Spinelectronics: From Basic Phenomena to Applications
John Slonczewski

We will miss you, John
Main goal:

Discover new phenomena taking advantage of the electrons’ spin and try to use them in devices having new functionalities or improved performances (higher sensitivity, lower power consumption...etc).

Started in 1988 with the discovery of Giant Magnetoresistance
Spintronics/nanomagnetism
broadening spectrum of interest

- Spin injection/detection/manipulation:
  - semiconductors (Si, GaAs)
  - Graphene and other 2D materials
  - Topological insulators
- Control of magnetic properties by electric field/strain:
  - Interfacial anisotropy
  - Multiferroics
- Antferro spintronics
  - TeraHertz emission
- Spincaloritronics
  - Interplay Heat/Spin/Charge
- Giant Magnetoresistance (GMR)
- Tunnel Magnetoresistance (TMR)
- Spin transfer torque (STT)
- Current induced motion of magnetic textures:
  - Domain walls, skyrmions
- Spin orbit torque (SOT)
  - Dzyaloshinskii-Moriya interaction (DMI)
- Spincaloritronics
  - Interconversion spin ↔ charge current

1989 2006 2010
1996 2000 2004
2004 2008 2013
1996-2010
2003-2007
1996-2010
2008-2010
2008
2008
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Spintronics/nanomagnetism broadening spectrum of interest

Magnetic recording:
- Heat Assisted
- Microwave assisted MR

MRAM
Standalone Embedded

Non-volatile logic
Normally-Off/Instant-On electronics

Spin-waves based logic

Race track
Shift registers

Memristor applications
Neuromorphic architecture

STT or SOT based RF devices
- oscillators, filters and demodulators
- data communication
- neuromorphic computing
- power harvesting

Energy:
Thermoelectricity with spincaloritronics effects

Sensors:
- MR heads
- 3D position sensors
- Biotechnology
Spinelectronics:
From Basic Phenomena to Applications

OUTLINE

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  - Tunnel magnetoresistance (TMR)
  - Spin-Transfer Torque (STT)
  - Spin-orbit Torques (SOT)

• Part 2 : Spintronics main applications
  - Magnetic Recording (Hard disk drives Read-heads)
  - MRAMs
  - Magnetic field sensors
  - RF applications
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Giant magnetoresistance (1988)

Fe/Cr multilayers

\[ \frac{R}{R_0} (H = 0) \]

(Fe 30 Å/Cr 18 Å)_{30}

(Fe 30 Å/Cr 12 Å)_{35}

(Fe 30 Å/Cr 9 Å)_{40}

Magnetic field (kG)

\[ \sim 80\% \]

Two geometries of measurement:

Current-in-plane

Current-perpendicular-to-plane

\[ GMR = \frac{R_{AP} - R_P}{R_P} \]


Antiferromagnetically coupled multilayers

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Albert Fert & Peter Grünberg received the Nobel Prize from His Majesty King Carl XVI Gustaf of Sweden at the Stockholm Concert Hall, 10 December 2007.
Other GMR systems

Multilayers with two different switching fields

(Co 30 Å/Cu 55 Å/NiFe 30 Å)₆

$\Delta R(\Omega)$

Field (Oe)

$M/M_S$

Yamamoto et al., JMMM 1991
Dupas et al, JAP 1990

Spin-valve structures

NiFe60Å/Cu22Å/NiFe40Å/FeMn70Å

$M(10^{-3}\text{ emu})$

Field (Oe)

$\Delta R/R(\%)$

Two current model (Mott 1930) for transport in magnetic metals

As long as spin-flip is negligible, current can be considered as carried in parallel by two categories of electrons: spin $\uparrow$ and spin $\downarrow$ (parallel and antiparallel to quantization axis)

$$\rho = \left( \frac{1}{\rho_\uparrow} + \frac{1}{\rho_\downarrow} \right)^{-1} = \frac{\rho_\uparrow \rho_\downarrow}{\rho_\uparrow + \rho_\downarrow}$$

Sources of spin flip: magnons and spin-orbit scattering

Negligible spin-flip often crude approximation (spin diffusion length in NiFe~4.5nm, 30% spin memory loss at Co/Cu interfaces)

Spin dependent transport in magnetic transition metals (1)

Band structure of 3d transition metals
In transition metals, partially filled bands which participate to conduction are s and d bands

Non-magnetic Cu :

\[
D_{\uparrow}(E) = D_{\downarrow}(E)
\]

Magnetic Ni :

\[
D_{\uparrow}(E) \neq D_{\downarrow}(E)
\]

Most of transport properties are determined by DOS at Fermi energy

Spin-dependent density of state at Fermi energy

Spin dependent transport in magnetic metals (2)

\[ m^*(d) \gg m^*(s) \quad J \text{ mostly carried by } s \text{ electrons in transition metals} \]

Scattering of electrons determined by DOS at \( E_F \):

Fermi Golden rule:

\[ P^\sigma \propto \langle i | W | f \rangle^2 D_f (E_F) \]

Most efficient scattering channel:

\[ \lambda_{Co}^{\uparrow} = 10 \text{nm}; \lambda_{Co}^{\downarrow} = 1 \text{nm} \]

Example:

\[ F_{\uparrow}(E) \]

\[ F_{\downarrow}(E) \]

\[ S_{\uparrow} \rightarrow S_{\uparrow} \rightarrow d_{\uparrow} \]

\[ S_{\downarrow} \rightarrow S_{\downarrow} \rightarrow d_{\downarrow} \]

\[ D_{\uparrow}(E) \]

\[ D_{\downarrow}(E) \]

Simple model of Giant Magnetoresistance

Parallel config

Antiparallel config

\[ \frac{\Delta \rho}{\rho_{ap}} = \left( \frac{\rho_\uparrow - \rho_\downarrow}{\rho_\uparrow + \rho_\downarrow} \right)^2 = \left( \frac{\alpha - 1}{\alpha + 1} \right)^2 \]

Key role of scattering contrast \( \alpha \)

\[ \alpha = \frac{\rho_\uparrow}{\rho_\downarrow} \]

Two configurations of GMR measurement

1) Current in-plane (CIP)

- Straightforward to measure at wafer level, no need for patterning
- Measured in 4 point probe geometry
- CIP-GMR described by Boltzmann formalism
- Important characteristic lengths: elastic spin-dependent mean free paths
  e.g. \(\lambda_{NiFe}^{↑} = 7\, nm\); \(\lambda_{NiFe}^{↓} = 1\, nm\)
2) Current Perpendicular to Plane GMR (CPP-GMR)

Much more difficult to measure but richer physics,
Either on macroscopic samples (0.1 mm diameter) with superconducting leads (R~ ρ . thickness / area ~ 10^{-5} Ω)
or on patterned microscopic pillars of area <μm^2 (R~ a few Ohms)

Current Perpendicular to Plane GMR

Measurement limited at 4K
Without spin-flip, serial resistance network can be used for CPP transport.

