Part 2

Tunneling Magnetorezistance (TMR) in Magnetic Tunnel Junctions (MTJ)

Prof. Dr. Coriolan TIUSAN UTCN - CNRS
**Tunnel effect** (1928 George Gamow):
NONZERO transmission of particle-associated wave across a thin potential barrier

The *nature of particles as waves* (de Broglie) determines the tunnel effect

- Pure QM approach
- No Classical approach

**Tunnel junction:**
= two metallic layers separated by a thin insulator:
=> electron propagation by tunneling

**Tunneling Magnetorezistance (TMR)**

consequence of spin-dependent tunneling
Some quantum mechanics

Free electrons $\Rightarrow$ Plane wave

$e^{ikx} + Re^{-ikx} \Rightarrow Te^{ikx}$

$Ae^{\kappa d} + Be^{-\kappa d}$

Transmission probability:

Transmission probability:

$T \sim \exp(-2\kappa d)$

Tunnel current (conductivity):

$I_{LR} = \int n_L(E)f_{L}^{FD}(E)T(E)n_R(E)(1 - f_{R}^{FD}(E))dE$

Total (net) current when biasing the junction

$I = I_{LR} - I_{RL} = \int n_L(E)T(E)n_R(E + eV)(f_{L}^{FD}(E) - f_{R}^{FD}(E + eV))dE$
Metallic layers = ferromagnetic

Spin dependent
- density of states $n_\sigma(E)$
- potential profile in the ferromagnet

Spin dependent transmission probability $T_\sigma(E)$

Spin dependent current

$$J_\sigma = \int n_1^\sigma(E) T_\sigma(E) n_2^\sigma(E) [f_1(E) - f_2(E)] dE$$
Two current model (2 independent channels)

Spin conservation during tunneling
- spin up: $J^\uparrow$
- spin down: $J^\downarrow$

$$J_{\text{tot}} = J^\uparrow + J^\downarrow$$

Quantum Mechanics

$$J_\sigma(V) = \int n_1^\sigma(E) T_\sigma(E) n_2^\sigma(E + eV) [f_1(E) - f_2(E + eV)] dE$$

$$T = \text{OK} \Rightarrow$$

$$J_\sigma(V) \propto n_1^\sigma(E_F) n_2^\sigma(E_F + eV)$$

Mechanisms of TMR

Spin transport by quantum tunneling
Tunnel magnetoresistance:

\[ TMR = \frac{\Delta R}{R} = \frac{R_{AP} - R_P}{R_P} \]

\[ \Delta R = \left( R_{AP} - R_P \right) = \frac{2PP_2}{1 - P_1P_2} \]

with \[ P_{1(2)} = \frac{n_{1(2)}^\uparrow - n_{1(2)}^\downarrow}{n_{1(2)}^\uparrow + n_{1(2)}^\downarrow} \]

Spin-valve effect

\[ R = \frac{R_p + R_{ap}}{2} + \frac{R_p - R_{ap}}{2} \cos(\theta), \]

\[ \theta = (\vec{M}_1, \vec{M}_2) \]
MAGNETIC TUNNEL JUNCTION – Large spin valve effect

\[ I_\sigma = f(\theta) \]

-> sensors

Spin dependent tunnel current

\[ P = \left( \frac{n^+ (E) - n^- (E)}{n^+ (E) + n^- (E)} \right) \]

I: Spin dependent tunneling

Field, rotation

HD-Read HDD
Key parameters for MTJ

- Control of magnetic properties of electrodes
- Control of barrier structure at nanometer scale

- $H_{c1} \neq H_{c2}$
- $R = f(\theta) = R(H)$
- $\Phi \sim d\sqrt{\Phi}$
Operating at low fields:

\[ H_{c1} < H < H_{c2} \]

Control of magnetic properties

Operating an MTJ:

\[ M(H) \iff R(H) \]

Hard-soft architecture
\[ |H| < H_{c2} \]

(1) Control of magnetic properties

Minor loop:
- Layer M_2 blocked
- Layer M_1 mobile

Hard-soft architecture

JTM: \( M(H) \leftrightarrow R(H) \)
Hardening: difficult task in 3d FM thin films

