2020/2/18 Lecture 7 (15:00-16:30)

Functional Oxide Spintronics and the material design

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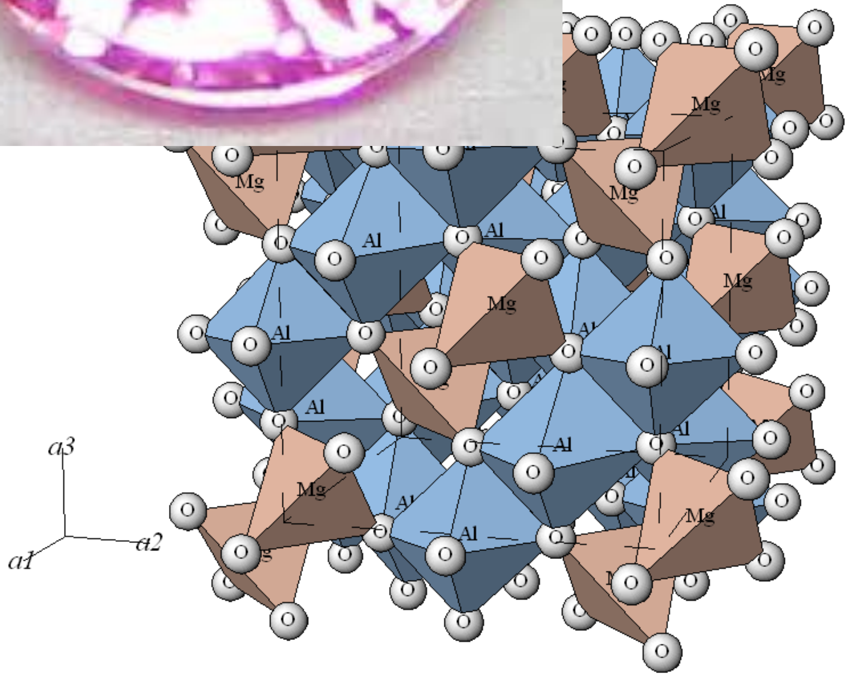
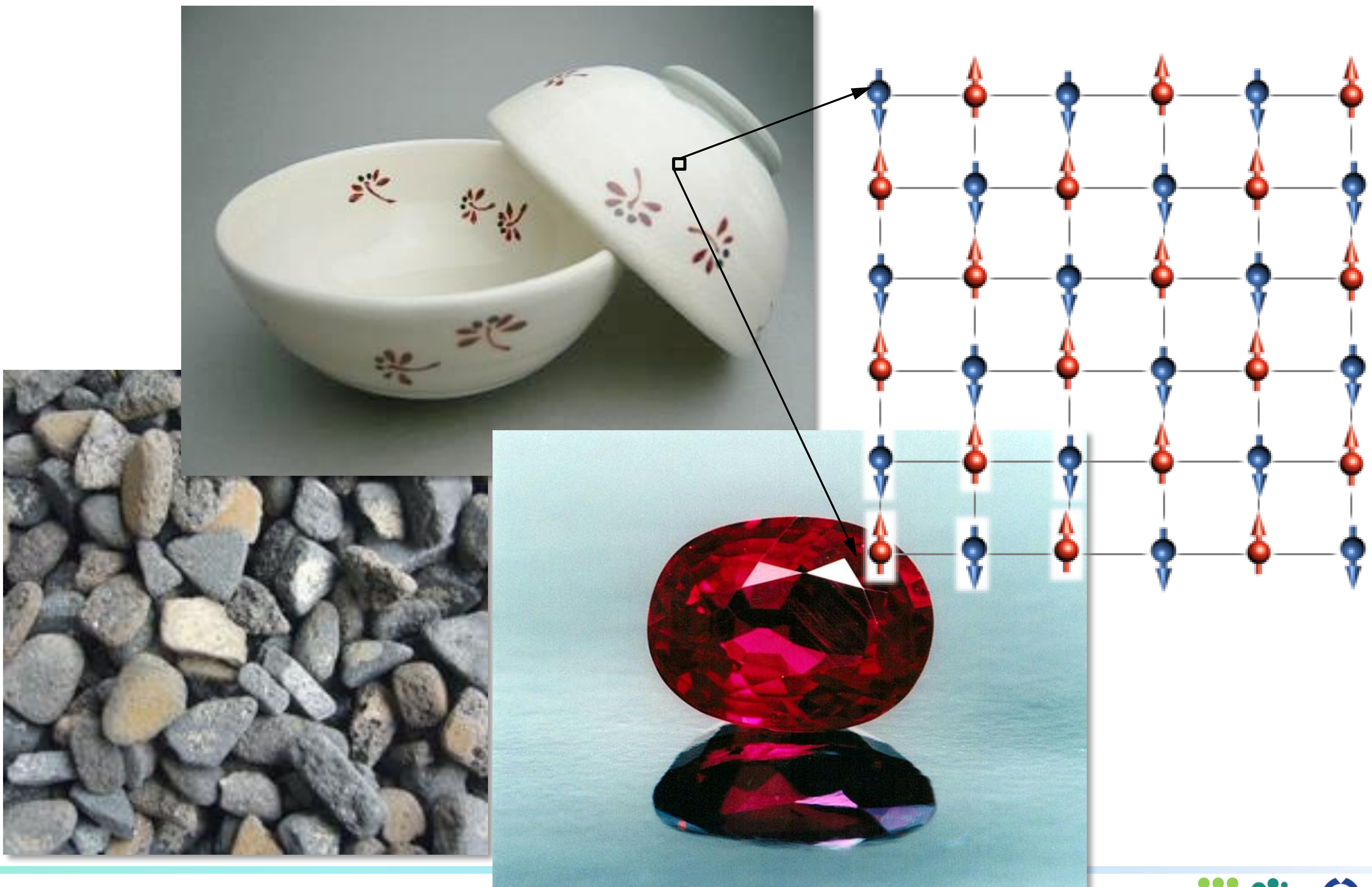
Ceramics

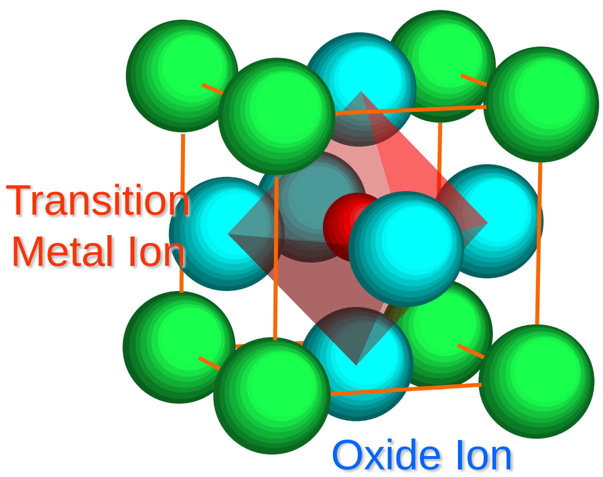
Jewelry (Spinel, Garnet)



Functional Oxides



Transition Metal Oxides



22 Ti	23 V	24 Cr	25 Mn	26 Fe	27 Co	28 Ni	29 Cu
47.87	50.94	52.00	54.94	55.85	58.93	58.69	63.55
チタン	バナジウム	クロム	マンガン	鉄	コバルト	ニッケル	銅
Titanium	Vanadium	Chromium	Manganese	Iron	Cobalt	Nickel	Copper

Ferro dielectrics   Anti-/Ferro magnetics   High temperature superconductors

Piezoelectrics   Colossal MR   Conductors

Memory (DRAM, FRAM、RRAM)   Magnetic head   Magnetic recorder

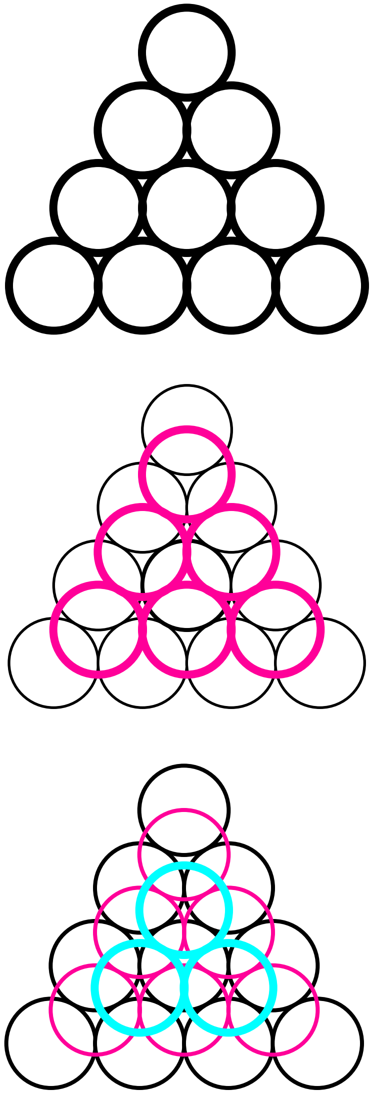
Josephson junction

Memory (MRAM)   electrode   SQUID

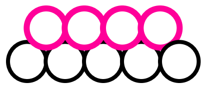
Piezoelectric devices   Bolometer

Information processing and data storage materials related with our daily life

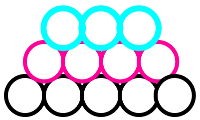
Face-centered cubic => Closed pack structure



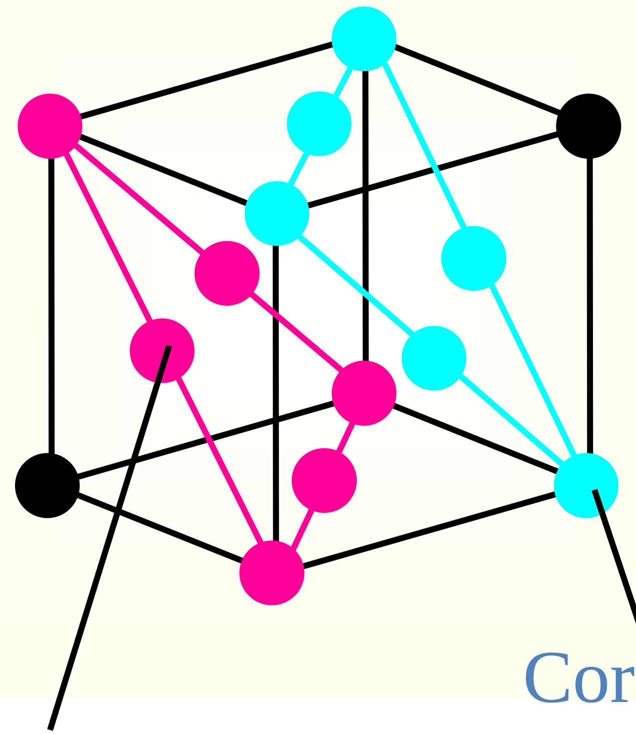
1st layer



2nd layer



3rd layer



Center face

$1/2 \times 6$ parts

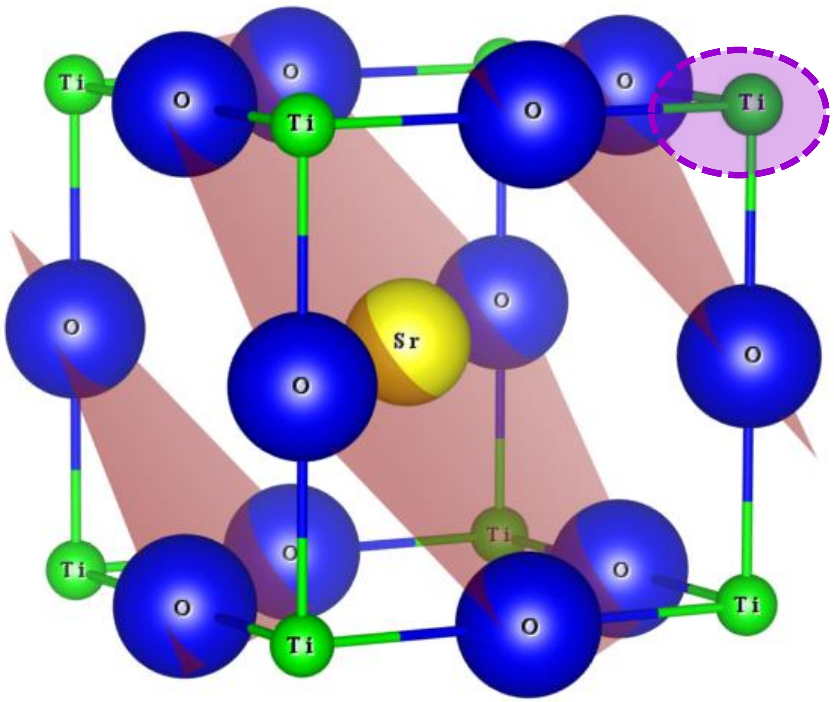
Corner

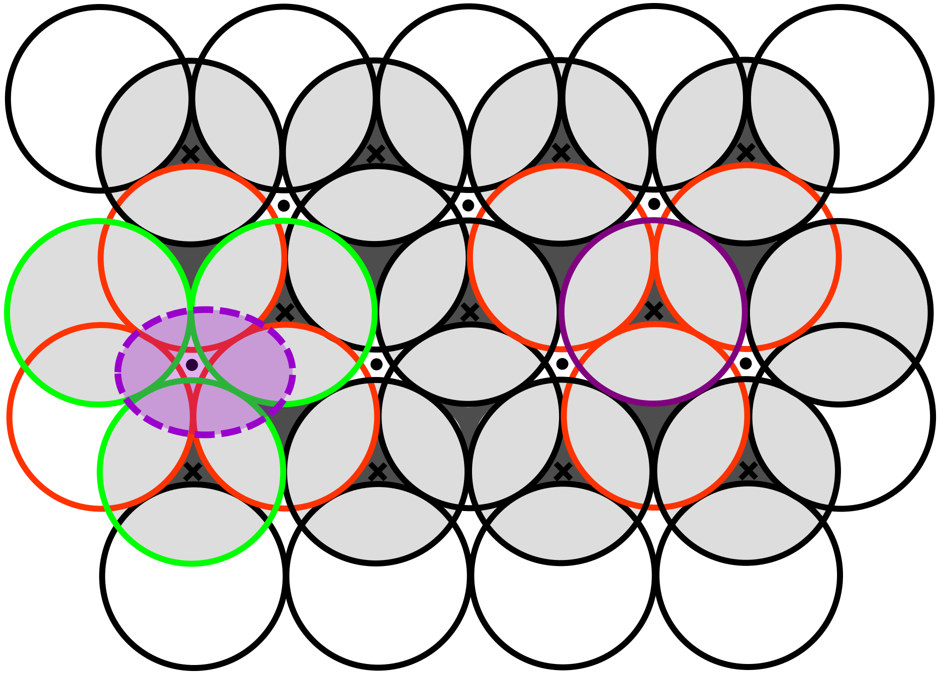
$1/8 \times 8$ parts

Perovskite structure：ABO$_3$ *e.g.* SrTiO$_3$

Interspace of close packed oxide ions：Octahedral interspace

≥0.414*r* O^{2-}=1.40Å, Sr^{2+}=1.26Å, Ti^{4+}=0.61Å,





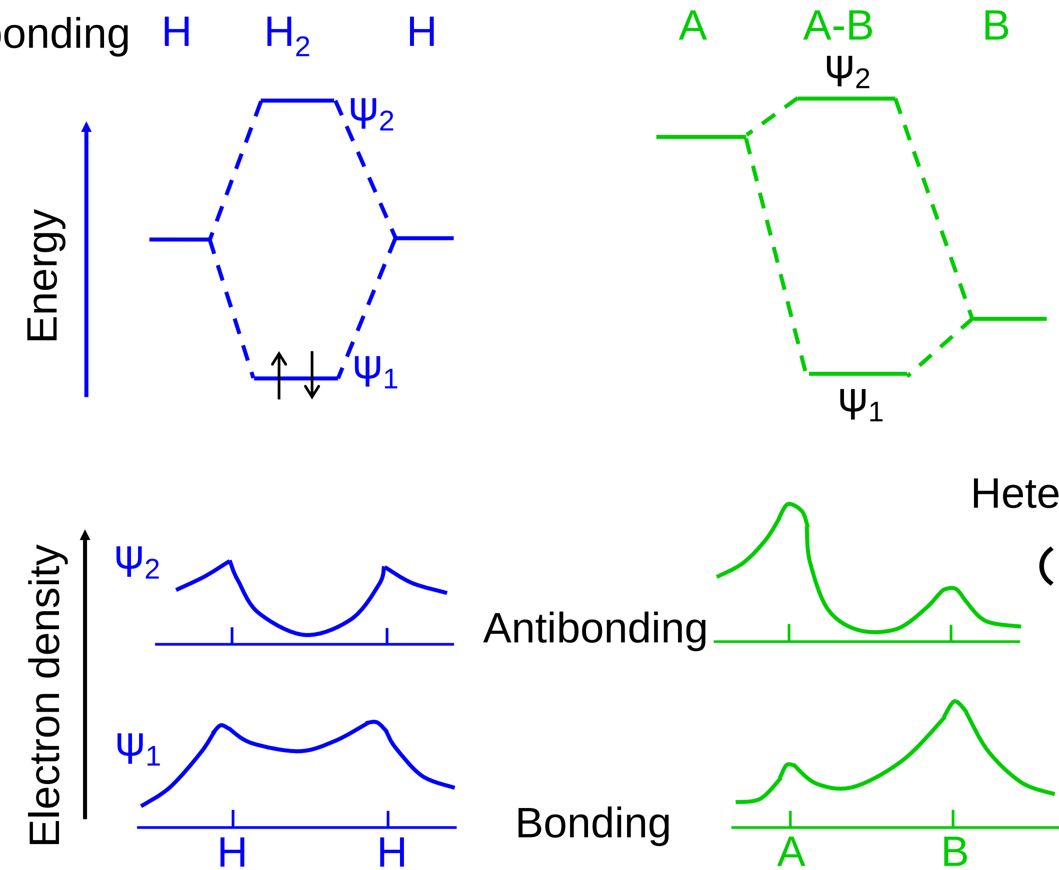
Orbital bonding

Bonding and Antibonding states ⇨ Valence and Conduction band

Covalent bonding

$\psi_2 = \chi_A - \chi_B$

$\psi_1 = \chi_A + \chi_B$



Ion bonding

$\psi_2 = a_2\chi_A - b_2\chi_B$

$\psi_1 = a_1\chi_A + b_1\chi_B$

Heteronuclear diatomic molecule

(Covalent or Ionic characters)

