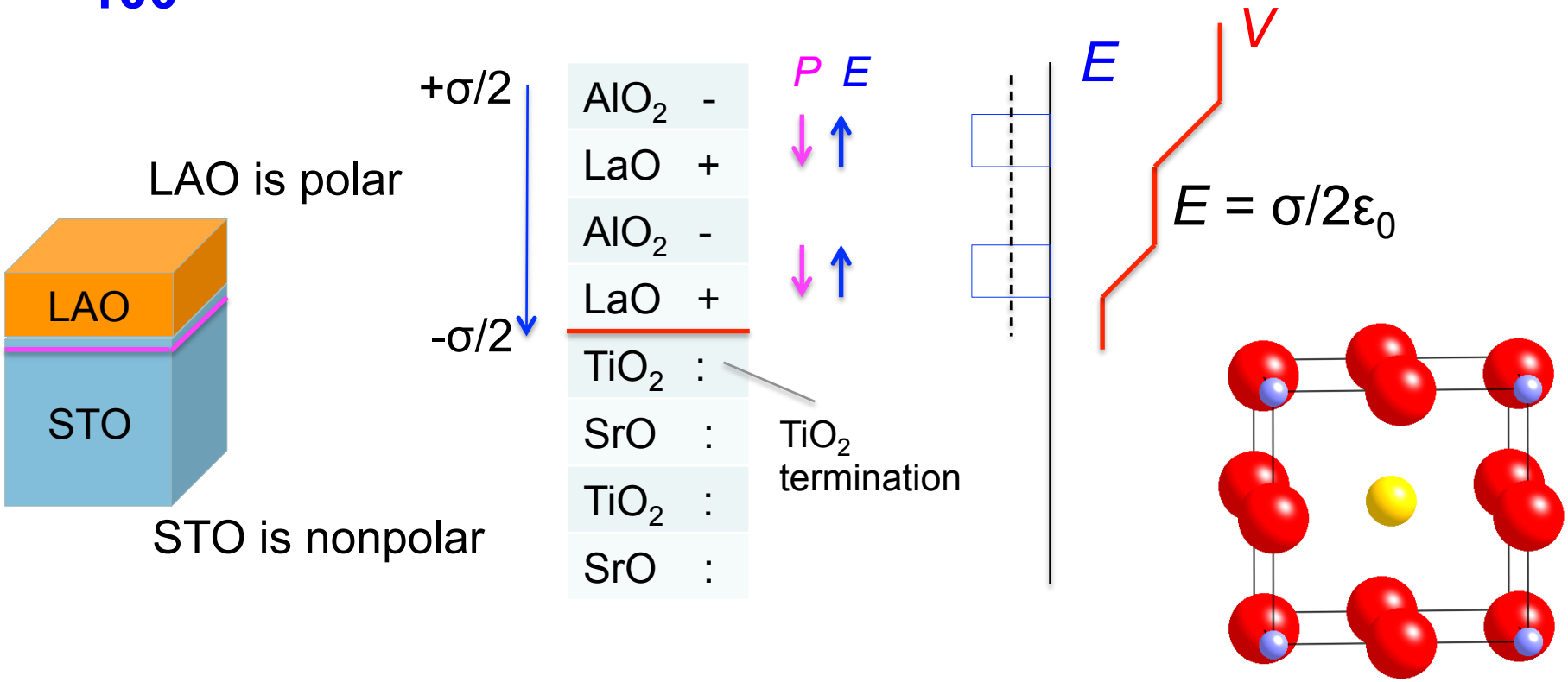
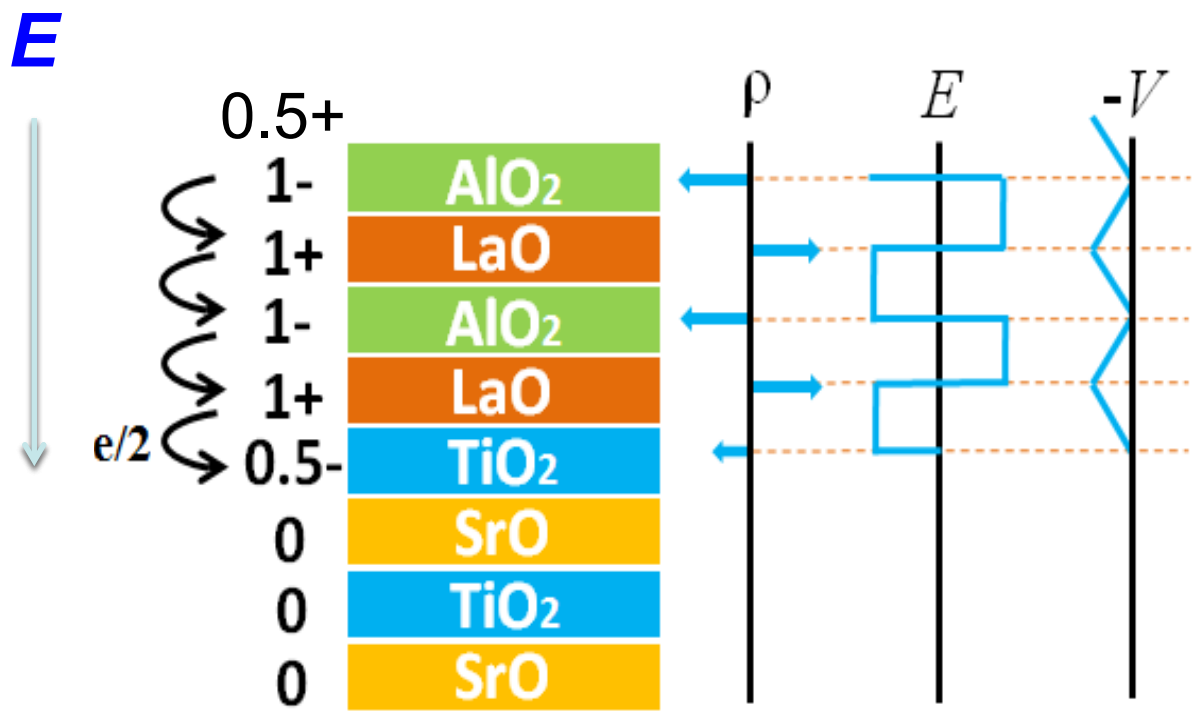


Charge transfer at the interface needed to avert the polar catastrophe is 0.5e / uc, or ~0.5 Cm^{-2} or 3.3 10^{18} electrons m^{-2}

Nakagawa, N. *et al. Nature Materials* 5, 204-209 (2006).

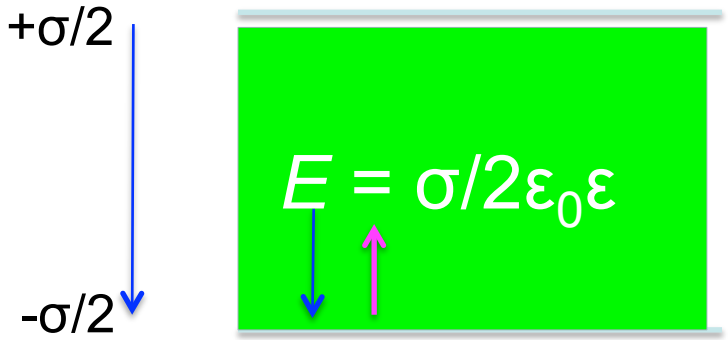


The surface charges of ±e/2 create a field ***E*** that prevents the internal field from diverging.

The top and bottom interfaces of the polar oxide are *coupled*

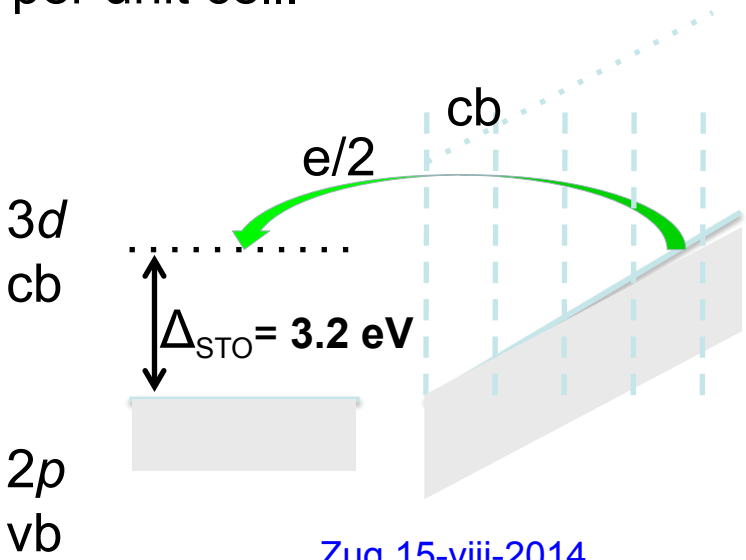
Where does the -σ/2 interface charge come from ?

$E_{ext} = \sigma/2\varepsilon_0$

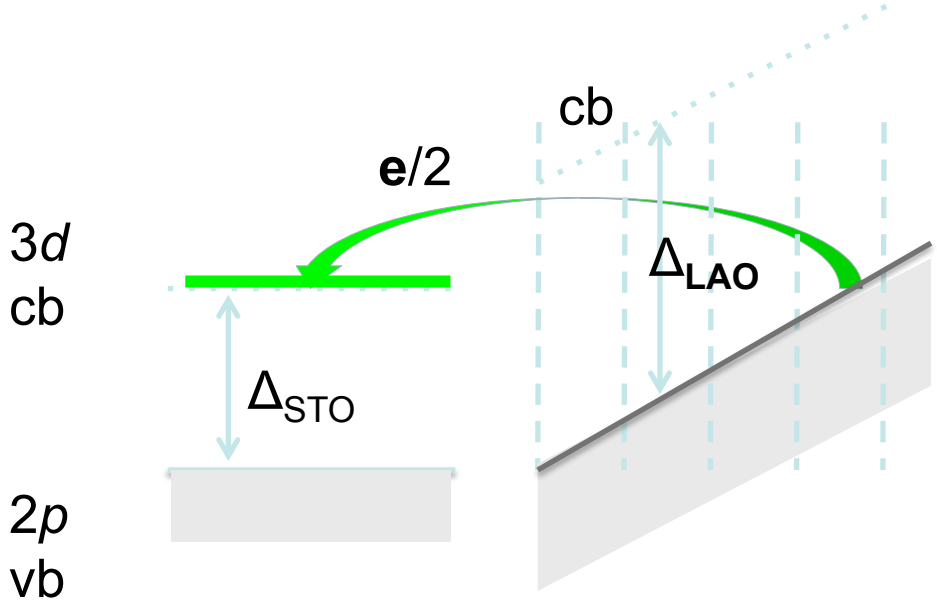


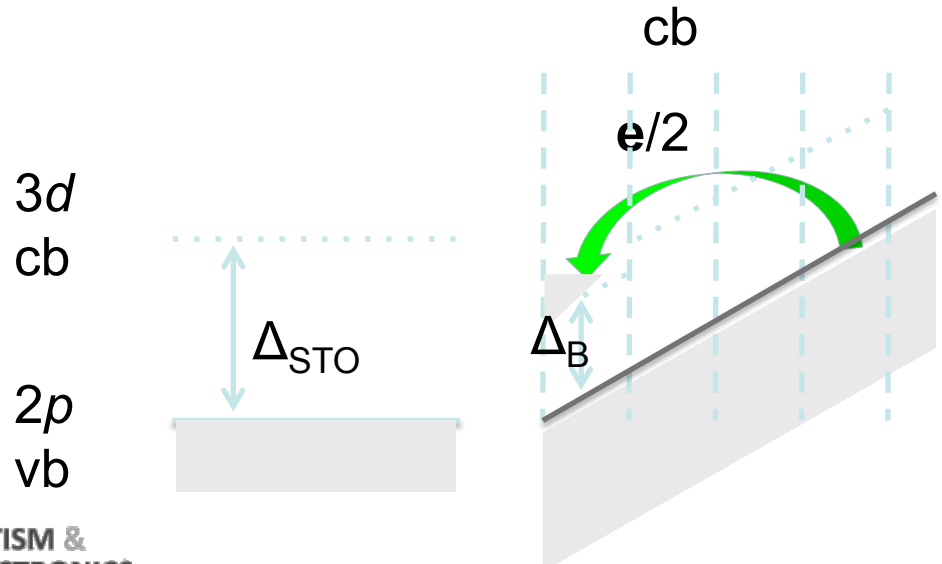
Polar LAO

The internal field in LAO is reduced by a factor ε from 57 V nm^{-1} to 2.4 V nm or 0.9 V per unit cell.

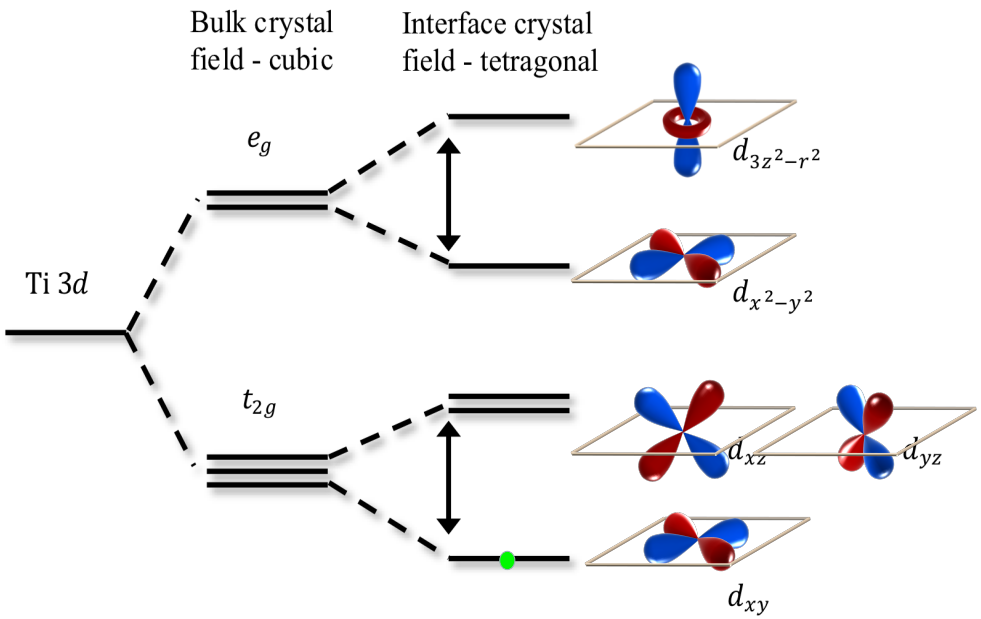


>4 uc of LAO are needed for electrons to be transferred to the bottom of the 3*d*(Ti) band.

