Magnetism

10. Interlayer Exchange Coupling
thin film growth: molecular beam epitaxy

- growth of ultrathin metallic layers under ultrahigh vacuum conditions
homoepitaxy: Fe on Fe(001)

- growth depends on temperature
- lower temperature causes higher roughness (smaller islands)
- layer-by-layer growth reveals perfect RHEED oscillations
- there is always a residual roughness – imperfect growth
Layered Magnetic Structures: Magnetic Coupling

We investigated exchange scattering from spin waves in sandwiched magnetic layers by means of light scattering from spin waves. As the Au thickness is increased, the magnetic coupling of the layers is weakened. We find antiferromagnetic coupling of the layers order antiparallel with the magnetization perpendicular to the layers.

PACS numbers: 75.30.Ds, 75.30.Hz

1986 – first step to Nobel Prize
BLS Setup

![Diagram of BLS Setup](image)
Consider two ferromagnetic layers separated by a thin spacer layer:

**Ferromagnet / Non-Ferromagnet / Ferromagnet**

The ferromagnetic layers interacts across the spacer and align ...

- **parallel**...
  - “ferromagnetic coupling”

- **antiparallel**...
  - “antiferromagnetic coupling”

- **at 90°**...
  - “biquadratic or 90°-coupling”
Typical hysteresis loops for different types of

- **FM coupling or decoupled**
- **AF coupling**
- **90° coupling**
- **Dominant 90° plus AF coupling**

The saturation and switching fields are approximate measures for the coupling strength

**BUT:** A quantitative determination of the coupling needs fitting.
Domain patterns in Fe/Cr/Fe
Measurement of spin-wave or magnons by BLS

Stokes condition:
magnon creation

anti-Stokes condition:
magnon annihilation

Magnon modes:

DE: Surface (or Damon-Eshbach) mode

SWn: Standing wave modes with n nodes
Spin-waves (magnons) of a single layer

Brillouin light scattering (BLS) of coupled magnetic layers

Single layer

Propagation of magnons

View along the magnetization axis on the precessional motions

Frequency shift
Spin-waves in a coupled, parallel aligned trilayer

Brillouin light scattering (BLS) of coupled magnetic layers

- Single layer: $M_1$
- Two parallel layers: $M_1$, $M_2$

View along the magnetization axis on the precessional motions:
- In-phase, acoustic
- Out-of-phase, optic

Frequency shift
- Opt.
- Ac.
Spin-waves in a coupled, antiparallel aligned trilayer
Example: BLS data of Fe / Al / Fe(001) trilayers

BLS data analysis requires fitting to a description of the magnetic system.
SEMPA

- SEMPA: Magnetic domain imaging
- Direct observation of the coupling
- Oscillation of coupling direction with film thickness
- Quantized electronic states in the Cr film

Phenomenological description

Contribution to the areal free energy density due to the interlayer coupling:

\[ E = -J_1 \cos(\Delta \Theta) - J_2 \cos^2(\Delta \Theta) \]

“bilinear” “biquadratic”

\( \Delta \Theta \) is the angle between the magnetizations of the two coupled layers.

\( J_1 \) and \( J_2 \) are parameters describing the coupling:

\( J_1 > 0 \): FM coupling

\( J_1 < 0 \): AF coupling

\( J_2 \) dominant and \( J_2 < 0 \): 90° coupling

Note: \( J_1(D) \) oscillates as a function of the spacer thickness \( D \)
Typical bilinear coupling strengths

