From spinwaves to Giant Magnetoresistance (GMR) and beyond

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Forschungszentrum Jülich, Germany

1. Introduction
2. Discovery of BLS from Damon Eshbach surface modes
3. Discovery of interlayer exchange coupling
4. Discovery of Enhanced Magnetoresistance (GMR)
5. Further development: TMR and CIMS
6. Applications
May I introduce myself

1969: PhD in Darmstadt (Germany) with „Optical Spectroscopy and Crystal Field Analysis in some Rare Earth Garnets“ Mentor K.H.Hellwege, Supervisor: St.Hüfner

1969-1972 postdoctoral fellow at Carleton University Ottawa Canada. Raman Spectroscopy on electronic states and phonons Supervisor: J. A.Koningstein

since 1972 Research Center Jülich, Institute for Magnetism founded in 1971 Investigation of magnetic semiconductors EuO, EuS Fabrication, magnetic and transport properties of layered magnetic structures Mentor: W.Zinn
Bulk and Surface Spinwaves in EuO

New instrumental development
Fig. VI.3. Raman spectrum from EuO [VI.2]. According to the orientation of the sample one observes the Damon-Eshbach spin waves (labelled as $M_1$) as a Stokes line (above) or as an anti-Stokes line (below), while the volume spin waves appear with equal intensity in both geometries, although higher intensity is observed for the anti-Stokes line [VI.3]
Coupled Damon-Eshbach-Spinwaves

Landau Lifshitz equation

\[ \frac{\partial M}{\partial t} = -\gamma M \times H_{\text{eff}} \]

Stokes

Antistokes

\[ \omega / \omega_\infty \]

\[ \omega / \omega_\infty \]

\[ qd_0 \]

\[ qd_0 \]

\[ d_0 \]

\[ 45 \]

\[ 10 \]

\[ 5 \]

?
What was known in 1984 about interlayer coupling apart from the dynamic coupling?

Pinhole coupling due to „magnetic bridges“

Orange peel or Neel type coupling caused by strayfields due to meandering interlayers
Coupled Damon-Eshbach-Spinwaves
Effect of exchange coupling
Coupled Damon-Eshbach-Spinwaves
First measurement of interlayer exchange coupling as a function of the interlayer thickness

\[ E_{\text{exch}} = -2A_{12} \frac{M_1 \ast M_2}{|M_1| \ast |M_2|} \]
Work on interlayer exchange coupling published in 1986

Oscillatory coupling in Gd/Y multilayers (Majkrzak et al)

Helical structures in Dy/Y multilayers (Salamon et al.)

AF coupling in Fe/Cr/Fe layered structures (Grünberg et al)
Fabry Perot model of interlayer exchange coupling

analogy: optical Fabry Perot interferometer

Short period oscillations after improvement of growth

Fe/Cr/Fe
Mott's two current model

Scattering event

ferromagnetic alloy

Equivalent circuit
What can we expect in magnetic multilayers?

Coupled Fe/Cr/Fe structures

Current

M

M
First measurement of GMR

Filing a patent: april 1988
First measurements of GMR in Fe/Cr/Fe

Fig. 5. GMR effect in a multilayer (A) and a double layer (B) of Fe interspaced by Cr. (B) The AMR effect in a single film of Fe with thickness 250 Å is also shown for comparison.
**First theories of GMR**

*Boltzmann transport equation: Camley-Barnas model*
Current in Plane (CIP)

\[ \lambda^{\uparrow} \approx \lambda^{\downarrow} \]

\[ D^{\uparrow} \approx 0.45 \]

\[ D^{\downarrow} \approx 0.08 \]

Theory and Experiment
Spin dependent transfer phenomena in layered magnetic structures

- Giant Magneto-resistance (GMR)
- Oscillating Interlayer exchange coupling
- Tunneling magnetoresistance (TMR)
- Current induced magnetic excitations and switching (CIMS)
CIMS – advanced magnetic switching concept

due to spin polarized currents

current induced magnetization switching and excitation of spinwaves proposed by J. Slonczewski and L. Berger in 1995

Four energetically nearly identical states give rise to two-step switching

R. Lehndorf, D. Bürgler, C. Schneider, Jülich
2007
Magnetization reversal of a thin-film element by a spin-polarized current

\[
\frac{dm}{dt} = -\gamma m \times H_{\text{eff}} + \alpha m \times \frac{dm}{dt} + \chi m \times (m \times p)
\]

- **Precession**
- **Damping**
- **Spin-transfer torque**

A. Kakay, R. Hertel, C. Schneider, IFF Jülich
Applications
Fig. 13 working principle and data for GMR sensor with AF coupled multilayer

by courtesy of NAOMI-Sensitec, Germany
Spinvalves

Here to monitor mechanical rotations

GMR effect

Spinvalves
Used in ABS- and ESP-Systems for cars
GMR sensors in read-heads for hard-disk drives