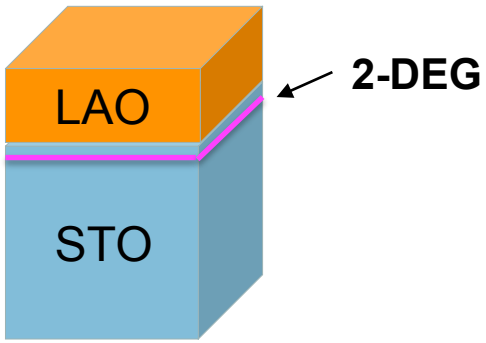

cb
e/2
3d
cb
Δ_{LAO}
Δ_{STO}
2p
vb

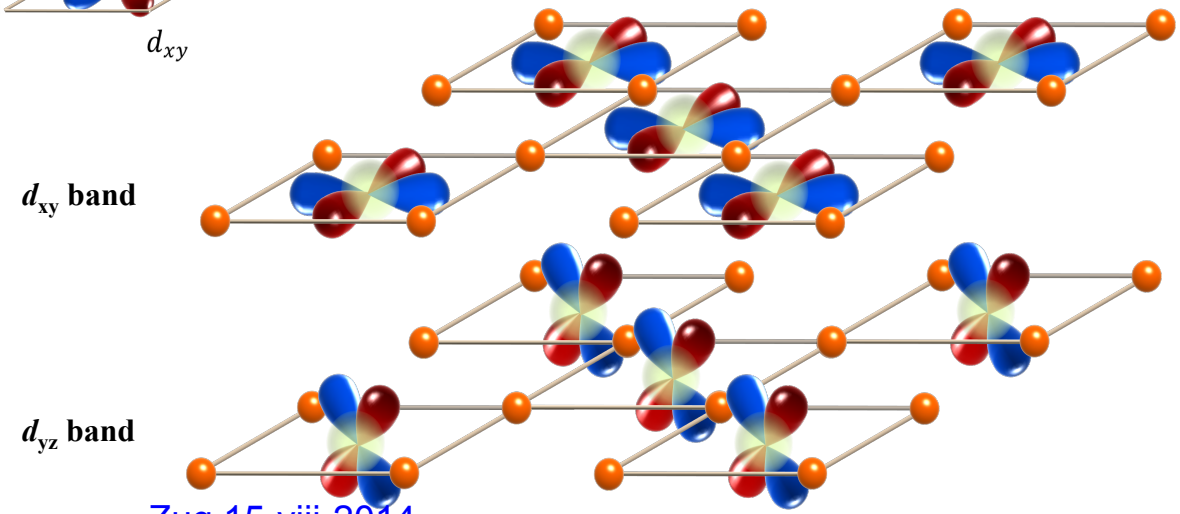

cb
e/2
3d
cb
Δ_{STO}
Δ_B
2p
vb

The 2-DEG at the STO interface is ferromagnetic



- Intrinsic or defect-induced ?
- d_{xy} or $d_{yz/zx}$ (or d_{x2-y2})
- Uniform or inhomogeneous?
- T_C ?





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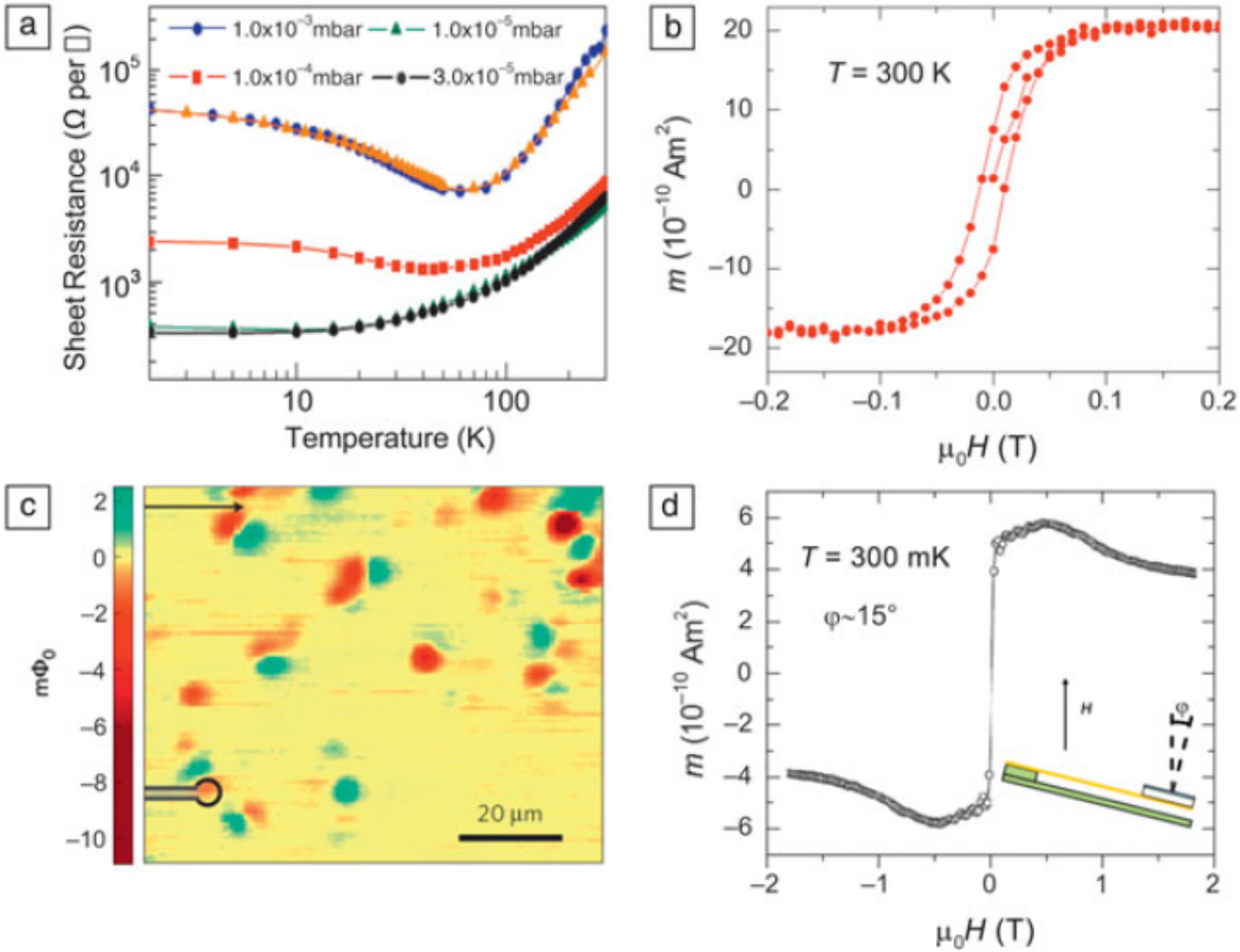
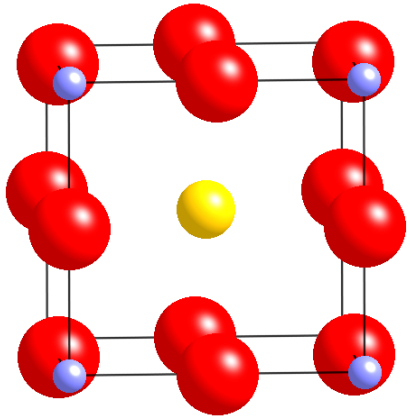


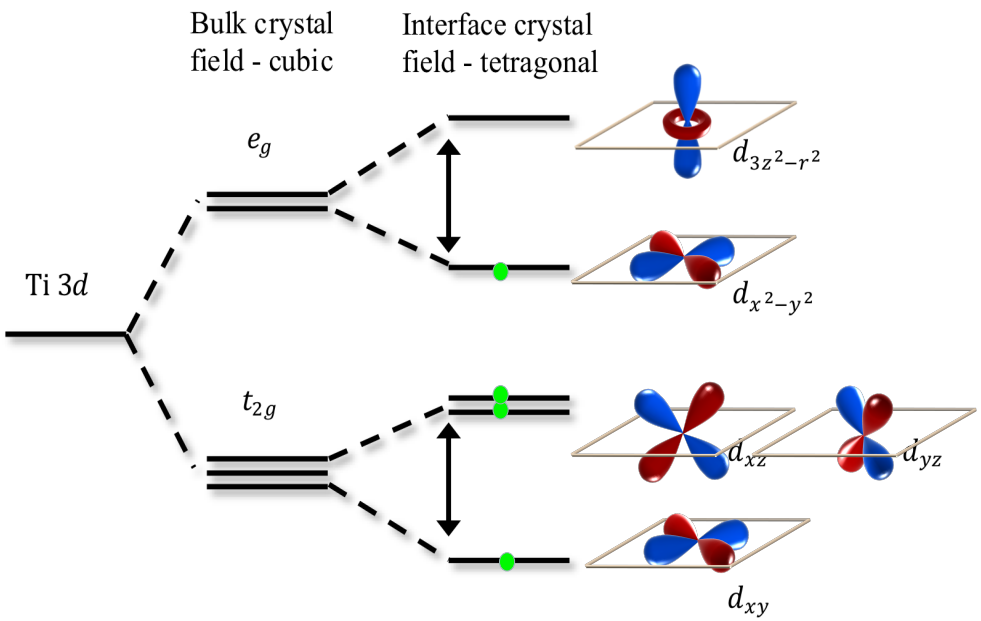
Figure 5. Evidence for magnetism of the two-dimensional electron gas at the $LaAlO_3/SrTiO_3$ interface. (a) Resistance showing a minimum associated with Kondo scattering for samples deposited at various oxygen pressures. Figure adapted with permission from Reference 51. (b) Magnetic moment measured with SQUID-VSM. Figure adapted with permission from Reference 52. (c) Direct imaging of a magnetic stray field using a scanning SQUID microscope. Figure adapted with permission from Reference 7. (d) Moment detected by torque magnetometry. Figure adapted with permission from Reference 54.

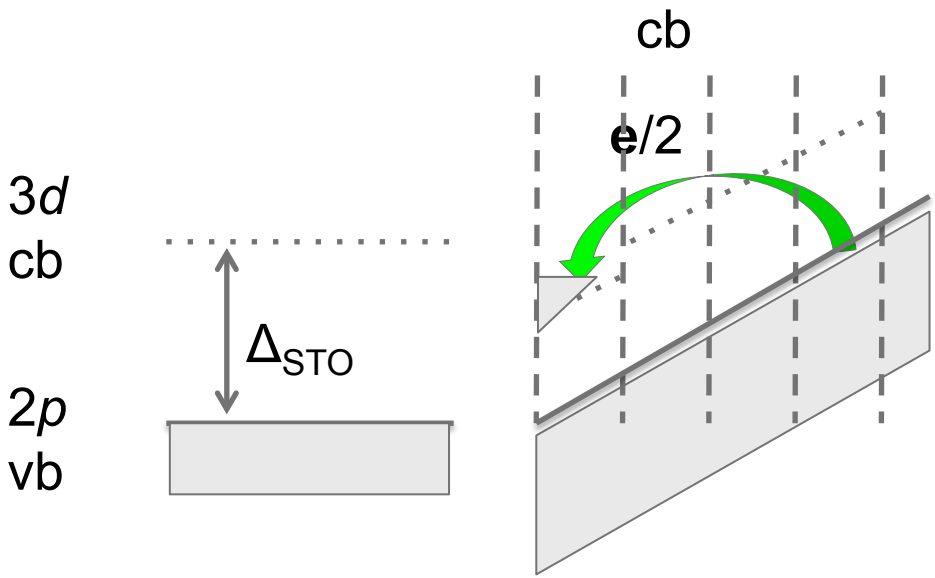
$LaMnO_3$

Orthorhombically-distorted perovskite $\sqrt{2}a_0, \sqrt{2}a_0, 2a_0$

Mn^{3+} $3d^4$ ($t_{2g}{}^3e_g$) is a Jahn-Teller ion that deforms its cubic environment. The oxide is an insulator, with in-plane orbital order and A-type antiferromagnetic order. T_N = 115 K.
Thin films are often ferromagnetic







In $LaMnO_3$, $\varepsilon = 70$, $E_0 = 0.85\ Vnm^{-1}$, $\Delta = 1.3$ eV $\Delta/E_0 = 4$ uc.

The charge transfer occurs within the manganite layer.

The extra electrons in the 3*d* band create some Mn^{2+} $3d^5$ states, and electron hopping introduces additional interlayer ferromagnetic exchange.