(1) Classically
- low K - soft
- large K - soft

- 2 materials ≠K crystalline phase
  Fe(bcc) vs Co(hcp)

- ≠ aspect ratios of FM electrodes
  Complex micromagnetic problems

(2) Exchange biasing
- low K - soft
  F1 →
- RKKY

 Exchange biased SyAF reduces stray-fields and Hard/soft dipolar coupling

Typical Magnetoresistance versus magnetic field

For applications
Beyond static => Complex micromagnetic problems

Dynamic magnetic properties related to fast and homogeneous magnetization switching have to be optimized:

Pillar shape, aspect ratio, FM material, switching mechanisms (field, spin-current/torques, thermal assisted...).

(II) Control of barrier structure

\[ T \propto \exp(-d\sqrt{U}) \]

Control of \( d \)

Control of \( U \)

- Optimisation of buffer layer
  \( \Rightarrow \) small roughness
  *C. Tiusan et al, JAP 85, 5276 (1999)*

- Control of epitaxial growth in epitaxial (single crystal or textured) MTJs

Tunnel cartography

- Homogeneity of tunnel current
  *V. DaCosta, C. Tiusan, T. Dimopoulos, K. Ounadjela, PRL 85, 876 (2000)*
### Polycrystalline MTJs
- Random distribution of crystallographic axes (amorphous barrier)
- \[ \Psi(r) = e^{ikr} \]
- \( \Rightarrow \) Tunnel transport independent of propagation direction

### Single crystal MTJs
- Single crystal electrodes: anisotropy of space
  \( \Rightarrow \) properties dependent of propagation direction
- \( \Rightarrow \) potential: crystal periodicity
- \( \Rightarrow \) beyond the free-electrons model: Bloch waves

### Fully epitaxial systems
- Conservation of symmetry across the stack

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**C. Tiusan et al., Appl. Phys. Lett. 82, 4507, (2003)**

1995 discovery of the TMR effect at RT

The first observation of reproducible, large room temperature magnetoresistance in a CoFe/Al2O3/Co MTJ

Early experiments and models

1. Experiments on spin-dependent tunnelling

Tedrow and Meservey

Measure the spin polarization of the tunnelling current originating from various ferromagnetic metals across an alumina insulating barrier in ferromagnet/insulator/superconductor (FM/I/S) tunnel junctions.

Superconducting Al film which acts as a spin detector

The results of these early experiments on SDT were interpreted in terms of the DOS of the ferromagnetic electrodes at $E_F$.

The inconsistency between measured $P$ and $P_{FM}$

The inconsistency between the experimental and theoretical SP = consequence of the fact that the tunneling conductance depends not only on the number of electrons at the Fermi energy but also on the tunneling probability, which is different for various electronic states in the ferromagnet.
2. **Stearns’ model**

Takes into account features of band structure in tunneling

- **transmission probability** depends on the effective mass which is different for different bands
- **localized d electrons** => large effective mass and therefore decay very rapidly into the barrier region
- **the dispersive s-like electrons** decay slowly

**The nearly free-electron (most dispersive bands) dominate the tunnelling current**

The heavy curves show the free-electron-like bands which dominate tunnelling. $k^\uparrow$ and $k^\downarrow$ are the Fermi wavevectors which determine the spin polarization of the tunnelling current:

$$P_{FM} = \frac{k^\uparrow - k^\downarrow}{k^\uparrow + k^\downarrow}$$

Using an accurate analysis of the electronic band structure, Stearns found that $P_{FM} = 45\%$ for Fe and $10\%$ for Ni, which are consistent with the experimental data

- **Stearns: introduces the notion of TDOS (tunneling density of states)**
  early indication that the understanding of SDT requires detailed knowledge of the electronic structure of MTJs
3. Julliere’s experiments and model

1975, first observation of TMR effect in Fe/Ge/Co MTJ (4.2K)

