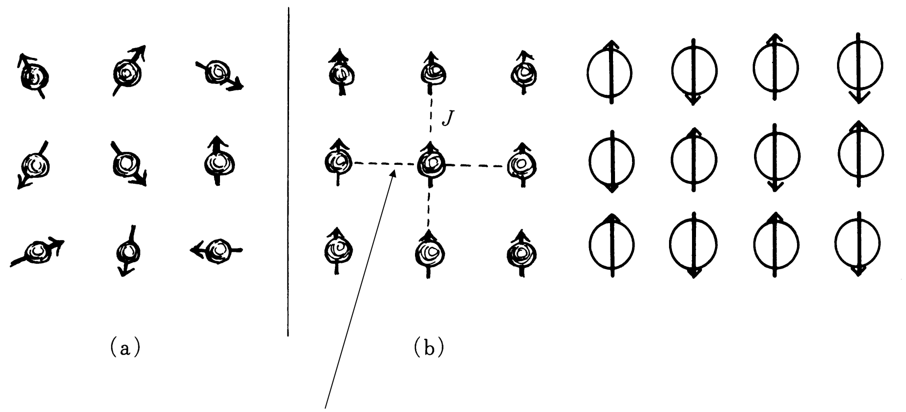
Introduction to Magnetism

Paramagnetism **Ferromagnetism** **Antiferromagnetism**



Hamiltonian in Magnetic Substances

$$H = -2J\,\Sigma_{ij}\,\boldsymbol{S}_i \cdot \boldsymbol{S}_j$$

***J* < 0** （in case of wave functions mixed ）

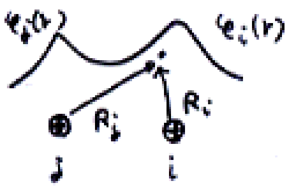
：Antiferromagnetism

***J* > 0** （in case of wave functions being orthgonalized ）

：Ferromagnetism

Model Hamiltonian for Strongly Correlated Electrons Systems

$$-t_{ij} = \int \varphi_j^*(\vec{r})\left[-\frac{\hbar^2}{2m}\Delta - \frac{e^2}{R_i} - \frac{e^2}{R_j}\right]\varphi_i(\vec{r})\,d\vec{r}$$



U: Coulomb repulsion

t: Transferred integral

$$\mathcal{H} = -\sum_{ij\sigma} t_{ij}\, a^\dagger_{i\sigma} a_{j\sigma} + U\sum_{i,\sigma} n_{i\sigma}\cdot n_{i,-\sigma}$$

$$-2J\,\Sigma_{ij}\,S_i \cdot S_j$$

(6-2) In order to improve the HL wave function;

$$\Phi_{HL} = \frac{1}{\sqrt{2(1+S^2)}}[\phi_a(1)\phi_b(2) + \phi_b(1)\phi_a(2)]$$

We incorporate the following states, using $\phi_a(1)\,\phi_a(2)$ and $\phi_b(1)\,\phi_b(2)$

$$\Phi' = \frac{1}{\sqrt{2}}[\phi_a(1)\phi_a(2) + \phi_b(1)\phi_b(2)]$$

Then, the improved trial wave function is expressed by $\Phi = c_1\Phi_{HL} + c_2\Phi'$.

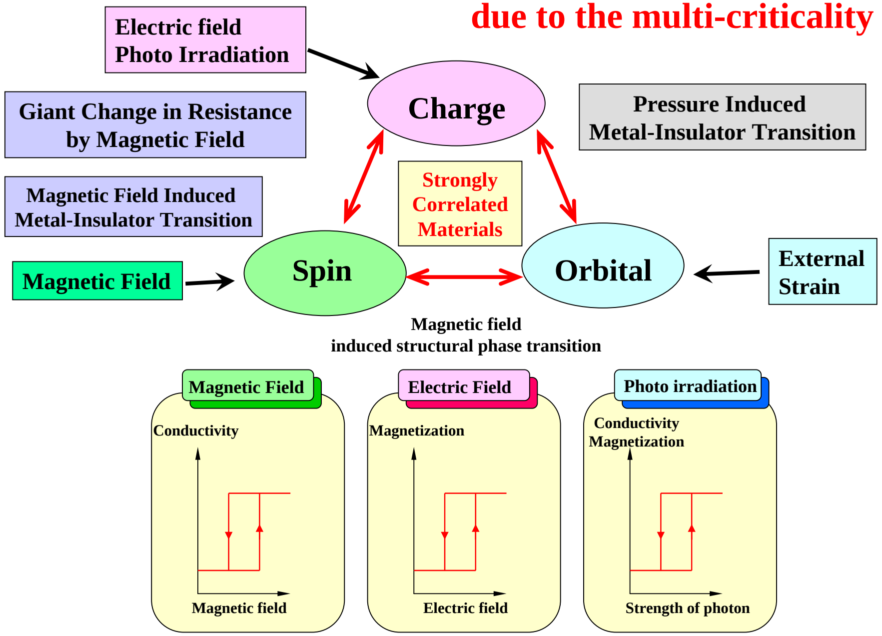
Show how to get the following relation and solve an eigen energy for this state