CPP transport through F/NM/F sandwich described by:

(a) Parallel magnetic configuration:

(b) Antiparallel magnetic configuration:
Spin accumulation – spin relaxation in CPP geometry

In F1: Different scattering rates for spin $\uparrow$ and spin $\downarrow$ electrons
⇒ different spin $\uparrow$ and spin $\downarrow$ currents.
Larger scattering rates for spin $\downarrow$ : $J_{\uparrow} >> J_{\downarrow}$ far from the interface.

In F2: Larger scattering rates for spin $\uparrow$ : $J_{\downarrow} >> J_{\uparrow}$ far from the interface.

Majority of incoming spin $\uparrow$ electrons, majority of outgoing spin $\downarrow$ electrons
Building up of a spin $\uparrow$ accumulation around the interface balanced in steady state by spin-relaxation


\( \mu_\sigma \): spin-dependent chemical potential

In homogeneous material, \( \mu = \varepsilon_F - e\phi \)

**Spin-dependent current driven by** \( \vec{V} \mu \)

\[
J_\sigma = \frac{1}{e\rho_\sigma} \frac{\partial \mu_\sigma}{\partial z}
\]

Generalization of Ohm law

**Spin relaxation:**

\[
e\rho_\sigma \frac{\partial J_\sigma}{\partial z} = \frac{\mu_\sigma - \mu_{-\sigma}}{2l_{SF}^2}
\]

\( l_{SF} = \) spin-diffusion length (\(~5\)nm in NiFe, \(~20\)nm in Co))
Interfacial boundary conditions

\[ \mu_{i+1}^{\uparrow(\downarrow)}(z_{i+1}) - \mu_i^{\uparrow(\downarrow)}(z_{i+1}) = r_{i+1}^{\uparrow(\downarrow)} J_i^{\uparrow(\downarrow)}(z_{i+1}) \]  

(Ohm law at interfaces)

\[ J_{i+1}^{\uparrow(\downarrow)}(z_{i+1}) = J_i^{\uparrow(\downarrow)}(z_{i+1}) \]  

(if no interfacial spin-flip is considered)

Note: Interfacial spin memory loss can be introduced by:

\[ J_{i+1}^{\uparrow(\downarrow)}(z_{i+1}) = \delta J_i^{\uparrow(\downarrow)}(z_{i+1}) \]

30% memory loss as at Co/Cu interface yields \( \delta = 0.7 \)
Input microscopic transport parameters to describe macroscopic CPP properties:

**Within each layer:**
- The measured resistivity $\rho$.
- The scattering asymmetry $\beta$.
- The spin diffusion length $l_{sf}$.

**At each interface:**
- The measured interfacial area*resistance product $r_{\text{measured}}$.
- The interfacial scattering asymmetry $\gamma$.

\[
\rho_{\uparrow(\downarrow)} = 2\rho \cdot [1 - (+)\beta] \\
\rho_{\text{measured}} = \frac{\rho_{\uparrow}\rho_{\downarrow}}{\rho_{\uparrow} + \rho_{\downarrow}} = \rho \cdot (1 - \beta^2) \\
\]

\[
\left(1_{\uparrow}\gamma\right)_{\text{measured}} = \frac{r_{\uparrow} r_{\downarrow}}{r_{\uparrow} + r_{\downarrow}} = r \cdot (1 - \gamma^2) \\
\]
### Examples of bulk parameters

<table>
<thead>
<tr>
<th>Material</th>
<th>Measured resistivity 4K/300K</th>
<th>( \beta ) Bulk scattering asymmetry</th>
<th>( I_{SF} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cu</td>
<td>0.5-0.7( \mu )Ω.cm 3-5</td>
<td>0</td>
<td>500nm 50-200nm</td>
</tr>
<tr>
<td>Au</td>
<td>2( \mu )Ω.cm 8</td>
<td>0</td>
<td>35nm 25nm</td>
</tr>
<tr>
<td>Ni(<em>{80})Fe(</em>{20})</td>
<td>10-15 22-25</td>
<td>0.73-0.76 0.70</td>
<td>5.5 4.5</td>
</tr>
<tr>
<td>Ni(<em>{66})Fe(</em>{13})Co(_{21})</td>
<td>9-13 20-23</td>
<td>0.82 0.75</td>
<td>5.5 4.5</td>
</tr>
<tr>
<td>Co</td>
<td>4.1-6.45 12-16</td>
<td>0.27 – 0.38 0.22-0.35</td>
<td>60 25</td>
</tr>
<tr>
<td>Co(<em>{90})Fe(</em>{10})</td>
<td>6-9 13-18</td>
<td>0.6 0.55</td>
<td>55 20</td>
</tr>
<tr>
<td>Co(<em>{50})Fe(</em>{50})</td>
<td>7-10 15-20</td>
<td>0.6 0.62</td>
<td>50 15</td>
</tr>
<tr>
<td>Pt(<em>{50})Mn(</em>{50})</td>
<td>160 180</td>
<td>0</td>
<td>1</td>
</tr>
<tr>
<td>Ru</td>
<td>9.5-11 14-20</td>
<td>0</td>
<td>14</td>
</tr>
</tbody>
</table>

Review on CPP-GMR: Bass, JMMM 408 (2016) 244–320
### Examples of interfacial parameters

<table>
<thead>
<tr>
<th>Material</th>
<th>Measured R.A interfacial resistance</th>
<th>γ Interfacial scattering assymetry</th>
</tr>
</thead>
<tbody>
<tr>
<td>Co/Cu</td>
<td>0.21mΩ·µm² 0.21-0.6</td>
<td>0.77 0.7</td>
</tr>
<tr>
<td>Co\textsubscript{90}Fe\textsubscript{10}/Cu</td>
<td>0.25-0.7 0.25-0.7</td>
<td>0.77 0.7</td>
</tr>
<tr>
<td>Co\textsubscript{50}Fe\textsubscript{50}/Cu</td>
<td>0.45-1 0.45-1</td>
<td>0.77 0.7</td>
</tr>
<tr>
<td>NiFe/Cu</td>
<td>0.255 0.25</td>
<td>0.7 0.63</td>
</tr>
<tr>
<td>NiFe/Co</td>
<td>0.04 0.04</td>
<td>0.7 0.7</td>
</tr>
<tr>
<td>Co/Ru</td>
<td>0.48 0.4</td>
<td>-0.2 -0.2</td>
</tr>
<tr>
<td>Co/Ag</td>
<td>0.16 0.16</td>
<td>0.85 0.80</td>
</tr>
</tbody>
</table>

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Magnetic tunnel junctions – Tunnel magnetoresistance

Structure of a magnetic tunnel junction

- Reference layer: CoFe 3nm
- Storage layer: CoFe 4 nm or NiFe-CoFe-Al(Zr)O_x-CoFe-IrMn 7nm
- Al_2O_3 barrier 1.5nm

Acts as a couple polarizer/analyzer with the spin of the electrons.