↓

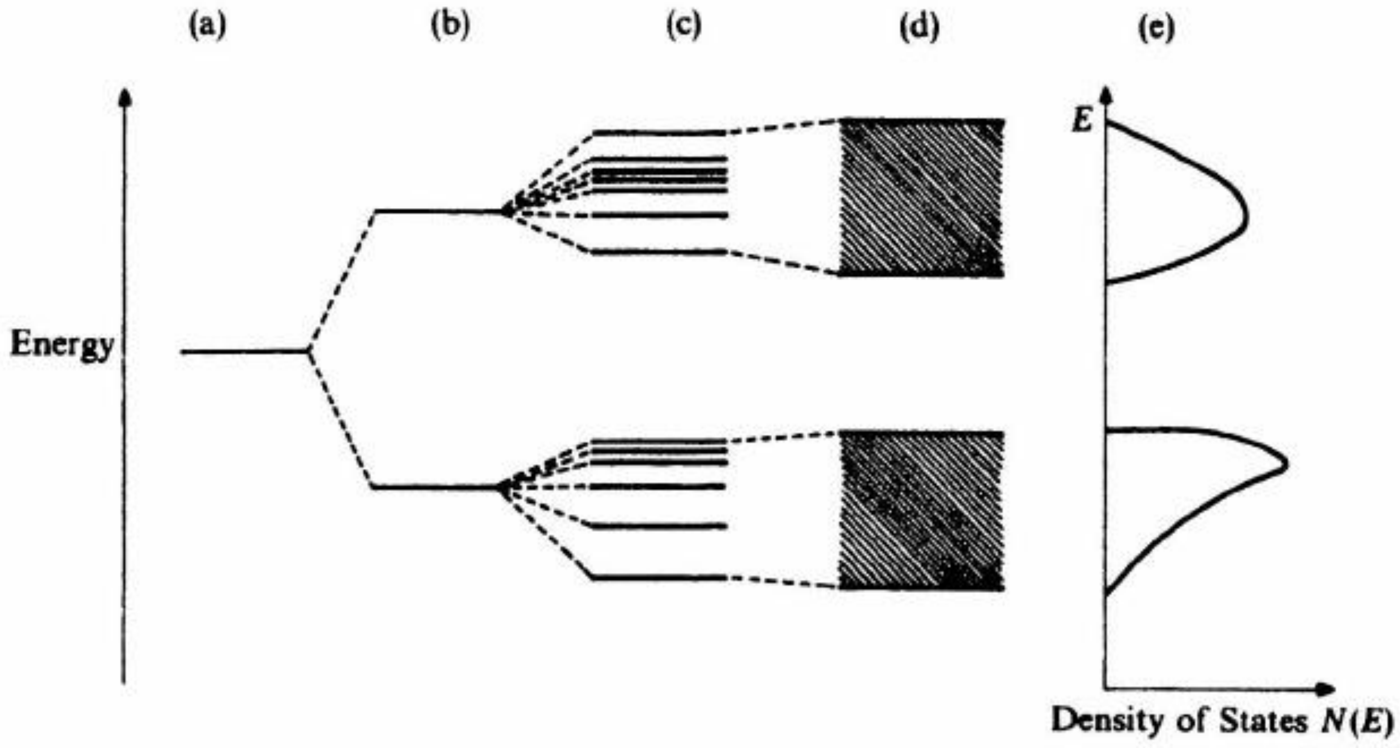
Different orbital level

Electronegativity
Ionization potential

(a) (b)

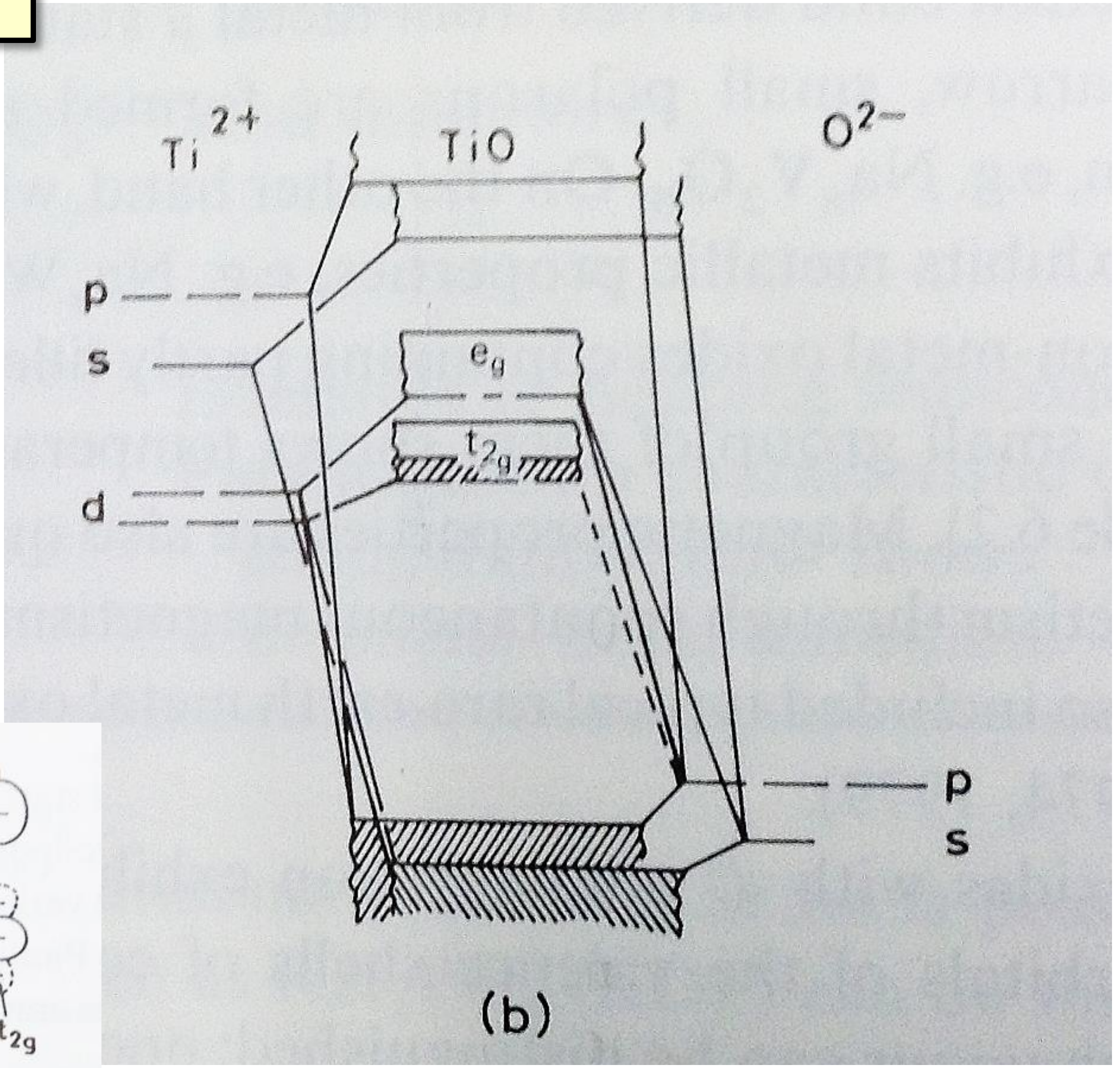
Electron distributions and energies of molecular orbitals in (a) H_2 and a heteronuclear molecule AB

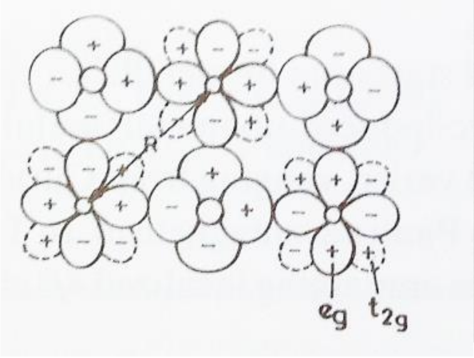
From orbital to band formation



Orbital energies of (a) atom, (b) small molecule, (c) large molecule, (d) solid, and (e) density of states corresponding to (d)

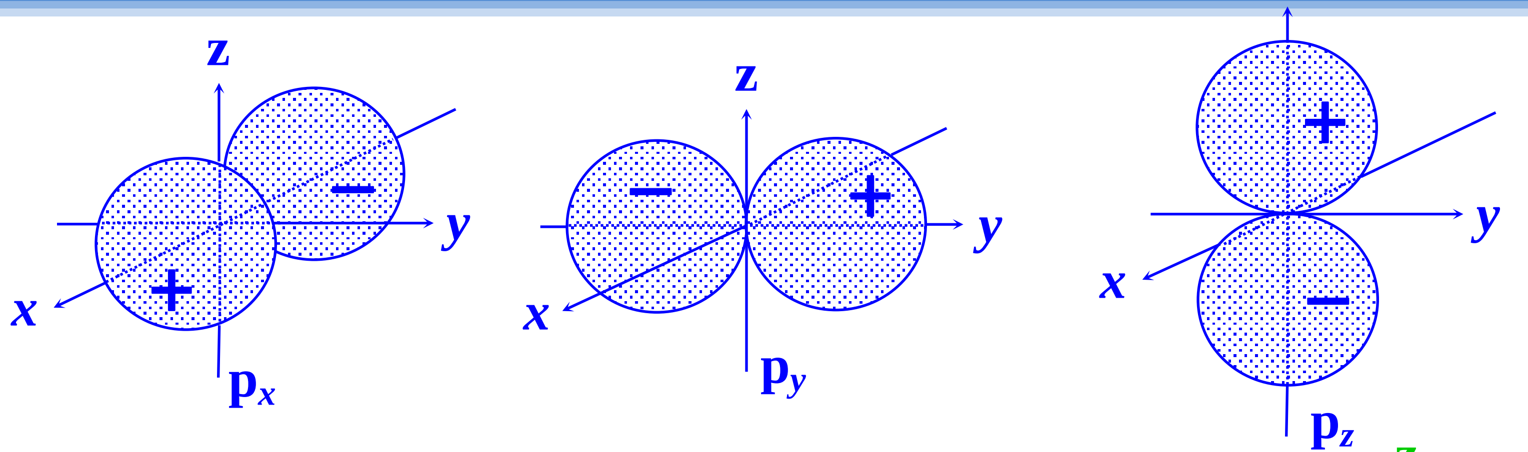
TiO



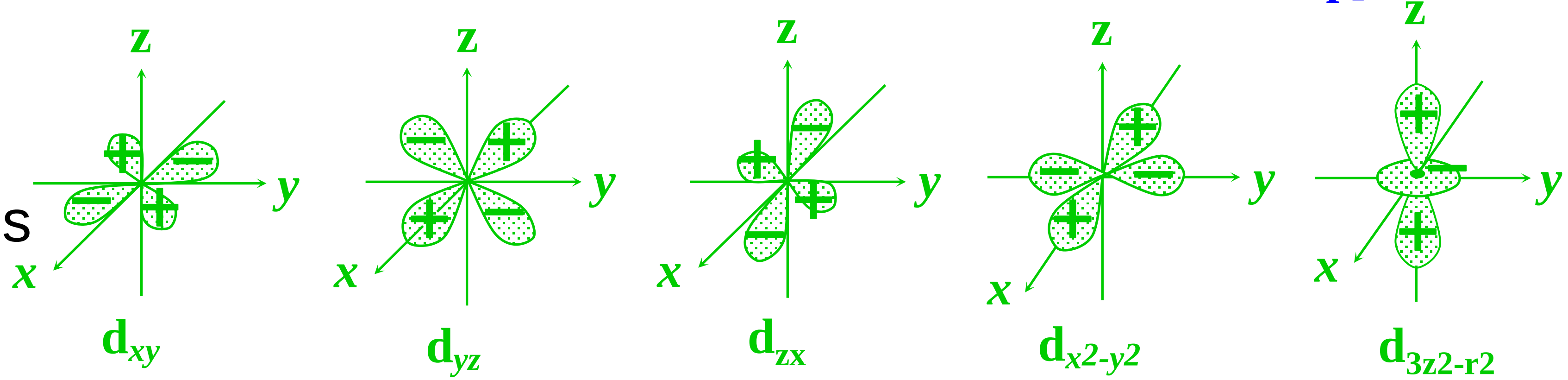


Existence of electrons・Orbital shape

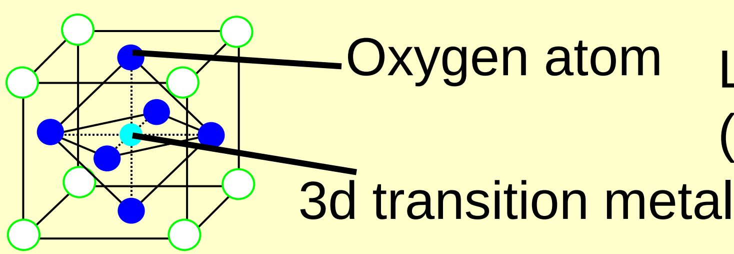
p orbitals



d orbitals



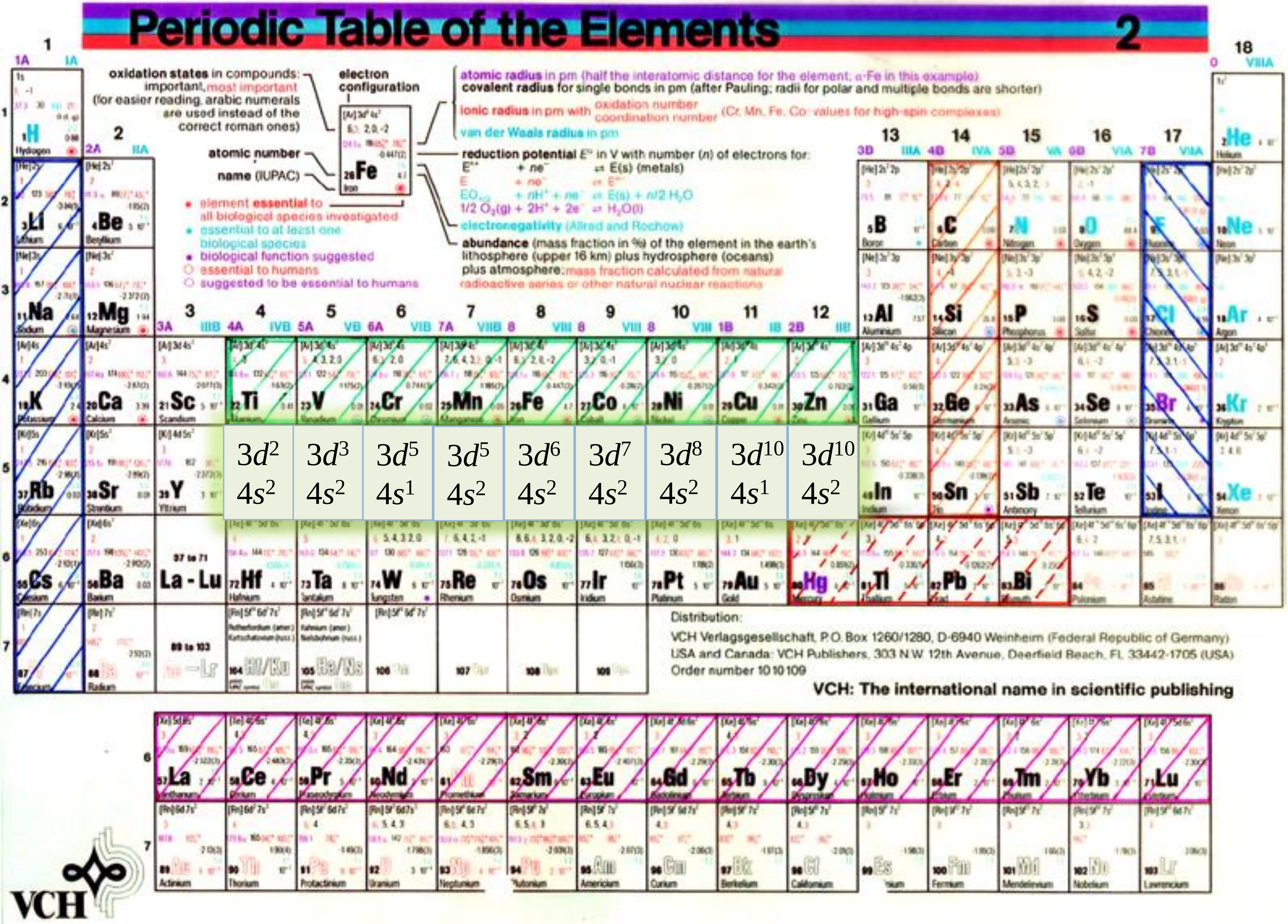
Perovskite structure



Ligand field splitting
(Crystal field splitting)

e_g — $x^2-y^2, 3z^2-r^2$

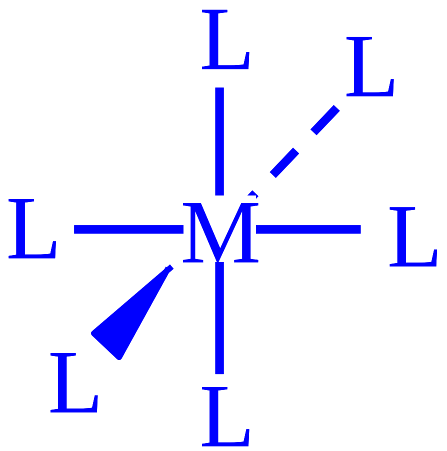
t_{2g} — xy, yz, zx

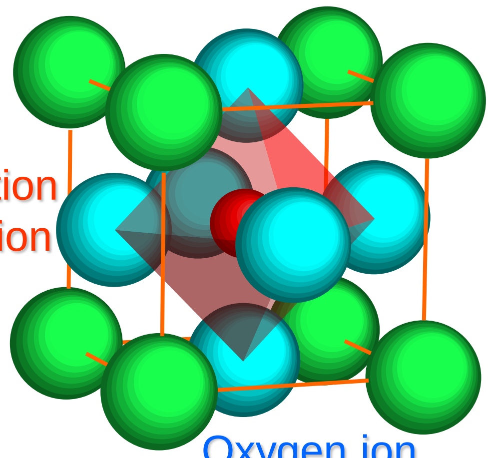


$3d^2$ $4s^2$	$3d^3$ $4s^2$	$3d^5$ $4s^1$	$3d^5$ $4s^2$	$3d^6$ $4s^2$	$3d^7$ $4s^2$	$3d^8$ $4s^2$	$3d^{10}$ $4s^1$	$3d^{10}$ $4s^2$

Crystal field splitting of perovskite structure

Octahedral ligands





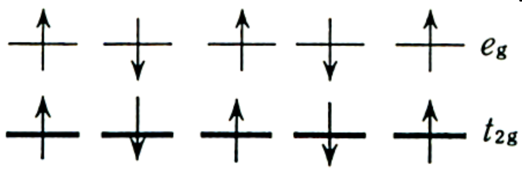
Energy gap
- e_g (z^2, x^2-y^2)
- t_{2g} (yz, xz, xy)

$La^{3+}Mn^{3+}O_3$

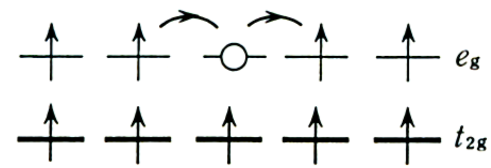
Required interaction for material design

Superexchange interaction | Double exchange interaction

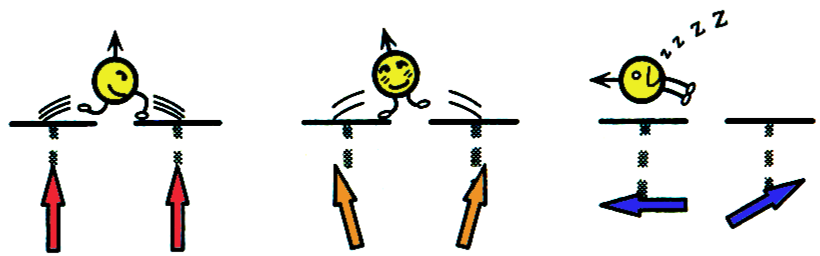
$LaMnO_3$ Carrier doping → **$(La,Sr)MnO_3$**