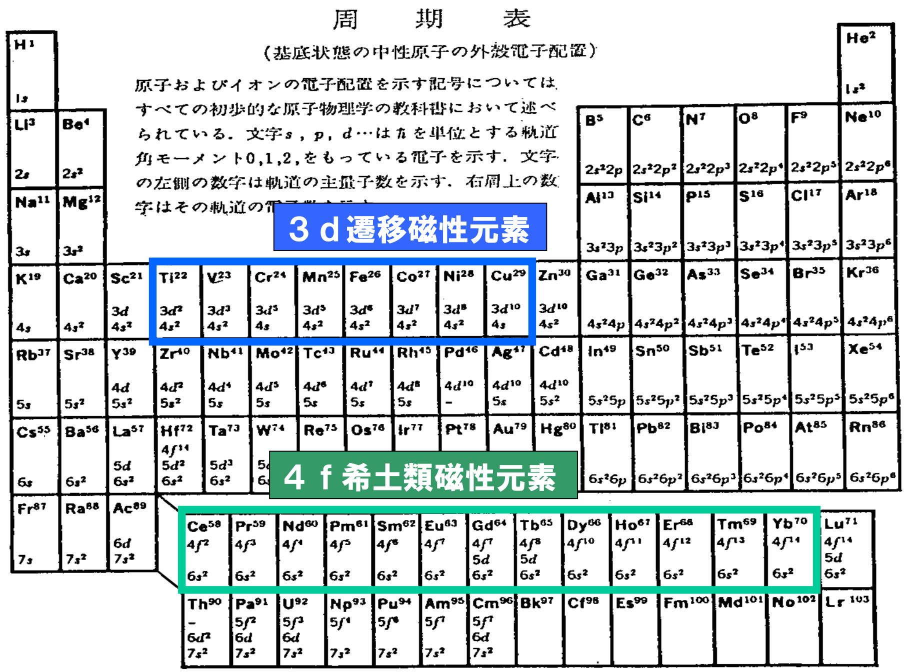
$$\begin{vmatrix} 2\varepsilon + U_1 + J' - E & 2t \\ 2t & 2\varepsilon + U_0 + J' - E \end{vmatrix} = 0$$

If $U_0 - U_1 >> |t|$ is valid for Mott insulator, show that the eigen energy is given as the follow;

$$E_{HL} = 2\varepsilon + U_1 + \boxed{J' - \frac{4t^2}{U_0 - U_1}}$$

Giant Response to magnetic and electric fields due to the multi-criticality





$$\mathcal{H}_{sl} = \Sigma_i \zeta l_i \cdot S/n = \zeta/n(\Sigma_i l_i) \cdot S = (\zeta/n) L \cdot S$$

$$\lambda = \zeta/n > 0$$

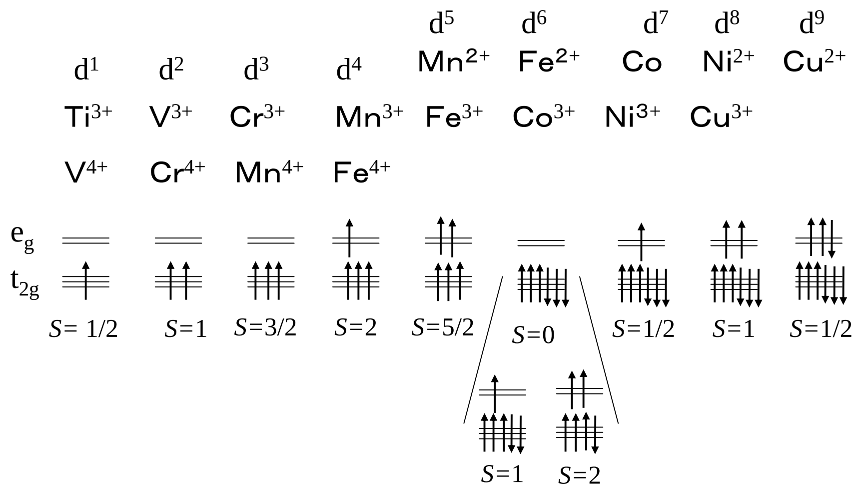
$$n > 2l+1 : \lambda = -\zeta/(4l+2-n) < 0$$

$$n = 2l+1 : L=0,\ S=(2l+1)/2 \rightarrow H_{sl}=0$$

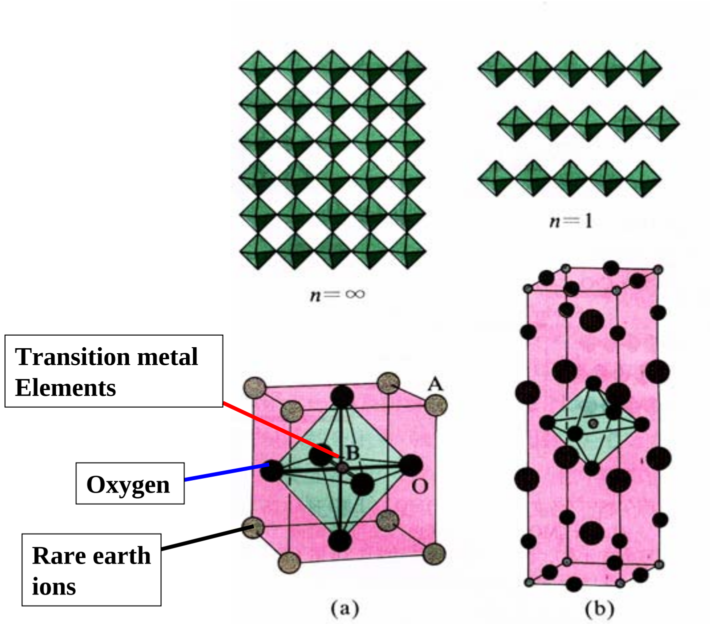
表 2-3　スピン軌道相互作用の定数

	電子数	電子状態	λ cm^{-1}
Ti^{3+}	d^1	^2D	154
V^{3+}	d^2	^3F	104
Cr^{3+}	d^3	^4F	87
Mn^{3+}	d^4	^5D	85
V^{2+}	d^3	^4F	55
Cr^{2+}	d^4	^5D	57
Fe^{2+}	d^6	^5D	−100
Co^{2+}	d^7	^4F	−180
Ni^{2+}	d^8	^3F	−335
Cu^{2+}	d^9	^2D	−828