5 billion (10⁹)

<table>
<thead>
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<th>Areal Density Gbits/in²</th>
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<td>Corsair</td>
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<td>1992</td>
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<td>2005</td>
<td>&gt;200</td>
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Ed Grochowski, HGST
AFC media

AFC stabilising magnetic domains on hard disc
TMR and MRAM (magnetic random access memory)

Conventional: writing by Oersted fields
Advanced: writing by CIMS

nonvolatile

information:

"0"  "1"

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Barriere
Ferromagnet
Antiferromagnet
Diode
AMR-and GMR-Sensor Applications

e.g. als Electronic Compass Combined with a Mobile GPS System

there are already mobiles on the market which include GPS, in future also compasses

- measurement of the Earth’s magnetic field in 2 or 3 axis
- accuracy of 1°
- low power consumption (2 years battery life)

For continous, retardation free alignment of map or direction of motion.
most vehicles contain parts of ferromagnetic materials

traffic control

indicate free parking lots on a display at the entrance of parkhouses
The motion of „Spirit and Opportunity“ on Mars are monitored by AMR sensors.
GMR-Field Sensor Applications

e.g. Detection of piston end positions

The GMR-sensor detects - due to its high magnetic sensitivity - the position of the piston even at large distances and different cylinder diameters.
GMR in medicine and biology

Solution to analyze

Magnetic Adsorbent

Suspension must be stable in absence of magnetic field

Magnetic Separation

Surfaces
- Straptavidin
- Protein A
- Protein G
- Other target specific ligands
- Silica
- COOH
- NH₂
- SH
- CHO
- C18-C4
- Tosyl

Antigen

Antibody

Functionalized Magnetic Nanoparticle
New applications - New challenges

for read out in HDD can't be small enough

for detecting magnetic beads: can't be large enough
 Hydra in the Greek mythology: cut one head, two new grow

Thank You

More Informations at www.fz-juelich.de/gmr
**Biosensor**: important ingredients

- Magnetic beads 1µ
- Magnetic nanoparticles 10nm

**GMR-TMR-Sensor Array**: see also „MRAM“

- 10x10 Sensors on 0.1x0.1mm² area

**Antibodies**
- Good guys

**Antigens**
- Bad guys

**Immune reaction**
### Largest GMR values in trilayers and multi layers at room temp

<table>
<thead>
<tr>
<th>system</th>
<th>GMR[%]</th>
<th>$t_{\text{mag}}$[nm]</th>
<th>ref.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fe/Cr/Fe</td>
<td>1.5</td>
<td>12</td>
<td>1)</td>
</tr>
<tr>
<td>Fe/Cr/Fe</td>
<td>2</td>
<td>5</td>
<td>2)</td>
</tr>
<tr>
<td>[Fe/Cr(1.2nm)]$_{50}$</td>
<td>42</td>
<td>.45</td>
<td>2)</td>
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<tr>
<td>Co/Au/Co</td>
<td>1.8</td>
<td>10</td>
<td>1)</td>
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<tr>
<td>Co/Cu/Co</td>
<td>2.0</td>
<td>10</td>
<td>1)</td>
</tr>
<tr>
<td>Fe/Cu/Fe</td>
<td>0.5</td>
<td>10</td>
<td>1)</td>
</tr>
<tr>
<td>Co/Cu/Co</td>
<td>15</td>
<td>3</td>
<td>3)</td>
</tr>
<tr>
<td>[Co/Cu(0.9nm)]$_{30}$</td>
<td>48</td>
<td>1.5</td>
<td>5)</td>
</tr>
<tr>
<td>[Co/Cu(0.9)]$_{16}$</td>
<td>65</td>
<td>1</td>
<td>6)</td>
</tr>
</tbody>
</table>


evaluation includes twisting of magnetization in the Fe films
Table 1: Comparison of interlayer coupling strengths for some structures with insulating, semiconducting, and metallic interlayers.

<table>
<thead>
<tr>
<th>Structure</th>
<th>Interlayer thickness [nm]</th>
<th>Coupling strength [mJ/m²]</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fe/MgO/Fe</td>
<td>0.5</td>
<td>-0.26</td>
<td>[12]</td>
</tr>
<tr>
<td>Fe/Si/Fe</td>
<td>0.6</td>
<td>-6.2</td>
<td>[11]</td>
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<tr>
<td>Co/Ru/Co</td>
<td>&lt;0.9</td>
<td>-5</td>
<td>[50]</td>
</tr>
<tr>
<td>Fe/Cr/Fe</td>
<td>0.5</td>
<td>-1.6</td>
<td>[51]</td>
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Le Creusot 1988

Europe