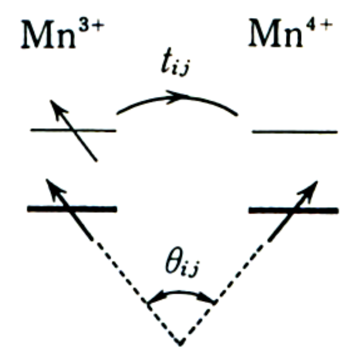
(a) $LaMnO_3$



(b) $La_{1-x}Sr_xMnO_3$ ($T \ll T_c$)



(a) (b) (c)



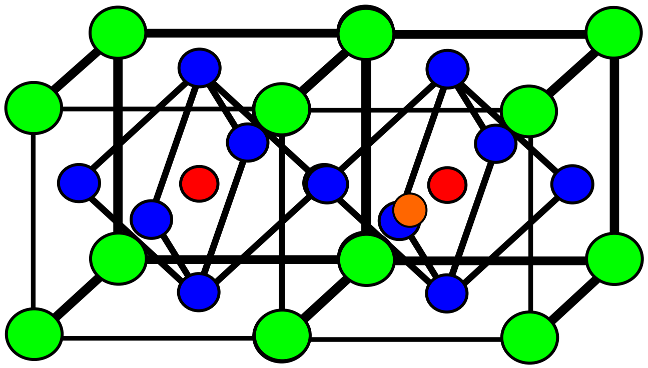
$t_{ij} = t\cos(\theta_{ij}/2)$

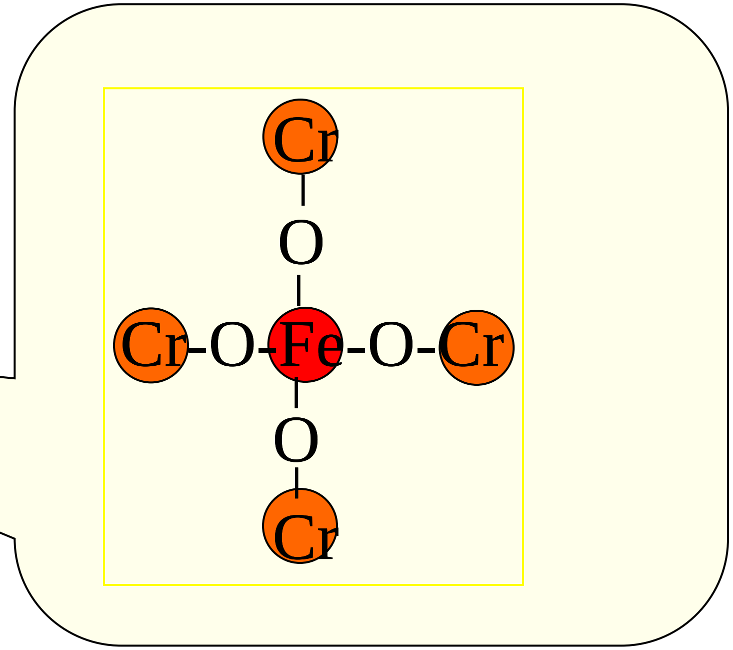
$$\boldsymbol{H} = -\boldsymbol{t}_{\mathrm{Mn-Mn}}\cos\left(\frac{\boldsymbol{\theta}}{2}\right) - K_{Hund}\boldsymbol{\sigma}\boldsymbol{S}_{\mathbf{Mn}} - J_{\mathrm{t2g}}\sum_{LMnO}\boldsymbol{S}_{\mathbf{Mn}}^{t2g}\boldsymbol{S}_{\mathbf{Mn}}^{t2g}$$

Kanamori-Goodenough rules

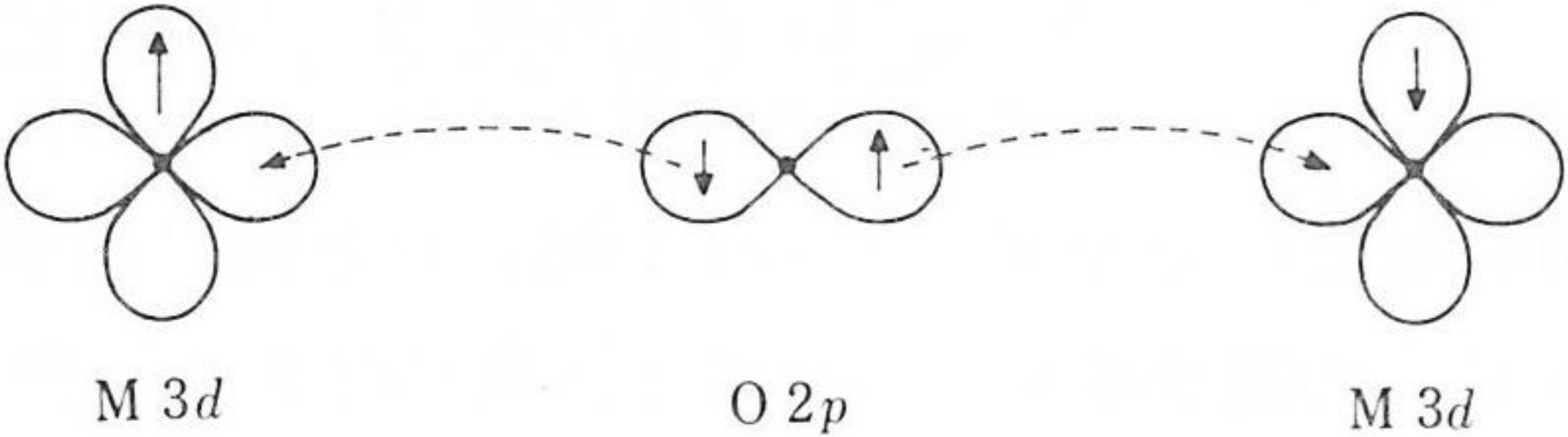
60 years ago

Kanamori former president of Osaka Univ.





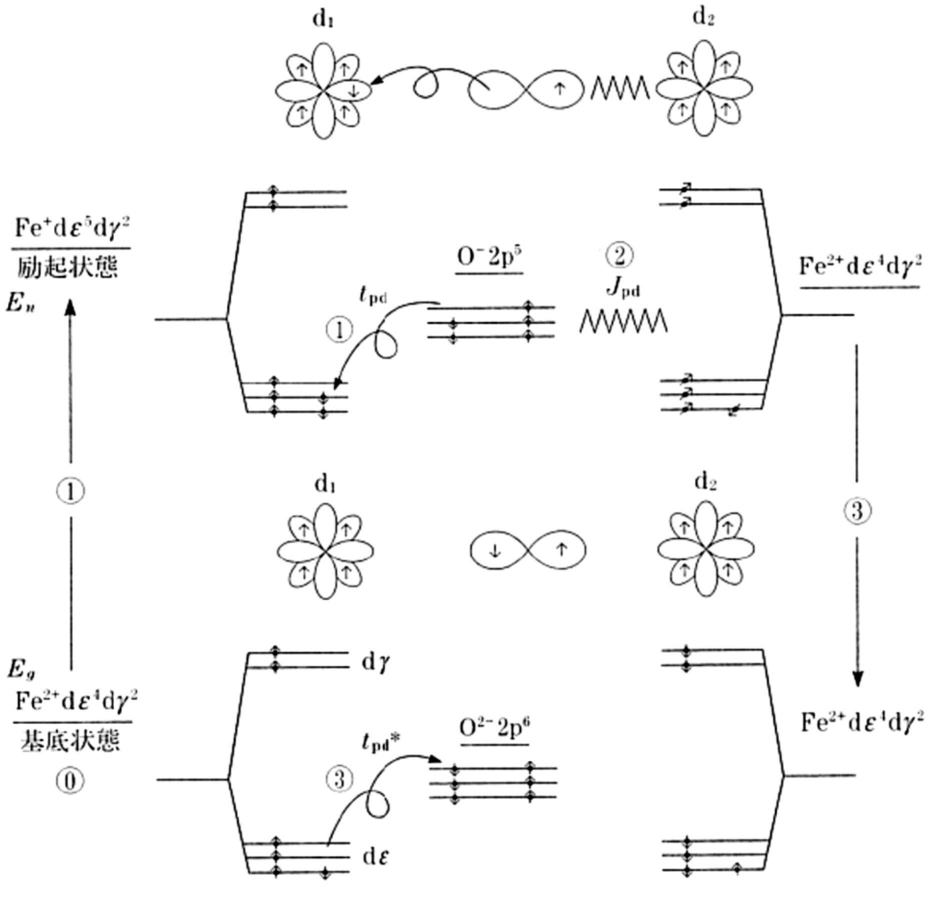
Superexchange interaction



Superexchange interaction

→Indirect interaction between two magnetic atoms through non-magnetic atom

Superexchange interaction



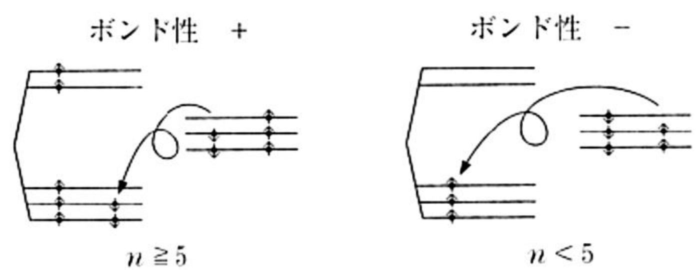
(a) Fe^{2+} - O^{2-} - Fe^{2+} 間の超交換相互作用模型

($3d^6$-$2p^6$-$3d^6$)

Considering an excited state in the case of electron transfer from 2*p* orbital to 3*d* orbital

(transfer integral) $t_{pd} = \int \phi_d {}^* V_{pd} \phi_p dr$

■bonding rule

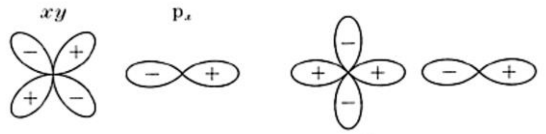


Considering a direct exchange interaction (J_{pd}) between 2p spin and 3d spin

Superexchange interaction

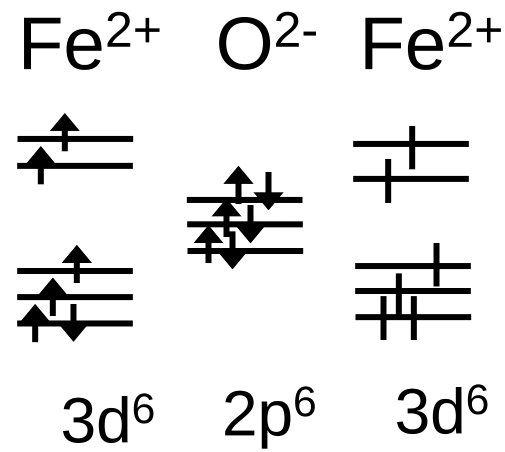
Sign of J_{pd} Ferromagnetic J_{pd}>0、Antiferromagnetic J_{pd}<0

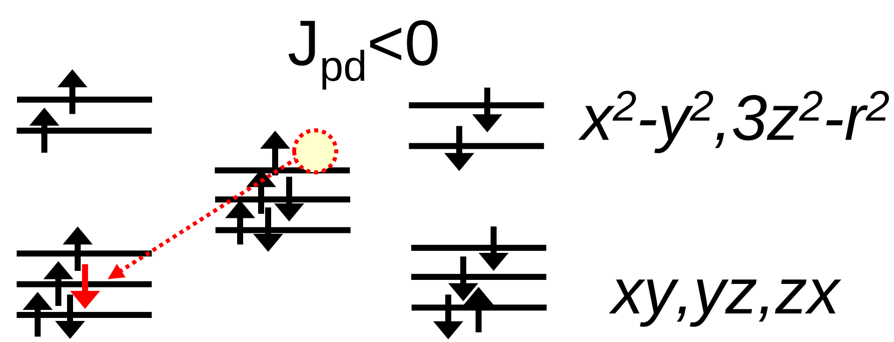
・・・ Orthogonal character of J_{pd}



(+：直交，−：非直交，(σ)，(π) は σ および π 結合)

d		p_x	p_y	p_z	s
$3z^2-r^2$	X	−(σ)	+	+	−(σ)
	Y	+	−(σ)	+	−(σ)
	Z	+	+	−(σ)	−(σ)
x^2-y^2	X	−(σ)	+	+	−(σ)
	Y	+	−(σ)	+	−(σ)
	Z	+	+	+	+
xy	X	+	−(π)	+	+
	Y	−(π)	+	+	+
	Z	+	+	+	+
yz	X	+	+	+	+
	Y	+	+	−(π)	+
	Z	+	−(π)	+	+
zx	X	+	+	−(π)	+
	Y	+	+	+	+
	Z	−(π)	+	+	+





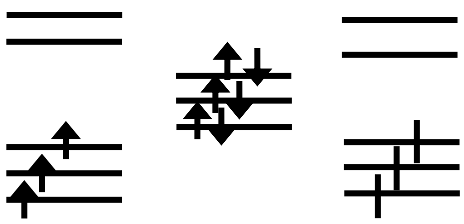
Orthogonal character table in case that d orbital function locates the origin and s and p orbitals arrenge Orthogonal coordinates of X,Y and Z axies

FeO is an antiferromagnetic material

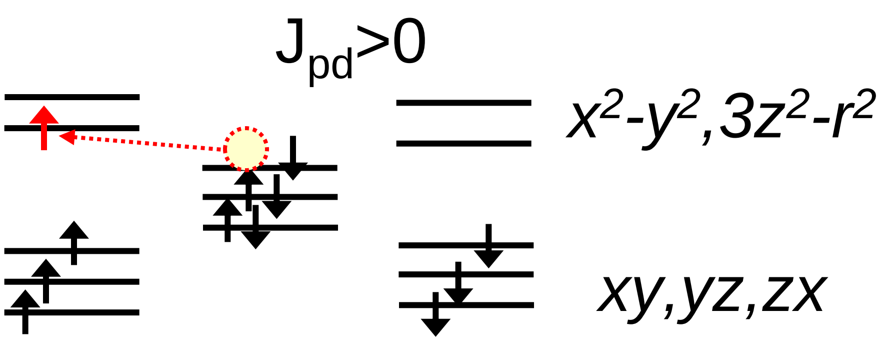
Superexchange interaction

Ex.) Mn^{4+} -Mn^{4+} : Antiferromagnetic

Mn^{4+} O^{2-} Mn^{4+}



$3d^3$ $2p^6$ $3d^3$



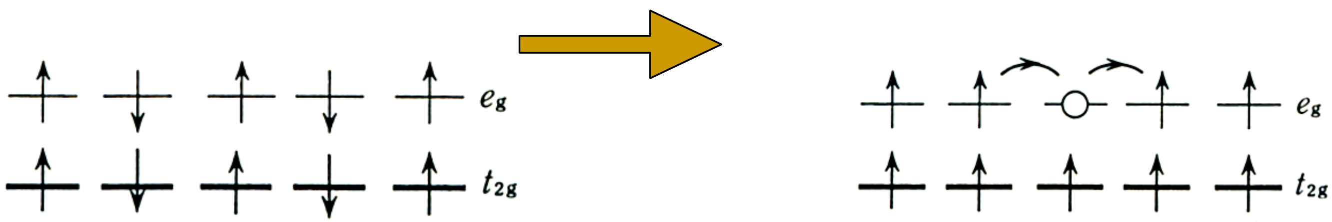
(＋：直交，－：非直交，(σ)，(π) は σ および π 結合)

d		p_x	p_y	p_z	s
$3z^2-r^2$	X	−(σ)	＋	＋	−(σ)
	Y	＋	−(σ)	＋	−(σ)
	Z	＋	＋	−(σ)	−(σ)
x^2-y^2	X	−(σ)	＋	＋	−(σ)
	Y	＋	−(σ)	＋	−(σ)
	Z	＋	＋	＋	＋
xy	X	＋	−(π)	＋	＋
	Y	−(π)	＋	＋	＋
	Z	＋	＋	＋	＋
yz	X	＋	＋	＋	＋
	Y	＋	＋	−(π)	＋
	Z	＋	−(π)	＋	＋
zx	X	＋	＋	−(π)	＋
	Y	＋	＋	＋	＋
	Z	−(π)	＋	＋	＋

Double exchange interaction

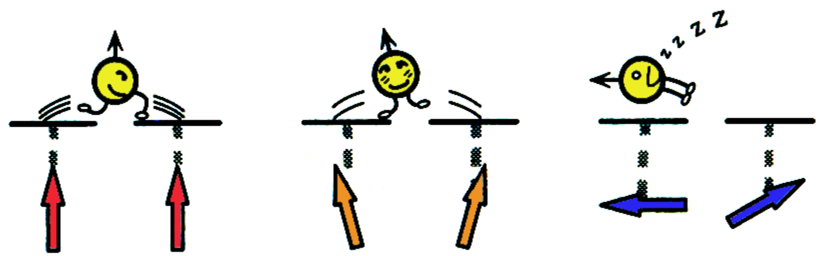
Superexchange interaction | Double exchange interaction

$LaMnO_3$ Carrier doping **$(La,Sr)MnO_3$**

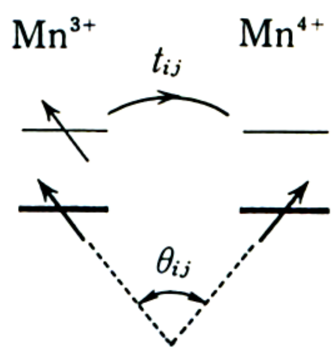


(a) $LaMnO_3$

(b) $La_{1-x}Sr_xMnO_3$ ($T \ll T_c$)



(a) (b) (c)