3. d^0 Magnetism

K. Ackland, M. Venkatesan, P. Stamenov, S. Sen J. M. D. Coey

J. M. D. Coey et al, New J Phys 12, 053025 (2010).

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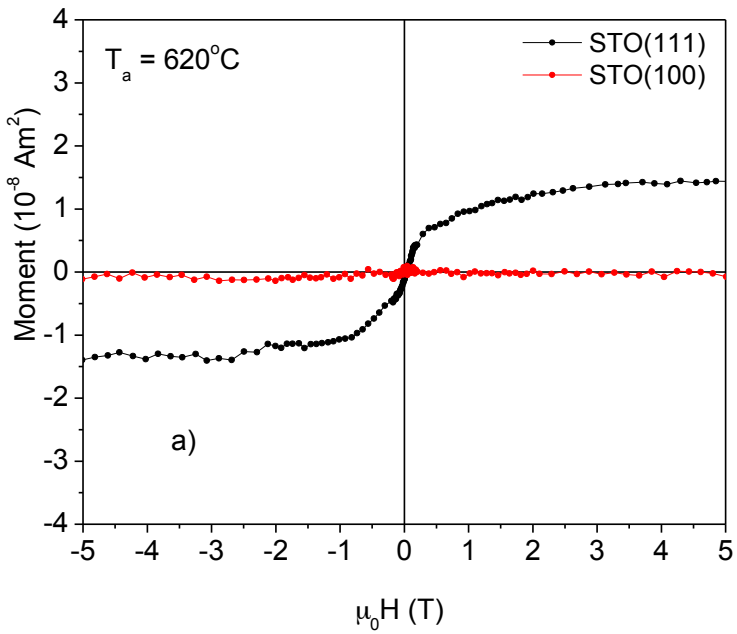
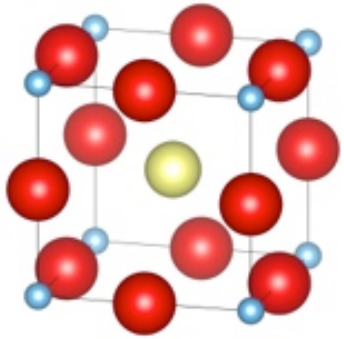
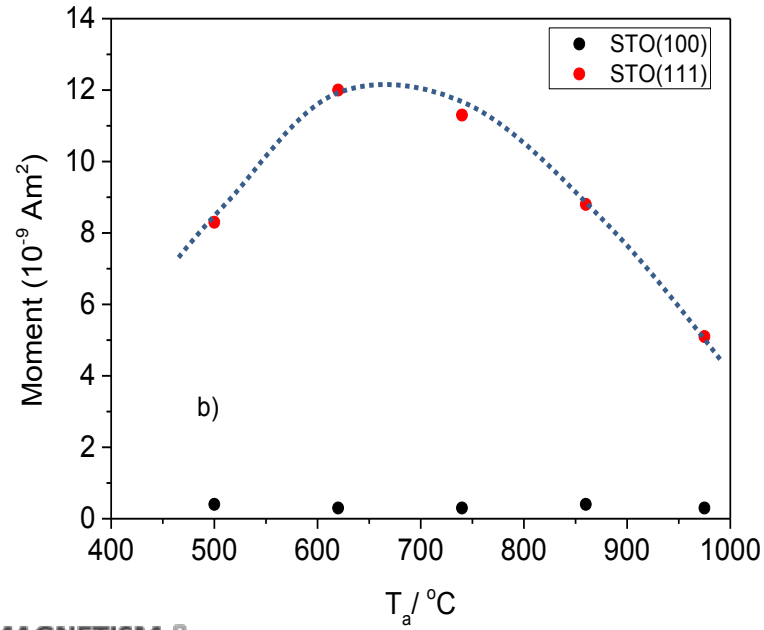


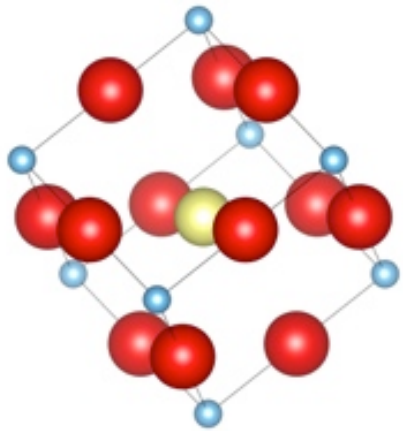
$SrTiO_3$

100





111



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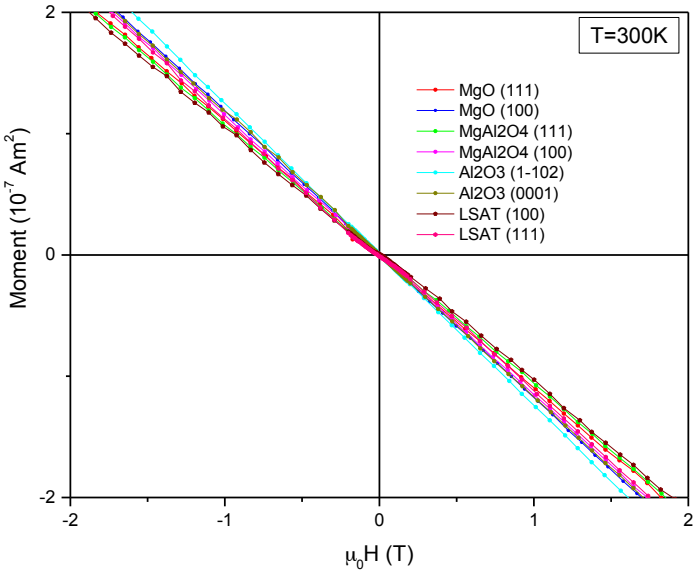


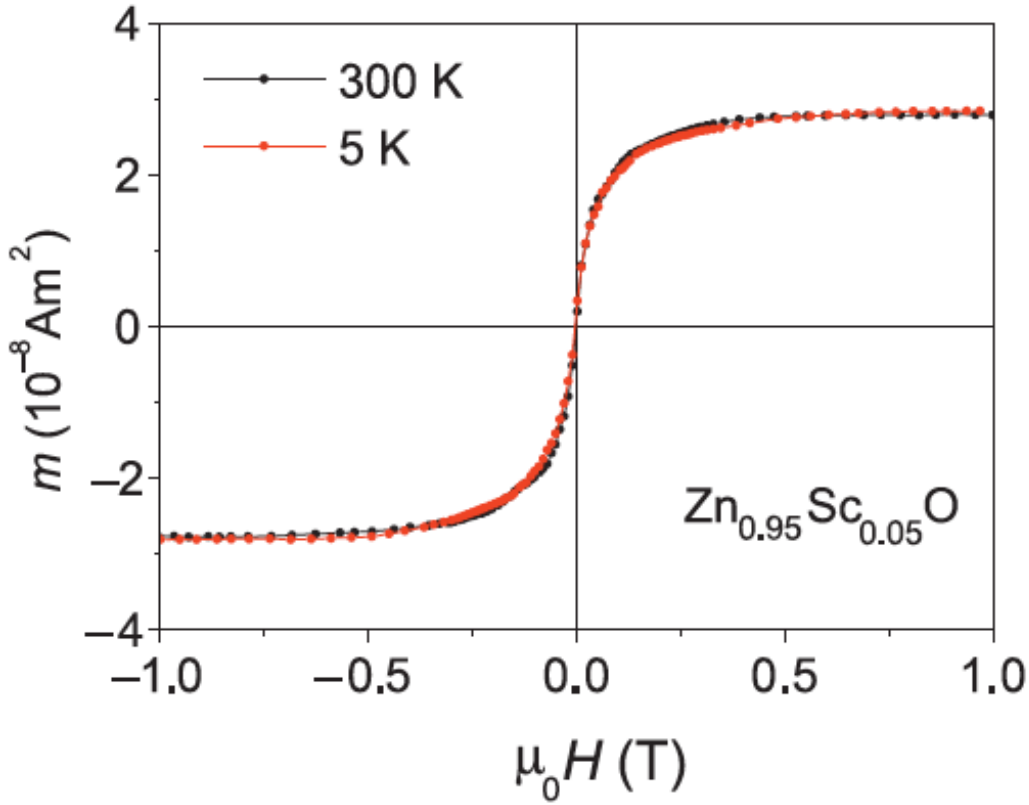
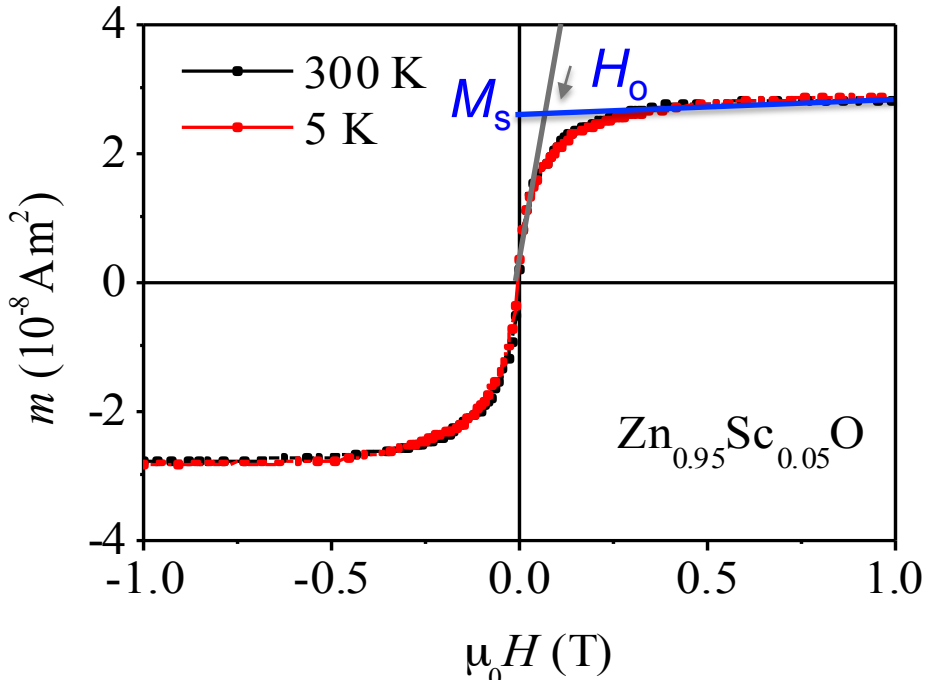


Figure 4. Magnetization of a typical d^0 material, a thin film of zinc oxide doped with scandium. The magnetization curves measured at temperatures between 4 K and 300 K exhibit a ferromagnetic-like saturation, with magnetization curves that superpose, after correction for the high-field slope. Figure adapted with permission from Reference 66.

d^0 magnetism



— Found for doped and undoped oxide thin films and nanoparticles

— At first they were thought to be ferromagnetic dilute magnetic semiconductors (DMS) $Zn_{0.95}Co_{0.05}O$

— 3*d* dopants do not order magnetically

— Magnetism is defect-related and *poorly-reproducible*

- Independent of temperature → T_C >> RT
- anhysteretic → dipole interactions
- M_s << H_0 → A tiny volume fraction *f* is ferromagnetic

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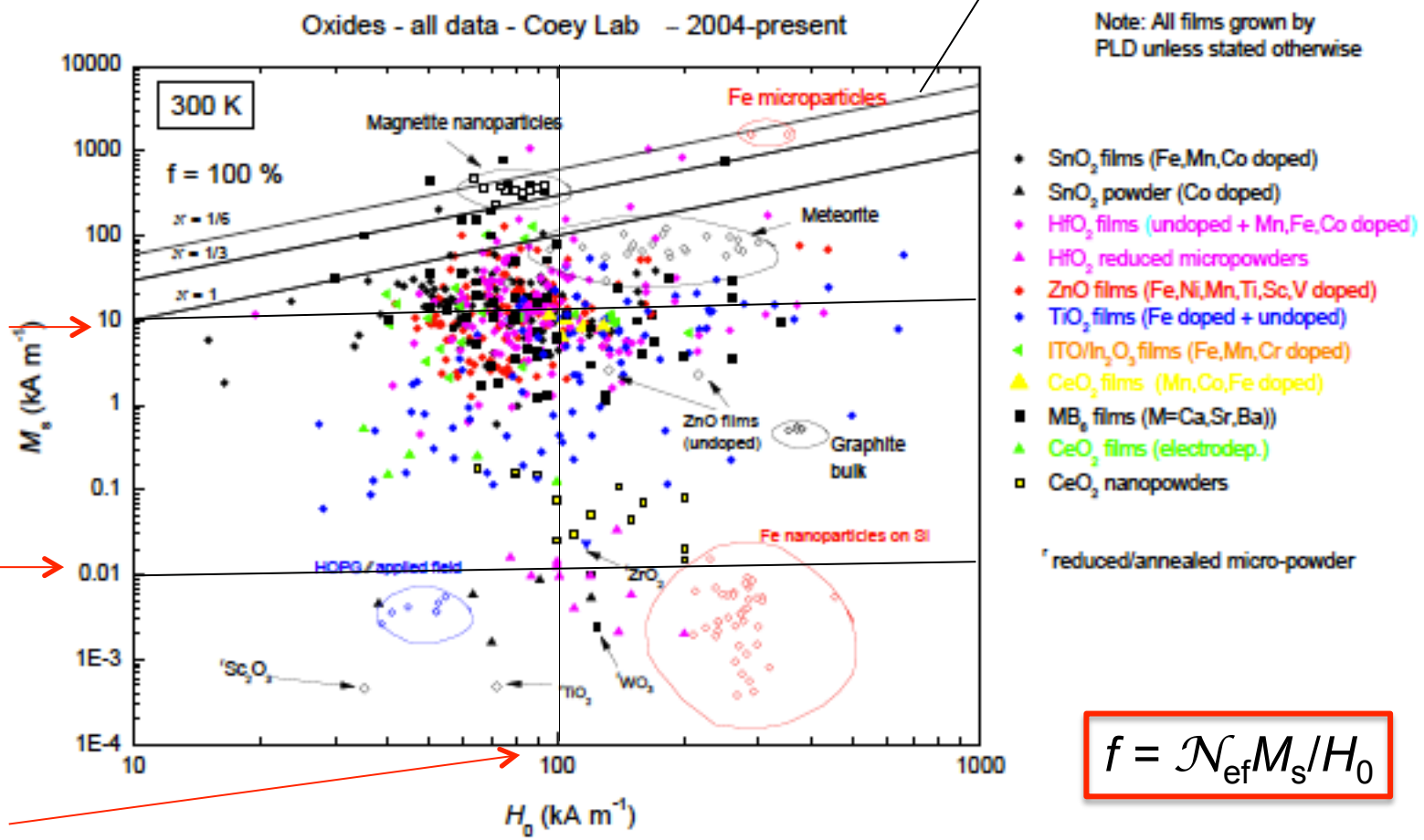
All Oxide data

100% volume fraction



$M_s \approx 10$ kA m^{-1}
films

$M_s \approx 10$ A m^{-1}
nanoparticles

$H_0 \approx 80$ kA m^{-1}

$$f = \mathcal{N}_{ef} M_s / H_0$$

$H_0 = -\mathcal{N}_{eff} M_0$ in thin films, only a few % of the volume is ferromagnetic

$M_0 \approx 240$ kAm^{-1} In nanoparticles, the volume fraction is ~ 10 – 100 ppm

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We need a ‘fruitfly’ system, where the data is reproducible, and no extraneous explanation is possible

CeO_2 nanoparticles - Literature

Literature data on magnetization, extrapolated saturation field H_0 and magnetic volume fraction f for CeO_2 nanoparticles

Av. radius r_0 (nm)	M_s (Am^{-1})	H_0 (kAm^{-1})	f * (10^{-6})	Surface treatment
3.5	7	60	40	-
7.5	11	40	90	-
5×1	550	80	2300	PEG
3	40	80	160	Oleic acid
3.5	1.5	120	4	Glutamic acid
2.7	25	70	120	NH_4OH
1.8	760	50	500	1,2 dodecandiol
2.5	150	32	1500	PEG
4.6	120	110	360	PVP
3.0	140	90	520	-
2.0	84(46)	120(38)	233	PEG