- First observation of TMR at low T in MTJ: Julliere (1975) (Fe/Ge/Co)
- \( \Delta R/R \sim 50\% \) in AlO_x based junctions

\[ \text{Junction: 4.7x2} \]
\[ T=300K \]

10mT 20mT

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Fermi Golden rule: proba of tunneling
\[ \mathcal{P}^\sigma \propto \langle i | W | f \rangle^2 D_2(E_F) \]
\[ \propto D_1(E_F) \]
\[ J^\sigma \propto D_1^\sigma(E_F) \times D_2^\sigma(E_F) \]

\[ J_{\text{parallel}} \propto D_1^\uparrow D_2^\uparrow + D_1^\downarrow D_2^\downarrow \]
\[ J_{\text{antiparallel}} \propto D_1^\uparrow D_2^\downarrow + D_1^\downarrow D_2^\uparrow \]

\[ P = \frac{D_1^\uparrow(E_F) - D_1^\downarrow(E_F)}{D_1^\uparrow(E_F) + D_1^\downarrow(E_F)} \]
\[ \text{TMR} = \frac{\Delta R}{R_P} = \frac{2 P_1 P_2}{1 - P_1 P_2} \]
\[ \text{TMR} = \frac{\Delta R}{R_{AP}} = \frac{2 P_1 P_2}{1 + P_1 P_2} \]

\[ P \sim 50\% \text{ in Fe, Co} \]
\[ \Delta R/R \sim 40 - 70\% \text{ with alumina barriers} \]
Giant TMR of MgO tunnel barriers


Very well textured MgO barriers grown by sputtering or MBE on bcc CoFe or Fe magnetic electrodes, or on amorphous CoFeB electrodes followed by annealing to recrystallize the electrode.
Amorphous barrier Vs Crystalline barrier

Amorphous barrier
ex: amorphous AlO

Crystalline barrier
ex: MgO(001)

No crystallographic symmetry in the barrier:
- Incoherent tunneling: Bloch states are not conserved during tunneling.
- Every electron symmetry contributes equally to the tunneling process.
- Observed TMR < 100% @RT

Epitaxially grown crystalline barrier:

- Coherent tunneling: the electrons' wave-functions in the FM are coupled with evanescent wave-functions having the same symmetry in the barrier.
- Tunneling probability of $\epsilon^-$ strongly depends on its orbital symmetry → possible effective symmetry filtering of the tunneling current.

*Butler et al., PRB 2001; Khvalkovskiy et al., J. Phys. D Appl. Phys 2013*
Crystalline barrier – The example of Fe/MgO/Fe

- Exponential tunneling decay is much stronger for Δ₂ and Δ₅ states than for Δ₁ states.
- Both majority and minority Δ₂ and Δ₅ symmetry states can be found at the Fermi level → low P.
- Only majority electrons fill Δ₁ symmetry states, implying a full polarization \( P_{\Delta_1} = 100\% \).

⇔ *Spin filtering* of the wave functions: large values of TMR expected in epitaxial or highly textured structures (TMR>1000% @RT).

*Butler et al., PRB 2001; Khvalkovskiy et al., J. Phys. D Appl. Phys 2013*
Standard out-of-plane MTJ stack

- **Storage**
  - CoFeB 1.4nm
  - Ta ~3nm

- **Tunnel Barrier**
  - MgO

- **Reference (SyAF)**
  - Ta 0.3nm
  - Co 0.5nm
  - Ru 0.7

- **Hard Layer**
  - (Pt0.4/Co 0.5)_4

- **Underlayer**
  - Ta/Ru/Ta or Ta/CuN/Ta

Must have a **bcc structure**
- (001 textured)
- for large TMR
- (4-fold symmetry)

Nanocrystalline material to enable fcc/bcc structural transition

Must have a **fcc structure**
- for strong perpendicular anisotropy
- (i.e. strong pinning)
- (3-fold symmetry, (111) texture)

Same basic problem of in-stack symmetry compatibility
Growth and annealing of the tunnel barrier


Problem of symmetry compatibility solved by using amorphous CoFeB electrodes during growth

**As-deposited**

![Diagram of tunnel barrier structure]
Annealing of the magnetic tunnel junction

Annealing at $T_{\text{anneal}} \approx 300^\circ \text{C}-400^\circ \text{C}$. The higher $T_{\text{anneal}}$, the better from the barrier formation standpoint.

<table>
<thead>
<tr>
<th>As-deposited</th>
<th>Annealing</th>
<th>After annealing</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cap layer (Ta or Ru)</td>
<td>Crystallization of bcc CoFe from the MgO interface and expulsion of the B out-of the CoFeB alloy</td>
<td>Cap layer (Ta or Ru)</td>
</tr>
<tr>
<td>Amorphous CoFeB</td>
<td>Improvement of MgO crystallization</td>
<td>B rich CoFeB</td>
</tr>
<tr>
<td>Polycrystalline (001) textured MgO</td>
<td>Crystallization of bcc CoFe from the MgO interface and expulsion of the B out-of the CoFeB alloy</td>
<td>bcc CoFe</td>
</tr>
<tr>
<td>Amorphous CoFeB</td>
<td></td>
<td>crystalline (001) textured MgO</td>
</tr>
<tr>
<td>Ru spacer</td>
<td></td>
<td>bcc CoFe</td>
</tr>
<tr>
<td></td>
<td></td>
<td>B rich CoFeB</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Ru spacer</td>
</tr>
</tbody>
</table>

• Important to attract B away from the tunnel barrier during the crystallization process. Choose materials which are good B getters on the opposite side of the free (storage) and reference layers (Ta, Ru, W, Mo, Nb, Zr, Hf, …).