- Correlates TMR and polarization $P$

Assumptions:
  - two independent current model (up, dn spin)
  - tunneling from DOS up1-up2, dn1-dn2 in $P$
  - and up1-dn2, dn1-up2 in $AP$

$$G_P \propto n_1^\uparrow n_2^\uparrow + n_1^\downarrow n_2^\downarrow$$
$$G_{AP} \propto n_1^\uparrow n_2^\downarrow + n_1^\downarrow n_2^\uparrow$$

$$TMR = \frac{G_P - G_{AP}}{G_{AP}} = \frac{R_{AP} - R_P}{R_P} = \frac{2P_1P_2}{1 - P_1P_2}$$

Consistency between measured SP (Tedrow-Mespervey) and TMR values
4. Slonczewski’s model

First accurate theoretical consideration of TMR

- Tunnelling between two identical ferromagnetic electrodes separated by a rectangular potential
- The ferromagnets described by two parabolic bands exchange splitted

\[ G(\Theta) = G_0 (1 + P^2 \cos \Theta) \]

\[ P = \frac{k^\uparrow - k^\downarrow}{k^\uparrow + k^\downarrow} \frac{\kappa^2 - k^\uparrow k^\downarrow}{\kappa^2 + k^\uparrow k^\downarrow} \]

SP depends on both electrode and barrier

\[ R = f(\cos(\theta)) \]

Additional term depending on barrier attenuation rate

\[ \kappa = \sqrt{(2m/\hbar^2)(U - E_F)} \]
Recent experiments

Angular dependence of TMR

Voltage dependence


Confirms Slonczewski and open area of angular sensors

Intrinsic mechanisms
- barrier decreased by V reduces P (see Slonczewski factor)
- electrode DOS dependence on energy

Extrinsic mechanisms:
- scattering by magnons at FM/I interface
  + other complex mechanisms related to tunneling

Important for applications
Temperature dependence

Co/Al2O3/Co MTJ

P. LeClair, PhD thesis, Univ. Eindhoven

➢ the tunnelling spin polarization $P$ decreases with increasing temperature
due to spin-wave excitations, as does the surface magnetization ($P$ and $M$ follow Bloch $3/2$ law)

$$M(T) = M(0)(1 - \alpha T^{3/2})$$


➢ Spin-flip scattering by magnetic impurities in the barrier (Veydiaev)
➢ Inelastic electron-phonon scattering without spin-flip in the presence of localized states in the barrier (Tsymbal)

+ other complex mechanism (e.g. electronic structure, defect assisted tunneling in realistic barriers, multiple hopping, etc...)

Ferromagnet dependence

- TMR tuned via the FM material nature

<table>
<thead>
<tr>
<th>Junction</th>
<th>TMR (%)</th>
<th>Julliere</th>
<th>Experiment</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ni/Al₂O₃/Ni</td>
<td>25</td>
<td>23</td>
<td></td>
</tr>
<tr>
<td>Co/Al₂O₃/Co</td>
<td>42</td>
<td>37</td>
<td></td>
</tr>
<tr>
<td>Co₇₅Fe₂₅/Al₂O₃/Co₇₅Fe₂₅</td>
<td>67–74</td>
<td>69</td>
<td></td>
</tr>
<tr>
<td>LSMO/SrTiO₃/LSMO</td>
<td>310</td>
<td>1800</td>
<td></td>
</tr>
</tbody>
</table>

- TMR tuned via FM layer crystal orientation

Directly via the tunneling polarization
Various FM materials tested as electrodes:

- Half- and full-Heusler: NiMnSb, Co₂MnSi,
- oxides Cr₂O, Fe₃O₄ perovskites LSMO...

combined with various other barriers
SrTiO₃, CeO₂, ZnO,...