Electron Configuration in Transition Metal Ions



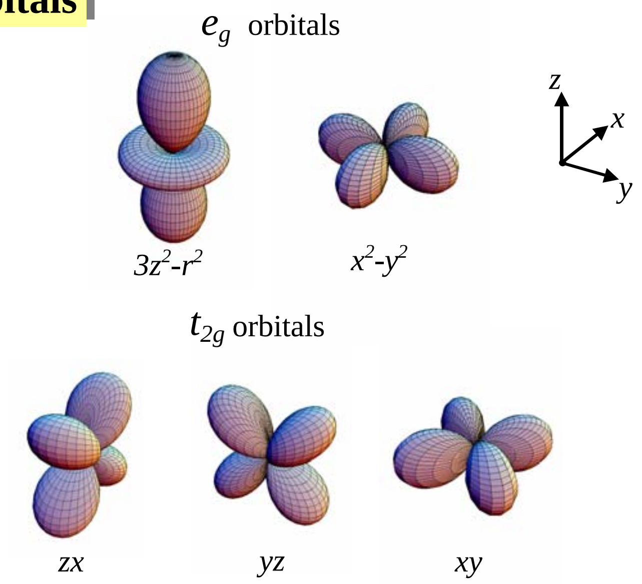
Hunds' rule and Crystal Electric Field Effect



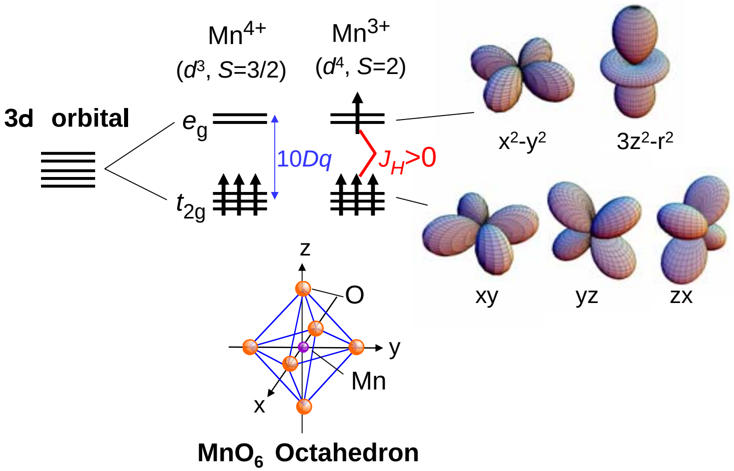
Perovskite

Layered Perovskite

3d orbitals



Electronic Structure of Manganese oxides



Hund's Coupling J_H > CEF splitting 10Dq

When J is negative due to the overlap of wave functions among nearest neighbor atomic sites, Spins are anti-parallel. On the other hand, if the wave function is orthogonalized, J is always positive and hence ferromagnetism is realized

Proof:

$$J_{n_1n_2} = \int \varphi_{n_1}^*(r_1)\varphi_{n_2}^*(r_2)\frac{e^2}{r_{12}}\varphi_{n_1}(r_2)\varphi_{n_2}(r_1)d\tau_1 d\tau_2$$

1 / r is expanded in a Fourier series as

$$\frac{e^2}{r_{12}} = \frac{1}{V}\sum_k \frac{4\pi e^2}{k^2} e^{ik\cdot(r_1-r_2)}$$

J = −2St + J' = J' (because of S=0)

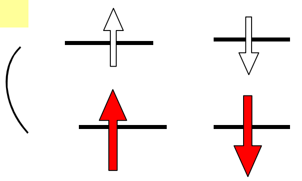
$$J_{n_1n_2} = \frac{1}{V}\sum_k \frac{4\pi e^2}{k^2}\int \varphi_{n_1}^*(r_1)\varphi_{n_2}(r_1)e^{ik\cdot r_1}d\tau_1$$

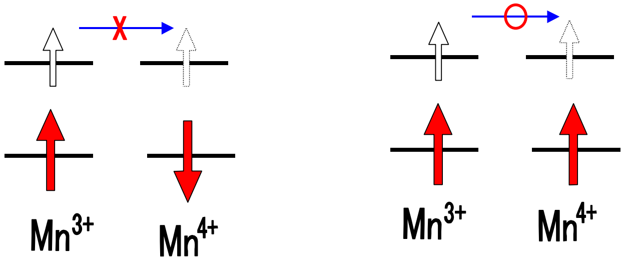
$$\times \int \varphi_{n_2}^*(r_2)\varphi_{n_1}(r_2)e^{-ik\cdot r_2}d\tau_2 > 0$$

のように書きかえられる．したがって $J_{n_1n_2}$ は常に正である．

Strong coupling of spin and charge degrees of freedom

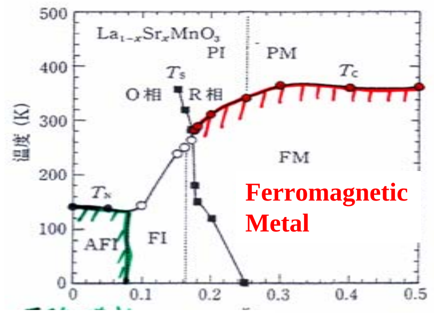
Hund's coupling



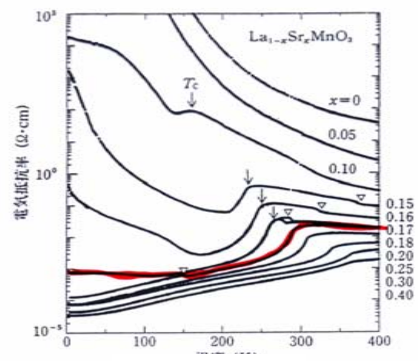


When carriers doped, metallic state is stabilized

Resistivity



Antiferromagnetic Insulator



Temperature (K)