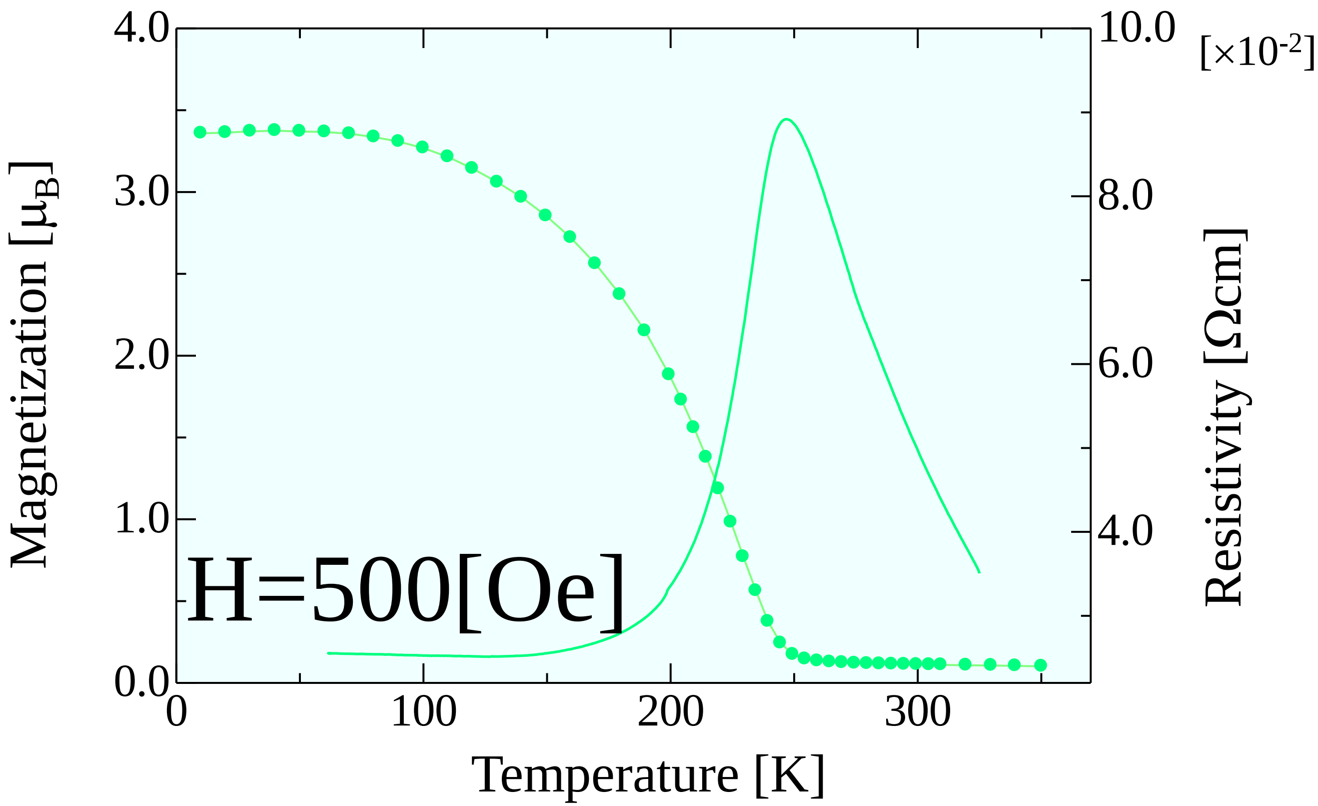


$t_{ij} = t\cos(\theta_{ij}/2)$

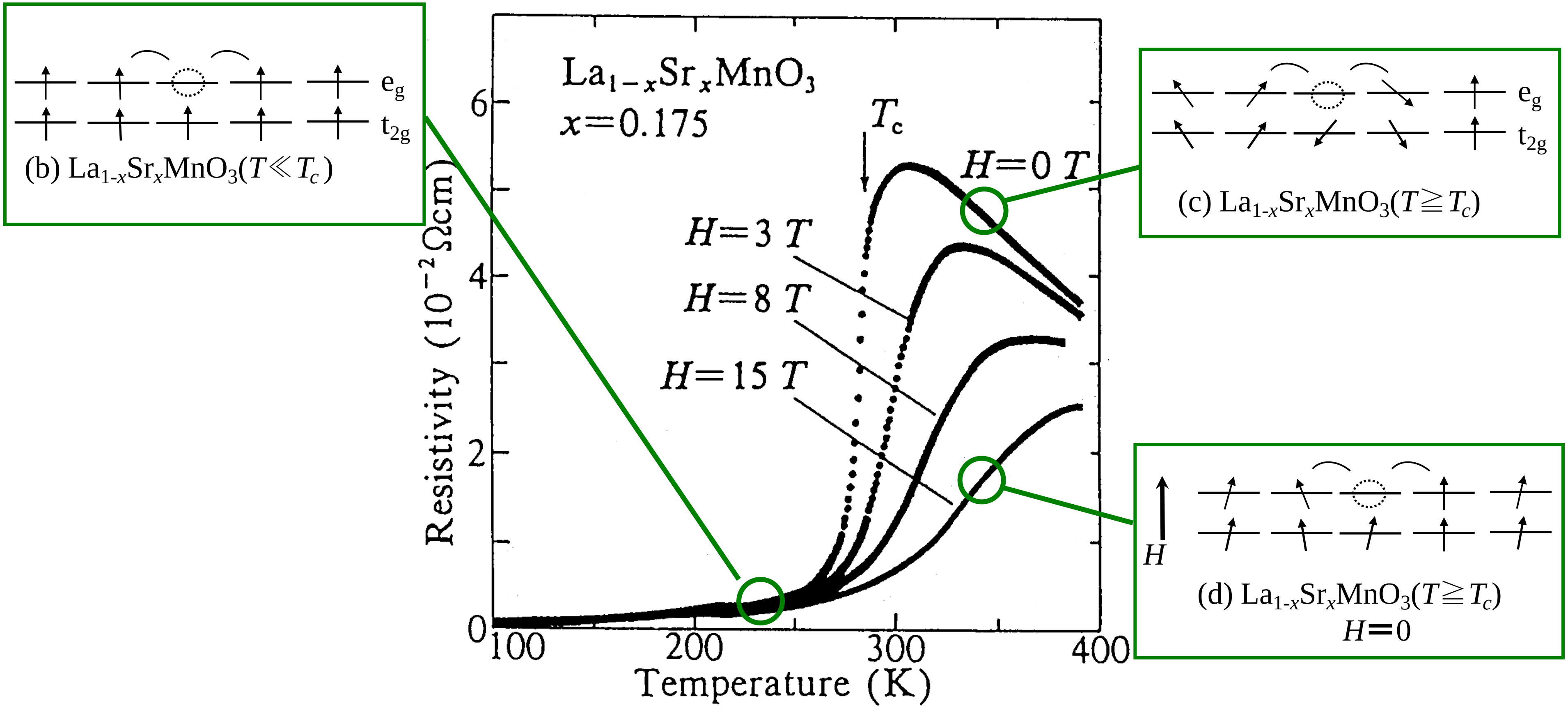
$$\boldsymbol{H} = -\boldsymbol{t}_{\mathrm{Mn-Mn}}\cos\left(\frac{\boldsymbol{\theta}}{2}\right) - K_{Hund}\boldsymbol{\sigma}\boldsymbol{S}_{\mathbf{Mn}} - J_{\mathrm{t2g}}\sum_{LMnO}\boldsymbol{S}^{t2g}_{\mathbf{Mn}}\boldsymbol{S}^{t2g}_{\mathbf{Mn}}$$

Magnetism modulation due to change of electron transfer integral

$$\boldsymbol{H} = -\boldsymbol{t}_{\mathrm{Mn-Mn}} \cos\left(\frac{\boldsymbol{\theta}}{2}\right) - K_{Hund}\sigma \boldsymbol{S}_{\mathbf{Mn}} - J_{\mathrm{t2g}} \sum_{LMnO} \boldsymbol{S}^{\boldsymbol{t2g}}_{\mathbf{Mn}} \boldsymbol{S}^{\boldsymbol{t2g}}_{\mathbf{Mn}}$$

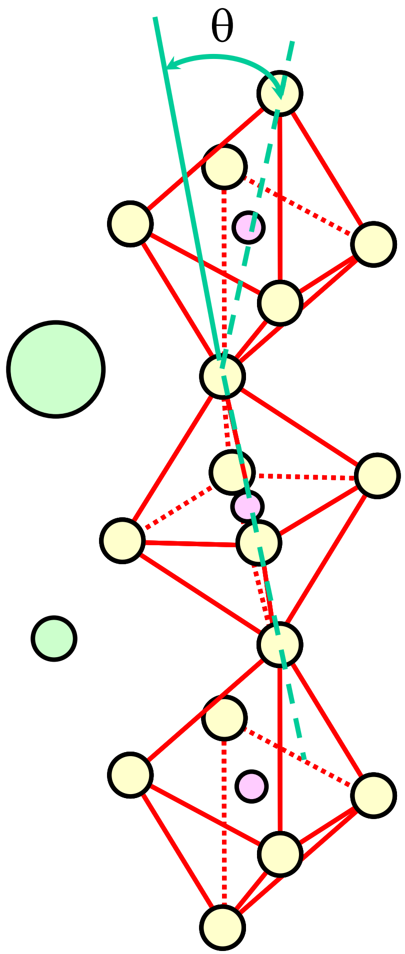


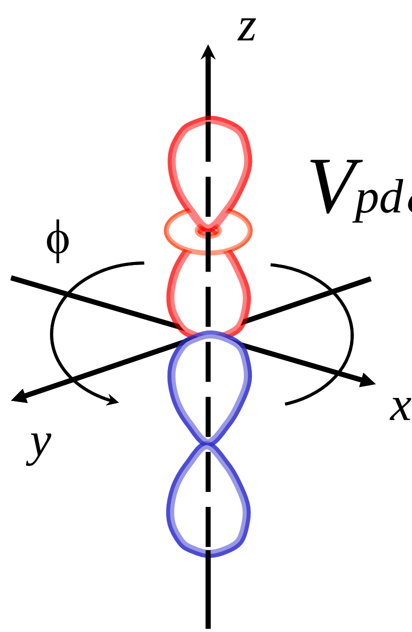
Colossal magneto resistance (CMR)



Temperature dependence of resistivity with a variety of magnetic fields in $La_{1-x}Sr_xMnO_3$ crystal（negative CMR）.
T_c indicates the Curie temperature at H=0 T.

Main parameters of transfer integral changes





Harrison's equation

$$V_{pd\sigma} = \langle \varphi_d | H | \varphi_p \rangle \sim d^{-7/2}$$

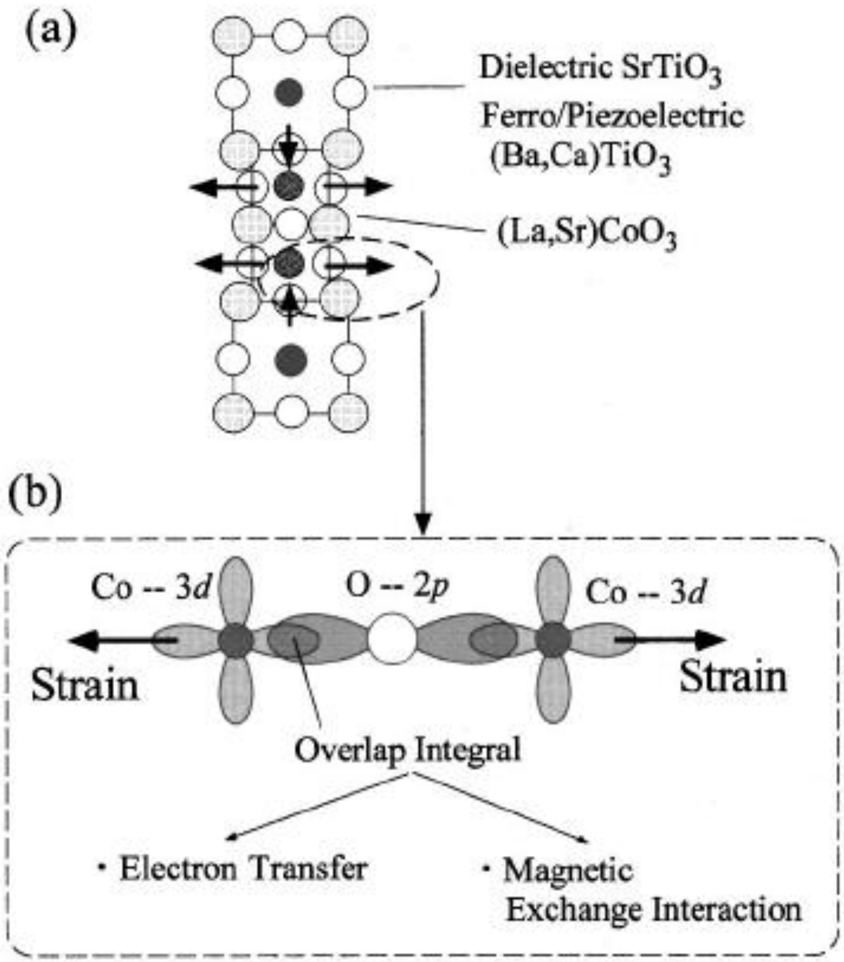
d: the distance between orbitals

ϕ: the bond angle

$$E_{3z^2-r^2,3z^2-r^2} = \left[n^2 - \frac{1}{2}(l^2+m^2)\right]^2 V_{dd\sigma} + 3n^2(l^2+m^2)V_{dd\pi} + \frac{3}{4}(l^2+m^2)^2 V_{dd\delta}$$

$$\approx \cos\phi$$

Main parameters of transfer integral changes



Tensile strain

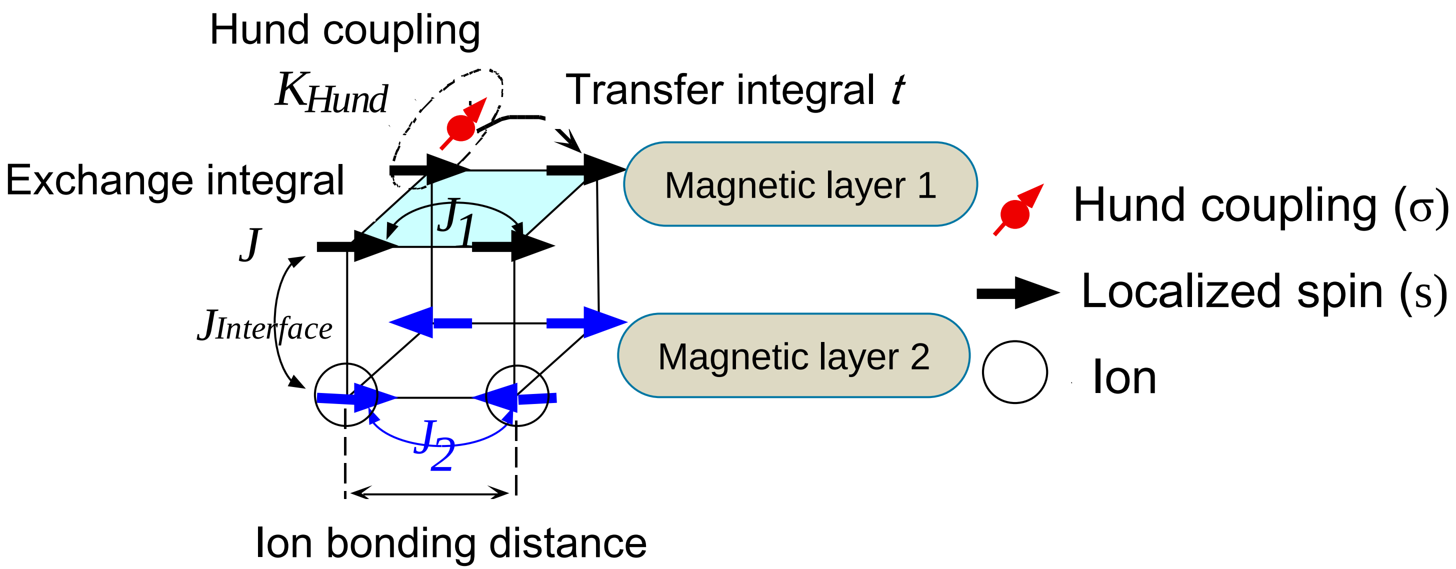
$$V_{pd\sigma} \sim d^{-7/2}$$

Compressive strain

Band width W＝2zV

z：Coordination number

Material design for oxide spintronics



d electron energy | Coulomb integral | Hund coupling | Exchange integral

$$H_{electron} = \sum E_d + \frac{1}{2}\sum U + K_{Hund}\sum_i \sigma S_i + \sum_{i,j} J_{ij} S_i S_j$$

$$+ \sum E_p + \sum t + A\sum_i dQd$$

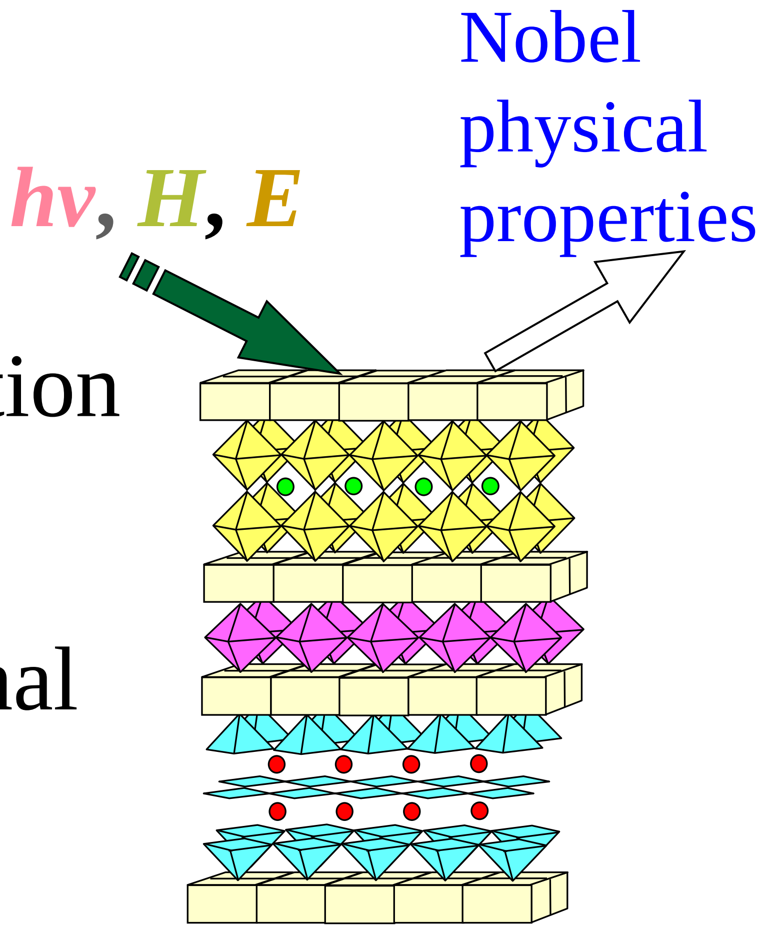
Transfer integral

Material design for oxide spintronics

(1) Introduce strain effect

(2)Introduce magnetic interaction between different layers

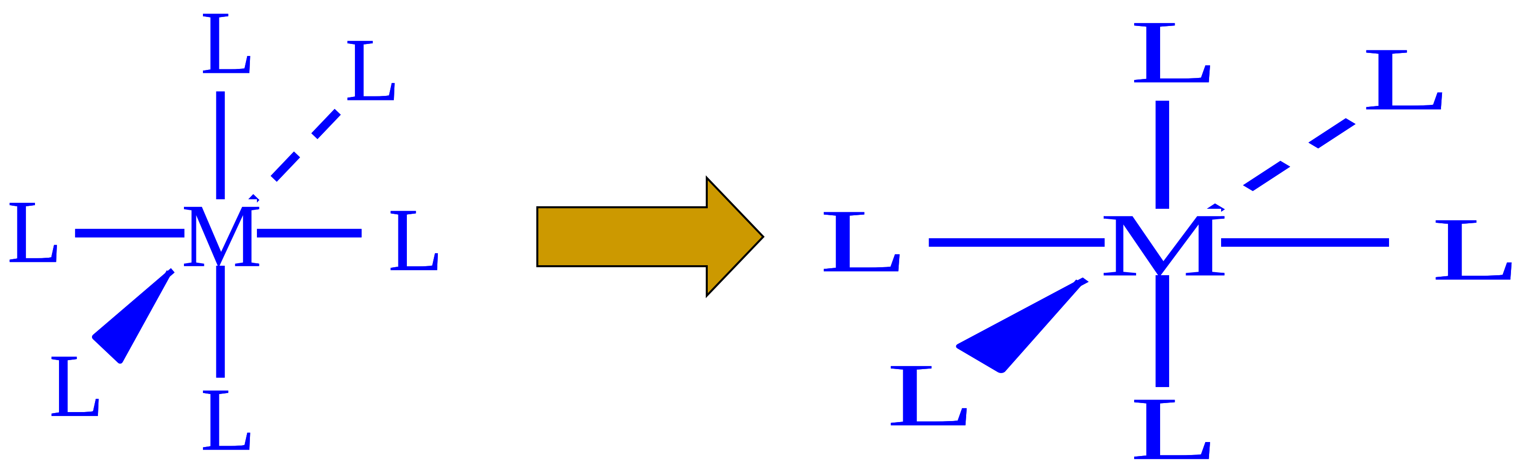
(3) Integrate different functional materials