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Magnetic tunnel junctions based on MgO tunnel barriers

- As-deposited, CoFeB amorphous, MgO polycrystalline
- Upon annealing, recrystallization of CoFeB from the MgO interfaces and improvement in MgO crystallinity with (100) bcc texture

Also, Yuasa et al. Applied Physics Letters, 2005
Giant TMR of MgO tunnel barriers

Amorphous: Incoherent tunneling of various Bloch states

Crystalline: Spin-filtering mechanism according to symmetry of Bloch states

Giant TMR:
- MgO-barrier MTJs
- Al₂O₃-barrier MTJs

Timeline:
- Hitachi & Tohoku Univ. (100)bcc: 604% (RT)
- AIST/Canon-ANELVA IBM
- CoFe/Cu/CoFe

Contact:
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Spintronics tutorial Richmond 03/06/2019
**MTJ : a reliable path for CMOS/magnetic 3D integration**

- Resistance compatible with CMOS (cell R ~ kΩ)
- MTJ used as a variable resistance driven by field or current/voltage.
- MTJ can be deposited at any metallic level in the CMOS technology in replacement of a via.
- Above IC technology (‘end-of-back-end’ process)
- Front-end contamination under control
- Low-T BE process (250°C-350°C) compatible with Cu interconnect process
- Easy / cheap to embed (3 add-masks, no trade-off with logic process)

Rapid progress in technology maturity thanks to the involvement of major IDM and equipment manufacturers.
No CMOS contamination during the integration
Etching of MTJ remains the main difficulty at advanced nodes
More and more fabs now enabled with 200/300mm magnetic BEOL lines
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Spin-Transfer Torque (STT)


**Giant or Tunnel magnetoresistance:**
Acting on electrical current via the magnetization orientation

**Spin transfer is the reciprocal effect:**
Acting on the magnetization via the spin polarized current

Reorientation of spin polarization ⇒ **Torque on the free layer magnetization**

A new way to manipulate the magnetization of magnetic nanostructures

---

The whole transverse part of spin current is absorbed next to the interface.

Incident spin direction is aligned along the magnetization of the pinned layer FM$_1$.

- Torque acting on the magnetization of FM$_2$?
Classical expression of the Spin Transfer torque

\[ \bar{\tau}_{STT} = \frac{d\vec{M}_2}{dt} \propto \text{absorbed transverse spin current} \]

- Transverse spin component for one incoming electron:
  \[ |\Delta S_\perp| = S \sin(\theta) \]
  \[ \Delta \vec{S}_\perp \perp \vec{S}_2 \]
  \[ \Rightarrow \Delta \vec{S}_\perp = \frac{\hbar}{2} \vec{m}_2 \times (\vec{m}_2 \times \vec{m}_1) \]

- Contribution to magnetization:
  \[ \Delta \vec{M} = -\frac{g \mu_B}{\hbar} \Delta \vec{S} \]

- Volume:
  \[ V = A \cdot t = \text{Area} \times \text{thickness} \]

- Number of incoming electrons per second:
  \[ \frac{dN_e^{-}}{dt} = \frac{I}{e} = \frac{J \cdot A}{e} \]

- Number of incoming spins per second:
  \[ \frac{dN_S}{dt} = P_{\text{spin}} \frac{J \cdot A}{e} \]

\[ \frac{d\vec{M}_2}{dt} = -P_{\text{spin}} \frac{J \cdot A}{e} \frac{g \mu_B}{\hbar} \frac{\hbar}{A t} \left( \vec{m}_2 \times (\vec{m}_2 \times \vec{m}_1) \right) \]

\[ \bar{\tau}_{STT} = \frac{d\vec{M}_2}{dt} = -P_{\text{spin}} \frac{J g \mu_B}{e} \frac{t}{2} \left( \vec{m}_2 \times (\vec{m}_2 \times \vec{m}_1) \right) \]

**Expression derived by Slonczewski, JMMM 1996**
Magnetization dynamics under Spin Transfer Torque (STT)

- Landau-Lifshitz-Gilbert-Slonczewski equation (LLGS):
  \[
  \frac{d\mathbf{m}_2}{dt} = -\gamma_0 (\mathbf{m}_2 \times \mathbf{H}_{\text{eff}}) - \alpha \left( \mathbf{m}_2 \times \frac{d\mathbf{m}_2}{dt} \right) - P_{\text{spin}} \frac{J g \mu_B}{e 2M_{S2} t} \left( \mathbf{m}_2 \times (\mathbf{m}_2 \times \mathbf{m}_1) \right)
  \]

- Precessional torque (precession around \(\mathbf{H}_{\text{eff}}\)):
  \(\mathbf{H}_{\text{eff}} = \mathbf{H}_{\text{applied}} + \mathbf{H}_{\text{anisotropy}} + \mathbf{H}_{\text{demag}}\)

- Damping torque (dissipation):

- Spin transfer torque depends on the sign of the current:
  - parallel to damping torque
  - opposite to damping torque

  Above a threshold current: the spin transfer torque causes the effective damping to become negative.

  Equilibrium state becomes unstable: The magnetization spirals away from the direction of \(\mathbf{H}_{\text{eff}}\) → Switching
Magnetization switching induced by a polarized current

STT magnetization switching first observed in metallic pillars (2000)

By spin transfer, a spin-polarized current can be used to manipulate the magnetization of magnetic nanostructures instead of by magnetic field.

⇒ Can be used as a new write scheme in MRAM

\[ j_{c}^{P-AP} = 1.9 \times 10^7 \text{A/cm}^2 \]
\[ j_{c}^{AP-P} = 1.2 \times 10^7 \text{A/cm}^2 \]
Magnetization switching induced by a polarized current


The bipolar current flowing through the MRAM cell is used to switch the magnetization of the storage layer.

Reading at lower current density then writing so as to not perturb the written information while reading.

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Rashba effect in thin MTJ electrodes with in-plane current

Breaking of inversion symmetry – Rashba effect
An interfacial effect due to the presence of an interfacial electrical field at metal/oxide interface

\[ \mathbf{B} = \frac{1}{c} \frac{1}{\sqrt{1 - v^2 / c^2}} \mathbf{v} \times \mathbf{E} \]

Pulse of in-plane current generates a pulse of in-plane transverse field

Field like torque \( \tau \sim J \mathbf{m} \mathbf{x} u_y \)

Charge transfer at Co/MO\(_x\) interface
Interfacial E field

Manchon et al., PRB 78, 212405 (2008)
Hane et al., PRB (2013)
H. Yang et al., PRL (2014)
Spin-Hall effect

In presence of spin-orbit interaction in heavy metals (Pt, Au, Bi etc), spin-up and spin-down electrons are differently deviated during scattering. Used in Mott detectors to measure the spin polarization of spin polarized electron beams.