- $f = \mathcal{N}_{eff} M_s / H_0$

$\mathcal{N} \approx 1/3$

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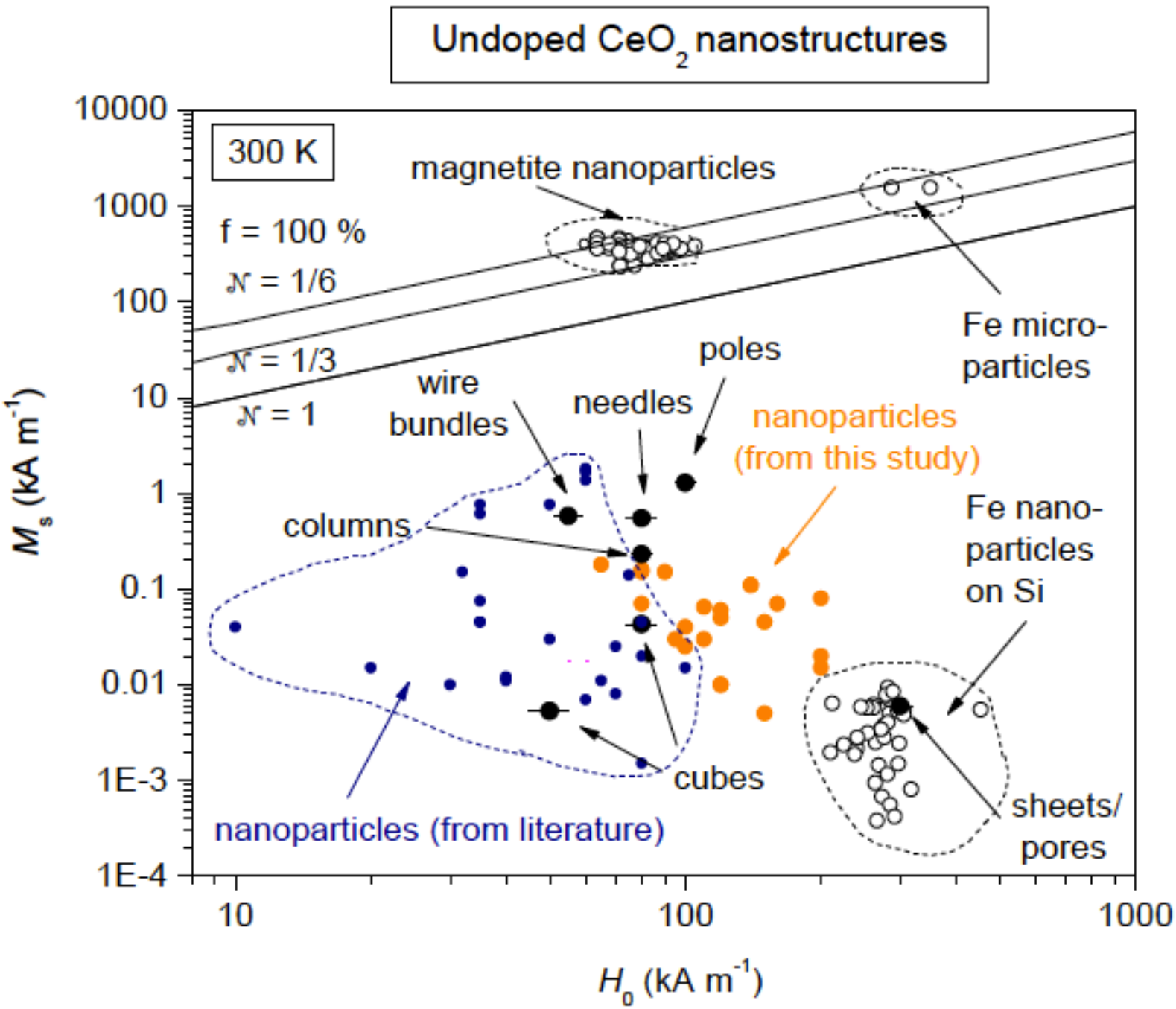
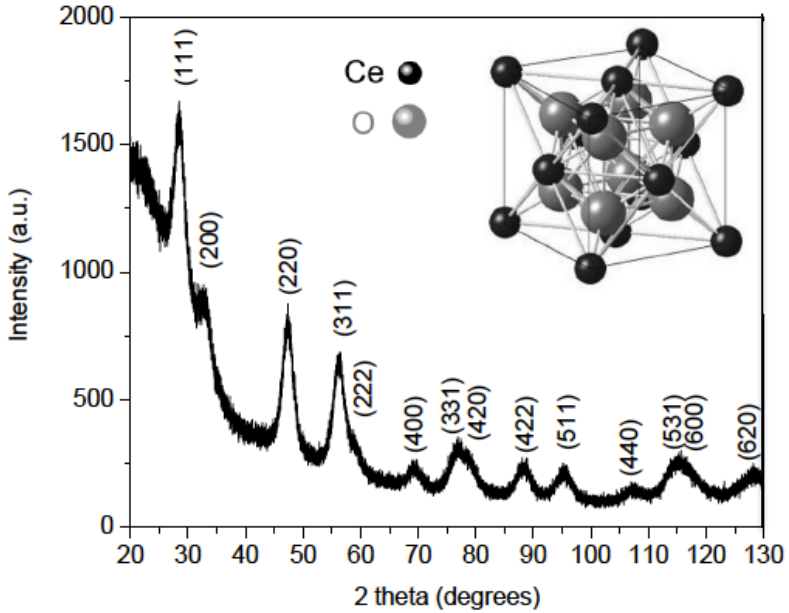
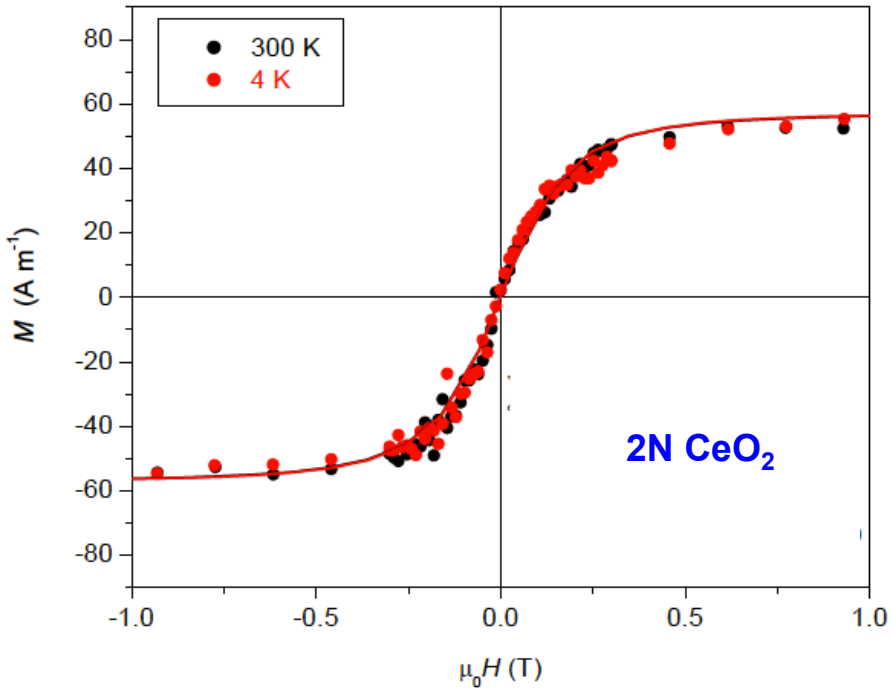
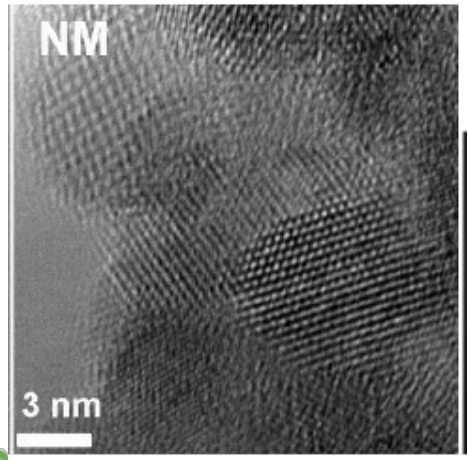
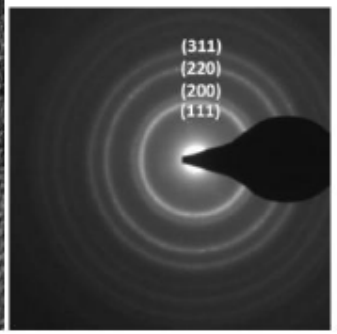

Undoped CeO2 nanostructures
300 K
f = 100 %
𝒩 = 1/6
𝒩 = 1/3
𝒩 = 1
magnetite nanoparticles
Fe micro-particles
poles
wire bundles
needles
nanoparticles (from this study)
columns
Fe nano-particles on Si
cubes
sheets/ pores
nanoparticles (from literature)
10000
1000
100
10
1
0.1
0.01
1E-3
1E-4
10
100
1000
Ms (kA m-1)
H0 (kA m-1)

CeO_2 nanoparticles - Characterization









Uniform 4 nm CaF_2-structure nano particles of $CeO_{2-\delta}$ are precipitated from $CeNO_3$ + PEG solution. Moment ~ $0.2\mu_B$/particle (900 Ce)

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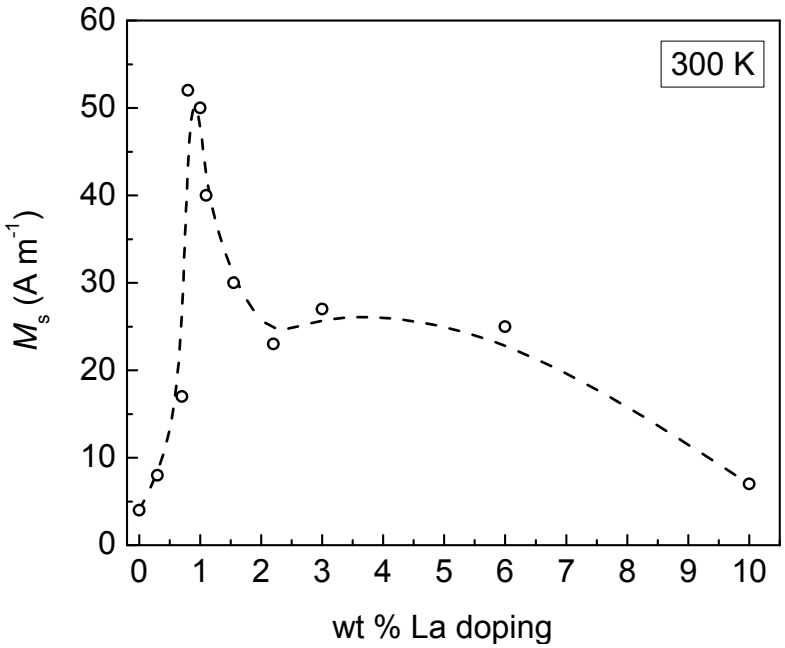
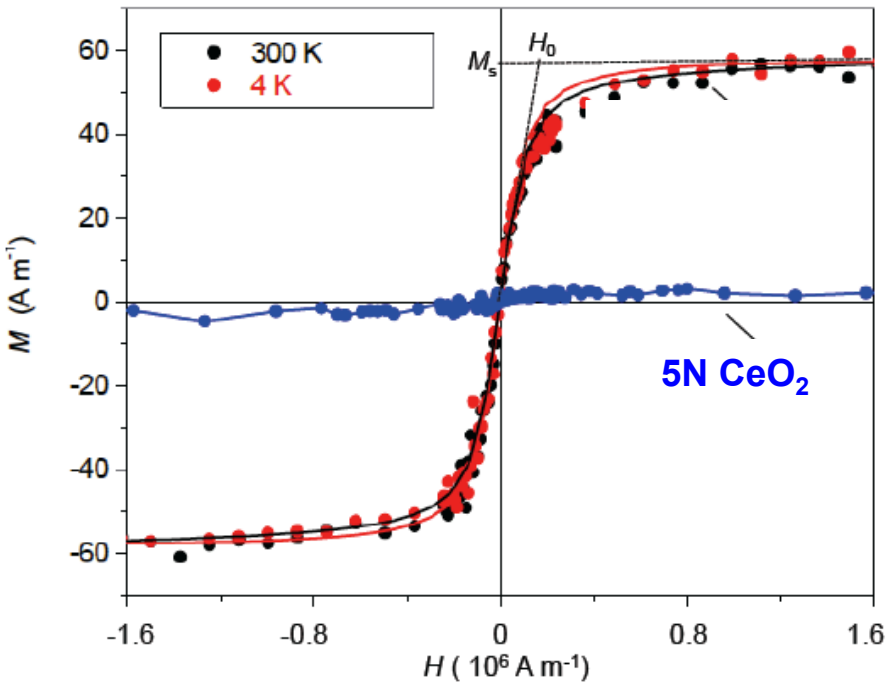
CeO_2 nanoparticles – La doping



La-doping of 5N pure $CeO_{2-\delta}$ turns on the moment — maximum for 1%



Nanoparticles from 5N precursor are not magnetic, but 2N particles showed 'ferro-magnetic" signal.

Σ 3*d* impurities < 10 ppm.