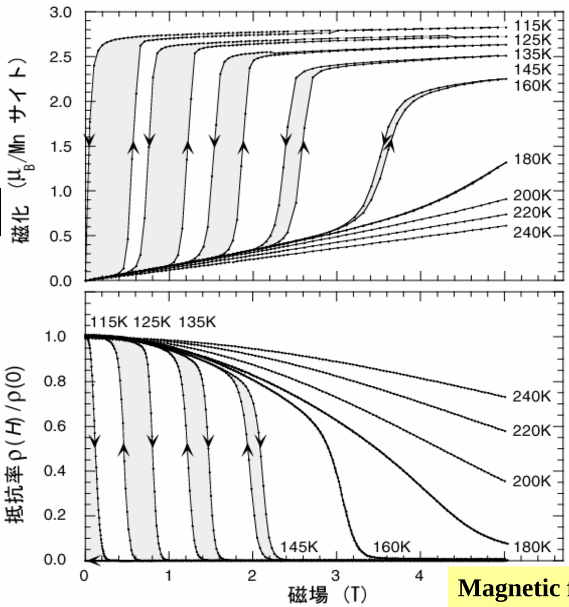
CMR effect

Colossal Magneto Resistance

Magnetization

Resistance

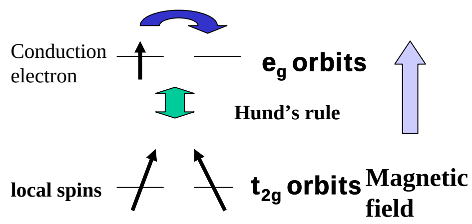
$(Nd,Sm)_{0.5}Sr_{0.5}MnO_3$

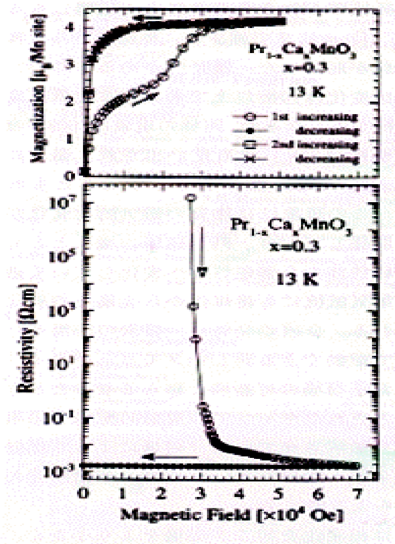


Magnetic field

Magnetic Field Control of Magnetic and Transport Properties in $Pr_{1-x}Ca_xMnO_3$

Competition between Ferromagnetic Metallic and charge ordered insulating phases





Conductivity controlled by Magnetic filed → local spins → mobile electrons

Resistance

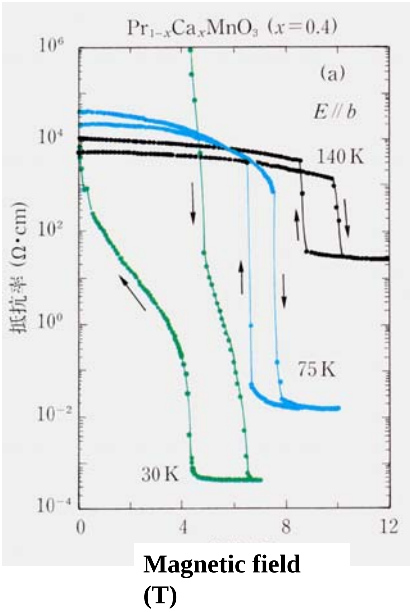
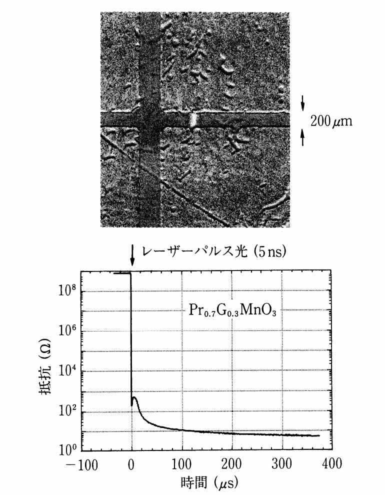
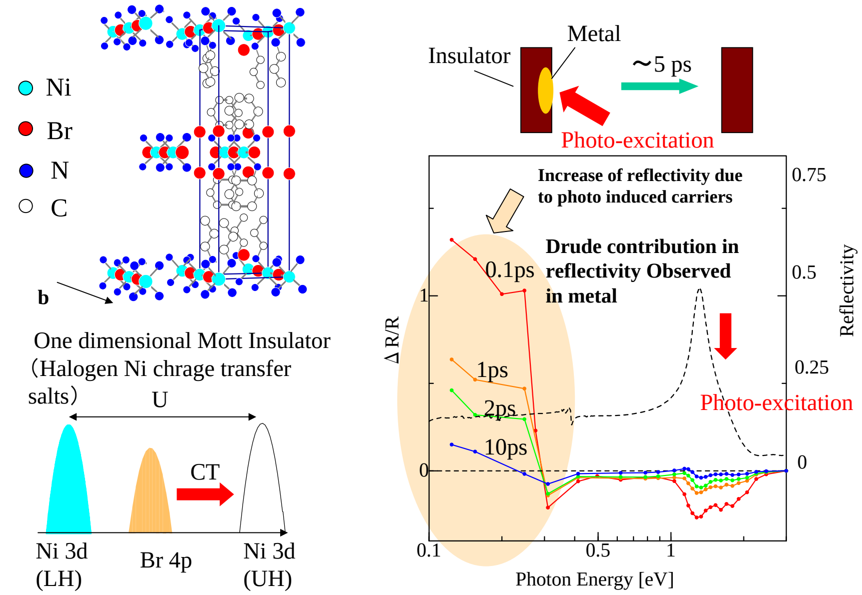


