A New Spin on Magnetism with Applications in Information Processing

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A New Spin on Magnetism with Applications in Information Processing

Outline

• Spintronics and spin-transfer torques
• Switching magnetization in magnetic tunnel junction nanopillars
• Magnetic skyrmions
• Center for Quantum Phenomena NYU NY
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Einstein-de Haas Effect

\[ \Gamma = \frac{dL}{dt} \]
\[ M = \gamma L \]
\[ \gamma = \frac{ge}{2m} = \frac{g\mu_B}{\hbar} \]


Proof of the existence of the Ampere molecular field
Giant Magnetoresistance (GMR)

The Nobel Prize in Physics 2007

"for the discovery of Giant Magnetoresistance"

Albert Fert
1/2 of the prize
France
Université Paris-Sud; Unité Mixte de Physique CNRS/THALES
Orsay, France
b. 1938

Peter Grünberg
1/2 of the prize
Germany
Forschungszentrum Jülich
Jülich, Germany
b. 1939

→ ‘Spintronics’ = Spin+Transport+Electronics: control of current using the spin of electrons
Magnetic Tunnel Junction

Two ferromagnetic metals separated by an insulating barrier

Parallel state (P)

Anti-parallel state (AP)

From:

\[ P_i = \frac{N_i\uparrow(E_F) - N_i\downarrow(E_F)}{N_i\uparrow(E_F) + N_i\downarrow(E_F)} \]

Julliere's formula:

\[ \text{TMR} = \frac{R_{AP} - R_P}{R_P} = \frac{2P_1P_2}{1 - P_1P_2} \]

W. H. Butler et al., Spin-dependent tunneling conductance of Fe|MgO|Fe sandwiches

PRB 63, 054416 (2001)
Prediction of Spin-Transfer Torques

2013 APS Oliver E. Buckley Prize

John Slonczewski

Luc Berger

Citation:
“For predicting spin-transfer torque and opening the field of current-induced control over magnetic nanostructures.”

Foundational papers:
Prediction of Spin-Transfer Torques

Conductance and exchange coupling of two ferromagnets separated by a tunneling barrier

J. C. Slonczewski
IBM Research Division, Thomas J. Watson Research Center, Yorktown Heights, New York 10598
(Received 27 June 1988)

A theory is given for three closely related effects involving a nonmagnetic electron-tunneling barrier separating two ferromagnetic conductors. The first is Julliere's magnetic valley effect, in which the tunnel conductance depends on the angle θ between the moments of the two ferromagnets. One finds that discontinuous change of the potential at the electrode-barrier interface diminishes the spin-polarization factor governing this effect and is capable of changing its sign. The second is an effective interfacial exchange coupling −J cosθ between the ferromagnets. One finds that the magnitude and sign of J depend on the height of the barrier and the Stoner splitting in the ferromagnets. The third is a new, irreversible exchange term in the coupled dynamics of the ferromagnets. For one sign of external voltage V, this term describes relaxation of the Landau-Lifshitz type. For the opposite sign of V, it describes a pumping action which can cause spontaneous growth of magnetic oscillations. All of these effects were investigated consistently by analyzing the transmission of charge and spin currents flowing through a rectangular barrier separating free-electron metals. In application to Fe-C-Fe junctions, the theory predicts that the valley effect is weak and that the coupling is antiferromagnetic J < 0. Relations connecting the three effects suggest experiments involving small spatial dimension.

TMR = \frac{2P_1P_2}{1 - P_1P_2}

In magnetic tunnel junctions

In magnetic metallic multilayers

J. C. Slonczewski, JMMM 159, L1-L7 (1996)
L. Berger, PRB 54, 9353 (1996)

Applications: Magnetic Random Access Memory, STT-MRAM

Nature Nanotechnology, March 2015
Spin-transfer-torque memory

Applications: New types of MRAM
Basic Physics of Spin Transfer

Based on conservation of angular momentum

\[ \frac{d\vec{S}_{\text{int}}}{dt} \rightarrow \vec{\tau} \]

\[ | \frac{d\vec{S}_{\text{int}}}{dt} | = \frac{\hbar}{2e} IP \sin \theta \]

\[ \frac{1}{\gamma} \frac{d\vec{M}}{dt} + \frac{d\vec{S}_{\text{int}}}{dt} = 0 \]

- Reference layer ‘sets’ spin-polarization of current
- Enables readout of magnetization state through the tunnel magnetoresistance (TMR), giant magnetoresistance (GMR), or anisotropic magnetoresistance (AMR) effects
Based on conservation of angular momentum