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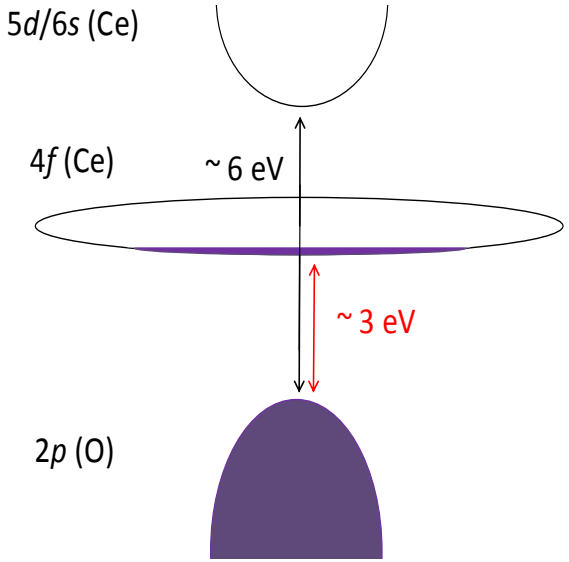
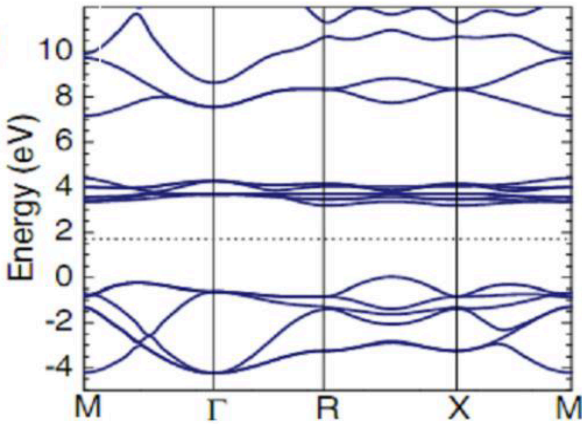
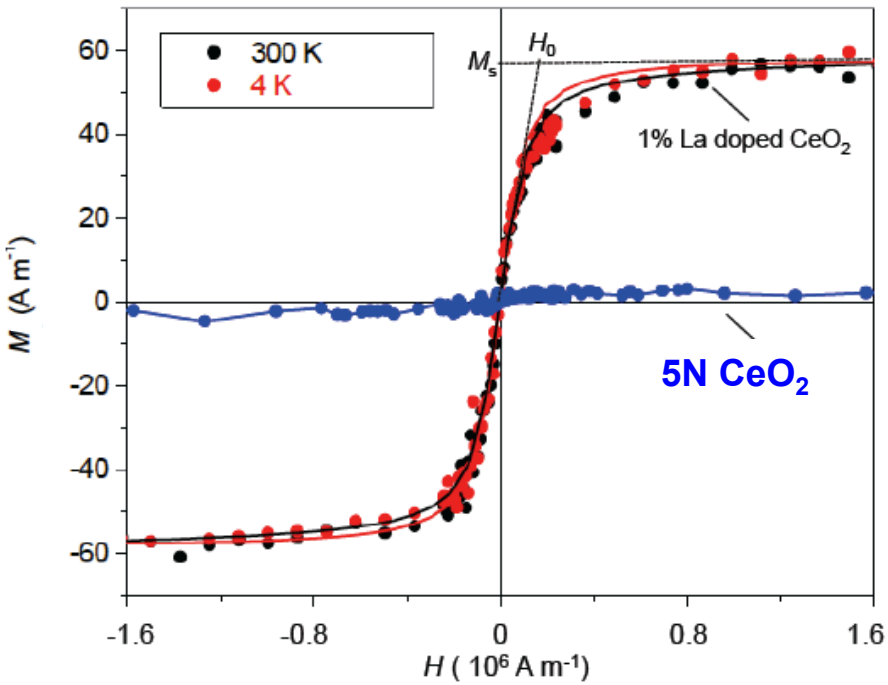
CeO_2 nanoparticles



Any Ce 4*f* electrons are delocalized (~ no Curie-law upturn in susceptibility < 0.4% of Ce).

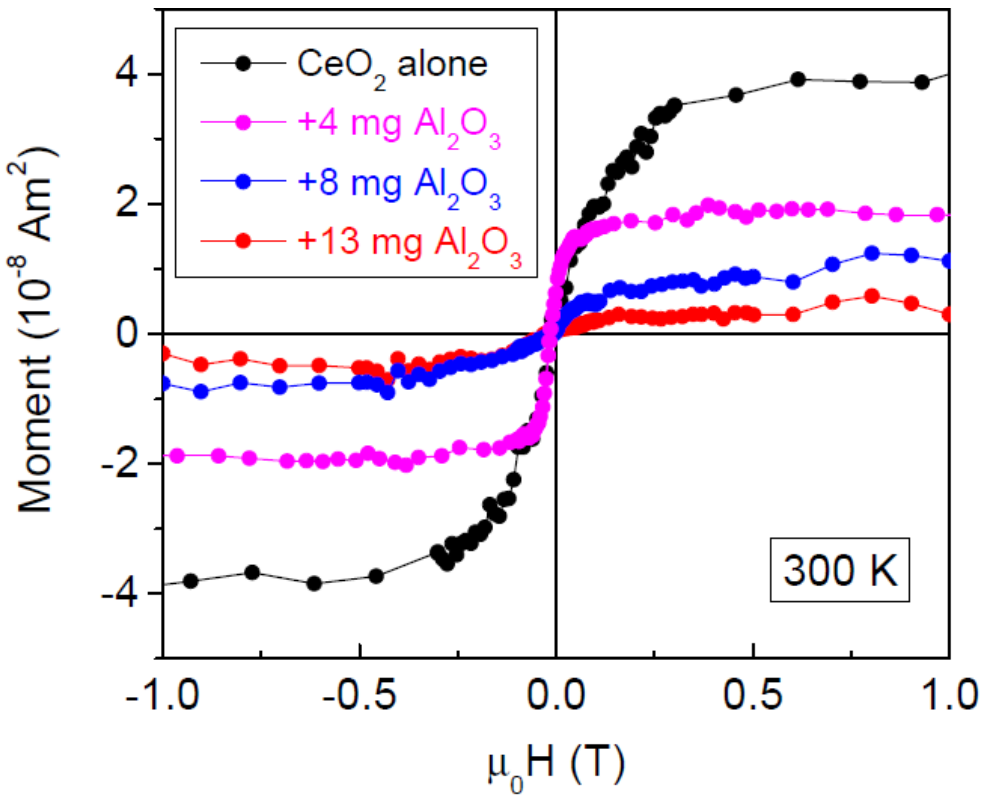


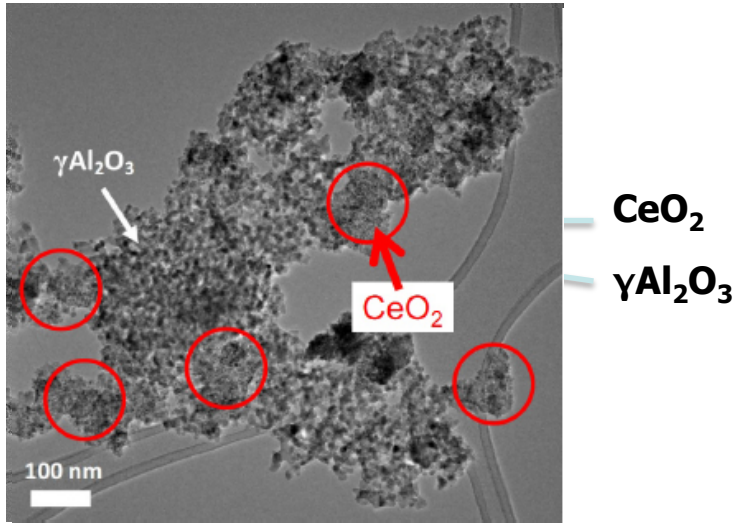


Nanoparticles from 5N precursor are not magnetic, but 2N particles showed 'ferro-magnetic" signal, due to La impurities

Surfaces of oyygen-deficient nanoparticles are conducting

Effect of dilution– 15nm γAl_2O_3





Progressive dilution with nonmagnetic 15nm γAl_2O_3 nanoparticles makes the moment disappear !

6 x dilution (by volume) reduces moment by 94%

Dilution with 15nm γAl_2O_3 breaks the CeO_2 into clumps < 100 nm in size

Moment is *stable* in time. It diminishes by < 10% in a year

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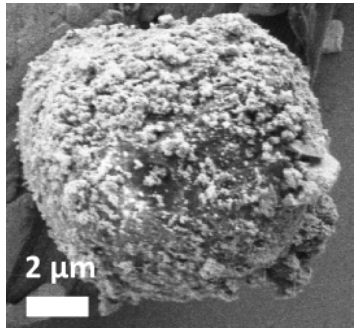
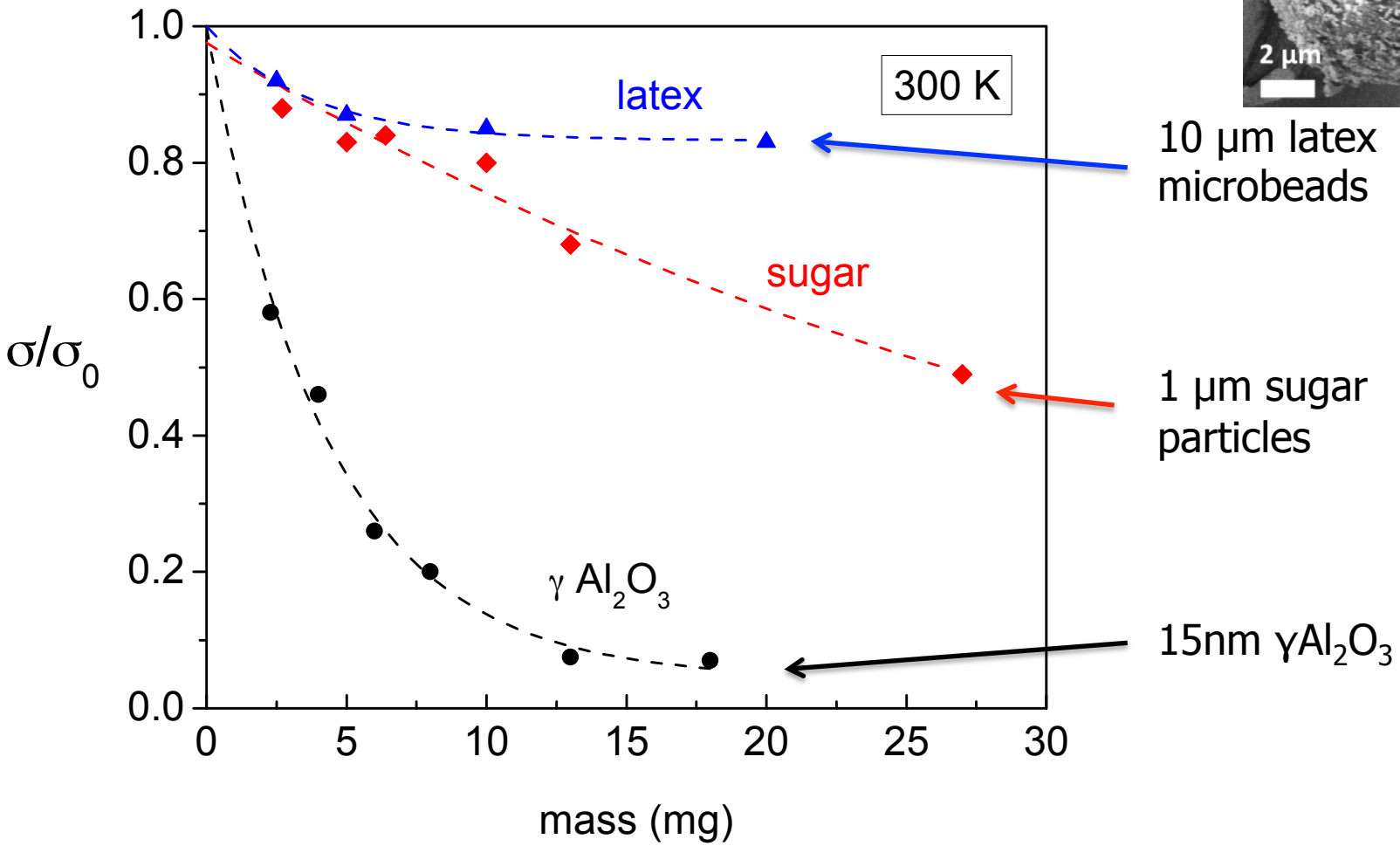
Dilution – Summary





The smallest particles are most effective.

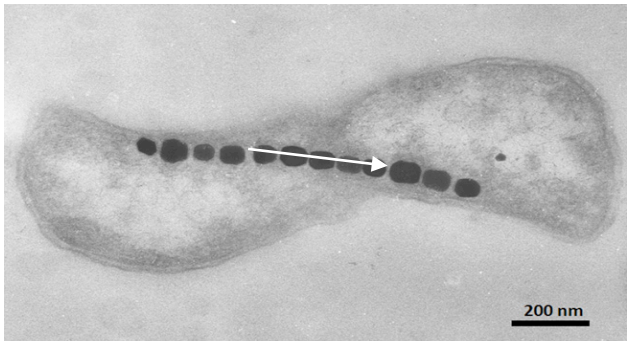
After dissolving the sugar, the moment reappears (increased)

Summary of results

This behavior seems unprecedented in the literature on magnetism: There is no evidence of superparamagnetism (scaling of M with H/T) and $H_{dipolar}$ is 1000 times too small for superferromagnetism

1. The energy scale is unusually large. The absence of temperature dependence from 4 K to 300 K suggests a 'Curie temperature' of order 1000 K

2. There is a mesoscopic length scale of order 100 nm needed for a collective magnetic response to appear.



Bacterium with ~50 nm Fe_3O_4 nanoparticles
Moment > 1000μ_B/particle

- How can we understand it ?

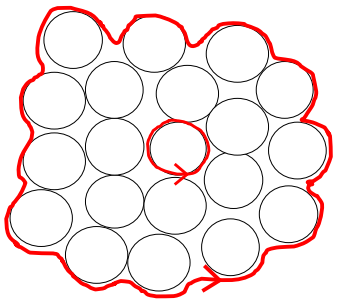
An explanation

— It has nothing to do with ferromagnetism (No Ce compound has T_c > 125 K!)

An explanation

— It has nothing to do with ferromagnetism (No Ce compound has T_c > 125 K!)

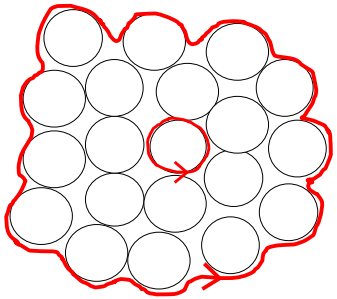
— We are looking at giant orbital paramagnetism associated with persistent electric currents in coherent domains > 100 nm is size.



An explanation

— It has nothing to do with ferromagnetism (No Ce compound has T_c > 15 K!)

— We are looking at giant orbital paramagnetism associated with persistent electric currents in coherent domains > 100 nm is size.



— Quantum field theory envisages such coherent domains due to resonance with vacuum fluctuations of the electromagnetic field. (cf Casimir force), which renormalizes the interaction by $\sqrt{N}$, where N is the number of particles (Ce atoms) in the coherent domain .

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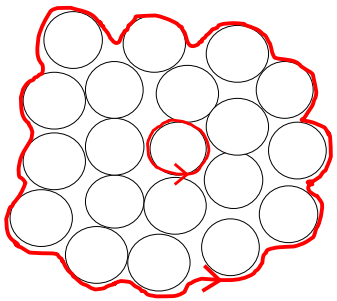


— Quantum field theory envisages such coherent domains due to resonance with vacuum fluctuations of the electromagnetic field. (cf Casimir force), which renormalizes the interaction by $\sqrt{N}$, where N is the number of particles (Ce atoms) in the coherent domain.