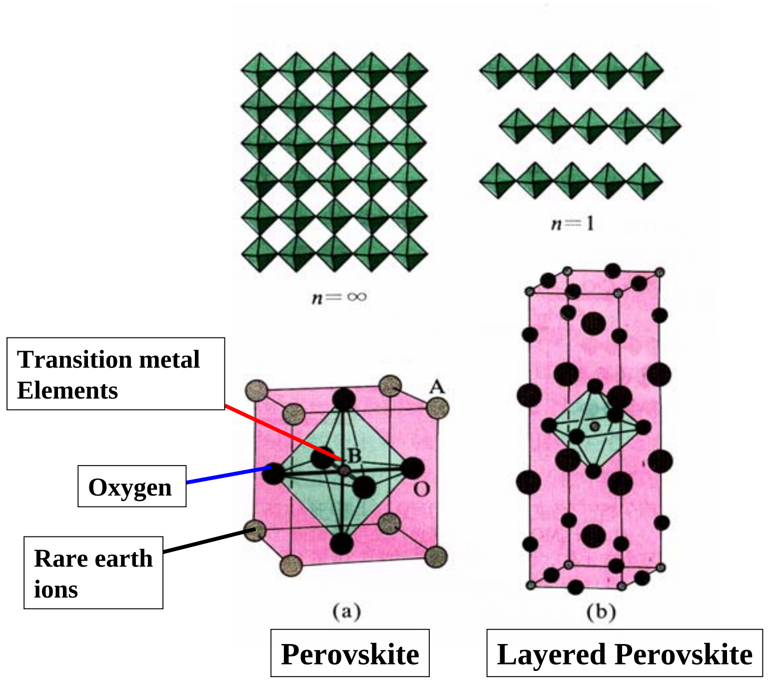
Photo-induced insulator – metal transition



第8図 $Pr_{1-x}Ca_xMnO_3$ (x＝0.3) 結晶のナノ秒パルス光励起に伴う光誘起金属化.

Ultra-fast Switching Phenomenon in Strongly Correlated One Dimensional Mott Insulators - Photo Induced Carrier Doping -





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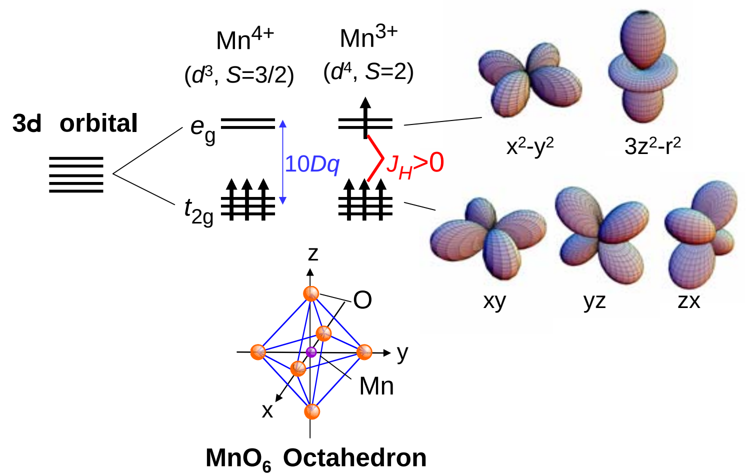
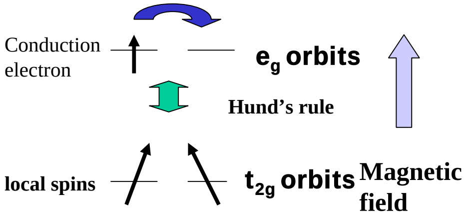


Hund's Coupling J_H **>** **CEF splitting** **10Dq**

Magnetic Field Control of Magnetic and Transport Properties in $Pr_{1-x}Ca_xMnO_3$

Competition between Ferromagnetic Metallic and charge ordered insulating phases



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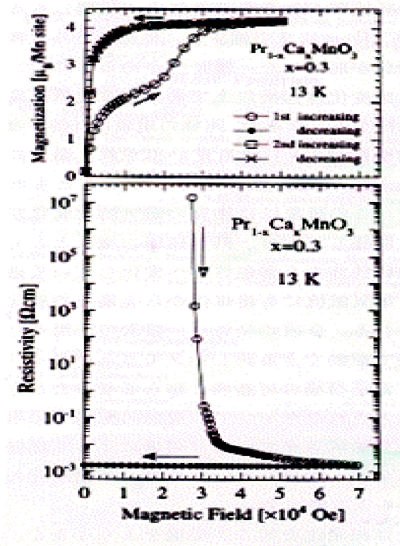


