Driving forces in the nano-magnetism world

Intra-atomic exchange, electron correlation effects:

LOCAL (ATOMIC) MAGNETIC MOMENTS

\[ m \]

\( d \) or \( f \) electrons

Hund’s rules

Inter-atomic exchange:

MAGNETIC ORDER

\[ H_{exc} = - \sum_{i \neq j} J_{ij} \cdot S_i \cdot S_j \]

Spin-Orbit Coupling:

MAGNETOCRYSTALLINE ANISOTROPY:

\[ K \]

\[ H_{s.o.} = \lambda L \cdot S = \sum \xi s_i \cdot l_i \]

Dipolar Interaction:

SHAPE ANISOTROPY

\[ H_{dip} = \frac{m_1 \cdot m_2}{r^3} - \frac{3 (m_1 \cdot r)(m_2 \cdot r)}{r^5} \]
The He atom: intra-atomic exchange

$$H_{\text{He}} = \sum_{i=1}^{2} \frac{p_i^2}{2m} - \frac{1}{4\pi\varepsilon_0} \sum_{i=1}^{2} \frac{Ze^2}{r_i^2} + \frac{e^2}{4\pi\varepsilon_0 |r_2 - r_1|} = H_0 + H_{e-e}$$

**Ground state** -> the two electrons occupy the 1s orbital
- the spatial part of the wavefunction is symmetric (electrons have identical quantum numbers $nlm=100$)
- the spin part must be antisymmetric (electrons are fermions)

$$\Psi_{\text{ground}} = \Psi_{\text{sym}}(r_1, r_2) \chi_{\text{antisym}}(s_1, s_2) = \frac{1}{2} [\Psi_{\text{100}}(r_1)\Psi_{\text{100}}(r_2) + \Psi_{\text{100}}(r_1)\Psi_{\text{100}}(r_2)][\alpha\beta - \beta\alpha]$$

From the previous Hamiltonian we can calculate the energy of the ground state. Because $H_{\text{He}}$ does not contain spin terms, the spin part of the wavefunction only needs to satisfy the antisymmetric condition

**Excited state** -> one electron occupies the 1s orbital ($nlm=100$); the second electron is in an excited state $nlm$
1) the spatial part of the wavefunction is symmetric and the spin part is antisymmetric

$$\Psi^S_{\text{exci}} = \Psi_{\text{sym}}(r_1, r_2) \chi_{\text{antisym}}(s_1, s_2) = \frac{1}{2} [\Psi_{\text{100}}(r_1)\Psi_{\text{nlm}}(r_2) + \Psi_{\text{nlm}}(r_1)\Psi_{\text{100}}(r_2)][\alpha\beta - \beta\alpha] \quad \text{Singlet } S=0$$

2) the spatial part of the wavefunction is antisymmetric and the spin part is symmetric

$$\Psi^T_{\text{exci}} = \Psi_{\text{antisym}}(r_1, r_2) \chi_{\text{sym}}(s_1, s_2) = \frac{1}{2} [\Psi_{\text{100}}(r_1)\Psi_{\text{nlm}}(r_2) - \Psi_{\text{nlm}}(r_1)\Psi_{\text{100}}(r_2)]\chi_{\text{sym}}(s_1, s_2) \quad \text{Triplet } S=1$$

$$\alpha = \frac{1}{2}; \beta = -\frac{1}{2}$$
$$\chi_{\text{sym}}(s_1, s_2) = \alpha\alpha; \beta\beta; \frac{1}{\sqrt{2}}(\alpha\beta + \beta\alpha)$$
The exchange interaction

The singlet and triplet wavefunctions applied to $H_0$ give the same energy; the $H_{e-e}$ contribution can be calculated with the perturbation theory

\[ I = \int \int |\Psi_{100}(r_1)|^2 \frac{e^2}{4\pi\varepsilon_0 |r_1 - r_2|} |\Psi_{nlm}(r_2)|^2 \, dr_1 dr_2 \]

\[ J = \int \int \Psi_{100}(r_1)\Psi_{nlm}(r_2) \frac{e^2}{4\pi\varepsilon_0 |r_1 - r_2|} \Psi_{100}^*(r_2)\Psi_{nlm}^*(r_1) \, dr_1 dr_2 \]

$I$ is the Coulomb integral -> electrostatic repulsion between the electrons ($\Psi(r)^2 \rightarrow \rho$ electron density)