LSMO/STO/LSMO MTJ TMR>100%

Sun J Z 2001 Physica C 350 215

Given the TMR dependence of the DOS of the ferromagnetic electrodes

MTJs with epitaxial electrodes and amorphous barrier

TMR at 2 K as a function of Al₂O₃ thickness for Fe(211), Fe(110), and Fe(100) epitaxial electrodes in Fe/Al₂O₃/CoFe

Barrier and interface dependence

de Teresa et al: the tunnelling spin polarization depends explicitly on the insulating barrier


LSMO as spin analyzer (100% positive SP)
• large inverse TMR (-50%)
  for Co/SrTiO3/LSMO
• Negative spin polarization for Co/SrTiO3
• Positive spin polarization for Co/Al

Polarization (amplitude, sign)
depends on hybridization at FM/I interface

Selection at interface of tunneling electrons
(AI2O3 selects s-like electrons, STO selects d-like electrons...)
Magnetic tunnel junction - Historically

1st generation

**Tunnel magnetoresistance at RT in amorphous Alumina based MTJ:**

Moordera et al, PRL (1995);

Al2O3 age

TMR~40-70%

Best (counterintuitive result) TMR = 70-80%
CoFeB/Al2O3

2nd generation

« Giant » tunnel magnetoresistance at RT in crystalline MgO based MTJ:

Parkin et al, Nature Mat. (2004);

MgO age

TMR~200-500%

Other (oxides) barriers have been checked but less successful
Magnetic tunnel junction - Historically

- **Amorphous / polycrystalline MTJs**

  1995 Moodera, Miyazaki (TMR ~ 20% with amorphous Al₂O₃)
  Bests results: CoFeB/Al₂O₃ (TMR ~ 80%)

- **Single crystal MgO based MTJs**

  2008: Tohoku (H. Ohno): 604% RT (1144% 5K) textured CoFeB/MgO/CoFeB (sputtering)
Why Fe(001)/MgO(001)/Fe(001) epitaxial MTJs

Ideal crystallographic structure

MODEL SYSTEM
Confront QM theory and experiment

Symmetry conservation

Conservation of kII
Single crystal MTJ– underlying physics

Modeling of tunnel transport in single crystal MTJs Fe(001)/MgO(001)/Fe(001)

Conservation of $k_{\parallel}$

Landauer formalism

\[ G = \frac{e^2}{\hbar} \sum_{k_{\parallel},j,i} T(k_{\parallel},j,i) \]

- The tunnel conductivity sums the transmission probability for each ($k_{\parallel}$) channel from the state ($k_{\parallel}; j$) to the state ($k_{\parallel}; i$)
- Each channel defined by a Bloch wave function in (Fe) for a given value of $k_{\parallel}$
  - Bloch wave preserve the symmetry invariance properties of the crystal
- Coherent transport with spin conservation
  - spin independent channels
  (two current model Fert-Campbell)
Tunnel transmission $T(k_{II},l,j)$, for a $k_{II}$ channel matching of the real Fermi Surface of the FM metal with the complex FS of insulator.

The partial conductance $G(k_{II})$ is a direct result of the overlapping of the majority spin surface spectral densities in the two electrodes, exponentially filtered through the MgO barrier.

Majority
Surface spectral density Fe(001)

Complex FS MgO
$\mathcal{g}_m k_{II}(k_x,k_y)$

Large MgO thickness transport « dominated » by $k_{II}=0$ (asymptotic regime)
1. Symmetry filtering within the electrodes

TUNNELING CHANNELS: Selection of Bloch wave functions in Fe

Fe(001): half-metal* % $\Delta_1$
$\Rightarrow P^{\Delta_1} = 100\%$

*Symmetry dependent half metallicity SDHM

But other channels exist:
$\Delta_1, \Delta_5, \Delta_2, \Delta_2'$
and $T(k_{||} \neq 0) \neq 0$
2. Symmetry dependent attenuation rates within the MgO

Large MgO thickness: \( \Delta_1 \) propagation dominates large polarisation, large TMR (> 1000%)

Importance of the asymptotic regime

\[ k_{II}=0 \]

\[ k_z = i \kappa \ (q=0, \text{point } \Gamma) \]

\[ T \sim e^{-2\kappa d} \]

\[ \kappa_{\Delta_1} < \kappa_{\Delta_5} << \kappa_{\Delta_2, \Delta_2'} \]

References:
LKKR:
(1) Complex MBE or UHV sputtering growth

- Various growth sources (e-gun, Knudsen cell, magnetrons)
- Variable growth/in-situ annealing temperature (70-1273K)
- in-situ analysis RHEED, Auger, XPS, photoemission,...