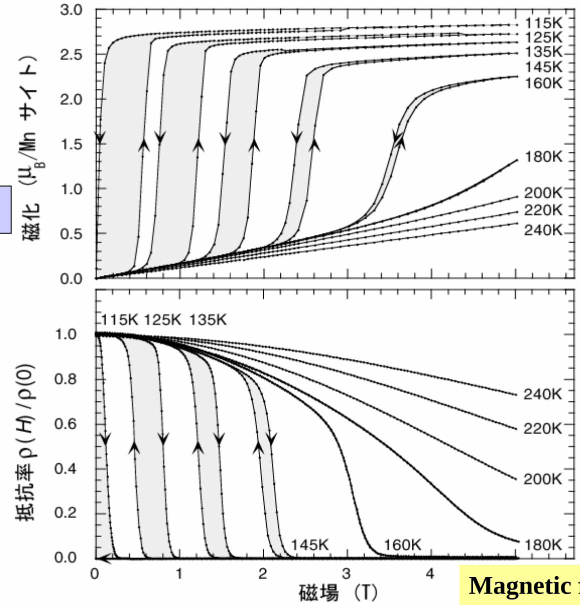
CMR effect

$(Nd,Sm)_{0.5}Sr_{0.5}MnO_3$

Colossal Magneto Resistance

Magnetization

Resistance



Magnetic field

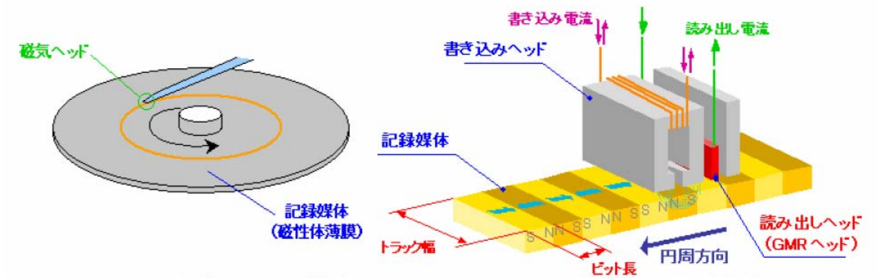


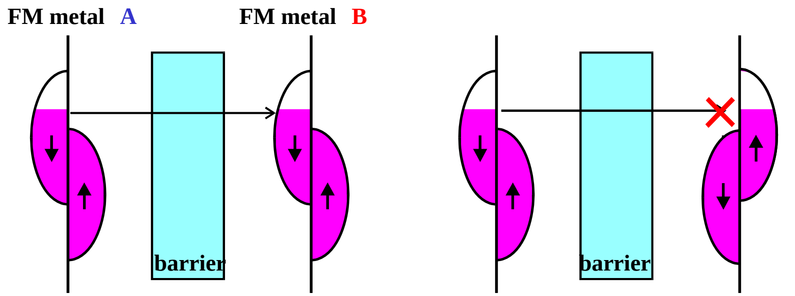
図1(A):ハードディスクの構造 図1(B):磁気ヘッドの構造

Spin polarization and Tunnel Magneto-Resistance (TMR)

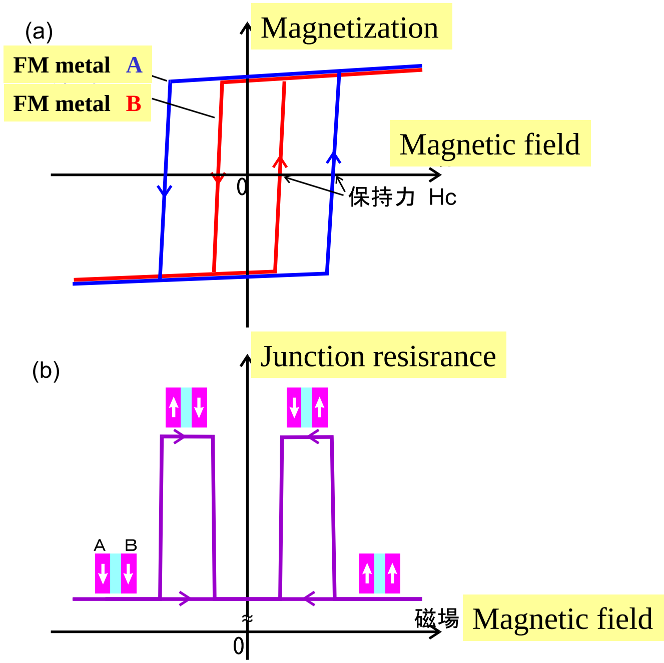
$$TMR = \frac{\rho_{AF} - \rho_F}{\rho_F} = \frac{2P_AP_B}{1-P_AP_B}$$

(P_A: spin polarization of **metal A**)