$J$ is the exchange integral -> energy associated with a change of quantum states between the electrons

\[ E_{e-e}^S = I + J \]
\[ E_{e-e}^T = I - J \]

Origin of Exchange interaction: -> Coulomb repulsion between electrons
-> total anti-symmetric wave function (Pauli exclusion principle)

J is positive 
-> triplet ground state $S=1$ 
-> parallel spins

J is negative 
-> singlet ground state $S=0$ 
-> antiparallel spins

Note: we get the exchange energy from an Hamiltonian not including spin terms !!!!!
The $H_2$ molecule: inter-atomic exchange

Hamiltonian $H = H_1 + H_2 + H_{12}$, where

\[
\begin{align*}
H_1 &= -\frac{\hbar^2}{2m} \Delta_1 - \frac{Ze^2}{r_1} \\
H_2 &= -\frac{\hbar^2}{2m} \Delta_2 - \frac{Ze^2}{r_2} \\
H_{12} &= +\frac{e^2}{r_{12}}
\end{align*}
\]
The \( \text{H}_2 \) molecule

\[
\psi_1 = \frac{1}{\sqrt{2 - 2l^2}} \left( \phi_a(r_1)\phi_b(r_2) - \phi_b(r_1)\phi_a(r_2) \right) (\alpha(r_1)\alpha(r_2)) \text{ triplet}
\]

\[
\psi_2 = \frac{1}{\sqrt{2 - 2l^2}} \left( \phi_a(r_1)\phi_b(r_2) - \phi_b(r_1)\phi_a(r_2) \right) (\beta(r_1)\beta(r_2)) \text{ triplet}
\]

\[
\psi_3 = \frac{1}{\sqrt{2 - 2l^2}} \left( \phi_a(r_1)\phi_b(r_2) - \phi_b(r_1)\phi_a(r_2) \right) \frac{1}{\sqrt{2}} \left( \beta(r_1)\alpha(r_2) + \alpha(r_1)\beta(r_2) \right) \text{ triplet}
\]

\[
\psi_4 = \frac{1}{\sqrt{2 + 2l^2}} \left( \phi_a(r_1)\phi_b(r_2) + \phi_b(r_1)\phi_a(r_2) \right) \frac{1}{\sqrt{2}} \left( \beta(r_1)\alpha(r_2) - \alpha(r_1)\beta(r_2) \right) \text{ singlet}
\]

\[
E = \frac{\left\langle \psi_i \mid H \mid \psi_i \right\rangle}{\left\langle \psi_i \mid \psi_i \right\rangle} = \left\langle \psi_i \mid H_1 + H_2 + H_{12} \mid \psi_i \right\rangle \quad \text{N.B. } \left\langle \psi_i \mid \psi_i \right\rangle = 1
\]

\[
= \frac{1}{2 \pm 2l^2} \int \int \left( \phi_a(r_1)\phi_b(r_2) \pm \phi_b(r_1)\phi_a(r_2) \right)^* (H_1 + H_2 + H_{12}) \left( \phi_a(r_1)\phi_b(r_2) \pm \phi_b(r_1)\phi_a(r_2) \right) d\mathbf{r}_1 d\mathbf{r}_2
\]

\[
= \frac{1}{2 \pm 2l^2} \left( I_1 + I_2 + K_{12} \pm J_{12} \right)
\]
Inter-atomic exchange

\[ E = \frac{\langle \psi_i | H | \psi_i \rangle}{\langle \psi_i | \psi_i \rangle} = \langle \psi_i | H_1 + H_2 + H_{12} | \psi_i \rangle \quad \text{N.B.} \quad \langle \psi_i | \psi_i \rangle = 1 \]

\[ = \frac{1}{2 \pm 2I^2} \int \int (\phi_a(r_1)\phi_b(r_2) \pm \phi_b(r_1)\phi_a(r_2))^* (H_1 + H_2 + H_{12})(\phi_a(r_1)\phi_b(r_2) \pm \phi_b(r_1)\phi_a(r_2)) \, dr_1 \, dr_2 \]

\[ = \frac{1}{2 \pm 2I^2} (I_1 + I_2 + K_{12} \pm J_{12}) \]

\[ I_1 = \int \phi_a^*(r_1)H_1\phi_a(r_1) \, dr_1 + \int \phi_a^*(r_2)H_2\phi_a(r_2) \, dr_2 \]