— The theory predicts that the magnetization curve should be of the form

$$M = M_s x/(1 + x)^{1/2} \qquad (1)$$

E del Guidice et al, PRL 61 1085 (1985)

An explanation

$$\mathcal{H} = \sum^{N}_{i=1} L_i^2/2mr^2 + \mathbf{A.J}$$

$$P = \mathbf{e}_{\mu}.\mathbf{e}_{B},$$

$$P = \kappa \sin 2\alpha \qquad \kappa \approx 0.37$$

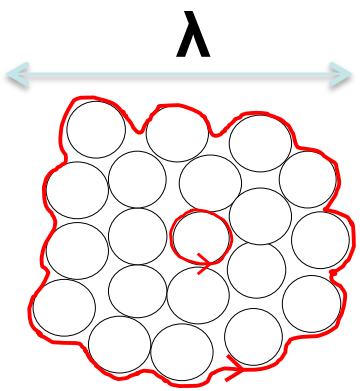
$$\tan \alpha = [1 + (1+x^2)^{1/2}]/x,$$

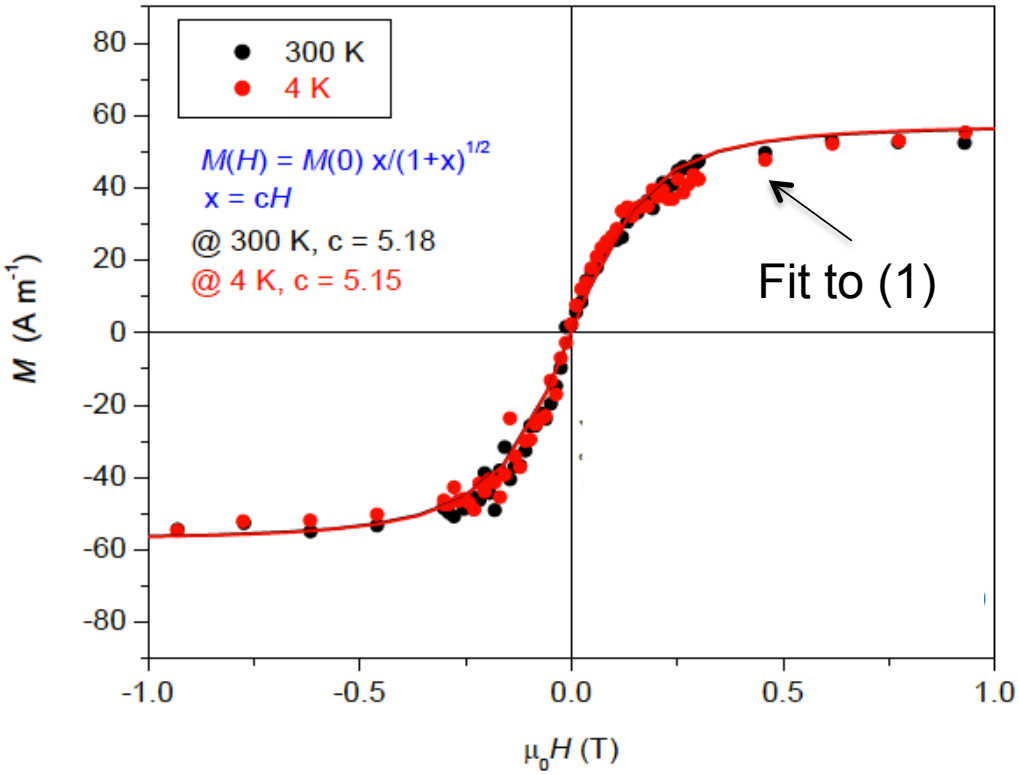
$$x = 2V/\hbar\omega = cB \qquad V = \mu B$$

$$P = \kappa\, x/(1 + x^2)^{1/2} \qquad \textbf{(1)}$$

$$c = 9.4 \pm 0.7\ \mathrm{T}^{-1} \text{ and } \kappa M = 58 \pm 1\ \mathrm{A\ m}^{-1}.$$

An explanation





$x = CB$ (2)

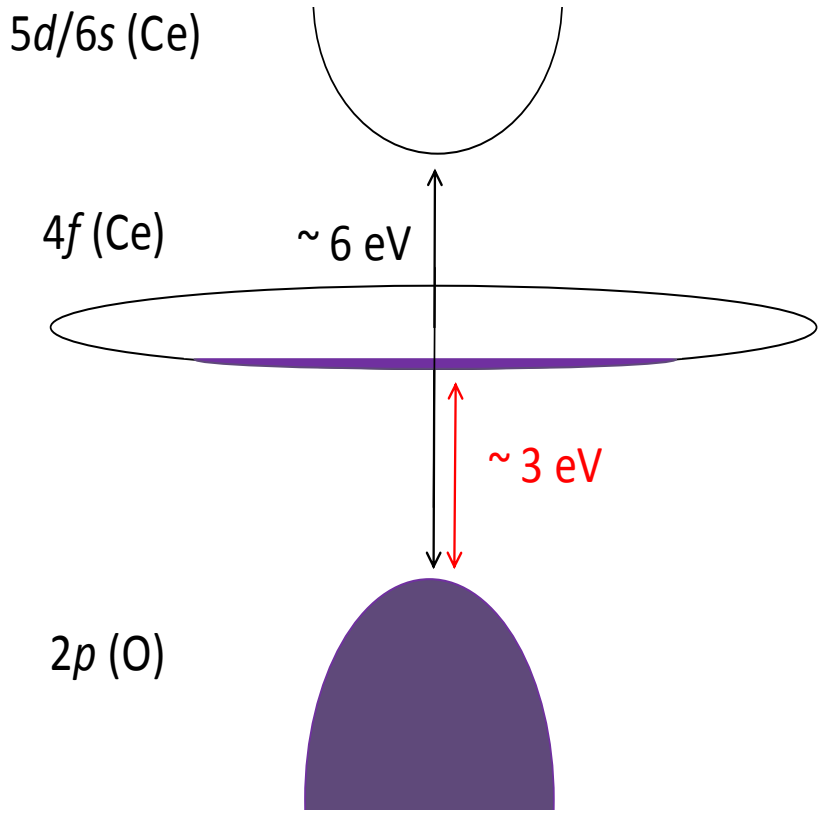
$x = 2V/\hbar\omega$ where $V = mB$
$= (\pi/6)\lambda^3 MB$

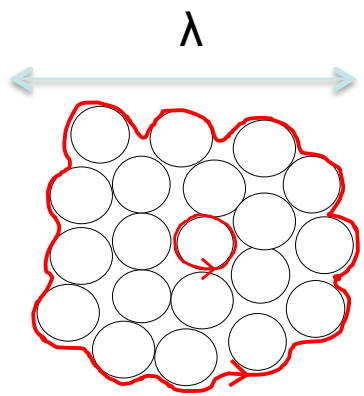
$\lambda = 2\pi c/\omega$ the wavelength of the em radiation is identified with the size of the coherent domain

$$\lambda^4 = 3hcC/\pi M_s \qquad (3)$$

— Fitting the magnetization curves gives both the length scale and the energy scale for the system

An explanation





C = 9.4 (7) T^{-1}

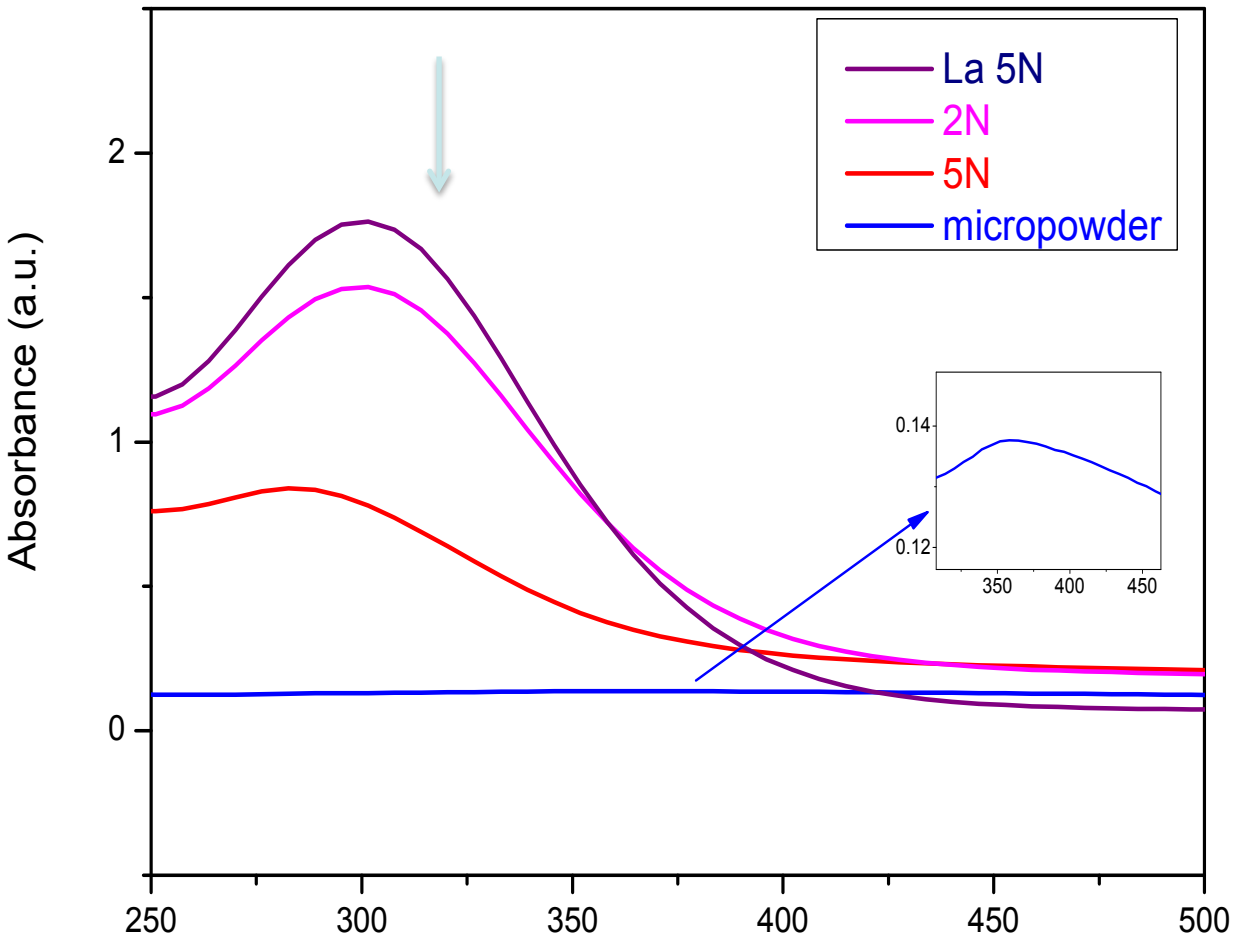
M = 58 Am^{-1}

λ = 327 nm

$\hbar\omega$ = 3.8 eV

A coherent domain is 320 nm in size contains $N = 5\ 10^8$ Ce atoms or ~ $5\ 10^5$ nanoparticles with a moment $\mu = 2\ 10^5\ \mu_B$. The moment per nanoparticles in the coherent domain is 2.4 μ_B ➔ 8% of the sample is in the coherent state.

UV absorption spectrum



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Summary

- Clusters of 4 nm CeO_2 nanoparticles exhibit *giant orbital paramagnetism.*
- The orbital currents are due to resonant coupling with zero-point fluctuations of the electromagnetic field in coherent domains ~ 300 nm is size.
- This *may* be the first evidence of an influence of these fluctuations in condensed matter.
- If true, many more manifestations of the effect are anticipated (Water at biological membranes, interfacial nanobubbles……)

Conclusions

- Magnetism at the edge is full of shocks and surprises
- Biaxial strain on an oxide substrate has enabled growth of Cubic $Mn_2Ru_{0.5}Ga$ is the first zero-moment half-metal. Its usefulness in spin electronics now has to be demonstrated.
- Large orbital moments may be lurking near the surface of (some) 3*d* ferromagnetic films.
- The 2-dimensional electron gas forming in 100 $SrTiO_3$ near an interface with 100 $LaAlO_3$ to avert a polar catastrophe is ferromagnetic.
- The same mechanism switches thin films of $LaMnO_3$ from antiferromagnetic to ferromagnetic
- d^0 magnetism cannot be explained within the existing paradigm
- $m_{\text{sample on substrate}} \neq m_{\text{sample}} + m_{\text{substrate}}$

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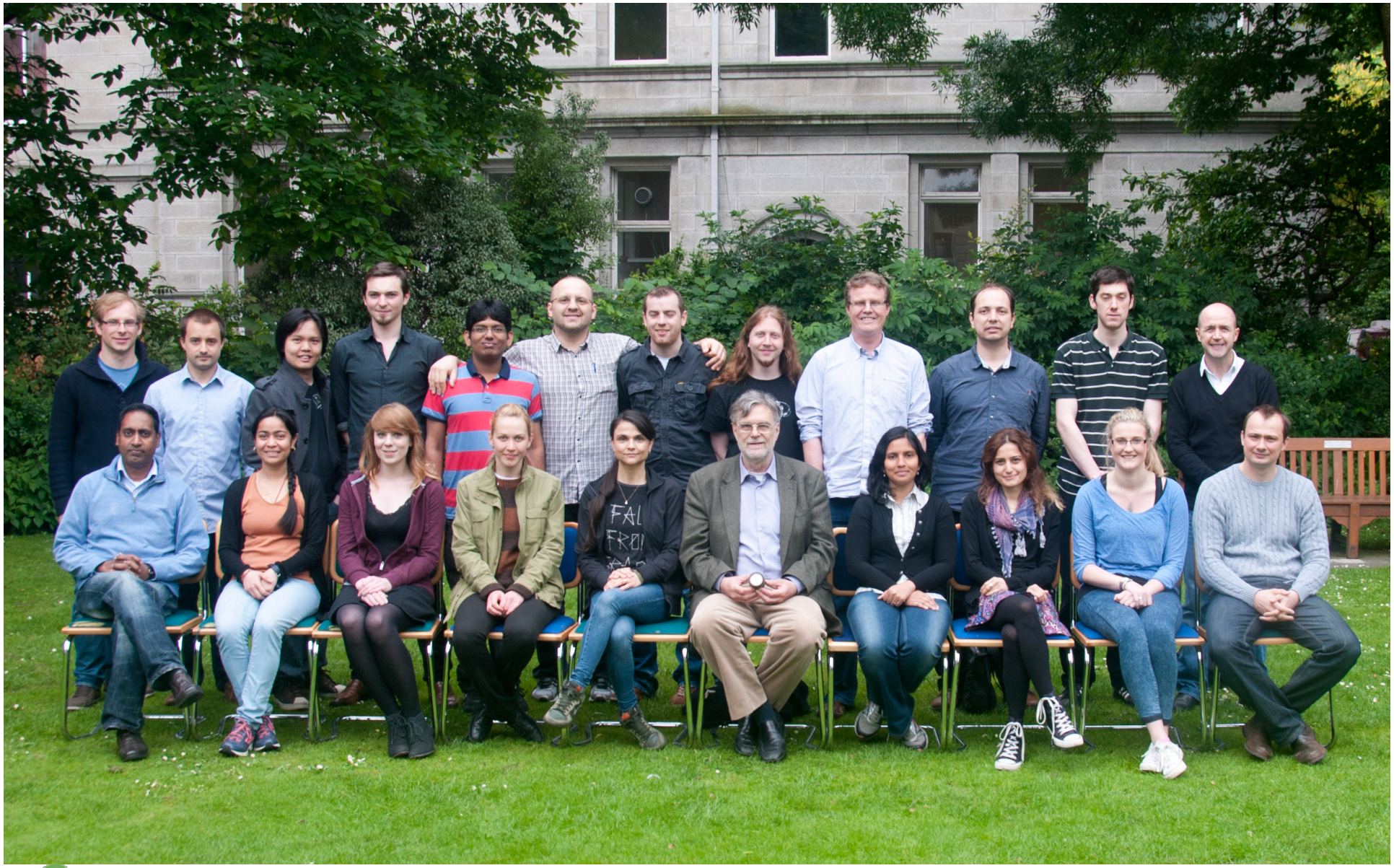