Spin transfer torques

$\Gamma_m = \frac{dS_{\text{int}}}{dt}$

Reference layer ‘sets’ spin-polarization of current

Enables readout of magnetization state through the tunnel magnetoresistance (TMR),
giant magnetoresistance (GMR), or anisotropic magnetoresistance (AMR) effects

All electrical (no mechanical parts) $\Rightarrow$ fast magnetic memory device
Spin-current amplifies the motion for currents greater than a critical value:

\[ I_{c0} = \frac{2e}{\hbar} \frac{\alpha}{P} \mu_0 M_s H_k V = \frac{4e}{\hbar} \frac{\alpha}{P} U \]

"anti-damping switching"  

\[ P = 1, \quad \alpha = 0.01, \quad U = 60kT \rightarrow I_{c0} = 15 \mu A \]
Charge Current to Spin Current Conversion

Ferromagnetic layers to polarize the current

Spin-orbit torques

Spin-polarization direction set by layer magnetization directions

Spin-polarization direction set by layer geometry and current flow direction

Spin-polarization direction set by layer magnetization directions

Spin-polarization direction set by layer geometry and current flow direction

Spin-torque foundational theory papers:


Heavy metals/Ferromagnet bilayers

M. Miron et al., Nature Materials 2010
L. Liu et al., Science 2012

Review articles:

V. Amin et al., Interfacial SOT, J. Appl. Phys. 128, 151101 (2020)
C. Safranski, J. Z. Sun & ADK, Appl. Phys. Lett. 120, 160502 (2022)
Ferromagnetic layers to polarize the current

\[ \frac{J_s}{J_c} \simeq P \]
\[ \frac{I_s}{I_c} \simeq P \]

Spin current is \( hJ_s/(2e) \)

\[ Q \sim \hat{m}_{RL} \otimes \hat{\zeta} \]

Spin-orbit torques

\[ \frac{J_s}{J_c} = \theta_{SH} \]
\[ \frac{I_s}{I_c} \simeq \theta_{SH}(\ell/t) \]

\[ Q = \frac{-\hbar}{2e} \xi \sigma_{SHE}(\hat{\zeta} \times \mathbf{E}) \otimes \hat{\zeta} \]

Spin torque foundational theory papers:


Review articles:

V. Amin et al., Interfacial SOT, J. Appl. Phys. 128, 151101 (2020)
C. Safranski, J. Z. Sun & ADK, Appl. Phys. Lett. 120, 160502 (2022)
**Spin Dynamics: LLG+Spin-Torque (LLGS)**

Landau-Lifshitz-Gilbert-Slonczewski Eqn:

\[
\frac{d\hat{m}}{dt} = -\gamma \mu_0 \hat{m} \times \hat{H}_\text{eff} + \alpha \hat{m} \times \frac{d\hat{m}}{dt} + \gamma a_J \hat{m} \times (\hat{m} \times \hat{m}_P)
\]

\[ \hat{H}_\text{eff} \]

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

Fast dynamics is associated with the gyroscopic term.

Damping and spin transfer terms are smaller by a factor of ~100.

If \( \textbf{m}_P \) and \( \textbf{H}_\text{eff} \) are collinear the adiabatic spin-torque can act as an “anti-damping” torque.

The adiabatic spin-torque is zero when \( \textbf{m} \) and \( \textbf{m}_P \) are strictly collinear.

\[ \frac{\gamma}{2\pi} = 28 \text{ GHz/T} \]

When the spin-torque exceeds the damping instabilities occur.

Also:

\[ b_J \hat{m} \times \hat{m}_P \]

‘Current-Induced Effective field’

Important in MTJs.

When the spin-torque exceeds the damping instabilities occur.

Also:

\[ b_J \hat{m} \times \hat{m}_P \]

‘Current-Induced Effective field’

Important in MTJs.

\[ \gamma a_J \hat{m} \times (\hat{m} \times \hat{m}_P) \]

\[ a_J = \frac{\hbar P I}{2eM_s V} \]
Sample Geometries and Materials

Important in nanostructures: Large current densities + STT dominate over Oersted fields

Heavy metals/Ferromagnet bilayers
M. Miron et al., Nature Materials 2010
L. Liu et al., Science 2012

Topological Insulators/FM
A. R. Melnik et al., Science 2014
Y. Fan et al., Nature Materials 2014

V. E. Demidov et al.
APL 105, 172410 (2014)


\[
\frac{d\hat{\mathbf{m}}}{dt} = \gamma \mu_0 \hat{\mathbf{m}} \times \hat{\mathbf{H}}_{\text{eff}} + \alpha \hat{\mathbf{m}} \times \frac{d\hat{\mathbf{m}}}{dt} + \gamma a_J \hat{\mathbf{m}} \times (\hat{\mathbf{m}} \times \hat{\mathbf{p}})
\]