A. Hoffmann, IEEE TRANSACTIONS ON MAGNETICS, 49, 5172 (2013)
Switching by spin-Hall effect

Spin Hall effect provides another spin-torque contribution originating from the bulk of the heavy metal stripe.

\[ \tau \sim \theta_{SH} J m \times (m \times u_y) \]

→ Vertical spin-current with transverse polarisation \( u_y \).
→ Spin-current related to Spin Hall angle \( \theta_{SH} \) and charge current by: \( J_s=\theta_{SH} J \)
→ Damping like torque \( \tau \sim \theta_{SH} J m \times (m \times u_y) \)

\[ \text{Liu et al., (Science 2012), Liu et. al (2012); Kim, Hayashi et al. Nature Mater. (2013);} \]
\[ \text{X. Fan, J. Xiao et. al, NatCom (2014)} \]
Switching by spin-Hall effect

Liu et al, SCIENCE, 336, 557 (2012)

Switching by an in-plane current in a 3-terminal device
Spintronic components

Magnetic field sensors

Write/read heads

R(H)

Memories

“1”

R_{\text{low}}

“0”

R_{\text{high}}

Logic circuits

RF components

Spintronic components
End part I

Questions ?

Coffee break
Spinelectronics: From Basic Phenomena to Applications

OUTLINE

• Part 1: Basic phenomena in spintronics:
  - Giant Magnetoresistance
  - Tunnel magnetoresistance (TMR)
  - Spin-Transfer Torque (STT)
  - Spin-orbit Torques (SOT)

• Part 2: Spintronics main applications
  - Magnetic Recording (Hard disk drives Read-heads)
  - MRAMs
  - Magnetic field sensors
  - RF applications
Magnetic recording technology has stimulated R&D in spintronics for more than 20 years.

Hard Disk Drive (HDD)

Progresses in magnetic recording technology more and more difficult to achieve

ASTC Technology Roadmap

PMR = Perpendicular Magnetic Recording

PMR* = PMR with Two Dimensional Magnetic Recording (TDMR) and/or Shingled Magnetic Recording (SMR)

HAMR* = Heat Assisted Magnetic Recording (HAMR) with TDMR and/or SMR

BPMR* = Bit Patterned Magnetic Recording (BPMR) with SMR and TDMR

HDMR = Heated-Dot Magnetic Recording (BPMR+HAMR*)

CAGR = 30%

Areal density (Tb/in²)

Year


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HDD R&D increasingly difficult but increasing demand for data storage

Coexistence of **Solid State Drives** (based on Flash memories: charge based storage) and **Hard Disk Drives** (magnetic « cold » storage)

- Handheld devices
  - Laptops, cell-phones…
- Servers farms
  - SSD+HDD

3D-Flash allows significantly increase the density of Flash disks
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  - RF components
Various MRAM families

Field-driven

Thermally Assisted (TAS)

STT (STT MRAM)
- Planar
- Perpendicular

DW motion

Spin-orbit torque (spin-Hall, Rashba)
Various MRAM families

Field-driven

Thermally Assisted (TAS)

STT (STT MRAM)

Planar

Perpendicularly

STT-TAS

Precessional

DW motion

Spin-orbit torque (spin-Hall, Rashba)
STT MRAM – scalability of write current

Writing “0”

\[ V_{dd} \quad \text{free pinned} \quad j_{\text{STT}} \quad \text{ON} \quad 0 \]

Writing “1”

\[ V_{dd} \quad \text{0} \quad j_{\text{STT}} \quad \text{ON} \]

• Writing determined by a current density:

\[
\dot{j}_{WR_{in\text{-plane}}} = \left( \frac{2e}{\hbar} \right) \frac{\alpha t_F}{P} \left( \frac{\mu_0 M_s^2}{2} + 2K \right)
\]

• Current through cell proportional to MTJ area

\[
\text{\dot{j}_{write\ SST\ in\text{-plane}}} \approx 8 \times 10^5 \text{A/cm}^2 \text{ quasistatic}
\]

\[
\approx 3 \times 10^6 \text{A/cm}^2 \text{ @10ns}
\]

Huai et al, Appl.phys.Lett.87, 222510 (2005) ;

Write current ~15-40µA at sub-20nm node
STT-MRAM – Write – influence of current pulse width

In-plane magnetized MTJ
Elliptical shape
115nm*155nm

Hosomi et al, Sony, 4Kbit demo (2005)

Ballistic STT switching

Thermally activated STT switching

Write Threshold Current [μA]

High → Low State

Low → High State

Write Pulse Width [sec] $\tau$

$\sim$10ns

Hosomi et al, Sony, 4Kbit demo (2005)
STT-MRAM – Distributions consideration

Read  STT Write  Breakdown

\[
\begin{align*}
0.15\text{-}0.2V & \quad 0.40\text{-}0.50V & \quad 1.2V\text{-}1.6V \\
V_{\text{switch}} & \ll V_{\text{breakdown}} \text{ for good write endurance} \\
V_{\text{read}} & \ll V_{\text{switch}} \text{ to avoid disturb during read} \\
V_{\text{read}} & \text{large enough for reasonable read speed (} \sim 10\text{ns).}
\end{align*}
\]
STT-MRAM – Key parameters

• $\Delta$ (thermal stability factor) ⇒ data retention, read disturb, operating temperature range, downsize scalability

  $\Delta$ should be between 30 and 90 depending on chip density and retention.

• TMR (read signal) ⇒ read speed, sense margin, tolerance on RA dispersion

  TMR above 200% to achieve fast (sub 10ns) read-out. The larger, the better.

• $J_{c0}$ (write current density) ⇒ cell size, write speed, write consumption, reliability

  $J_c$ below $1.10^6$A/cm² is desirable to insure select transistor size smaller than MTJ.

• $V_{bd}$ (MTJ breakdown voltage) ⇒ reliability, endurance

  $V_{bd}$ should be above 3 times write voltage (typically $V_{bd}$~1.5V at 10ns and $V_{write}$~0.5V) to achieve a write endurance above $10^{16}$ cycles.
2013: 1st STT-MRAM product

Everspin Introduces
The 64Mb DDR3 ST-MRAM

November 2012
In-plane versus out-of-plane STT switching

\[ j_c^{\text{in-plane}} = \left( \frac{4e}{\hbar} \right) \frac{\alpha k_B T}{g(0) pA} \left( \Delta + \frac{\pi M_s^2 V}{k_B T} \right) \]

\[ j_{c,\text{perp}} = \left( \frac{4e}{\hbar} \right) \frac{\alpha k_B T}{g(0) pA} \Delta \]

Thermal stability determined by in-plane anisotropy (shape anisotropy)

Simpler materials but additional penalty in \( j_c \) due to out-of-plane precession

More complex materials but lower \( j_c \) expected thanks to direct proportionality between \( J_c \) and thermal stability \( \Delta \)
Perpendicular Magnetic Anisotropy (PMA) at magnetic metal/oxide interface