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Magnetic Periodic Table

Atomic Number → 66 Dy ← Atomic symbol
162.5 ← Atomic weight
Typical ionic change → 3 + 4f⁹
Antiferromagnetic T_N(K) → 179 | 85 ← Ferromagnetic T_C(K)

1 H 1.00																	2 He 4.00
3 Li 6.94 $1 + 2s^0$	4 Be 9.01 $2 + 2s^0$											5 B 10.81	6 C 12.01	7 N 14.0	8 O 16.00 35	F 19.00	10 Ne 20.18
11 Na 22.99 $1 + 3s^0$	12 Mg 24.21 $2 + 3s^0$											13 Al 26.98 $3 + 2p^6$	14 Si 28.09	15 P 30.97	16 S 32.07	17 Cl 35.45	18 Ar 39.95
19 K 38.21 $1 + 4s^0$	20 Ca 40.08 $2 + 4s^0$	21 Sc 44.96 $3 + 3d^0$	22 Ti 47.88 $4 + 3d^0$	23 V 50.94 $3 + 3d^2$	24 Cr 52.00 $3 + 3d^3$ 312	25 Mn 55.85 $2 + 3d^5$ 96	26 Fe 55.85 $3 + 3d^5$ 1043	27 Co 58.93 $2 + 3d^7$ 1390	28 Ni 58.69 $2 + 3d^8$ 629	29 Cu 63.55 $2 + 3d^9$	30 Zn 65.39 $2 + 3d^{10}$	31 Ga 69.72 $3 + 3d^{10}$	32 Ge 72.61	33 As 74.92	34 Se 78.96	35 Br 79.90	36 Kr 83.80
37 Rb 85.47 $1 + 5s^0$	38 Sr 87.62 $2 + 5s^0$	39 Y 88.91 $2 + 4d^0$	40 Zr 91.22 $4 + 4d^0$	41 Nb 92.91 $5 + 4d^0$	42 Mo 95.94 $5 + 4d^1$	43 Tc 97.9	44 Ru 101.1 $3 + 4d^5$	45 Rh 102.4 $3 + 4d^6$	46 Pd 106.4 $2 + 4d^8$	47 Ag 107.9 $1 + 4d^{10}$	48 Cd 112.4 $2 + 4d^{10}$	49 In 114.8 $3 + 4d^{10}$	50 Sn 118.7 $4 + 4d^{10}$	51 Sb 121.8	52 Te 127.6	53 I 126.9	54 Xe 83.80
55 Cs 13.29 $1 + 6s^0$	56 Ba 137.3 $2 + 6s^0$	57 La 138.9 $3 + 4f^0$	72 Hf 178.5 $4 + 5d^0$	73 Ta 180.9 $5 + 5d^0$	74 W 183.8 $6 + 5d^0$	75 Re 186.2 $4 + 5d^3$	76 Os 190.2 $3 + 5d^5$	77 Ir 192.2 $4 + 5d^5$	78 Pt 195.1 $2 + 5d^8$	79 Au 197.0 $1 + 5d^{10}$	80 Hg 200.6 $2 + 5d^{10}$	81 Tl 204.4 $3 + 5d^{10}$	82 Pb 207.2 $4 + 5d^{10}$	83 Bi 209.0	84 Po 209	85 At 210	86 Rn 222
87 Fr 223	88 Ra 226.0 $2 + 7s^0$	89 Ac 227.0 $3 + 5f^0$															
			58 Ce 140.1 $4 + 4f^0$ 13	59 Pr 140.9 $3 + 4f^2$	60 Nd 144.2 $3 + 4f^3$ 19	61 Pm 145	62 Sm 150.4 $3 + 4f^5$ 105	63 Eu 152.0 $2 + 4f^7$ 90	64 Gd 157.3 $3 + 4f^7$ 292	65 Tb 158.9 $3 + 4f^8$ 229 | 221	66 Dy 162.5 $3 + 4f^9$ 179 | 85	67 Ho 164.9 $3 + 4f^{10}$ 132 | 20	68 Er 167.3 $3 + 4f^{11}$ 85 | 20	69 Tm 168.9 $3 + 4f^{12}$ 56	70 Yb 173.0 $3 + 4f^{13}$	71 Lu 175.0 $3 + 4f^{14}$
			90 Th 232.0 $4 + 5f^0$	91 Pa 231.0 $5 + 5f^0$	92 U 238.0 $4 + 5f^2$	93 Np 238.0 $5 + 5f^2$	94 Pu 244	95 Am 243	96 Cm 247	97 Bk 247	98 Cf 251	99 Es 252	100 Fm 257	101 Md 258	102 No 259	103 Lr 260	

Nonmetal
Metal
Radioactive

Diamagnet
Paramagnet
BOLD Magnetic atom

Ferromagnet T_C > 290K
Antiferromagnet with T_N > 290K
Antiferromagnet/Ferromagnet with T_N/T_C < 290 K

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Figure 1

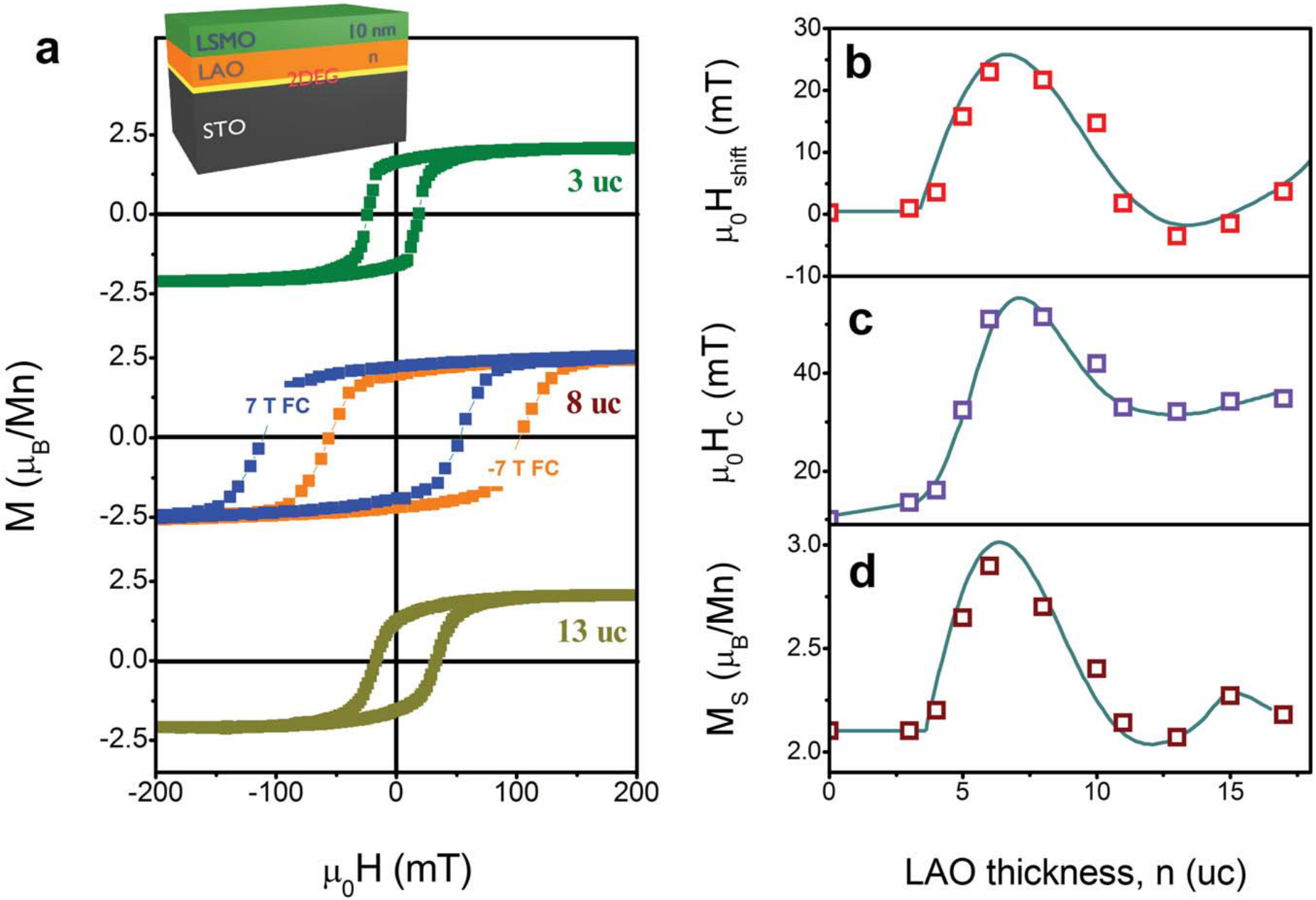
a
LSMO
10 nm
LAO
n
2DEG
STO
3 uc
8 uc
13 uc
7 T FC
-7 T FC
M (μ_B/Mn)
μ_0H (mT)
b
c
d
$\mu_0 H_{shift}$ (mT)
$\mu_0 H_C$ (mT)
M_S (μ_B/Mn)
LAO thickness, n (uc)

Figure 2

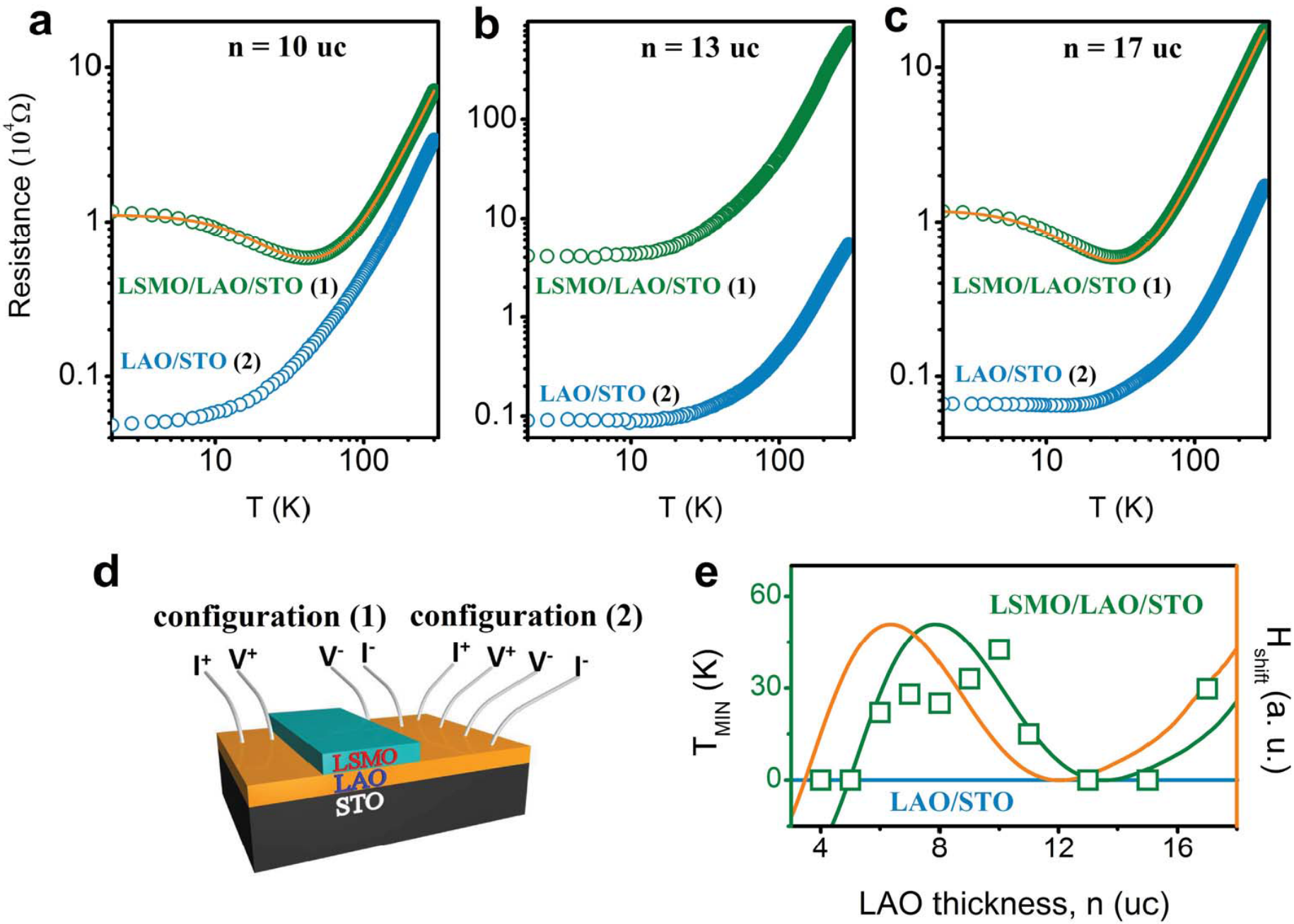
a
n = 10 uc
Resistance ($10^4\Omega$)
LSMO/LAO/STO (1)
LAO/STO (2)
T (K)
b
n = 13 uc
LSMO/LAO/STO (1)
LAO/STO (2)
T (K)
c
n = 17 uc
LSMO/LAO/STO (1)
LAO/STO (2)
T (K)
d
configuration (1)
configuration (2)
I+ V+ V- I-
I+ V+ V- I-
LSMO
LAO
STO
e
LSMO/LAO/STO
LAO/STO
T_{MIN} (K)
H_{shift} (a. u.)
LAO thickness, n (uc)