STT can compensate damping in regions in the material
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• Spintronics and spin-transfer torques
• **Switching magnetization in magnetic tunnel junction nanopillars**
• Magnetic skyrmions
• Center for Quantum Phenomena NYU NY
A perpendicular-anisotropy CoFeB–MgO magnetic tunnel junction

S. Ikeda¹,², K. Miura¹,²,³, H. Yamamoto¹,²,³, K. Mizunuma², H. D. Gan¹, M. Endo², S. Kanai², J. Hayakawa³, F. Matsukura¹,² and H. Ohno¹,² *

Figure 1 | MTJ structure. a, Schematic of an MTJ device for TMR and CIMS measurements. b, Top view of an MTJ pillar taken by scanning electron microscope.

Applications: New types of MRAM

Field induced free layer switching
Current-induced switching

Also, D.C. Worledge et al., Applied Physics Letter 98, 022501 (2011)
Switching Magnetization of MTJ Nanopillars


N. Statuto et al., PRB 103, 014409 (2021)
P. Bouquin et al., APL 113, 222408 (2018)
I. Volvach et al., APL 116, 192408 (2020)
J. B. Mohammadi et al., APL 118, 132407 (2021)
Scaling down to 20 nm diameters

Resistance [kOhm] vs Design size (nm)

Each die:
- Devices (~20 to 90nm)
- 4k chips
- Memory chips (DM) or
- 4Mb chips

Two e-beam exposures were used in checkerboard pattern

Slide courtesy of Mustafa Pinarbasi
High Speed Magnetization Switching


\[ \frac{1}{\tau} = \frac{1}{\tau_0} \left( \frac{I - I_c}{I_c} \right) \]

\[ \tau_0 I_c = I \tau - I_c \tau \]

critical number of transmitted charges \( N_c \)

\[ eN_c \]

Write energy: \( \lesssim 250 \text{ fJ} \)
Reducing the Switching Energy

Reducing the magnetic moment of the free layer in a spin valve nanopillar

50 × 110 nm² In-plane magnetized elliptical nanopillar

<table>
<thead>
<tr>
<th>Sample</th>
<th>$I_c$ (μA)</th>
<th>$\Lambda$</th>
<th>$\tau_0$ (ns)</th>
<th>$\mu_0M_{s,3K}$ (mT)</th>
</tr>
</thead>
<tbody>
<tr>
<td>PyCu FL</td>
<td>395 ± 2</td>
<td>1.16</td>
<td>0.475 ± 0.007</td>
<td>240</td>
</tr>
<tr>
<td>Py FL</td>
<td>432 ± 2</td>
<td>1.44</td>
<td>1.18 ± 0.01</td>
<td>860</td>
</tr>
</tbody>
</table>

Write energy: $\lesssim 40$ fJ

Increasing the Switching Speed

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Magnetic Skyrmions

Control magnetic interactions

\[ H = - \sum_{\langle ij \rangle} \left( J_{ij} \vec{S}_i \cdot \vec{S}_j - D_{ij} \cdot (\vec{S}_i \times \vec{S}_j) \right) - \sum_i K S_z^2 \]

Isolated skyrmions

DW racetrack memory

Skyrmion racetrack memory

\[ \text{Skyrmion-based memory} \]

\[ \text{Write head} \]

\[ \text{Read head} \]

\[ \text{Racetrack} \]

NYU AD: Center for Quantum and Topological Systems

F. Büttner et al, Scientific Reports 8, 4464 (2018)
Growth and characterization of ferrimagnetic CoGd thin films

- Control of the DMI and SOTs is important to improve current-induced skyrmion motion.
- Study² of a trilayer system to simultaneously vary DMI and SOTs (θ_{SHE}).
- Bottom and top HM layer are sources of:
  - Spin-Orbit Coupling (⇒ DMI, stability of SKs)
  - Spin currents (⇒ enhanced dynamics)
- CoGd alloy compositions were chosen in a way that:
  - Low $M_s$ i.e. $T_M$ close to RT ideal for small SKs
  - $T_A$ close to RT: fast spin dynamics

Pt (2 nm) 
X (3 nm) 
Co$_x$Gd$_{1-x}$ ($t$ nm) 
Pt (6 nm) 
Ta (4 nm) 
Si/SiO$_2$

X = Ta, W or Ir

Y. Quessab et al., Advanced Science 8, 2100481(2021)
Current-induced domain wall motion

- **Goal**: characterize the SOT-induced DW dynamics in Pt/CoGd(5 nm)/(W or Ta)
- DW motion is induced by 5-ns current pulses using a GSG probe.
- Imaging is done by a home-made polar MOKE microscope.
Current-induced domain wall motion