Surprisingly large perpendicular anisotropy at magnetic metal/oxide interface
(Monso et al APL 2002)

L. Nistor et al, IEEE Trans Mag., 46 (2010), 1412

First observation of PMA at Co/AlOx
PMA at Co or CoFe/MgO, CrO, TaO
XPS, XAS, interpretation of PMA at M/Ox
Influence of annealing on PMA at Co/AlOx
Correlation PMA - TMR at CoFe(B)/MgO

Very general phenomenon of perpendicular anisotropy observed at a wide variety of M/Ox interfaces with M=Co, CoFe, CoFeB and Ox= AlOx, MgO, TaOx, CrO2,…

Due to hybridization between Co dz² and O sp orbitals

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P-MTJ based on interfacial PMA (i-PMA)

Ikeda et al, Nat.Mat.2804 (2010)

No Pt nor Pd in the stack

\[
\text{TMR} = 124\% \\
\text{RA} = 18\Omega \cdot \mu m^2
\]

\[\Delta = 43\]

(70 required for 1Gbit)
Sub-20nm STT-MRAM

Bottom pinned with double MgO barrier:

Benefit from the PMA at these two interfaces. Increases the thermal stability of the free layer.

TMR \sim 100-130\%

H. Ohno’s group (Tohoku Univ 2013), IEDM 2014
STT-MRAM assets

- **Non-volatility**

- **Downsize scalability**

- **Write speed**

- **Write endurance**
  (at least for pulse duration >20ns)

1) e-FLASH, 2) non-volatile SRAM .... 3) Non-volatile DRAM

---

Bernard Dieny, CEA

8 Mbit fully functional demo from TDK/Headway Techno now transferred to TSMC

11nm STT-MRAM cell (IBM)

10^{20} cycles à 0.6V

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An increasing number of industrial actors active in the MRAM arena
Samsung Electronics the world leader in semiconductor technology, today announced that it has commenced mass production of its first commercial embedded magnetic random access memory (eMRAM) product based on the company’s 28-nanometer (nm) fully-depleted silicon-on-insulator (FD-SOI) process technology, called 28FDS.

As eFlash has faced scalability challenges due to a charge storage-based operation, eMRAM has been the most promising successor since its resistance-based operation allows strong scalability while also possessing outstanding technical characteristics of memory semiconductors such as nonvolatility, random access, and strong endurance. With today’s announcement, Samsung has proved its capability to overcome technical hurdles and demonstrated the possibility for further scalability of embedded memory technology to 28nm process node and beyond.

Samsung’s 28FDS-based eMRAM solution offers unprecedented power and speed advantages with lower cost. Since eMRAM does not require an erase cycle before writing data, its writing speed is approximately a thousand times faster than eFlash. Also, eMRAM uses lower voltages than eFlash, and does not consume electric power when in power-off mode, resulting in great power efficiency.
Conclusion on p-STT-MRAM

• Perpendicular MTJs offer better downsize scalability than in-plane magnetized MTJs due to larger anisotropy and lower write current for a given thermal stability factor.

• In p-MTJs, taking advantage of the interfacial anisotropy at CoFe/MgO interface allows to circumvent the issue of combining large PMA with low Gilbert damping.

• Etching of the MTJ stack remains the main technological difficulty at sub-28nm node yielding too large variability. However, great progress are made and demonstrators of embedded STT-MRAM at 28nm node have been successfully realized.

• Main foreseen applications:
  • Replacement of embedded FLASH
  • Replacement of SRAM
  • Remplacement of DRAM (longer time goal….)
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  - RF components
Different kinds of magnetoresistive sensors


### TYPICAL KEY PROPERTIES OF MAGNETORESISTIVE SENSORS

<table>
<thead>
<tr>
<th>AMR</th>
<th>GMR</th>
<th>Spinvalves</th>
<th>TMR - Magnetic Tunnel Junctions</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Physical principle</strong></td>
<td>Anisotropic MR</td>
<td>Giant MR</td>
<td>Spin dependent tunneling</td>
</tr>
<tr>
<td>Thin film structure</td>
<td>Simple</td>
<td>Multilayers, several material compositions</td>
<td>Complex multilayers, several material compositions</td>
</tr>
<tr>
<td></td>
<td>Buffer/free/cap</td>
<td>Buffer/free/spacer/reference/pinning/cap</td>
<td>Buffer/free/barrier/reference/pinning/cap</td>
</tr>
<tr>
<td><strong>Magnetoresistance (MR) [%]</strong></td>
<td>2-6</td>
<td>6-20</td>
<td>50% (Al₂O₃ amorphous barrier)</td>
</tr>
<tr>
<td><strong>Sensor linear range [μT]</strong></td>
<td>0.1-1</td>
<td>1-5</td>
<td>300% (MgO crystalline barrier)</td>
</tr>
<tr>
<td><strong>Thermal treatment [°C]</strong></td>
<td>Not required</td>
<td>Typically 220-280°C</td>
<td>2-10</td>
</tr>
<tr>
<td><strong>Reference layer</strong></td>
<td>No, needs external</td>
<td>Yes (interface exchange biased through an antiferromagnetic film)</td>
<td>Typically 280-340°C</td>
</tr>
<tr>
<td><strong>Electrical robustness against electrostatic discharge</strong></td>
<td>Excellent</td>
<td>Excellent</td>
<td>Good</td>
</tr>
<tr>
<td><strong>General geometry and readout scheme</strong></td>
<td><img src="image1" alt="AMR Diagram" /></td>
<td><img src="image2" alt="GMR Diagram" /></td>
<td><img src="image3" alt="TMR Diagram" /></td>
</tr>
</tbody>
</table>

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## Sensors matrix (from NIST, 2003)