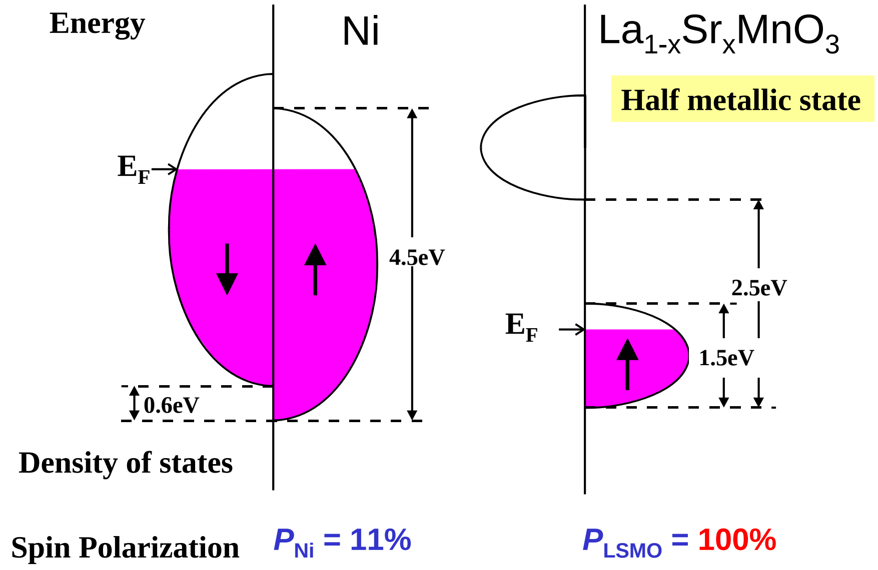
・If $P_A=P_B=1$, then TMR → ∞



Parallel spin **Antiparallel spin**

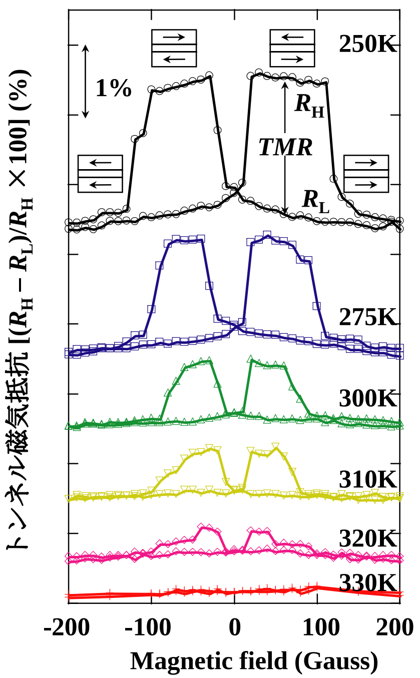


Strong coupling of spin and charge degrees of freedom

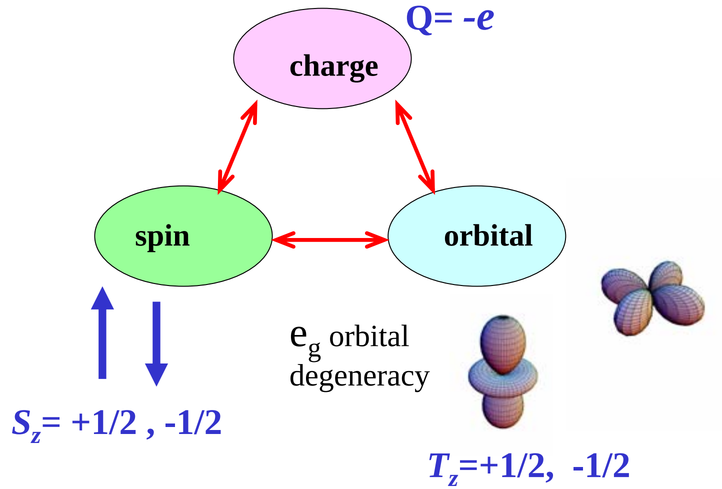


Tunnel Magneto-Resistance (TMR) at room temparatue

LSMO/STO/LSMO Junction



Rich electron phases due to three degrees of freedom in strongly correlated matters



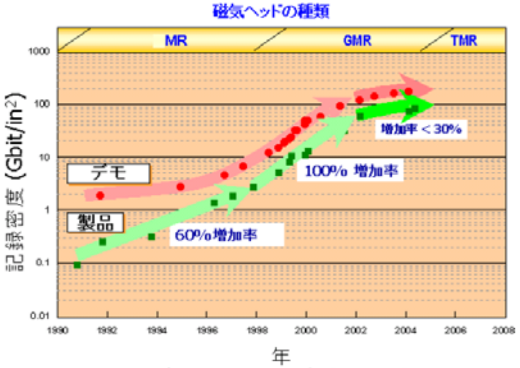
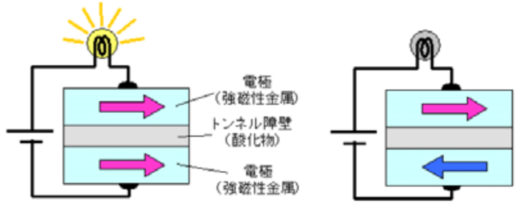


図2:ハードディスクの記録密度の歴史



磁気抵抗比 ＝ $(R_A - R_P) \div R_P$

図3: TMR素子のトンネル磁気抵抗(TMR)効果

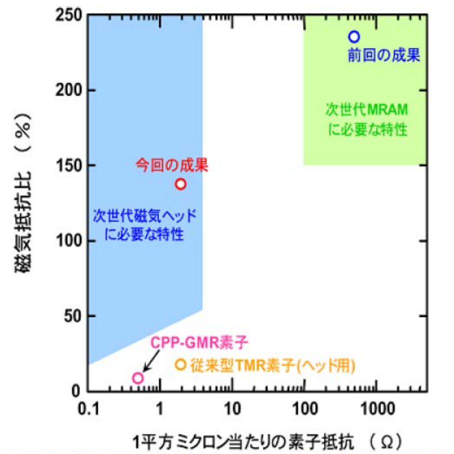


図4:次世代の磁気ヘッドに要求される特性

Electric-field control of ferromagnetism

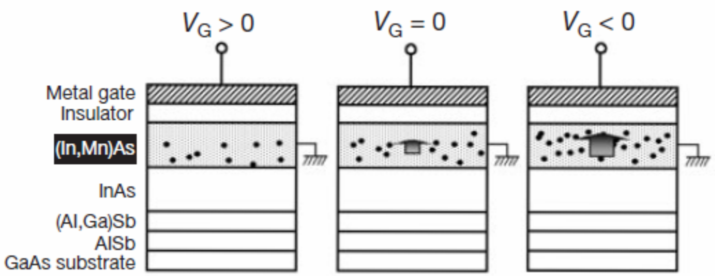


Figure 1 Field-effect control of the hole-induced ferromagnetism in magnetic semiconductor (In,Mn)As field-effect transistors. Shown are the cross-sections of a metal-insulator–semiconductor structure under gate biases V_G. This controls the hole concentration in the magnetic semiconductor channel (filled circles). Negative V_G increases hole concentration, resulting in enhancement of the ferromagnetic interaction among magnetic Mn ions, whereas positive V_G has an opposite effect. The arrow schematically shows the magnitude of the Mn magnetization. The InAs/(Al,Ga)Sb/AlSb structure under the (In,Mn)As layer serves as a buffer relaxing the lattice mismatch between the structure and the GaAs substrate to produce a smooth surface on which the magnetic layer is grown.