- DW displacement direction reverses by changing the current polarity
- Down-up and up-down DWs move in the same direction
- Consistent with SOTs-driven motion of Néel DWs.
- $v_{\text{max}}(\text{Ta}) \sim 448 \text{ m/s}; v_{\text{max}}(\text{W}) \sim 460 \text{ m/s}$

CoGd racetracks have very low DW pinning and density of natural defect $\implies$ ideal to study SK motion

$v_{\text{DW}} = \frac{\pi}{2} \frac{Dj}{\sqrt{(S_{\text{net}}(T)j)^2 + (\alpha S_{\text{tot}}j)^2}}$

$\lim_{j\to\infty} v_{\text{DW}}(j) = \frac{\pi}{2} \frac{D}{S_{\text{net}}(T)}$

Current-induced nucleation of skyrmions

- Observation of zero-field nucleation of SK bubbles by a single 5-ns current pulse
- Nucleation does not depend on initial magnetization direction and current polarity ➔ thermal process
- Zero field nucleation of 200-nm skyrmion by a train of 5-ns current pulses

\[ \mu_0 H_z = 0 \text{ mT}; j_x = 1.81 \times 10^{12} \text{ A m}^{-2} \]

\[ \mu_0 H_z = 0 \text{ mT}; j_x = 8.6 \times 10^{11} \text{ A m}^{-2} \]
Current-induced skyrmion motion

- The SK displacement changes when reversing the current polarity.
- SKs with a core pointing up or down move in the same direction.
- The SK motion is indeed induced by SOTs.
- Stochastic annihilation is possible due to Joule heating.

\[ \mu_0 H_z = -5.7 \text{ mT}; \ j_x = 1.8 \times 10^{12} \text{ A m}^{-2}; \ v_{SK} \sim 400 \text{ m s}^{-1} \]
Current-induced skyrmion motion

- High mobility of SK bubbles at RT with a maximum velocity of $v_{SK} \approx 610 \text{ m s}^{-1}$ (highest SK velocity reported thus far!)
- SKs move faster in Pt/CoGd/W than in Pt/CoGd/Ta
- Theory predicts a plateau ($S_{net} \neq 0$) but a decrease of the SK velocity is observed at large current densities
- Deviation from the Thiele approximation, we cannot entirely consider the SK as a rigid texture.
**Perspective: skyrmions and quantum applications**

- Skyrmions can be used to nucleate (anti)-vortices in superconductors.
- Can the topological phase emerge without using a global magnetic field?
- Spatial variation of the skyrmion stray field can create a spatial-dependent SOC that can enable Majorana Fermions

  ➞ Growth of ferromagnet on top of a semiconductor/superconductor heterostructure that exhibits a topological phase

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*Physical Review Letters* 126, 117205 (2021)

*Communication Physics* 4, 163 (2021)
New Magnetic Nanotechnologies

Nanoelectronics, from new phenomena to low power electronics

International Associated Laboratory (LIA)
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NYU Center for Quantum Phenomena

Paul Chaikin - CMP Experiment
Andy Kent - CMP Experiment
Aditi Mitra - Theory
Dries Sels - Theory
Davood Shahrjerdi - ECE Experiment
Dan Stein - Theory
Andrew Wray - CMP Experiment
NYU Center for Quantum Phenomena

• Quantum Materials and Devices
• Out-of-Equilibrium Quantum Systems
• Quantum Information

• CQP inauguration: June 2017
• Official opening: September 1, 2017
• Laboratory space dedicated to CQP and new facilities

Center has 9 physics faculty, with associated faculty in Engineering
• There is a search this academic year for two QCMP/AMO experimental physicists
• There are ties to faculty at NYU Shanghai
• There are affiliated faculty in the NYU Tandon School of Engineering
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Acknowledgments


Collaborators
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-NYU: Gabriel Chaves and Dan Stein
-University of Barcelona and ICMAB-CSIC: Nahuel Statuto & Ferran Macia
-UVA: Joseph Poon and Avik Ghosh
-BBN Raytheon: Tom Ohki, Colm Ryan & Graham Rolands
-Spin Memory: Georg Wolf, Bartek Kardasz, Steve Watts & Mustafa Pinarbasi
-Sandia National Lab: Shashank. Misra, J. Darby Smith, J. Brad Aimone
-KTH, Sweden: B. Gunnar Malm
-University of Lorraine: Carlos Rojaz Sanchez, Stephane Mangin & Sebastien Petit-Watelot
-U. Paris Saclay, C2N: Dafine Ravelosona
-UCSD: Eric Fullerton
-WD-HGST: Jordan Katine