<table>
<thead>
<tr>
<th>Sensor type</th>
<th>Sensitivity/Field range</th>
<th>Frequency Range</th>
<th>Operation Temperature</th>
<th>Minimum sensor size/Scalability</th>
<th>Vectorial/Scalar</th>
<th>Cost</th>
<th>Advantages</th>
<th>Disadvantages</th>
<th>Status</th>
</tr>
</thead>
<tbody>
<tr>
<td>Search coil</td>
<td>30 fT</td>
<td>&gt;1 Hz</td>
<td>RT</td>
<td>1 mm</td>
<td>vector</td>
<td>Moderate</td>
<td>Low cost for the sensitivity</td>
<td>Limited to &gt; 1Hz, sensitive to angular vibrations, Loose sensitivity as decrease size</td>
<td>Mature</td>
</tr>
<tr>
<td>Hall probe/EMR</td>
<td>100 nT/1 nT</td>
<td>&lt; 1 kHz</td>
<td>RT</td>
<td>&lt; 1 µm</td>
<td>Vector</td>
<td>Moderate</td>
<td>Large range, linear</td>
<td>Temperature dependent</td>
<td>Mature</td>
</tr>
<tr>
<td>Fluxgate</td>
<td>1 pT/Hz$^{0.5}$ @ 1Hz</td>
<td>&lt; 1 kHz</td>
<td>RT</td>
<td>Loose S/N scaling down</td>
<td>Vector</td>
<td>Moderate</td>
<td>High sensitivity</td>
<td>Cost, size, energy consumption</td>
<td>Bulk films versions possible</td>
</tr>
<tr>
<td>SQUID</td>
<td>1 fT</td>
<td>&lt;1 kHz</td>
<td>&lt;77K</td>
<td>&lt; 1 µm (system large)</td>
<td>Vector</td>
<td>Expensive</td>
<td>Sensitivity</td>
<td>Need for low temperature</td>
<td>Mature</td>
</tr>
<tr>
<td><strong>GMR</strong></td>
<td>20 nT</td>
<td>0-5 GHz</td>
<td>RT</td>
<td>&lt; 1 µm</td>
<td>Vector</td>
<td>Cheap</td>
<td>Low cost in large quantities. Small sensors. Wide frequency range</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>TMR</strong></td>
<td>1 nT</td>
<td>0-1 GHz</td>
<td>RT</td>
<td>&lt; 1 µm</td>
<td>Vector</td>
<td>Cheap</td>
<td>Large MR, low cost in large quantities</td>
<td>High 1/f noise, hysteretic</td>
<td></td>
</tr>
<tr>
<td>GMI</td>
<td>100 pT</td>
<td>&lt;500 kHz</td>
<td>RT</td>
<td>1 mm</td>
<td>Vector</td>
<td>Moderate</td>
<td>Cost, size, high power</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Magneto-optic</td>
<td>100 pT</td>
<td>0-5GHz</td>
<td>RT</td>
<td>1 mm</td>
<td>Vector</td>
<td>Moderate</td>
<td>No electrical connection</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Resonance</td>
<td></td>
<td>DC</td>
<td>RT</td>
<td>10 mm</td>
<td>Scalar</td>
<td>Expensive</td>
<td>Insensitive to angular vibrations</td>
<td>Cost, power consumption, loss of sensitivity at higher frequencies</td>
<td></td>
</tr>
<tr>
<td>Optical pumping</td>
<td>10-1000 fT</td>
<td>&lt; 100 Hz</td>
<td>RT</td>
<td>10 mm</td>
<td>Scalar or vector</td>
<td>Expensive</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Magnetostrictive</td>
<td>1 nT</td>
<td>RT</td>
<td>10 µm</td>
<td>Vector</td>
<td>Moderate</td>
<td>Low power</td>
<td>Large output</td>
<td>Sensitive to vibrations</td>
<td></td>
</tr>
</tbody>
</table>
Various approaches for linearization of magnetoresistive sensors

Aspect ratio >20


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Magnetoresistive sensors often used in Wheatstone bridge configuration

\[ H = 0 ; V_{\text{out}} = 0 \]

**Difficulty is to set the two pairs of sensors in opposite pinning directions:**
- Use different deposits (different field during deposition or AF with different TB or SAF differently compensated…)
- Or use local heating lines
- Or use local field generating lines

Example of bridge magnetoresistive sensor

Example: spin-valve based bridge sensor
Glass/Ta 2nm /NiFe 3nm / CoFe 2 / Cu 1.9 / CoFe 2 / Ru 8 / CoFe 1.5 / MnIr 6 / Ta 3nm
GMR=8%
30 GMR elements in series in each branch with individual dimension 3*170mm
Very elongated shape to insure single domain behavior

With TMR: bridge sensitivity 32mV/V/Oe or 26.7 mV/mW/Oe
Spintronics sensors for ultra-low field detection


<table>
<thead>
<tr>
<th>Active sensor</th>
<th>Details</th>
<th>Magnetic flux guides</th>
<th>Operation temperature</th>
<th>Detectivity at 1 Hz (T/Hz^0.5)</th>
<th>Device footprint</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>AMR-bridge</td>
<td>Honeywell commercial AMR HMC1001</td>
<td>N</td>
<td>RT</td>
<td>100 pT</td>
<td>N/A</td>
<td>Stutzke et al. (2005)</td>
</tr>
<tr>
<td>GMR-bridge</td>
<td>NVE commercial GMR devices</td>
<td>Y</td>
<td>RT</td>
<td>4 nT</td>
<td>N/A</td>
<td>Stutzke et al. (2005)</td>
</tr>
<tr>
<td>GMR-single</td>
<td>Spin valves with ferromagnetic FGs</td>
<td>Y</td>
<td>RT</td>
<td>7–20 nT</td>
<td>&gt;470 × 400 μm^2^b</td>
<td>Leitao et al. (2012); Guedes et al. (2007)</td>
</tr>
<tr>
<td>GMR-single</td>
<td>Spin valves with MEMs–FGs</td>
<td>Y</td>
<td>RT</td>
<td>40–600 nT^b</td>
<td>900 × 2,400 μm^2^b</td>
<td>Guedes et al. (2008, 2012)</td>
</tr>
<tr>
<td>GMR-single</td>
<td>Spin-valve with YBaCuO loop</td>
<td>Y</td>
<td>77 K</td>
<td>~200 fT</td>
<td>3 × 3 cm^3^c</td>
<td>Pannetier et al. (2004)</td>
</tr>
<tr>
<td>GMR-bridge</td>
<td>GMR wheatstone bridge with Nb loop</td>
<td>Y</td>
<td>4 K</td>
<td>3 pT</td>
<td>3 × 3 cm^3^c</td>
<td>Pannetier-Lecoeur et al. (2011)</td>
</tr>
<tr>
<td>TMR-single</td>
<td>MTJ</td>
<td>N</td>
<td>RT</td>
<td>350 nT</td>
<td>N/A</td>
<td>Mazumdar et al. (2007)</td>
</tr>
<tr>
<td>TMR-bridge</td>
<td>NVE SDT</td>
<td>N</td>
<td>RT</td>
<td>~4 nT</td>
<td>N/A</td>
<td>Stutzke et al. (2005)</td>
</tr>
<tr>
<td>TMR-series</td>
<td>MTJ series</td>
<td>N</td>
<td>RT</td>
<td>16.2 nT</td>
<td>500 × 500 μm^2^2</td>
<td>Guerrero et al. (2009)</td>
</tr>
<tr>
<td>TMR-single</td>
<td>Al₂O₃ MTJ with ferromagnetic FGs</td>
<td>Y</td>
<td>RT</td>
<td>534 pT</td>
<td>2,210 × 1,775 μm^2^b</td>
<td>Jander et al. (2003)</td>
</tr>
<tr>
<td>TMR-single</td>
<td>MgO MTJ sensor with ferromagnetic FGs</td>
<td>Y</td>
<td>RT</td>
<td>300 pT</td>
<td>500 × 500 μm^2^2</td>
<td>Chaves et al. (2007, 2011)</td>
</tr>
</tbody>
</table>
Integration of sensors on flexible substrates possible

Interesting for instance for implantable devices, bendable electrodes (neurosciences). Example: GMR spin-valves on polyimide

Applications: 1) metal surface inspection

Principle: To excite the metal surface with a RF field at ~1MHz and detect the stray field due to eddy current from the metal surface. Eddy currents are very sensitive to local resistivity which changes significantly if a defect is present.