UHV $10^{-11}$ Torr

- High chemical purity of films
- Conservation of spin coherence in CPP transport
Atomic level control of insulator thickness

RHEED feature
Surface –diffraction technique

RHEED Intensity (a.u.) vs. Time (s)

v = 0.089 ml/s

3 ML MgO

Fe

Fe

Courtesy E. Snoek CEMES, Toulouse
(2) UV, EBEAM lithography patterning of MTJ pillars
Giant TMR in Fe/MgO/Fe epitaxial MTJs


Giant TMR ~ 200% (RT), 340% (10K)

JTM Fe/MgO/Fe MTJ
UV, EBEAM lithography

Electron transport physics: beyond the free electron model
TMR amplitude: explained by spin and symmetry dependent transport

AIST MTJs with a single-crystal MgO(001) barrier
Symmetry dependent tunneling—demonstrated by tunneling spectroscopy

\[ \frac{dI}{dV} \propto n(E_F + eV) \]

Configuratie P

Voltage(V)

G/G_p(0)

Spins UP

0.2eV

Top of \( \Delta_5 \) band

Both \( \Delta_1 \) cand \( \Delta_5 \) contribute to tunneling

\( \Delta_5 \) channel activated at low voltages

However, record TMR in sputtered MTJs

TMR limited to 250% (Fe/MgO, 410% Co/MgO)

Epitaxial MTJ

Defects: dislocations

Imperfect filtering:
- multichannel transport
- coherent+diffusive, incoherent

E. Snoek
CEMES, Toulouse


WR 604% RT (1144% 5K)

UHV Sputtered structures Annealed at HT
No disclocations, grain to grain epitaxy

Modulation of tunnel transport in single crystal Fe/MgO/Fe MTJs

Single crystal epitaxial MTJ: model system where theory and experiment meet => QM experiments

MTJ: multi channel transport; channel=[spin, symmetry]

- **FM Emitter:** selects the different $\Delta_i$ injected symmetries
- **Insulator:** filter 
  Symmetry dependent attenuation rate
- **FM Collector:** selects / impose the reception states $\Delta_i$

3 sub-systems coupled by the wave function matching at the interfaces
interface quality/ chemistry, interfacial electronic structure

Strong impact on the tunnel characteristics

By controlling the interfacial structure

Engineering of spin filtering
100% Surface polarization competing with 100% $\Delta_1$ bulk polarization

Bulk electronic structure
$k_{\parallel}=0$ (asymptotic regime)

No up $\Delta_1$ in left electrode at $E_F$

Surface electronic structure (minority spin)

Fe(001) minority spin surf. State:
$\Delta_5$ electrons ($k_{\parallel}=0$)
IRS in ($k_{\parallel} \neq 0$)

Strong contribution of IRS to the Minority spin tunneling

Enhanced magnetoresistance by monoatomic roughness in epitaxial Fe/MgO/Fe tunnel junctions

A. Duluard, C. Tiusan et al,

PHYSICAL REVIEW B 91, 174403 (2015)

Quenching IRS, increases TMR
TUNNELING ANISOTROPIC MAGNETORESISTANCE (TAMR)

Angular dependence of the tunneling resistance attributed to a significant anisotropy in the DOS linked to the magnetization direction along different crystal axes –SOC related


!!! 2nd FM electrode not necessary
Spin-orbit coupling effect by minority interface resonance states in single-crystal magnetic tunnel junctions

SO negligible in 3D FM metals, however large in IRS
If IRS activated = large SO effects in transport


IRS demonstrated by tunneling spectroscopy experiments (see next slide)
By tunneling spectroscopy on probe empty states in the Right electrode (occupied in the L but seeing larger barrier)
Interfacial SO effects at Fe/MgO interface responsible on large PMA