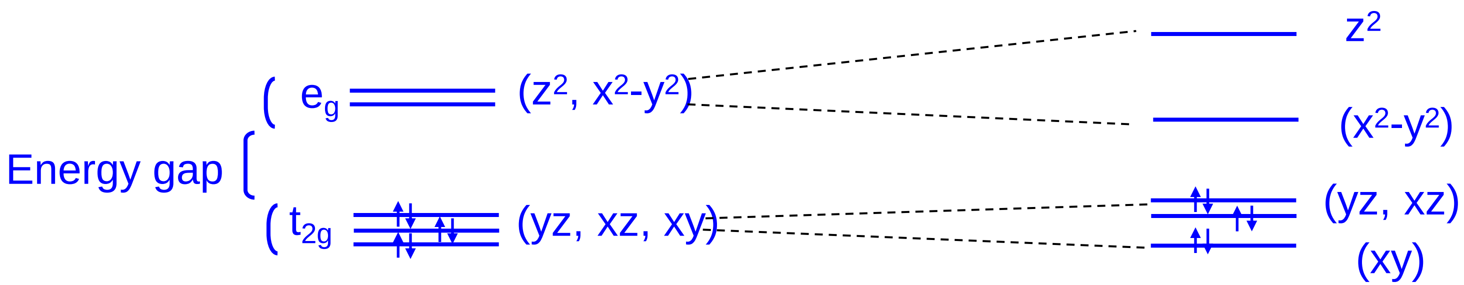


Control of crystal field splitting due to strain effect

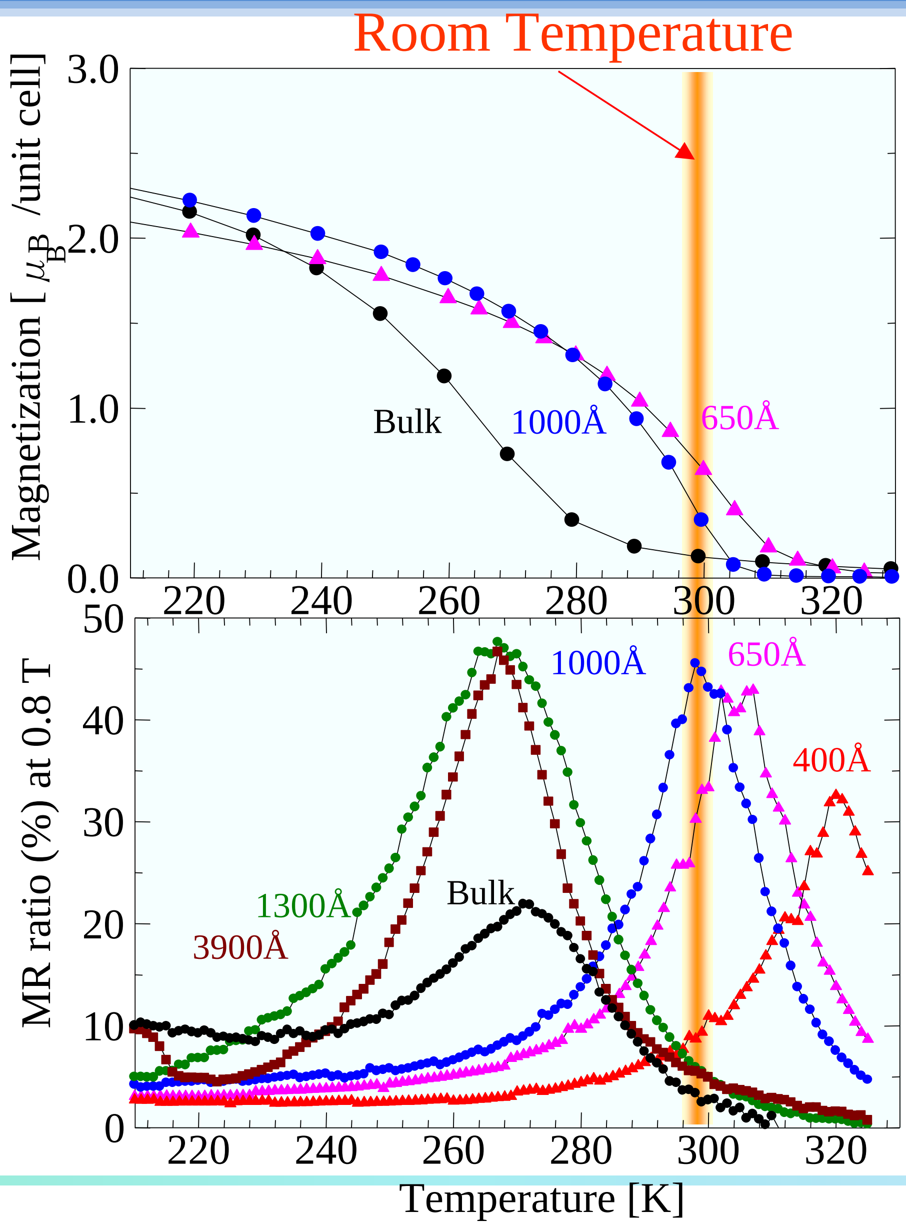
Octahedral coordination

In-plane tensile strain



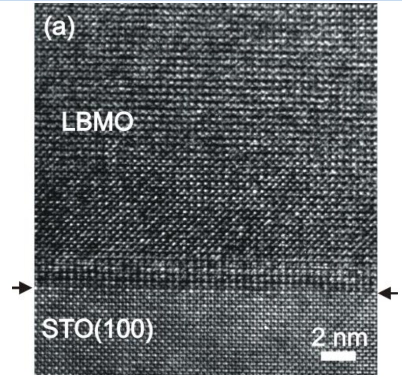


Design of room temperature CMR materials



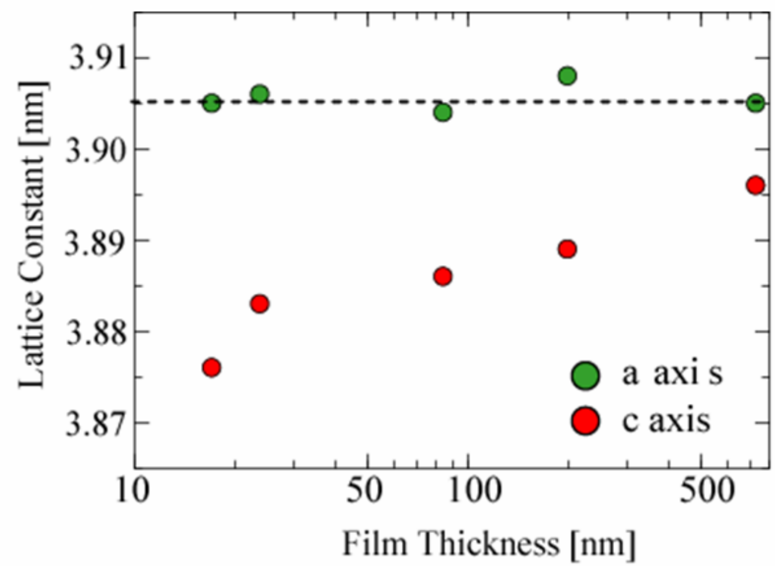
$(La_{0.8}Ba_{0.2})MnO_3$

$SrTiO_3$ substrate



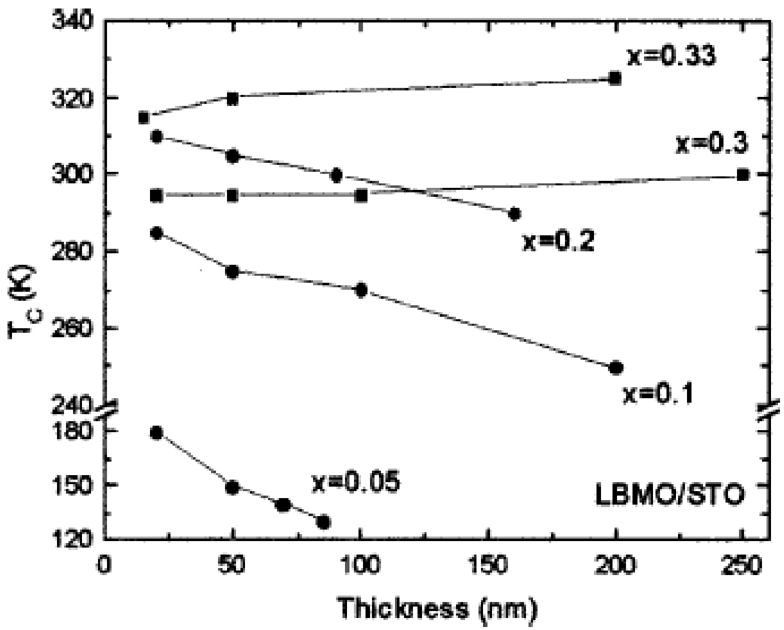
Tensile strain

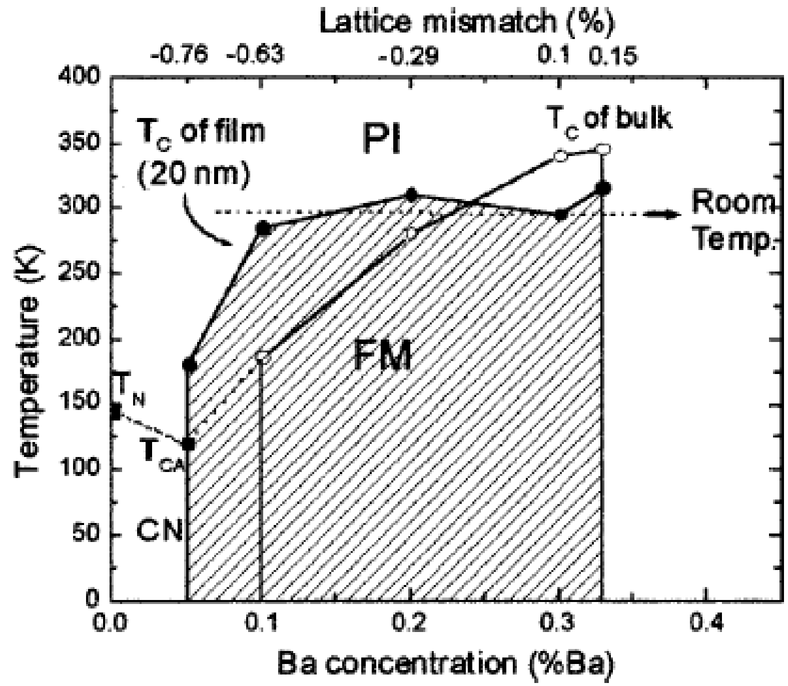
(0.3%)



Phys. Rev. B ***64***, *224418(2001)*

Strain effect vs T_C in LBMO films





Tensile strain ⇦ | ⇨ Compressive strain

x	0.05	0.1	0.2	0.3	0.33
Lattice mismatch (%)	−0.76	−0.63	−0.29	0.1	0.15
Strain type	*T*	*T*	*T*	*C*	*C*
T_C of bulk (K)	120[a]	185	280	340	345
T_C of film (20 nm) (K)	180	285	310	290	315

[a]For $x = 0.05$, spin canting transition temperature $T_{CA} = 120$ K.

Tensile strain

Increase in T_C

Compressive strain

decrease in T_C

Phys. Rev. B ***64***, *184404(2001)*

Stability of double exchange magnetism

Stability of magnetism induced by double exchange interaction

$$\Delta\varepsilon_{ex}^{D} = zxt_{ij} = zxb_{\sigma}\left\langle \cos(\theta_{ij}/2) \right\rangle$$

C. Zener: Phys. Rev. **82** (1951) 403
P. W. Anderson and H. Hasegawa: Phys. Rev. **100** (1955) 675
P. G. de Gennes:Phys. Rev. **118** (1960) 141

Z: the coordination number of nearest neighbor atoms ;Z=6

t_{ij}: the transfer energy

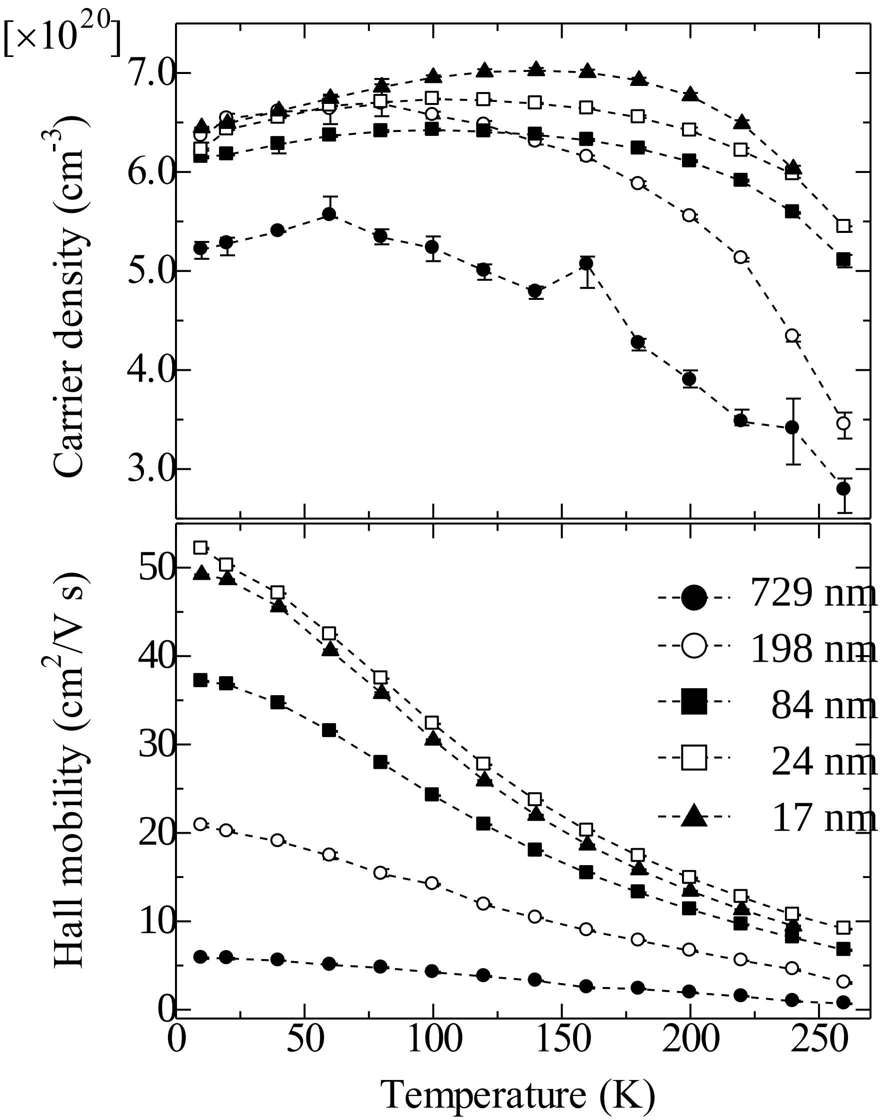
θ_{ij}: the spin angle between Mn_i and Mn_j

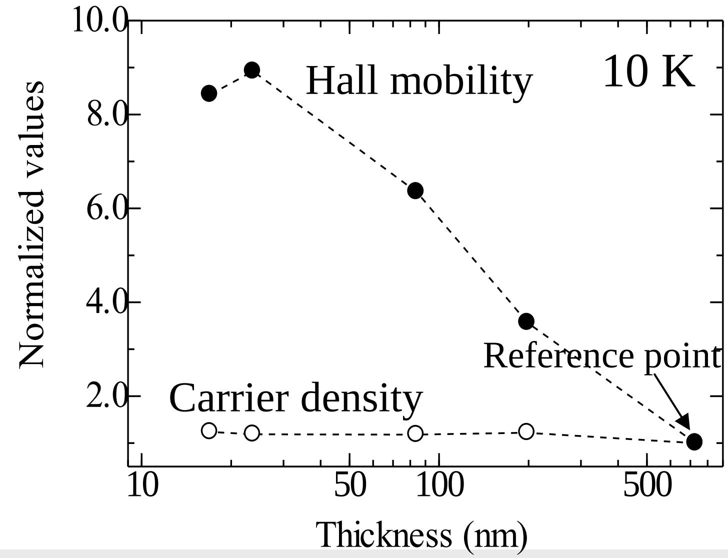
Main parameters indicating the stability of double exchange magnetism

x: the number of carriers per a Mn site

b_{σ}: Spin-independent components
（dependence of orbital overlap and bond angle of Mn-O-Mn）