$$R_{Hall} = \frac{R_0}{d} B + \frac{R_S}{d} M$$

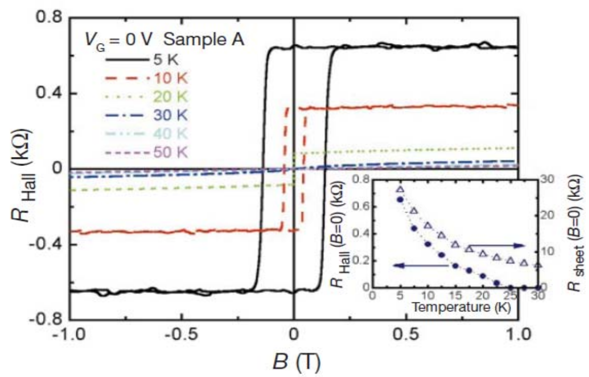


Figure 2 Magnetic-field dependence of the sheet Hall resistance R_{Hall} proportional to the magnetization of the magnetic semiconductor layer. R_{Hall} is used to measure the small magnetization of the channel. Shown are R_{Hall} as a function of field perpendicular to the layer at temperatures T = 5–50 K of sample A at V_G = 0 V. Clear hysteresis observed at $T \leq 20$ K is evidence of ferromagnetism. Inset, the temperature dependence of the remanence of R_{Hall} (solid circles), showing that the ferromagnetic transition temperature T_C is above 20 K. Open circles indicate the channel sheet resistance R_{sheet} at zero field, which shows moderate negative T-dependence.

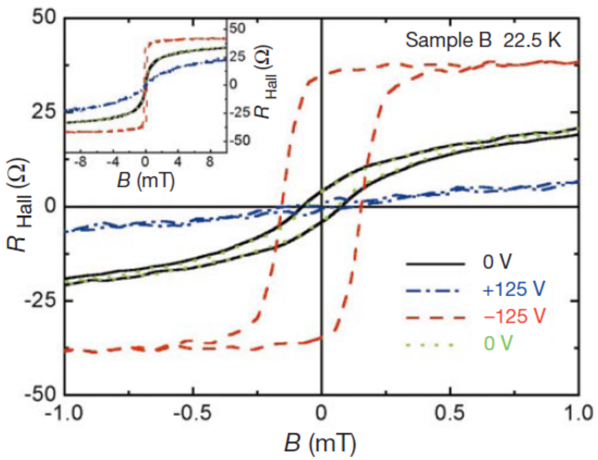


Figure 3 R_{Hall} versus field curves under three different gate biases. Application of $V_G = 0$, +125 and −125 V results in qualitatively different field dependence of R_{Hall} measured at 22.5 K (sample B). When holes are partially depleted from the channel ($V_G = +125$ V), a paramagnetic response is observed (blue dash-dotted line), whereas a clear hysteresis at low fields (<0.7 mT) appears as holes are accumulated in the channel ($V_G = -125$ V, red dashed line). Two R_{Hall} curves measured at $V_G = 0$ V before and after application of ±125 V (black solid line and green dotted line, respectively) are virtually identical. Inset, the same curves shown at higher magnetic fields.

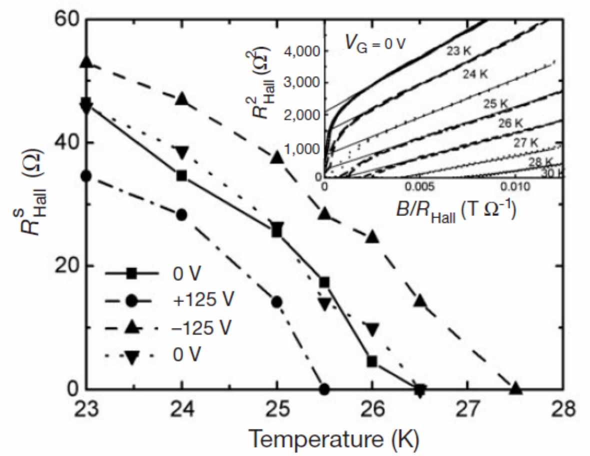


Figure 4 Temperature dependence of spontaneous Hall resistance R^S_{Hall} under three different gate biases. R^S_{Hall} proportional to the spontaneous magnetization M_S indicates ±1 K modulation of T_C upon application of $V_G = \pm 125$ V (sample A). T_C is the temperature at which R^S_{Hall} (and hence M_S) goes to zero. Data at $V_G = 0$ V before and after application of ±125 V are shown by squares and down triangles, respectively. In order to minimize the effect of domain rotation and magnetic anisotropy, R^S_{Hall} is determined by extrapolation of R_{Hall} from moderate fields (0.1–0.7 T) to 0 using Arrott, plots (R^2_{Hall} versus B/R_{Hall} plots shown in inset).

Magnetism on Report (deal line: 11/11)

Read the reference;

H. Ohno, D. Chiba, F. Matsukura, T. Omiya, E. Abe, T. Dietl, Y. Ohno, and K. Ohtani, "Electric-field control of ferromagnetism", Nature 408, 944 (2000).

1. Describe the origin of ferromagnetism in Mn-doped semiconductors.

2. Consider why the decrease (increase) of the hole concentration by the application of electric field results in a reduction (an increase) of hole-mediated ferromagnetic exchange interaction among localized Mn spins.