_M. Chsiev et al, PHYSICAL REVIEW B 88, 184423 (2013)_

Anatomy of perpendicular magnetic anisotropy in Fe/MgO magnetic tunnel junctions:

- the origin of the large PMA values is far beyond simply considering the hybridization between Fe-3d and O-2p orbitals

- anisotropy energy is not localized at the interface but it rather propagates into the bulk showing an attenuating oscillatory behavior depending on the orbital character of the state

- The MgO thickness has no influence on PMA, and the PMA oscillates as a function of Fe thickness with a period of 2 ML

Even if SO is small in 3D metals, for some orbitals it can be significant, Lifts degenerancies for some states and affects the occupation and energies !important for anisotropies, transport, etc...
Engineering of the voltage response in single crystal MTJ by interfacial chemistry/electronic structure

Clean Fe/MgO interface

C layer at Fe/MgO interface

Applications: MTJ operated at finite voltage

TMR(V) extremely important

Optimization of the output signal by interfacial structure


• TMR enhancing by eliminating the $\Delta_5$ contribution
  → candidate: \textit{bcc} Co(001)

• Eliminate (reduce) the $\Delta_1$ contribution to have a complete overview of filtering effect in Fe/MgO-based MTJs
  → candidate: \textit{bcc} Cr(001)
Symmetry dependent interfacial barriers

**Concept:**

- **Barrier for \( \Delta_1 \) symmetry**
  - Candidate: \( M = bcc \text{ Cr}(001) \)

\[ \begin{align*}
\text{Cr (001) symmetry dependent barrier (1eV)} & \rightarrow \text{attenuation of } \Delta_1 \\
\end{align*} \]
Layer by layer growth of Cr on Fe: precise control of thickness

Lattice mismatches
- Fe-Cr $\rightarrow$ 1.5%
- Cr-MgO $\rightarrow$ 2.25%
  (rotation 45°)
→ Symmetry conservation

Cr(001) behaves as a metallic tunnel barrier.

Building quantum well structure for $\Delta_1$

Insertion of thin Fe between Cr and MgO

Potential profiles for $\Delta_1$ in parallel configuration (P)

Symmetry dependent quantum well structure for $\Delta_1$ electrons (RT)

Increasing $t_{Fe}$:

- conductivity maxima shifted towards lower voltages
- quantum well states for $\Delta_1$

Polarisation (TMR) amplitude tuning using FeCo alloy bcc electrodes

Preserve bcc(001) symmetry and all filtering properties of MgO(100) but enhance polarization of FM:

adjunction of Co in Fe shift upwards $E_F$, enhances spectral density of majority $\Delta 1$, shifts downwards the minority IRS

**FIG. 1 (color online).** TMR measured at 20 K and 300 K on a series of bcc Fe$_{1-x}$Co$_x$/MgO/Fe$_{1-x}$Co$_x$(001) MTJs grown by MBE.

Textured Fe/MgO/Fe≈
single crystal Fe/MgO/Fe

Textured MTJS grown by MBE

*grain-to-grain epitaxy*

Similar TMR ratios and conductivity vs voltage curves

*A. Duluard, C. Tiusan et al,*

APPLIED PHYSICS LETTERS 100, 072408 (2012)
I. **TMR**: current control via the magnetization configuration

Recall Bauer, Slonczewski torque in half-metals

II. ? Magnetization control via the current

Spin filtering in an ideal FM removes from the current the $\sin \theta \downarrow$ component of the spin angular moment. This is adsorbed by the magnetization, $\Rightarrow$ torque.