<table>
<thead>
<tr>
<th>Sample</th>
<th>Maximum strength $-J_1$ in mJ/m² (at spacer thickness in nm)</th>
<th>Periods in ML and (nm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Co/Cu/Co (100)</td>
<td>0.4 (1.2)</td>
<td>2.6 (0.47); 8 (1.45)</td>
</tr>
<tr>
<td>Co/Cu/Co (110)</td>
<td>0.7 (0.85)</td>
<td>9.8 (1.25)</td>
</tr>
<tr>
<td>Co/Cu/Co (111)</td>
<td>1.1 (0.85)</td>
<td>5.5 (1.15)</td>
</tr>
<tr>
<td>Fe/Au/Fe (100)</td>
<td>0.85 (0.82)</td>
<td>2.5 (0.51); 8.6 (1.75)</td>
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<tr>
<td>Fe/Cr/Fe (100)</td>
<td>$&gt;1.5$ (1.3)</td>
<td>2.1 (0.3); 12 (1.73)</td>
</tr>
<tr>
<td>Fe/Mn/Fe (100)</td>
<td>0.14 (1.32)</td>
<td>2 (0.33)</td>
</tr>
<tr>
<td>Co/Ru(0001)</td>
<td>6 (0.6)</td>
<td>5.1 (1.1)</td>
</tr>
<tr>
<td>Co/Rh/Co (111)</td>
<td>34 (0.48)</td>
<td>2.7 (0.6)</td>
</tr>
</tbody>
</table>

Experimental values are often much smaller than theoretically predicted due to roughness, interdiffusion, etc.

Compare to direct exchange in Fe: $J \approx \frac{k_B T_C}{a^2} = 170 \text{ mJ/m}^2$; $T_C = 1040$ K, $a = 2.9$ Å
Ruderman, Kittel, Kasuya, and Yoshida considered in the 1950’s magnetic impurities in a non-magnetic metal host and calculated their interaction:

\[ \lambda = \pi/k_F \]

Screening with \( k < k_F \):
- Spin (or charge) density wave with
  \[ k = 2k_F \]
- \( \rightarrow \) RKKY oscillations
  \( (\rightarrow \) Friedel oscillations)
The interaction of two magnetic impurities is oscillating with their separation $r$ and decays with $r^3$:

\[
\begin{align*}
H(r) &\sim j(r) \vec{s}_1 \cdot \vec{s}_2 \\
j(r) &\sim \frac{r \cos(2k_F r) - \sin(2k_F r)}{r^4}
\end{align*}
\]

Two magnetic impurities in a sea of free electrons with Fermi wave vector $k_F$. 
Extension to two layers of “magnetic impurities”: The interaction oscillates with the layer separation $z$ and decays with $z^2$:

$$H(z) \sim J(z) \vec{m}_1 \cdot \vec{m}_2$$

$$J(z) \sim -\frac{\sin(2k_Fz)}{z^2}$$

Periodicity of $J(z)$:

$$Q = 2k_F$$

⇒ Simple and intuitive, but not simply applicable to real spacer materials.
Quantum interference model for bilinear coupling

Consider spin-dependent quantum well states (QWS) due to spin-dependent reflectivities at the interfaces between spacer and FM layers.

For a certain spacer thickness $D$ there is a series of QWS fulfilling the condition:

$$D = n \frac{\lambda}{2} ; \quad n = 1, 2, 3, ... \quad \lambda = \frac{2\pi}{k_\perp}$$

$$\Rightarrow k_\perp^{(n)} = n \frac{\pi}{D} ; \quad n = 1, 2, 3, ...$$
What is the origin of spin-dependent reflectivity?

Spin-dependent reflectivity arises from the “potential landscape” seen by the electrons due to the layered structure. The two spin channels experience different potential steps at the interfaces between the spacer and the FM layers.

Example Co / Cu / Co:

Similar band structure (low potential steps and low reflectivity) for majority electrons and shifted band structure (high potential step and high reflectivity) for minority electrons:
Spin-dependent QWS only form for parallel alignment of the FM layers, but not for antiparallel alignment!
The energy related to \( k_\perp \) is quantized. The energy levels shift when the spacer thickness \( D \) is varied. A new level crosses \( E_F \) when \( D \) is changed by

\[
\Delta D = \frac{\lambda}{2} \quad \Rightarrow \quad \text{Periodicity} \quad Q = \frac{2\pi}{\Delta D} = \frac{4\pi}{\lambda} = 2k_\perp
\]

(Note: \( Q_{\text{RKKY}} = 2k_F \))

(Similar to an electron in a box, where \( E \) decreases with increasing \( D \))
Aliasing (or backfolding into first Brillouin zone)

Typical $\Delta D$ are of the order of a few Å, i.e. interatomic distances

\[ \sin(2k \perp D) \approx \frac{\sin(2k \perp D)}{D^2} \]

\[ k_{osc} = |2k \perp - k_p| \]

\[ \Rightarrow \text{Each } k \perp \text{ gives rise to an oscillation of } J(D) \text{ with a periodicity given by } k_{osc} = |2k \perp - k_p| \]
Which $k$ are important?