\[ \text{on atom } a \quad \text{on atom } a \]

\[ I_2 = \int \phi_b^*(r_2)H_2\phi_b(r_2) \, dr_2 + \int \phi_b^*(r_1)H_1\phi_b(r_1) \, dr_1 \]

\[ \text{on atom } b \quad \text{on atom } b \]

\[ K_{12} = \int \int \phi_a^*(r_1)\phi_b^*(r_2)H_{12}\phi_a(r_1)\phi_b(r_2) \, dr_1 \, dr_2 + \int \int \phi_a^*(r_2)\phi_b^*(r_1)H_{12}\phi_a(r_2)\phi_b(r_1) \, dr_1 \, dr_2 \]

\[ \text{on different atoms} \quad \text{on different atoms} \]

\[ J_{12} = \int \int \phi_a^*(r_1)\phi_b^*(r_2)H_{12}\phi_b(r_1)\phi_a(r_2) \, dr_1 \, dr_2 + \int \int \phi_a^*(r_2)\phi_b^*(r_1)H_{12}\phi_b(r_2)\phi_a(r_1) \, dr_1 \, dr_2 \]

\[ \text{exchange interaction: } e_1, e_2 \text{ swap from } b \text{ to } a \text{ and } a \text{ to } b \text{, respectively, due to the action of } H_{12} \]
The $\text{H}_2$ molecule

\[ E_s = \frac{1}{2 + 2l^2} \left( I_1 + I_2 + K_{12} + J_{12} \right) \]
\[ E_t = \frac{1}{2 - 2l^2} \left( I_1 + I_2 + K_{12} - J_{12} \right) \]

\[ E_s - E_t = \frac{1}{4 - 4l^4} \left[ -4l^2 \left( I_1 + I_2 + K_{12} \right) + 4J_{12} \right] \]

Ground state depends on the relative strength of $J_{12}$ (always > 0) in respect to $-4l^2(I_1+I_2+K_{12})$

$J_{12} > 4l^2(I_1+I_2+K_{12}) \rightarrow \text{ground state is magnetic (triplet)}$

$J_{12} < 4l^2(I_1+I_2+K_{12}) \rightarrow \text{ground state is non magnetic (singlet)}$

Ex: $\text{H}_2$ molecule $J_{12} < 0 \rightarrow \text{singlet ground state}$

The molecule magnetic ground state depends on the interaction between electrons belonging to two different atoms
The Heisenberg Hamiltonian is an effective Hamiltonian extending to larger atoms the electron-electron interaction seen in the He atom

\[ H_{\text{Heisenberg}} = H_0 + H_{\text{Coulomb}} + H_{\text{exchange}} \]

\[ H_{\text{exchange}} = -2 \sum_{i<j}^N J_{ij} s_i \cdot s_j; \]

\[ J_{ij} = \int \int \psi_i^*(r_i) \psi_j^*(r_j) \frac{e^2}{4\pi\varepsilon_0 |r_i - r_j|} \psi_i(r_j) \psi_j(r_i) \, dr_i \, dr_j \]

The Heisenberg Hamiltonian is used to describe:
- coupling of individual spins located on the same atom (intra-atomic exchange)
- coupling of atomic spin moments on different atoms (inter-atomic exchange)

**BUT**

Intra-atomic (a,c) and inter-atomic (b) exchange have different energies

a),c) -> intra-atomic \( V_{e-e} \) in the isolated atom (Hund’s rules) or Stoner band approach

[Stö06]
Magnetic coupling between atoms: inter-atomic exchange

Generalization to N-atoms system:

• Coulomb interaction + Pauli’s principle → The spins of the electrons are correlated
  i.e., there is a magnetic splitting in the energy spectrum of electrons in systems of atoms with open el. shells, true for systems of any size, doesn’t tell what type of magnetic coupling

• The energy spectrum is represented by a model system of pairwise interacting spins

\[ H = -\sum_{i\neq j} J_{ij} S_i \cdot S_j \quad \text{Heisenberg model} \]