**Incident electron**

$|\theta\rangle = \cos \theta \uparrow + \sin \theta \downarrow$

**Torque on magnetization** $\sim \sin \theta$

**Transmission of component** $\uparrow$

**Reflecton of component** $\downarrow$

**Current induced spin transfer torque**
Particle transport

Particle density:

\[ n(r) = \sum_{i, \sigma} \psi_{i\sigma}^*(r) \psi_{i\sigma}(r) \]

Current density:

\[ j(r) = \text{Re} \sum_{i, \sigma} \psi_{i\sigma}^*(r) \hat{\nabla} \psi_{i\sigma}(r) \]

where \( \hat{\nabla} = -(i\hbar/m)\nabla \)

Continuity equation:

\[ \nabla \cdot j + \frac{\partial n}{\partial t} = 0 \]

Spin transport

Spin density:

\[ m(r) = \sum_{i, \sigma, \sigma'} \psi_{i\sigma}^*(r) \mathbf{s}_{\sigma, \sigma'} \psi_{i\sigma'}(r) \]

Spin current density:

\[ Q(r) = \sum_{i, \sigma, \sigma'} \text{Re}\left[ \psi_{i\sigma}^*(r) \mathbf{s}_{\sigma, \sigma'} \otimes \hat{\nabla} \psi_{i\sigma'}(r) \right] \]

where \( \mathbf{s} = (\hbar/2) \sigma \rightarrow \) Vector of Pauli matrices

Continuity equation:

\[ \nabla \cdot Q + \frac{\partial m}{\partial t} = - \frac{\delta m}{\tau_{\uparrow\downarrow}} + n_{\text{ext}} \]

External torques

Spin accumulation
Spin density:

\[ m(\mathbf{r}) = \sum_{i\sigma\sigma'} \psi_{i\sigma}^*(\mathbf{r}) s_{\sigma,\sigma'} \psi_{i\sigma'}(\mathbf{r}) \]

\[ m_x = \frac{\hbar}{2} \sum_i (\psi_{i\uparrow}\psi_{i\downarrow} + \psi_{i\downarrow}\psi_{i\uparrow}) \]

\[ m_y = \frac{\hbar}{2} \sum_i (i \psi_{i\uparrow}\psi_{i\downarrow} - i \psi_{i\downarrow}\psi_{i\uparrow}) \]

\[ m_z = \frac{\hbar}{2} \sum_i (\psi_{i\uparrow}\psi_{i\uparrow} - \psi_{i\downarrow}\psi_{i\downarrow}) \]

Spin current density:

\[ Q(\mathbf{r}) = \sum_{i\sigma\sigma'} \text{Re}[\psi_{i\sigma}^*(\mathbf{r}) s_{\sigma,\sigma'} \otimes \hat{\nabla} \psi_{i\sigma'}(\mathbf{r})] \]

\[ Q_x = \text{Re} \sum_i (\psi_{i\uparrow}^* \hat{\nabla} \psi_{i\downarrow} + \psi_{i\downarrow}^* \hat{\nabla} \psi_{i\uparrow}) \]

\[ Q_y = \text{Re} \sum_i (i \psi_{i\downarrow}^* \hat{\nabla} \psi_{i\uparrow} - i \psi_{i\uparrow}^* \hat{\nabla} \psi_{i\downarrow}) \]

\[ Q_z = \text{Re} \sum_i (\psi_{i\uparrow}^* \hat{\nabla} \psi_{i\uparrow} - \psi_{i\downarrow}^* \hat{\nabla} \psi_{i\downarrow}) \]

Tensor quantity with elements \( Q_{ij}(\mathbf{r}) \) with \( i=x,y,z \) in spin space and \( j=x,y,z \) in real space

\[ \nabla \cdot \mathbf{Q} = \partial_k Q_{ik} \]

Current flows in \( \mathbf{x} \) direction

\[ \begin{cases} Q_{xx} \neq 0 \\ Q_{yx} \neq 0 \\ Q_{zx} \neq 0 \end{cases} \]
General continuity equation (spin+magnetization)

\[ \nabla \cdot Q + \frac{\partial m}{\partial t} = - \frac{\delta m}{\tau^{\uparrow \downarrow}} + n_{\text{ext}} \]

Spin accumulation
\[ \delta m = (|m| - m_{\text{eq}}) \hat{m} \]

All external torques
For example, Landau-Lifshitz-Gilbert torque density:
\[ n_{\text{ext}} = - (g \mu_B / \hbar) m \times B_{\text{eff}} + \alpha \hat{m} \times \dot{m} \]