E. E. Kriezis et al, Proceedings of the IEEE, 80(10), 1559-1589, 1992
Applications: 2) MR sensors for Power measurements

Contactless measurement of the stray field created by a current flowing in a wire

Applications: 3) Medical/biological diagnosis
Biosensing through magnetic nanoparticles labelling

Use MR sensors to detect magnetic particles flowing in a microfluidic channel


Startups:
http://www.magarray.com (Stanford, Pr S.Wang)
http://www.zeptolife.com (Minnesota)
http://www.magnomics.pt (INESC, Portugal)
Applications: 4) Position/rotation encoders

- MR sensors used as linear or rotation encoders
- More than 100 of them in a car. Often based on Hall sensors but GMR increasingly used.
- One difficulty with GMR or TMR is the temperature sensitivity. Must be somehow compensated (example: anisotropy field $H_k(T)$ decreasing at same rate as GMR($T$) amplitude versus $T$ so that $dR/R/dH$ remains constant vs $T$)
- Must be very low cost.
Applications: 5) MR sensors used as compass


Can complement GPS signal when the latter is not available (tunnels, underground parking lot, GPS breakdown...)

3D sensing also developed: Difficulty is to measure $B_z$ with integrated components (these sensors must be low cost)
Industrial actors in MR sensors

- **Asahi KASEI** (Japan)
- **Honeywell** (USA)
- **MEMSIC** (USA)
- **MICRONAS** (Switzerland)
- **NXP** (Netherlands)
- **Allegro** (USA)
- **Infineon** (Germany)
- **Melexis** (Belgium)

**PRODUCTS**
- Current Sensor ICs
- Magnetic Digital Position Sensor ICs
- Magnetic Speed Sensor ICs
- Sanken Products
- Magnetic Linear and Angular Position Sensor ICs
- Motor Driver and Interface ICs
- Regulators and Lighting
Spinelectronics: From Basic Phenomena to Applications

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RF oscillators based on spin-transfer torque

- Injection of electrons with out-of-plane spins in a layer of in-plane magnetization;
- Steady precession of the magnetization of the soft layer adjacent to the tunnel barrier.

Precession (2GHz-40GHz) + Tunnel MR $\Rightarrow$ RF voltage
Large-band frequency tunable RF oscillators

$D.$ Houssamedine et al, Nat. Mat 2007
Spintronics RF Functions

Function 1: DC-to-RF converter
RF Signal generation

Function 2: Injection locking
Signal synchronisation

Function 3: Modulation and Mixing
Communication

Function 4: RF-to-DC conversion
Frequency selective microwave detection
Assets of spintronics RF components

- **Low power**, active device
- **Nanoscale dimension** – small chip size, compact alternative to LC tanks
- **Large range of base frequencies** (configuration)
- **Frequency tuning** via I and H – reconfigurable communication
- **Multifunctional** (signal generation, injection locking, modulation, detection)
- **CMOS compatible** and radiation hard

However, not yet ready for practical applications….
Remaining problems towards practical spintronics RF oscillators

1) RF power still too low:

Large microwave generation from current-driven magnetic vortex oscillators in magnetic tunnel junctions, A. Dussaux et al, Nature Com. 2010, DOI: 10.1038/ncomms1006

PtMn 15 nm / CoFe 2.5 nm / Ru 0.85 nm / CoFeB 3 nm / MgO 1.075 nm / NiFe 15 nm / Ru 10 nm.

170nm pillar diameter
Free layer in vortex configuration

Vortex oscillators provide the largest output power among all STO but weak tunability and power still too low for practical applications (by several orders of magnitude).

2) Instability of the precessional motion:

Large tunability is intrinsically associated with large non-linearity in magnetization dynamics (frequency depends on magnetization trajectory amplitude). But then thermal fluctuations, by perturbing the magnetization trajectories, more strongly hamper the coherence of the magnetization dynamics yielding large noise.
Most probable first application:
RF rectifiers: spin-torque diodes

Highly sensitive nanoscale spin-torque diode

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Highly sensitive microwave devices that are operational at room temperature are important for high-speed multiplex telecommunications. Quantum devices such as superconducting bolometers possess high performance but work only at low temperature. On the other hand, semiconductor devices, although enabling high-speed operation at room temperature, have poor signal-to-noise ratios. In this regard, the demonstration of a diode based on spin-torque-induced ferromagnetic resonance between nanomagnets represented a promising development, even though the rectification output was too small for applications (1.4 mV mW⁻¹). Here we show that by applying d.c. bias currents to nanomagnets while precisely controlling their magnetization-potential profiles, a much greater radiofrequency detection sensitivity of 12,000 mV mW⁻¹ is achievable at room temperature, exceeding that of semiconductor diode detectors (3,800 mV mW⁻¹). Theoretical analysis reveals essential roles for nonlinear ferromagnetic resonance, which enhances the signal-to-noise ratio even at room temperature as the size of the magnets decreases.

RF diodes are important components in RF communications for frequency detection.
In the sub-threshold regime (just before magnetization switching), high sensitivity of magnetization trajectory on RF power.

In Japan, spin-torque diodes considered as a promising RF application of STT.

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Spintronics/nanomagnetism
broadening spectrum of interest

**Spintronics applications**

**Sensors:**
- MR heads
- 3D position sensors
- Biotechnology

**Energy:**
Thermoelectricity with spincaloritronics effects

**Magnetic recording:**
- Heat Assisted
  - Microwave assisted MR

**MRAM**
- Standalone
- Embedded

**Non-volatile logic**
- Normally-Off/Instant-On electronics

**Spin-waves based logic**

**Race track**
- Shift registers

**STT or SOT based RF devices**
- Oscillators, filters and demodulators
- Data communication
- Neuromorphic computing
- Power harvesting

**Memristor applications**
- Neuromorphic architecture

**RF devices**

**Neuromorphic architecture**
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