≈ correct to 2nd order in the overlap orbitals, cannot be proven rigorously

• There are many possible exchange-interaction Hamiltonians…

\[ H = -J_z \sum_{i\neq j} S_i^z S_j^z - J_\perp \sum_{i\neq j} \left( S_i^x S_j^x + S_i^y S_j^y \right) \quad \text{Anisotropic Heisenberg model and XY model (} J_z = 0) \]

\[ H = -J_z \sum_{i\neq j} S_i^z S_j^z \quad \text{Ising model} \]
Magnetic coupling between atoms: FM and AFM coupling

\[ H = -\sum_{i \neq j} J_{ij} S_i \cdot S_j \]

\[ \begin{cases} 
J > 0 & \text{ferromagnetic coupling} \\
J < 0 & \text{antiferromagnetic coupling} 
\end{cases} \]

\[ J < 0, \text{ depending on formula unit, system dimensions, topology:} \]

- fully compensated AFM
- ferrimagnetism (uncompensated AFM)
- frustrated AFM

Cr(100) surface

G-type

C-type

A-type
Exchange energy

All spins in the grain must be ferromagnetically aligned

equation

exchange energy $J$ coupling spins

$H_{exc} = -\sum_{i \neq j} J_{ij} S_i \cdot S_j$

$S_i$ is the atomic spin

Coupling is destroyed and the net magnetic moment is zero

Domain formation -> magnetic moment is strongly reduced

Gain in the magnetostatic energy at the expenses of the exchange energy
Weiss-Heisenberg model

Which is the origin of the aligned atomic spin moments in a ferromagnetic domain (spontaneous magnetization)?

**Weiss** -> molecular field $H_W$ (or mean field theory) of unknown origin

**Heisenberg** -> molecular field originating from the interaction of the atomic spin moment with the spin sea of all the other atoms

$$E_i = -2s_i \sum_j J_{ij} s_j = -m_i H_W; \quad H_W = -\frac{2}{g\mu_B} \sum_j J_{ij} s_j$$

Example:

Two energy levels: $+\mu_B H$ with an occupation probability given by $\exp(+/-\mu_B H/kT)$

Sea of spin $s=1/2$  

$$M(H,T) = M^+ - M^- = N\mu_B \left( \frac{e^x}{e^x + e^{-x}} - \frac{e^{-x}}{e^x + e^{-x}} \right) = N\mu_B \tanh(x); \quad x = \frac{\mu_B H}{k_B T}$$

Curie temperature: temperature at which the spontaneous magnetization ($H=0$) goes to zero

$M(T) \rightarrow 0$ when $\tanh(x) \rightarrow 0$

when $x \rightarrow 0$ i.e. $\tanh(x) = x$

$$M(T_c) \approx N\mu_B x = N\mu_B \frac{\mu_B (\beta M(T_c))}{k_B T_c} \Rightarrow T_c = \frac{N\mu_B^2}{k_B} = \frac{\mu_B}{k_B} \frac{\beta M(0)}{k_B}$$

The magnetization goes to zero when the thermal energy ($k_B T_c$) equals the energy of a single spin in the molecular field ($g\mu_B H_W = g\mu_B \beta M(0)$).
Curie and Neel temperatures

For a general spin value $s$ and moment $m = -g \mu_B s$

$$T_C = \frac{2 \langle s \rangle^2 J_0}{3k_B}; \quad J_0 = \sum_j J_{ij} = NJ_{01}$$

$$H_W = \frac{2 \langle s \rangle^2 J_0}{3m}$$

<table>
<thead>
<tr>
<th>element</th>
<th>$\langle s \rangle^2 J_{01}$ [meV]</th>
<th>$N$</th>
<th>$N \langle s \rangle^2 J_{01}$ [meV]</th>
<th>$\langle s \rangle^2 J_0$ [meV]</th>
<th>$T_C$ [K]</th>
<th>$B_W$ $[10^3 T]$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fe (bcc)</td>
<td>19.5</td>
<td>8</td>
<td>156</td>
<td>183</td>
<td>1414</td>
<td>2.9</td>
</tr>
<tr>
<td>Co (fcc)</td>
<td>14.8</td>
<td>12</td>
<td>178</td>
<td>212</td>
<td>1654</td>
<td>4.3</td>
</tr>
<tr>
<td>Ni (fcc)</td>
<td>2.8</td>
<td>12</td>
<td>34</td>
<td>51</td>
<td>397</td>
<td>2.9</td>
</tr>
</tbody>
</table>

Neel temperature: is the equivalent to the Curie temperature for an antiferromagnet