$I(D)$ is dominated by $k_\perp$ with the highest density of states at $E_F$.

$\Rightarrow$ Consider $k_\perp$ at stationary point

$k_{osc} = |2k_\perp - k_p|$

Several stationary points may exist

$\Rightarrow I(D)$ is a superposition of oscillations
e.g. 2.5 and 8 ML for Au(001)

Real Fermi surfaces are non-spherical

$\Rightarrow$ Oscillations depend on growth direction
Example Fe / Au / Fe(001)

Epitaxially grown Fe/Au/Fe(001) [1]

⇒ Oscillations periods are well described by the quantum interference model [2]
Fe(001) surface states

- Photoelectron spectroscopy to study the electronic structure in the ferromagnet
Quantum well states (inverse photoemission)

FIG. 1. Inverse photoemission spectra for Cu on Co(100) at normal incidence. The s,p band continuum of bulk Cu(100) (top) is discretized into quantum well states for thin Cu films. For the film thicknesses see the data points in Fig. 2.

Quantum well states in Co/Cu

- multiple quantum well states formed in the Cu band structure
• Fermi surfaces of Cu and Co↑ match closely, if lattice deformation in multilayers is taken into account.
Transfer of magnetic moments

- XMCD measurement on Co/Cu multilayers and alloys
- Proximity of Co and Cu at the interface leads to transfer of magnetic moment
- First Cu monolayer is “magnetic” with different contributions in sp- and d-states

\[
\begin{align*}
\mu_{Co} &= 1.50 \mu_B \\
\mu_{Cu} &= 1.85 \mu_B \\
\mu_{Cu} &= 0.02 \mu_B
\end{align*}
\]
Co/Cu: A model system

- perfect layer structure within grains
- \{111\} texturized grains
- structural quality improves with number of periods
Fluctuation mechanism

For a oscillation period of 2 ML $J_1$ locally changes sign at each step edge!

Examples for short-period oscillations:
- 2.5 ML for Au(100)
- 2.6 ML for Cu(100)
- 2 ML for Cr(100)
- 2 ML for Mn(100)

Competition between local fluctuations of the bilinear coupling due to spacer thickness fluctuations

and

direct exchange within the FM layers

on

a lateral length scale shorter than the FM domain wall width.
Magnetic dipole mechanism

Interface roughness can give rise to interlayer coupling of different types depending on the vertical correlation of the roughness.

Ferromagnetic “orange-peel” coupling for correlated roughness.
Interface roughness can give rise to interlayer coupling of different types depending on the vertical correlation of the roughness.

Antiferromagnetic “Néel” coupling for anti-correlated roughness.
Influence of interface roughness

Epitaxial Fe / Cr-wedge / Fe(001) grown at different substrate temperatures

STM images:
400 nm x 400 nm

100 nm x 40 nm

Coupling versus spacer thickness (MOKE)
Influence of interfacial roughness: Fe/Cr/Fe

- combinatorial approach – domain imaging w/ SEMPA
- short coupling period appears only for smooth interfaces
- growth of Cr on Fe(100) is critical for interfacial roughness
- surface roughness kills short oscillation period
- accumulated roughness in the Cr wedge eventually destroys the coupling pattern
Fe/Cr multilayers

- asymptotic behavior $\sim 1/t_{Cr}^2$
- reduction of the GMR with interlayer thickness can be understood as shunting of the resistance by the nonmagnetic films
## Beyond Fe/Cr

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<th>Cr</th>
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- Co/TM multilayers
- also measured with Fe, Ni and Ni$_{81}$Fe$_{19}$

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