Carrier density and Hall mobility





Carrier density : Constant

➡ the number of carrier *x*: constant

➡ **Not generating cataion deficiency**

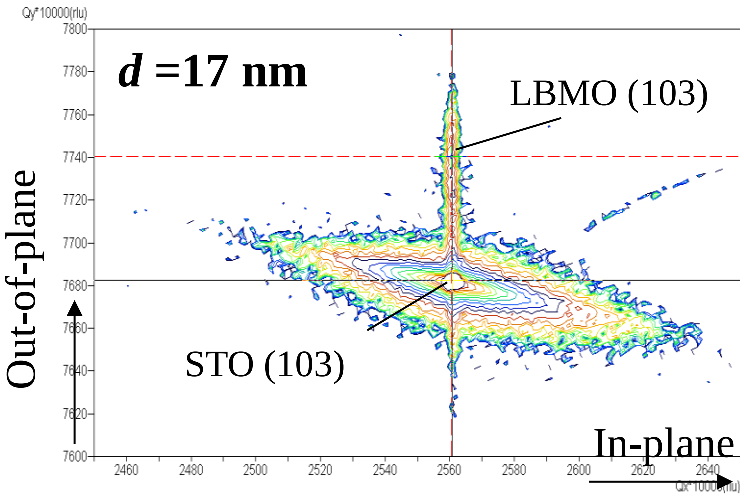
Hall mobility : Increase

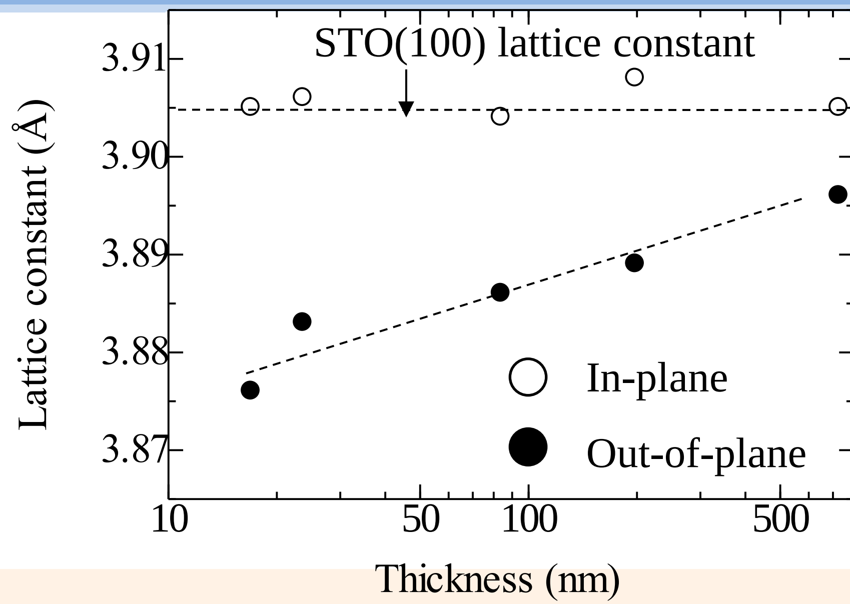
➡ Increase in transfer integral

➡ **change in orbital overlap state due to lattice strain effect**

Phys. Rev. B ***71****, 012403(2005)*

Stability of transfer integral due to lattice strain effect

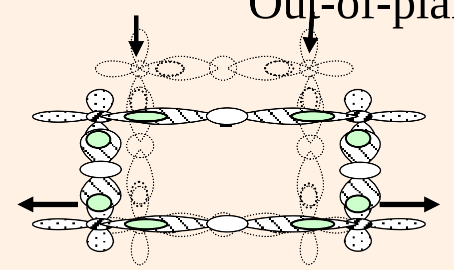




Calculation of stability in double exchange interaction every thickness

◆ **stability of double exchange interaction**

$$\Delta\varepsilon_{ex}^{D} = z\Delta x\Delta t_{ij} \propto \Delta x\Delta b_{\sigma} \propto \Delta b_{\sigma}$$



x: the number of carriers per a Mn site

b_{σ}: Spin-independent components
（dependence of orbital overlap and bond angle of Mn-O-Mn）

Z: the coordination number of nearest neighbor atoms ；Z=6

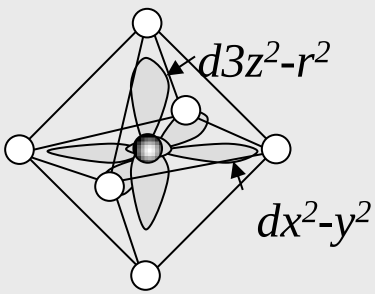
Contribution elements of stability in double exchange interaction

1. In-plane and Out-of-plane orbital overlap

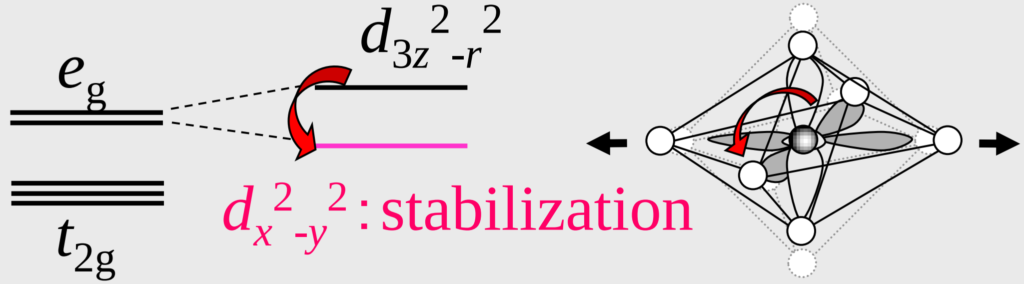
→ determination from lattice constants obtained by experiments

matrix element between *p* and *d* orbitals: $V_{pd}=d_{\text{Mn-O}}^{-7/2}$ Mn-O-Mn bond angle: 180°

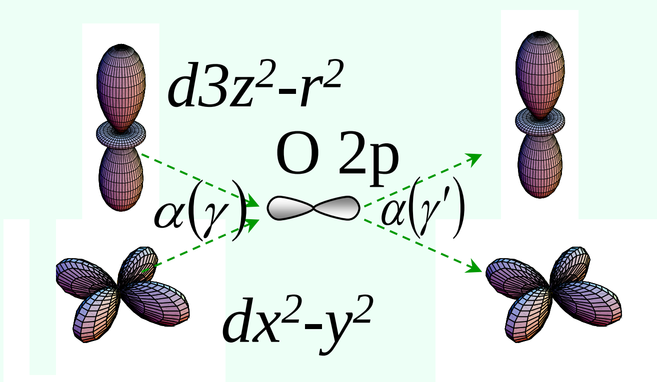
2. Redistribution of e_g electrons due to lattice strain effect → calculation by the DV-$X\alpha$ method



Tensile strain



3. Anisotropy of *d* orbital



Transfer strength	Out-of-plane		In-plane	
$\gamma \backslash \gamma'$	$\lvert x^2-y^2\rangle$	$\lvert 3z^2-r^2\rangle$	$\lvert x^2-y^2\rangle$	$\lvert 3z^2-r^2\rangle$
$\lvert x^2-y^2\rangle$	0	0	3/4	$\sqrt{3/4}$
$\lvert 3z^2-r^2\rangle$	0	1	$\sqrt{3/4}$	1/4

Phys. Rev. B ***64****, 224418(2001)*

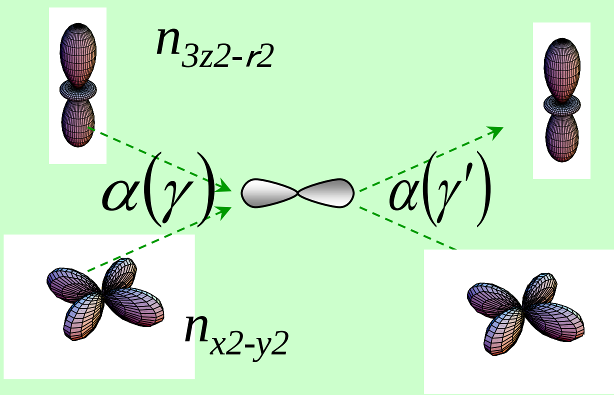
Contribution elements of stability in double exchange interaction

Stability of averaged double exchange interaction

$$\Delta\varepsilon_{ex}^{D} \propto \sum_{<i,j>} (n_{x^2-y^2}, n_{3z^2-r^2}, \alpha(\gamma_i)\alpha(\gamma'_j), d_{in}^{-7}, d_{out}^{-7})$$

Transfer strength from Mn3*d* orbital to O2*p* orbital $\alpha(\gamma)$

Transfer strength from O2*p* orbital to Mn3*d* orbital $\alpha(\gamma')$



d_{in} : the in-plane Mn-O length

d_{out} : the out-of-plane Mn-O length

➡ derived by XRD measurement

$n_{x2\text{-}y2}$: the ration of occupied electrons in $d_{x2\text{-}y2}$ orbital

$n_{3Z2\text{-}r2}$: the ration of occupied electrons in $d_{3z2\text{-}r2}$ orbital

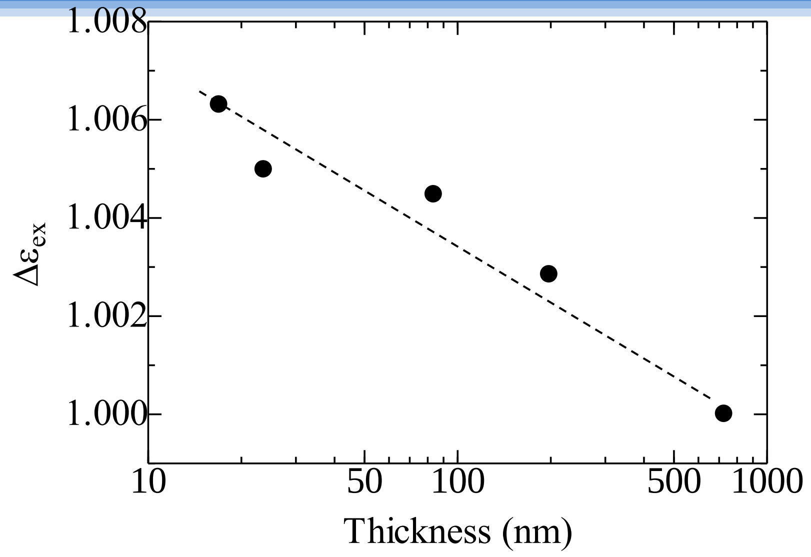
➡calculation by the DV-*Xα* method using experimental lattice constants

In-plane: 4 directions

Out-of-plane : 2 directions

$$\Delta\varepsilon_{ex}^{D} \propto \left((3+\sqrt{3})n_{x^2-y^2} + (1+\sqrt{3})n_{3z^2-r^2}\right)d_{in}^{-7} + 2n_{3z^2-r^2}d_{out}^{-7}$$

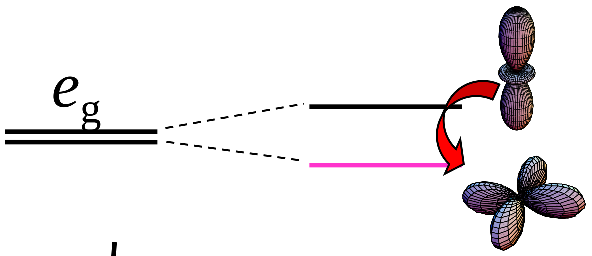
Stability of double exchange magnetism



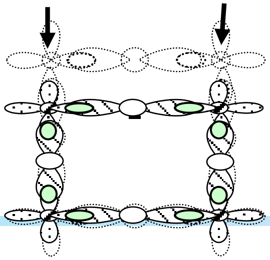
Stabilization of double exchange interaction with decreasing film thickness

What is main factors of T_C increase in strained (La,Ba)MnO_3 thin films

- redistribution effect by e_g electrons due to anisotropy d orbital.



- Orbital overlap of in-plane and out-of-plane

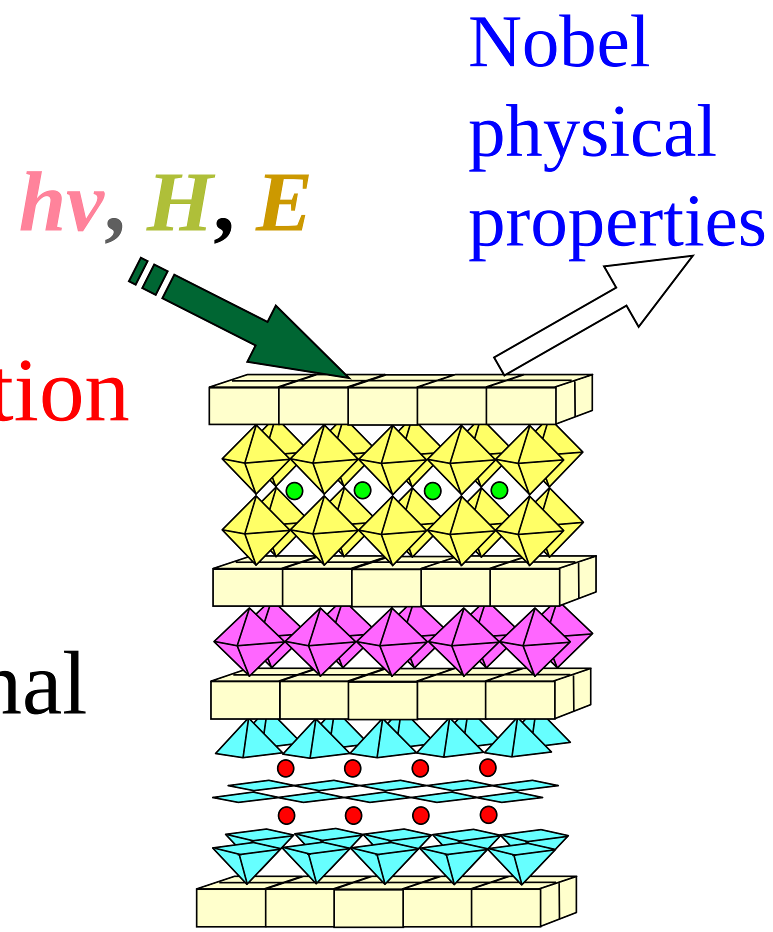


Function of interface

(1) Introduce strain effect

(2)Introduce magnetic interaction between different layers

(3) Integrate different functional materials



Control of interface magnetic interaction

Conductive electron

Localized spin

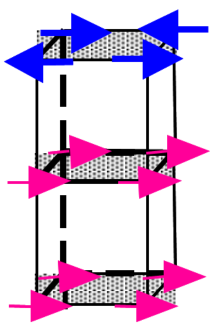
Hund coupling

$$\boldsymbol{H} = -t_{\mathrm{Mn-Mn}}\cos\left(\frac{\theta}{2}\right) - K_{Hund}\,\sigma \boldsymbol{S}_{\mathbf{Mn}} - J_{\mathrm{t2g}}\sum_{LMnO} \boldsymbol{S}^{t2g}_{\mathbf{Mn}} \boldsymbol{S}^{t2g}_{\mathbf{Mn}}$$

$$- J_{\mathrm{Fe-Mn}}\,\boldsymbol{S}^{t2g}_{\mathbf{Mn}} \boldsymbol{S}_{\mathbf{Fe}} - \sum_{LFeO} J_{\mathrm{Fe-Fe}}\,\boldsymbol{S}_{\mathbf{Fe}} \boldsymbol{S}_{\mathbf{Fe}}$$

Interface magnetic interaction

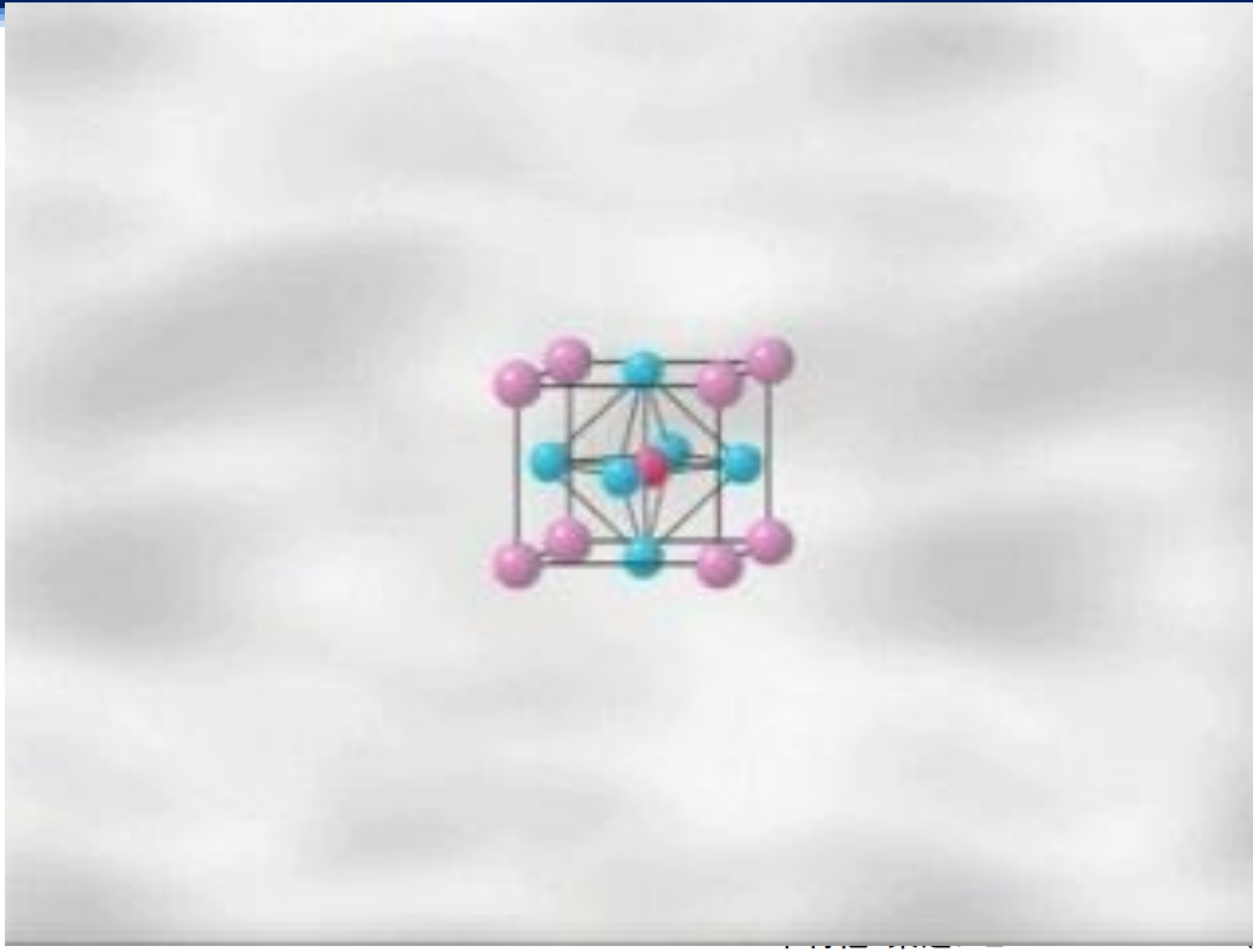
Antiferromagnet $LaFeO_3$



Combined with two materials

Ferromagnet $(La,Sr)MnO_3$

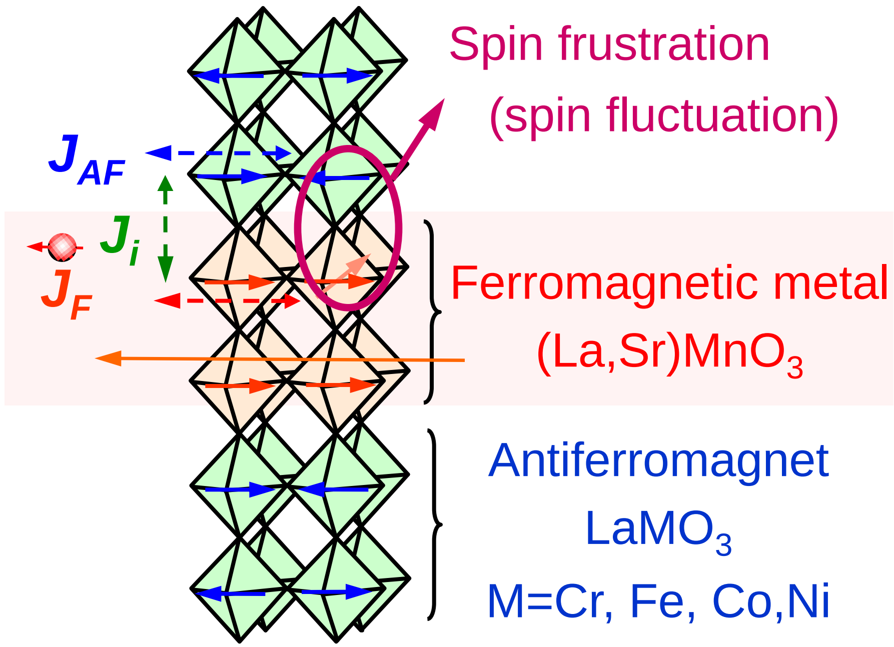
Spin frustration superlattice

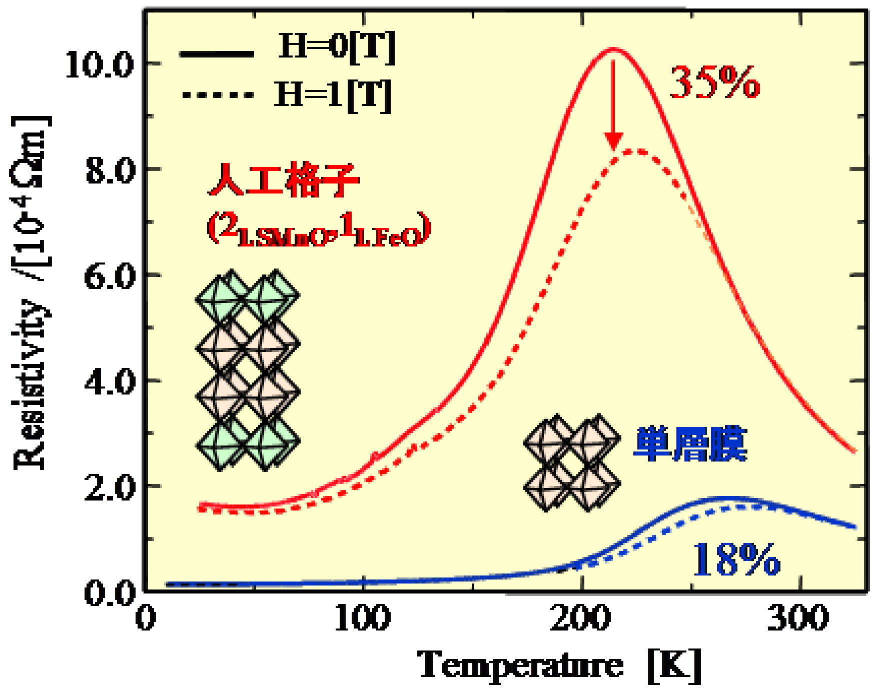


2006)