A few Neel temperatures

- NiO $T_N = 525$ K
- CoO $T_N = 290$ K
- FeO $T_N = 298$ K
Curie temperature size dependence

\[ T_C = \frac{2\langle s \rangle^2 J_0}{3k_B} \quad ; \quad J_0 = \sum_j J_{ij} = NJ_{01} \]

\( T_C \) depends on the atomic coordination

\[ T_c \text{ nanostructures} < T_c \text{ bulk} \]

The number of magnetic neighbours (N) is reduced in a thin film

\[
\overline{N} = \frac{t_b N_b + t_i N_i}{t_b + t_i} = z_b - 2 \frac{N_b - N_i}{t}
\]
Curie temperature size dependence

Critical Temperatures of Ising Lattice Films

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\[ T_C(\infty) - T_C(t) = t^{-\lambda}, \quad \lambda = 1 \]

Experiments and finite-size scaling model:

\[ \left( \frac{T_C(\infty) - T_C(t)}{T_C(\infty)} \right) = \left( \frac{t}{t_0} \right)^{-\lambda'}, \quad \lambda' = 1 - 1.6 \]


This model accounts for the decrease of \( T_C \) with \( t \) down to a critical thickness \( t_0 \approx 4 \) monolayers.

\( t \) is a continuous parameter \( \rightarrow \) in the ultra thin limit \( t \) becomes discrete (number of atomic layers)

Ultra thin limit: linear decrease

\[ \left( \frac{T_C(\infty) - T_C(t)}{T_C(\infty)} \right) = A - (n - 1) / 2N_0 \]

\( N_o \) is the spin-spin coupling range (typically a few atomic sites)
A takes into account the observation that for \( n=1 \) ferromagnetism can exist

Curie temperature and band structure

**Paramagnet**
the magnetic moments are randomly oriented due to thermal fluctuations

\[ T > T_C \]

**Ferromagnet**
unlike the moments in a paramagnet, these moments will remain parallel even when a magnetic field is not applied

\[ T < T_C \]

**Antiferromagnet**
Adjacent magnetic moments from the magnetic ions align anti-parallel to each other without an applied field.

\[ E - E_F (\text{eV}) \]

Spin resolved inverse photoemission spectroscopy for 3d bands as a function of temperature for Ni(110)

\[ T = T_C \rightarrow \text{spin transition from minority and majority states are equal } \Rightarrow \Delta = 0 \]

[Stö06]
Where exchange energy gets in play

Curie (Neel temperature) -> magnetic order in a ferromagnetic (antiferromagnetic) nanostructure

Super-exchange -> mediated interaction between magnetic atoms

Bias exchange -> interaction at the interface of FM – AFM structures

Kondo effect -> interaction between a magnetic impurity and the conduction band electrons

RKKY interaction -> interaction between magnetic impurities mediated by the conduction band electrons
Super-exchange

In many materials (oxides), magnetic atoms are separated by non-magnetic ions (oxygen) (ex: MnO)

Indirect interactions through oxygen atoms

In the antiferromagnetic configuration, electrons of atoms A and B can both hybridize with 1 p-electron of Oxygen

energy depends on the relative spin orientation
The Kondo interaction $J S \sigma$ couples itinerant electrons of the host with spin $\sigma = 1/2$ to a magnetic impurity with spin $S$. For exchange interaction $J < 0$, antiferromagnetic (AFM) coupling of the spins of the conduction electrons screens the impurity spin. The ground state at temperatures $T$ below the Kondo temperature $T_K$ is a spin $S - \sigma$ (red area). For $J > 0$, the ferromagnetic (FM) coupling tends to create a cloud of spins aligned parallel to the impurity spin, which becomes asymptotically free at low temperatures.

**For $S = 1/2$ complete screening**
**For $S > 1$ under-screening Kondo**
RKKY interaction

Indirect exchange couples moments (in impurities or magnetic layers) over relatively large distances

\[ J(r) = J_0 \cdot \cos(2 \cdot k_F \cdot r)/(2 \cdot k_F \cdot r)^D \]

D represent the system dimensionality

\[ \lambda_F = 2\pi/k_F \] Fermi wave length

(in metal is of the order of a few nm)
Co/Pt(111): RKKY interaction

\[ J(r) = J_0 \cdot \cos(2k_F \cdot r)/(2k_F \cdot r) \]

\[ \lambda_F = 2\pi/k_F \approx 3 \text{ nm} \]