Figure 3

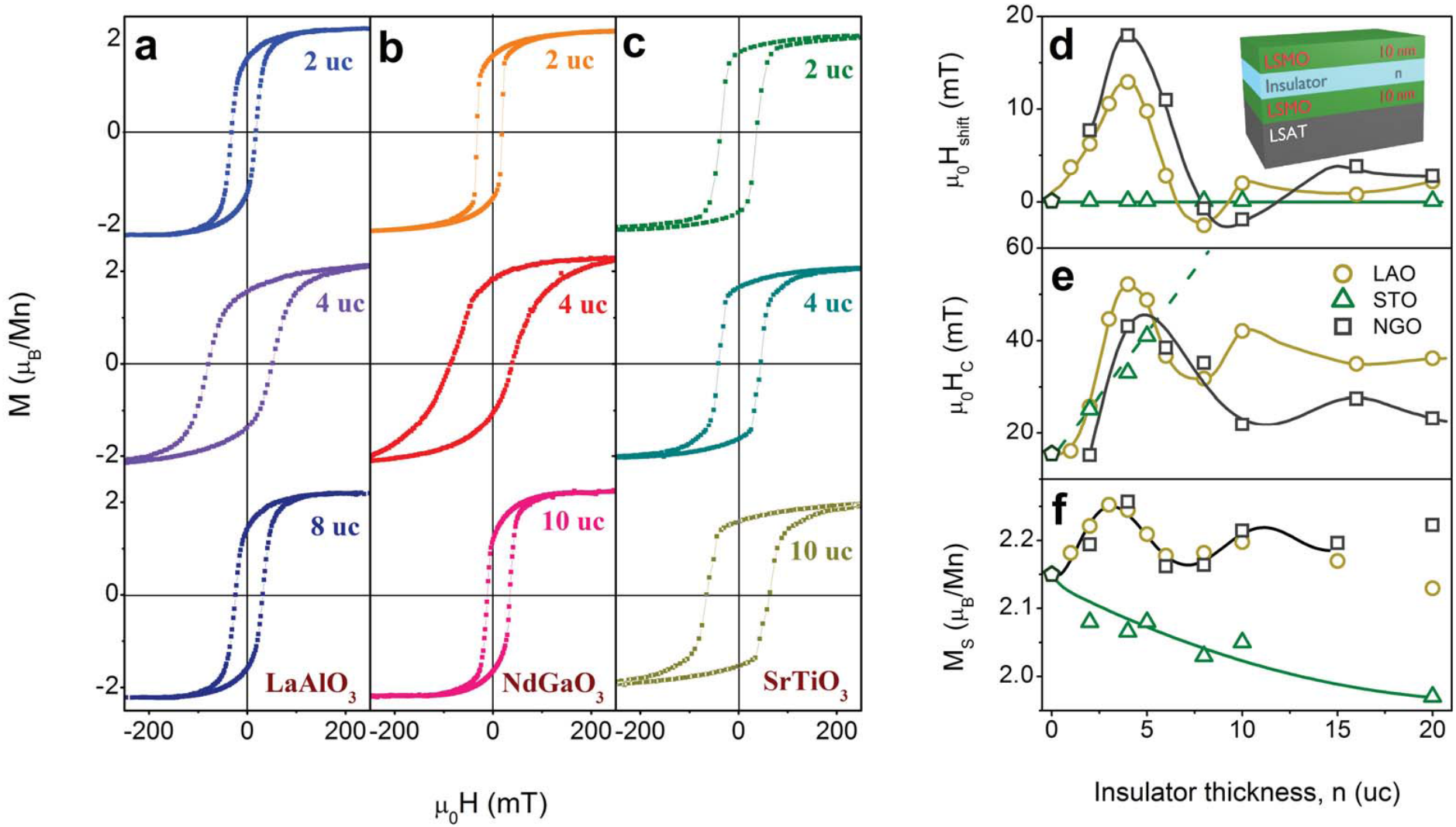

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Figure 4

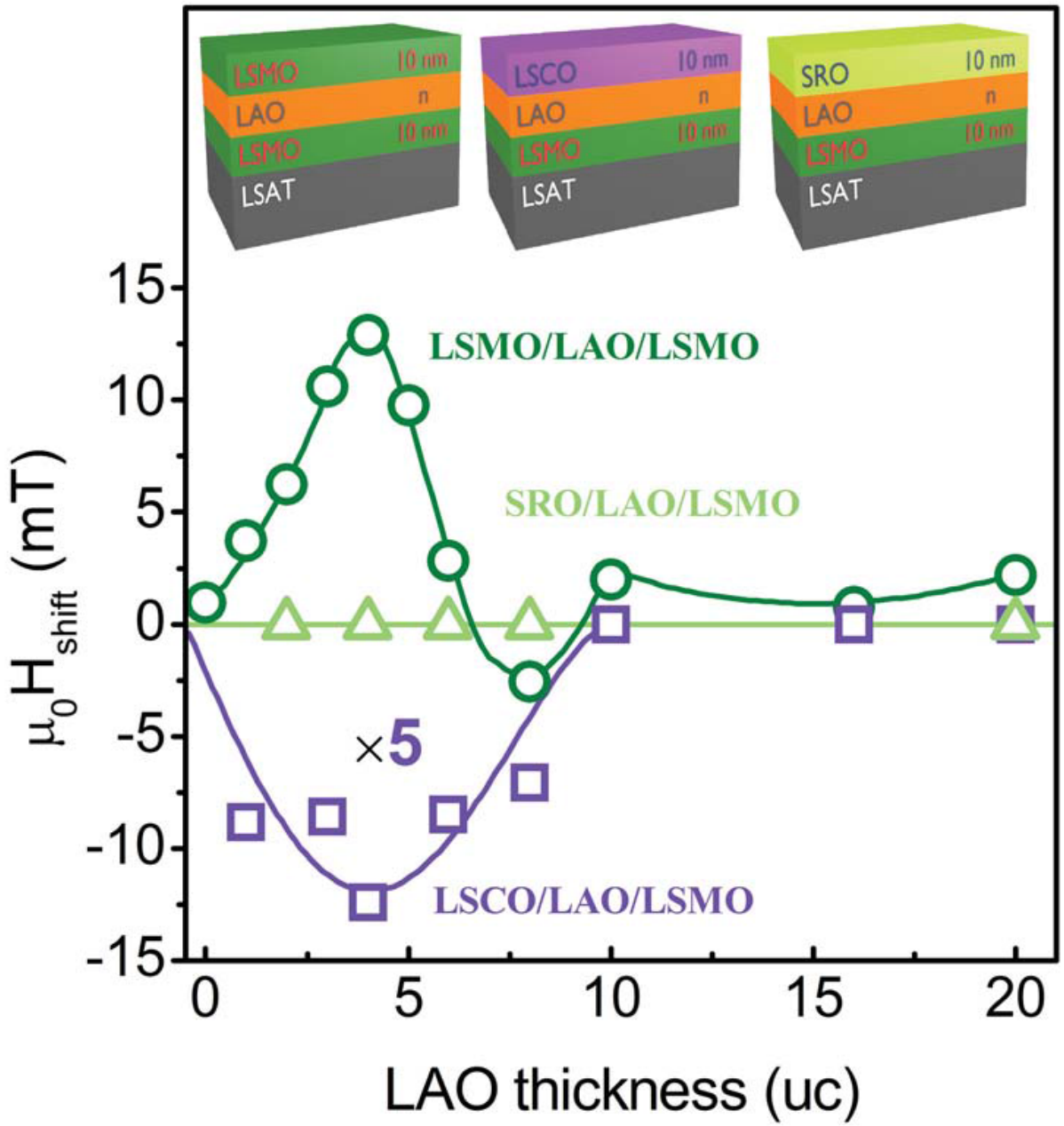

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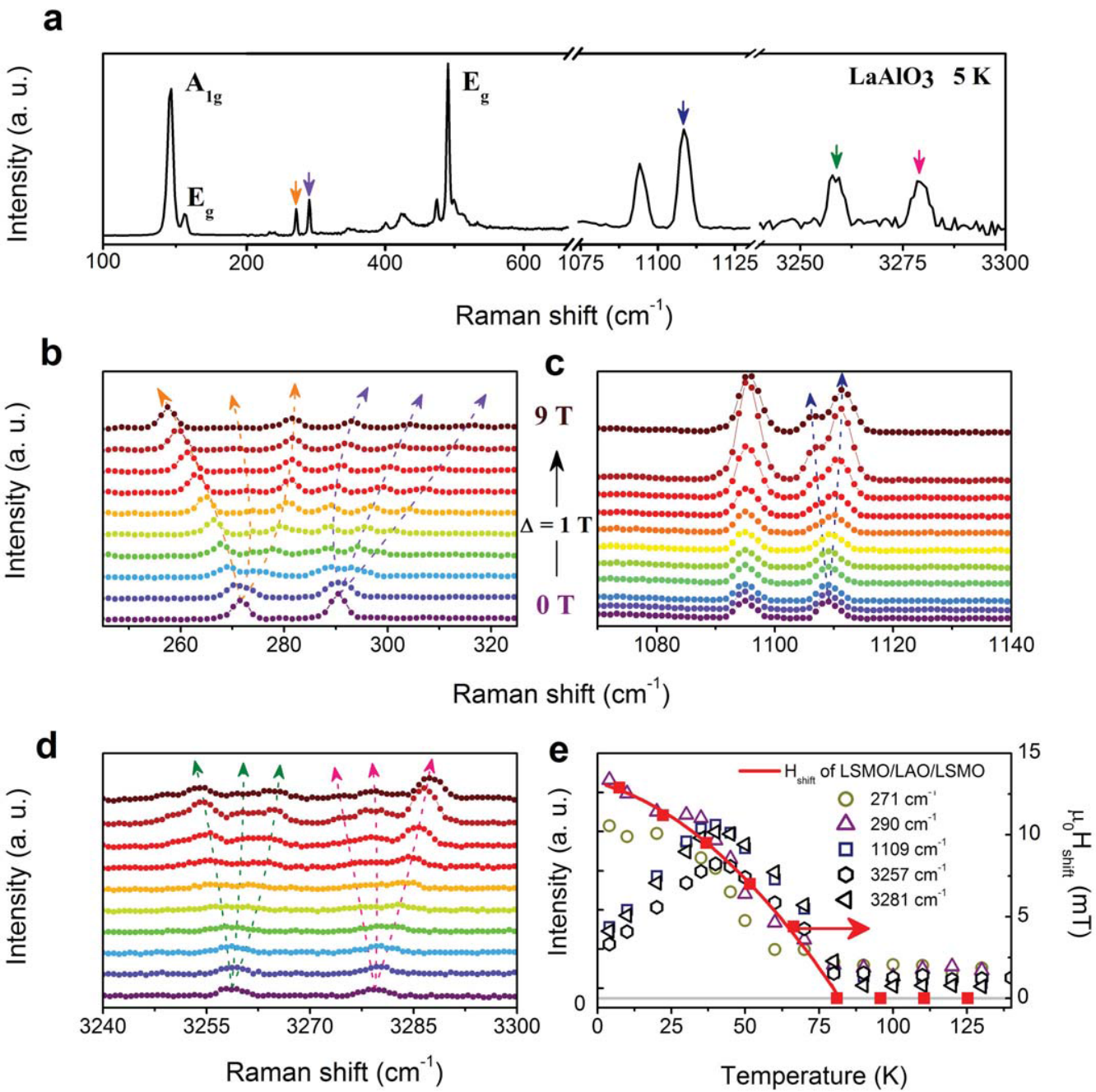
Figure 5



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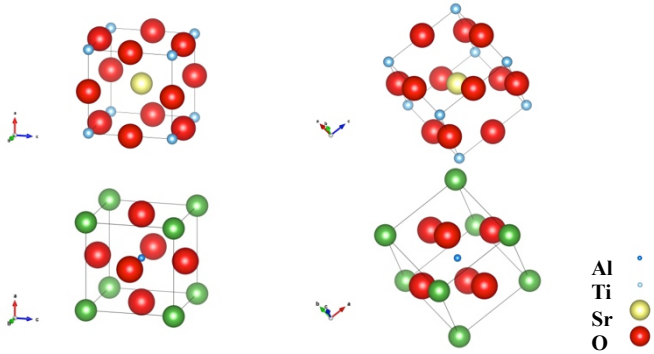

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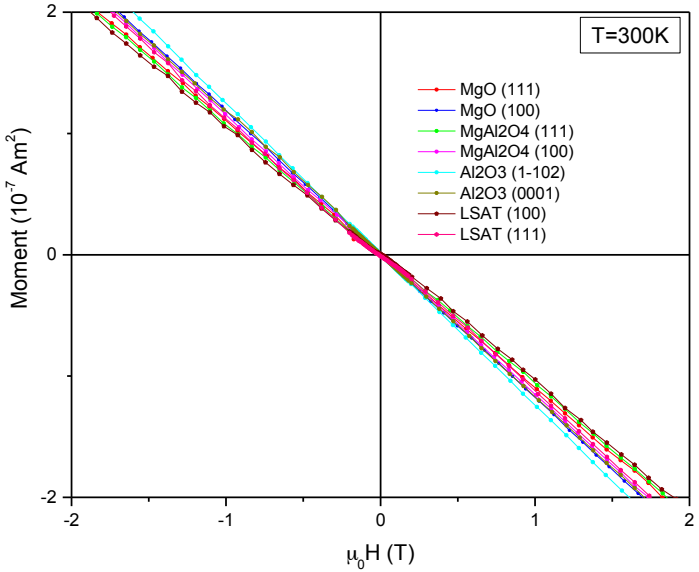

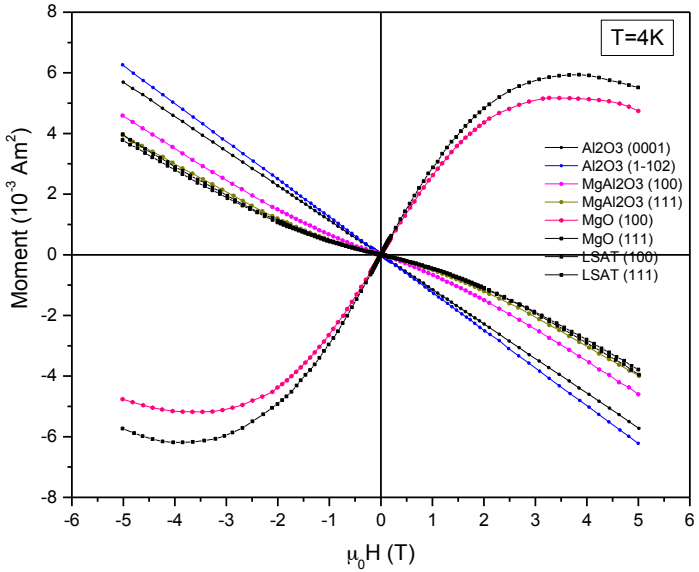

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