High sensitive response by magnetic field

Spin frustration superlattice

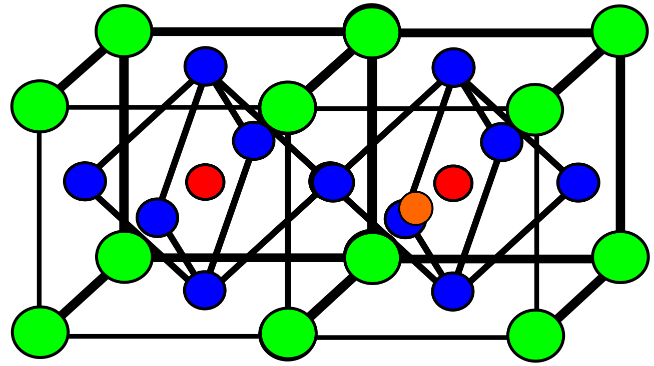


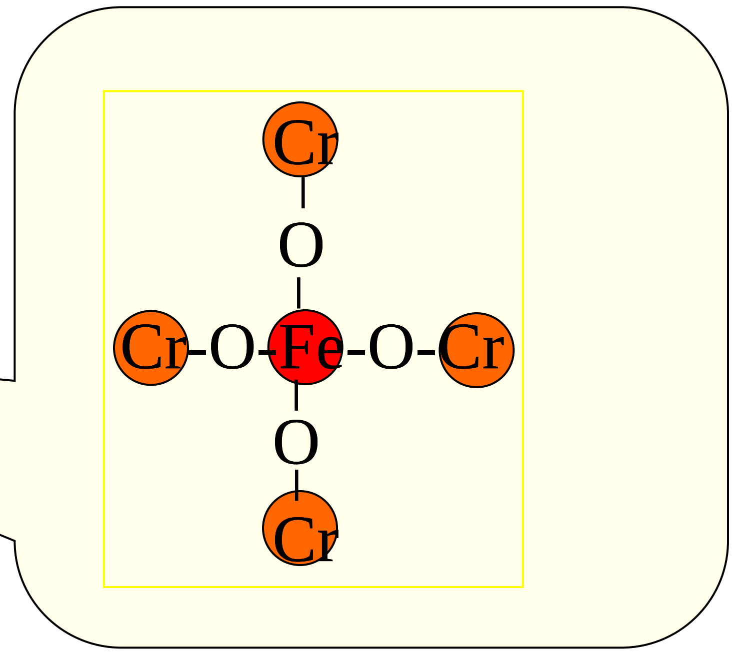


Theoretical prediction：New ferromagnet

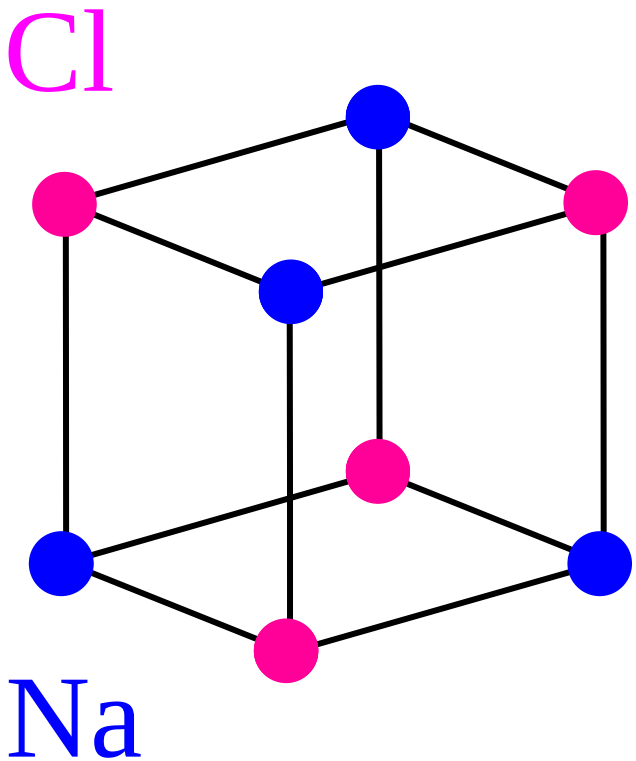
60 years ago

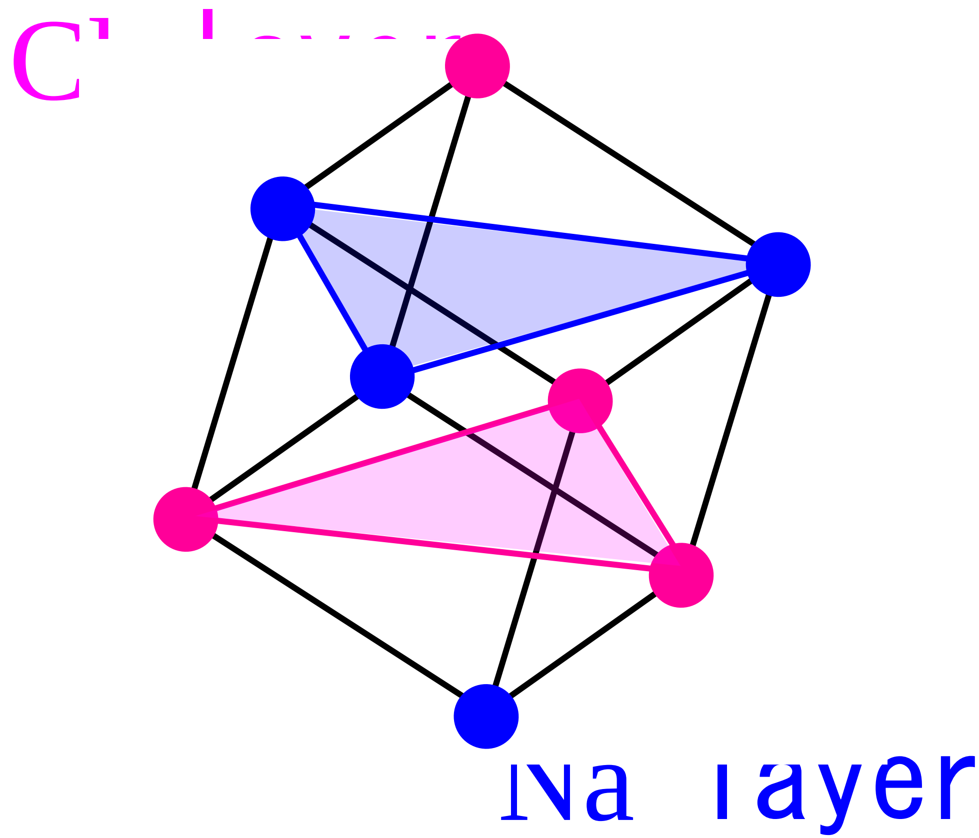
Kanamori former president of Osaka Univ.