Atom-by-atom engineering and magnetometry of tailored nanomagnets

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Bias exchange

a) In an external field and above the Néel temperature $T_N$, antiferromagnetic spins located at the interface with the ferromagnet are aligned, like the ferromagnet, with the external field.

b) Once cooled below $T_N$, these interface spins keep their orientation and appear "pinned" because they are tightly locked to the spin lattice in the bulk of the antiferromagnet, which is not sensitive to external fields. Consequently these pinned spins produce a constant magnetic field at the interface that causes the hysteresis loop of the ferromagnet to shift.

c) This intuitive picture overestimates the magnitude of the loop shift by orders of magnitude.

$$\frac{H_b}{H_c} \approx \frac{W}{\xi} \approx 2 \text{ eV} / 50 \text{ meV} \approx 30$$

When $T < T_N$ you need several tens of tesla to reverse the AFM coupled spins ("pinning")

only a small fraction (5\%) of interfacial spins is actually pinned, and these cause the horizontal hysteresis loop shifts.

\[ H_B = \frac{\sigma}{M_{\text{FM}}t_{\text{FM}}} = J \frac{S_{\text{AFM}}S_{\text{FM}}}{a_{\text{AFM}}^2M_{\text{FM}}t_{\text{FM}}} \]

TABLE I. Effective and corrected interface energies \( \sigma \) calculated from the macroscopic loop shift and the coverage with pinned spins \( \rho \).

<table>
<thead>
<tr>
<th>Sample</th>
<th>( \rho ) (ML)</th>
<th>( \sigma_{\text{eff}} ) (mJ/m(^2))</th>
<th>( \sigma ) (mJ/m(^2))</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>3 nm Co/NiO</td>
<td>0.04 ± 0.01</td>
<td>0.052 ± 0.005</td>
</tr>
<tr>
<td>B</td>
<td>2 nm Co/IrMn</td>
<td>0.04 ± 0.01</td>
<td>0.168 ± 0.020</td>
</tr>
<tr>
<td>C</td>
<td>1 nm CoFe/PtMn</td>
<td>0.03 ± 0.01</td>
<td>0.124 ± 0.014</td>
</tr>
<tr>
<td>D</td>
<td>2 nm CoFe/PtMn</td>
<td>0.04 ± 0.01</td>
<td>0.188 ± 0.015</td>
</tr>
<tr>
<td>E</td>
<td>3 nm CoFe/PtMn</td>
<td>0.04 ± 0.01</td>
<td>0.229 ± 0.027</td>
</tr>
</tbody>
</table>

The exchange break layer is need to decouple the recording layer from the soft underlayer (necessary to close the magnetic flux lines)
The inter-grain exchange interaction is stopped by the oxide layer.
GMR: giant magneto resistance

$\Delta R / R = \frac{R_{\uparrow\downarrow} - R_{\uparrow\uparrow}}{R_{\uparrow\uparrow}}$
GMR: why is working

Available states with the same spin:
Low resistance

Absence of states with the same spin:
High resistance

Science 282, 1660 (1998); Nat. mater. 6, 813 (2007)
Pinned layer: bias exchange

Electric current

Pinned layer

Free layer

J. Appl. Phys. 69, 4774 (1991)
Role of the NM spacer: decoupling the two FM layers

The atom spins are coupled together

In non magnetic materials $H_{ex} = J S_i S_j = 0$

Domain wall between two pinned ferromagnetic materials with opposite orientation of the magnetization

Without the spacer two (negative) scenarios depending on the strength of the exchange force in respect to the pinning force:

a) The free layer magnetization always aligns parallel to the magnetization of the pinned layer

b) A domain wall forms which produces the spin current depolarization

$H_{exc} = - \sum_{i \neq j} J_{ij} S_i \cdot S_j$

J. Appl. Phys. 69, 4774 (1991)
Magnetic random access memory (MRAM)

Ferromagnetic (FM) - nonmagnetic (NM) - ferromagnetic (FM) junction

Science 282, 1660 (1998); Nat. mater. 6, 813 (2007)
GMR applications: reading head

Reading-writing head in HDD

Reading:
the bit stray field defines the magnetization direction of the free layer

Giant Magnetoresistance (GMR)

Current Perpendicular to Plane (CPP)
Current In Plane (CIP)