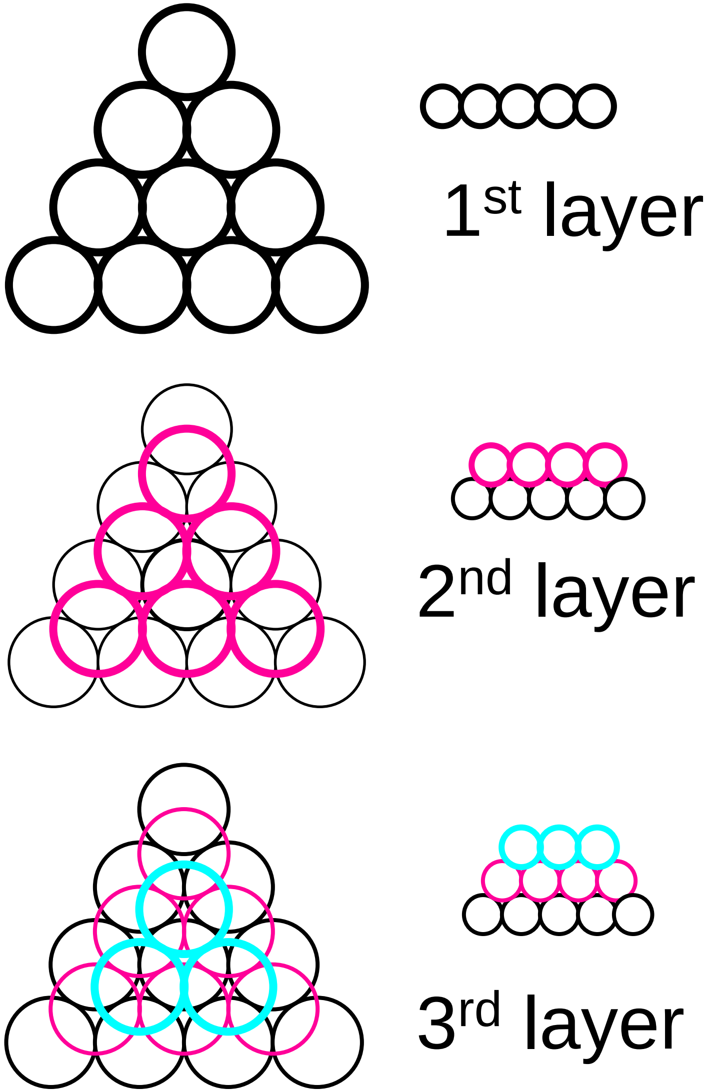


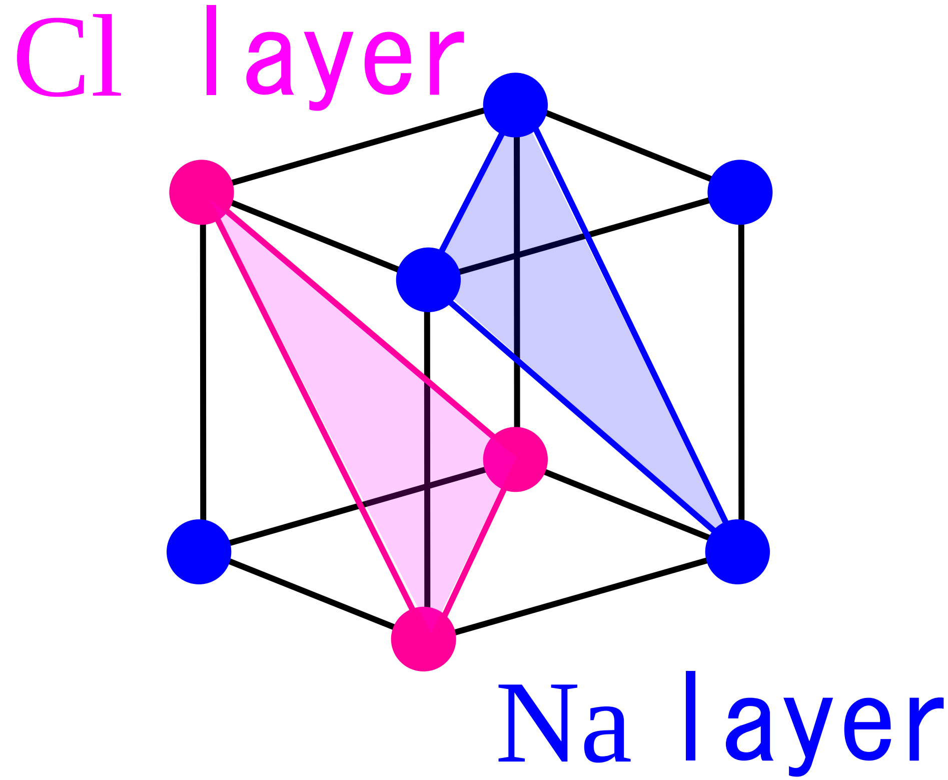
NaCl structure



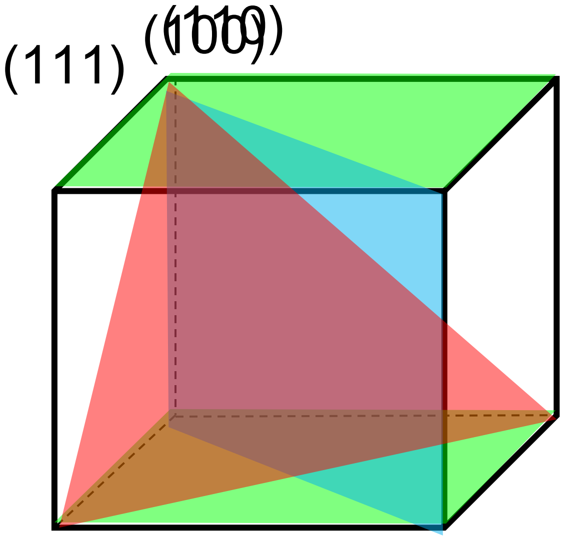


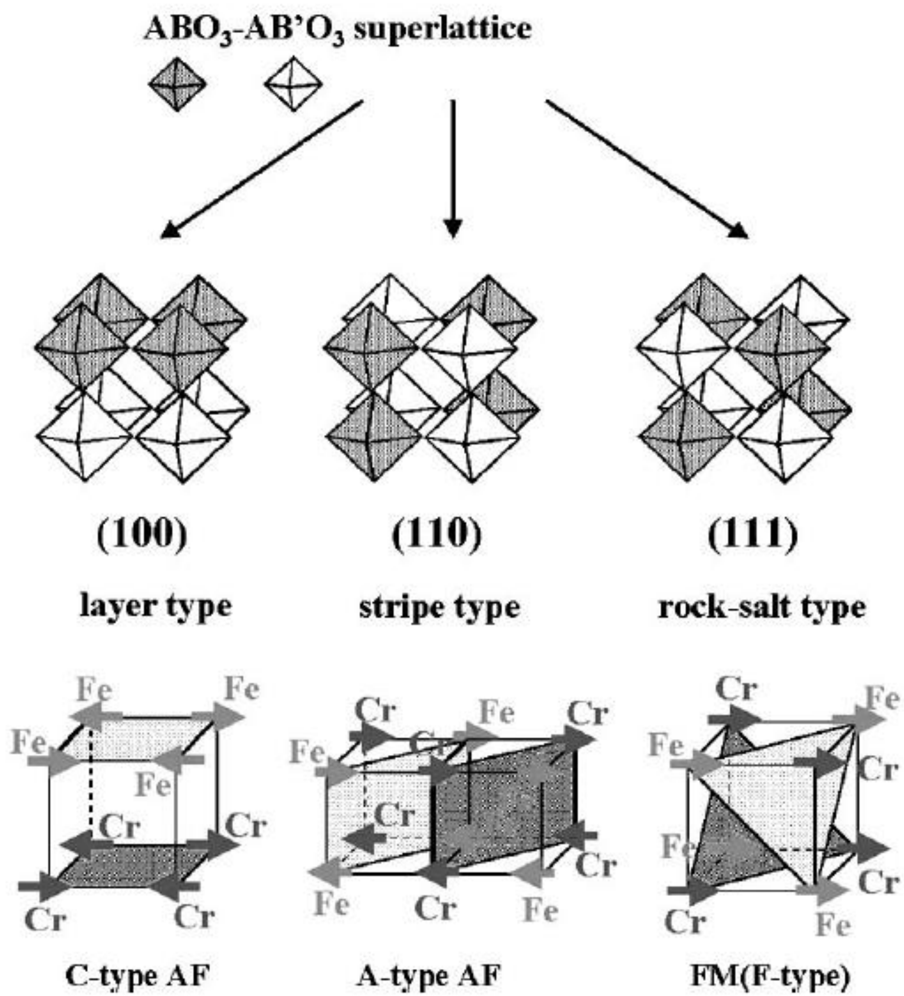
Lattice-direction control superlattice





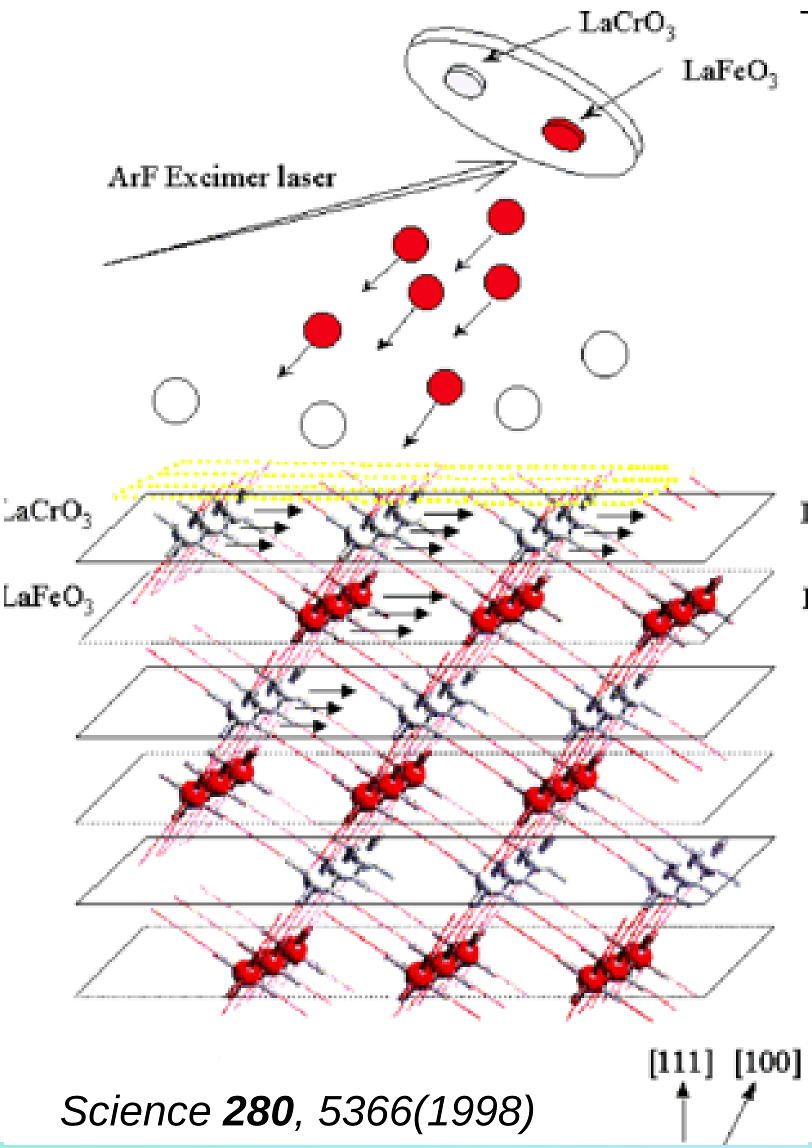
Lattice-direction control superlattice



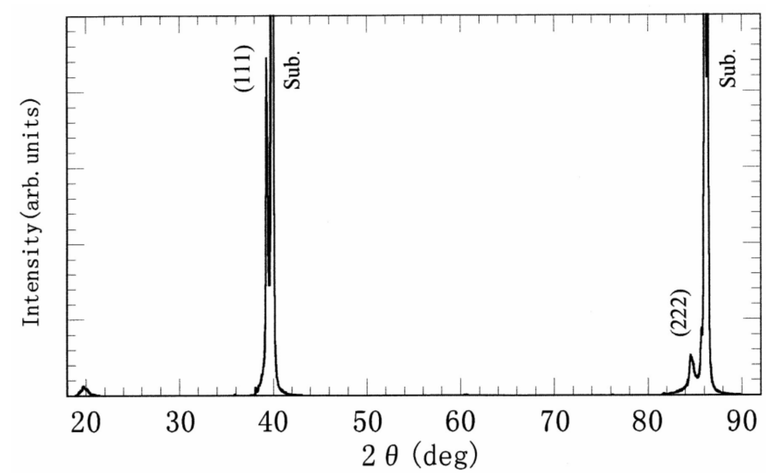


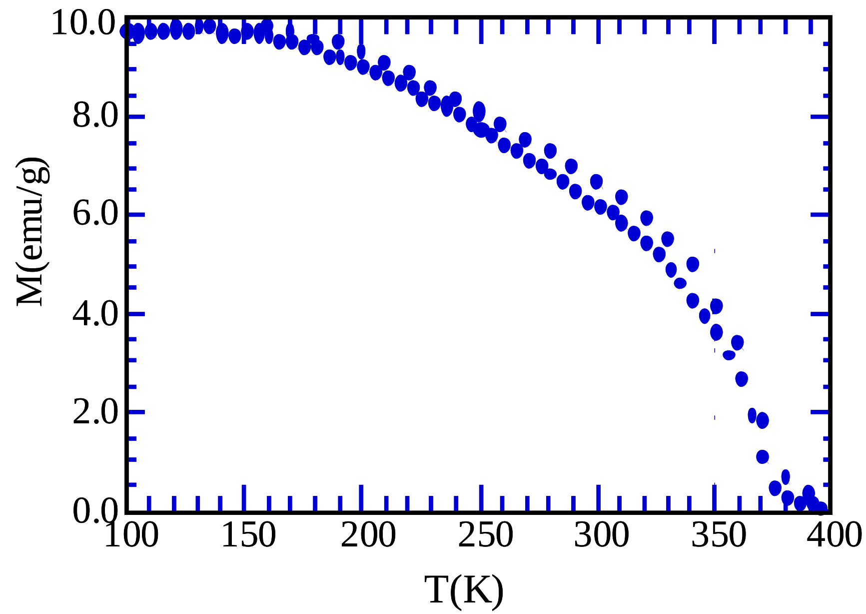
J. Appl. Phys. ***89***, *2847(2001)*

Lattice-direction control superlattice



Science ***280***, *5366(1998)*



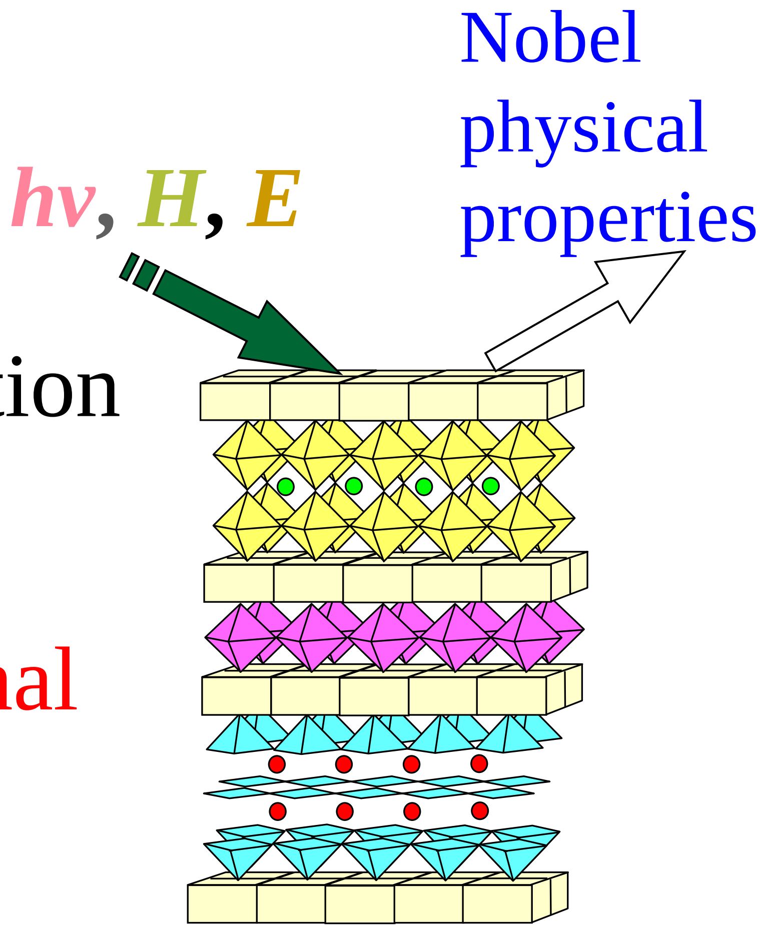


Integration of different functional materials

(1) Introduce strain effect

(2)Introduce magnetic interaction between different layers

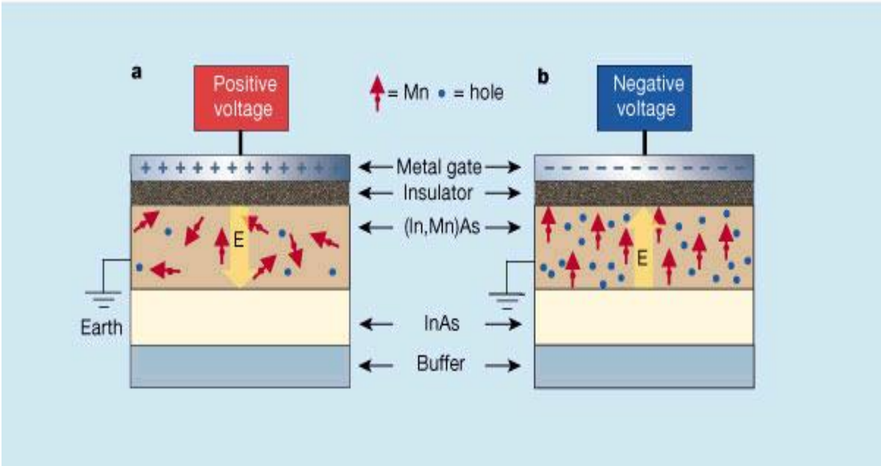
(3) Integrate different functional materials

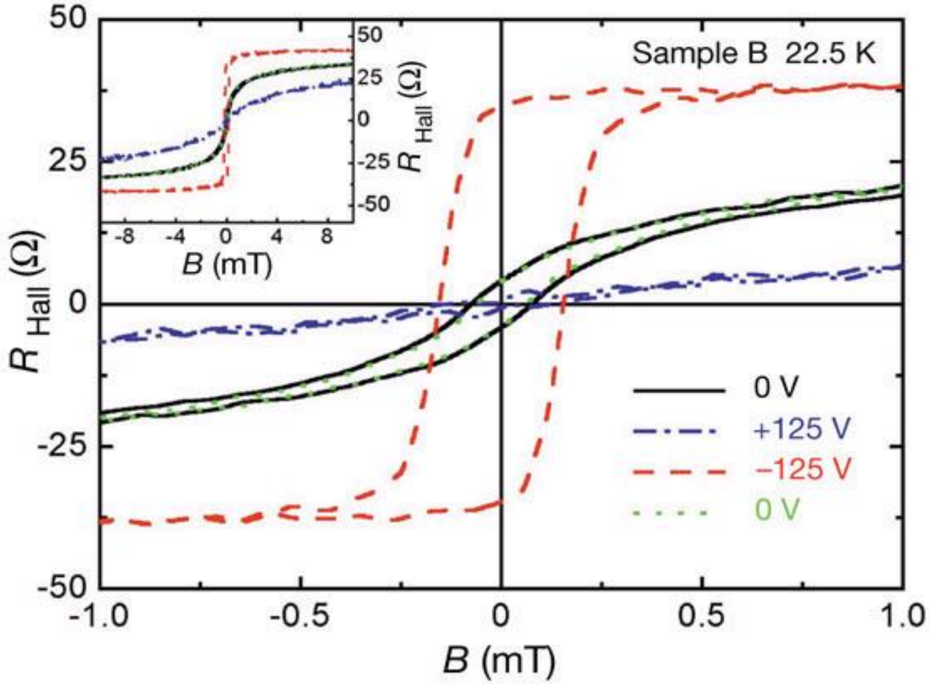


Ferromagnet/Ferroelectric material combination

Diluted magnetic semiconductor-- (In,Mn)As

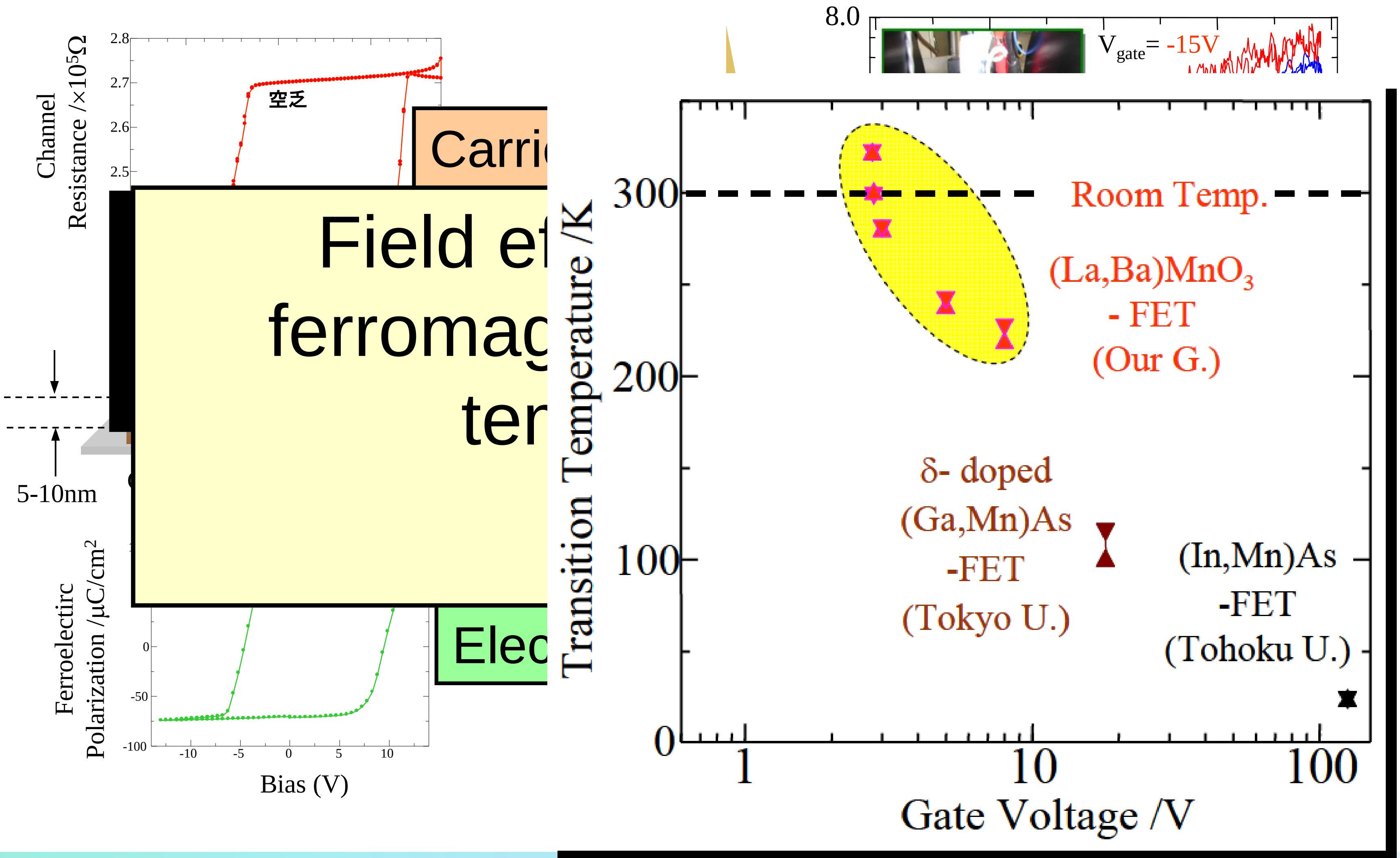
Field effect transistor





Nature ***408***, *944(2000)*

Ferromagnet/Ferroelectric material combination



Ferromagnet/Ferroelectric material combination

Conductive electron

Hund coupling

Localized spin

$$\boldsymbol{H} = -\boldsymbol{t}_{\mathrm{Mn-Mn}} \cos\left(\frac{\theta}{2}\right) - K_{Hund} \sigma \boldsymbol{S}_{\mathbf{Mn}} - J_{\mathrm{t2g}} \sum_{LMnO} \boldsymbol{S}_{\mathbf{Mn}}^{\boldsymbol{t2g}} \boldsymbol{S}_{\mathbf{Mn}}^{\boldsymbol{t2g}}$$

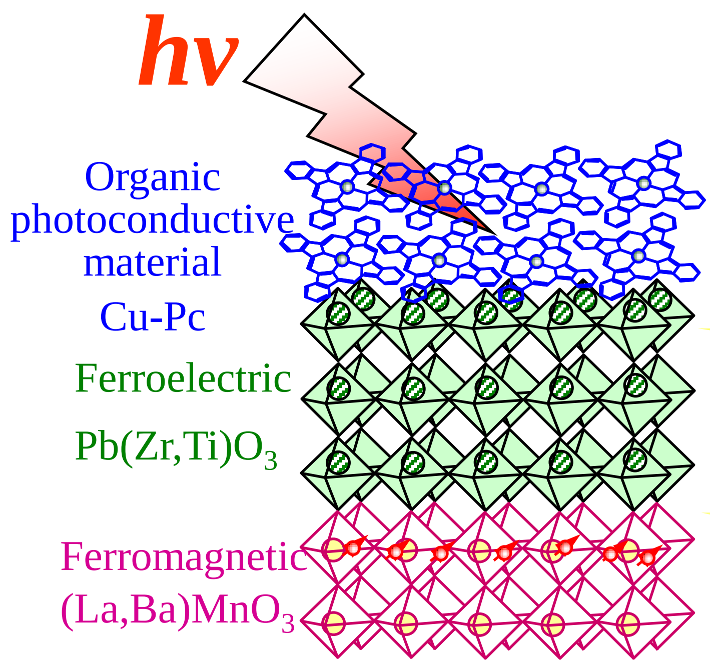
$\times$

N (The number of carriers)

Electric field

Photonic/Ferroelectric/magnetic material combination

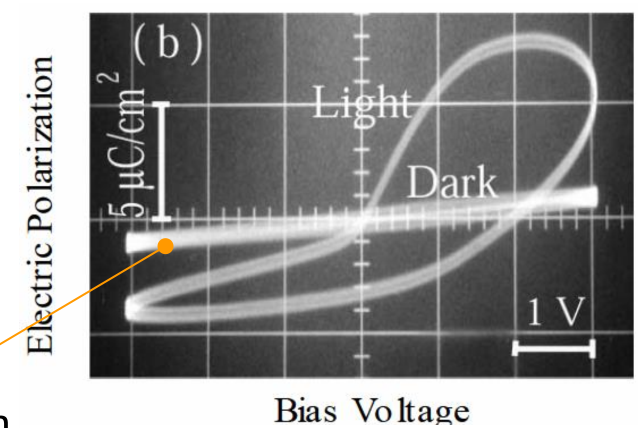
Photon→Electric dipole → Carrier spin

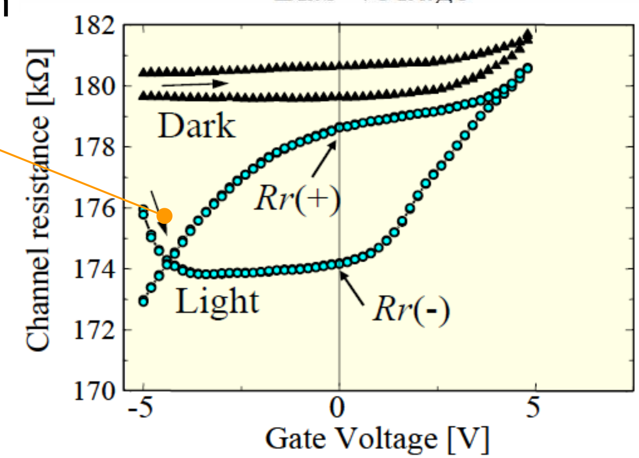


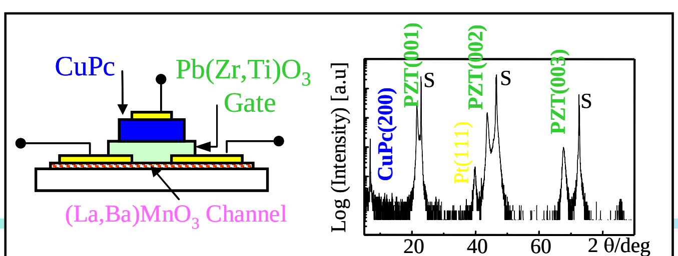
Decrease resistance (by photon)

Dielectric polarization (electric dipole)

Field effect (Carrier / Spin)







Summary: Oxide spintronics

(1) Introduce strain effect --------- Room temperature CMR

(2)Introduce magnetic interaction --- Magnetic superlattice
between different layers Design of magnetic susceptibility

(3) Integrate different functional ------ Ferromagnetism
materials + Ferroelectric