Current-induced contribution to the torque density

(M. D. Stiles and A. Zangwill, PRB 66 (2002) 014407)
Spin current influences the magnetization dynamics (LLG eq.)

\[
\frac{\partial \mathbf{m}}{\partial t} = -\gamma \mathbf{m} \times (\mathbf{H}_E) + \alpha \mathbf{m} \times \frac{\partial \mathbf{m}}{\partial t} - \gamma b_{\text{damp}} \mathbf{m} \times \mathbf{p} - a_{\text{damp}} \mathbf{m} \times (\mathbf{m} \times \mathbf{p})
\]

Field like term
Spin transfer term

Magnetization manipulation by spin transfer torque

- Magnetization control strategy in STT-RAM and ST-HFO

When a current is applied, the direction of the spin transfer torque is either parallel to the damping torque or antiparallel to it, depending on the sign of the current.
Trajectories of spin-torque-driven dynamics for the magnetization vector $\mathbf{M}$

- For the sign of the current that produces a spin-torque contribution in the same direction as the damping, there are no current induced instabilities in the free-layer orientation. The current increases the value of the effective damping, and $\mathbf{M}$ simply spirals more rapidly back to the $H_{\text{eff}}$ direction.

- For the sign of the current that produces a spin-torque contribution opposite to the direction of the damping (STT=acts as negative damping) => large angle magnetization dynamics excited

=> From steady precession to switch through spin current

Moment in an applied field along $\mathbf{z}$ with no anisotropy

Spin torque effects in MTJs

**MTJ: Experimental request for out-of-equilibrium spin torque analysis**

- \( \text{torque} \sim \exp(-kd) \Rightarrow \) thin barriers required
- \(+ \) high current density \( J \) for stable precession and switching \((10^6 \cdot 10^7 \text{ A/cm}^2)\)

nanometric MTJ pillars required

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**Figure 31.** Cross-sectional TEM image of MgO-TMR read head for HDD with recording density of 250 Gbit/inch\(^2\). (Courtesy of Fujitsu Corporation.)

**Complex patterning (lithographic) issues**
Current driven magnetization switching

First experiments on pillars:
- Cornell (Katine et al, PRL 2000)
- CNRS/Thales (Grollier et al, APL 2001)
- IBM (Sun et al, APL 2002)

MTJ: Out of equillibrium torque

Average $J_c \approx 8 \times 10^5$ A/cm$^2$

typical switching current $MTJ \approx 10^6$A/cm$^2$): target $5 \times 10^5$A/cm$^2$ tailoring materials

with low damping and large polarization (e.g. Heusler)

switching time can be as short as 0.1 ns (Chappert et al)

Applications: STT-MRAM
Switching of reprogrammable devices (example: MRAM)

1) By external magnetic field
*(present generation of MRAM, nonlocal, risk of «cross-talk» limits integration)*

2) «Electronic» reversal by spin transfer from current
*(ST-MRAM: next generation of MRAM, with demonstrations by EVERSPIN, Sony, Hitachi, NEC, etc)*
Spin torque nano-oscillator:
*Spin torque compensates damping*

(a) In-plane magnetized fixed (polarizer) layer and an out-of-plane magnetized free layer. (b) Microwave spectra as a function of d.c. current bias I at zero applied magnetic field.

**Comparison Voltage controlled Oscillator vs Spin Torque Oscillator**

- **Undamped Resonator**
- **Damped Resonator**
- **Auto-Oscillator**
  - Damped Resonator & Energy Feedback
  - Active element to supply external energy and compensate energy losses

Adapted from ursula.ebels@cea.fr

A. Slavin, J. V. Kim et al

Spin Transfer Oscillators (STO) (communications, microwave pilot)

**Future telecommunications:** multi standard / multi band applications require to cover a large range of frequencies using a single device

**VCO’s**
- Limited frequency tuning range (few hundred MHz)
- Large space due to inductances (mm²)
- Long tuning time (µs to ms)

**STO Advantages:**
- Enhance tuning range GHz; direct oscillation in the microwave range (5-40 GHz)
- Agility: control of frequency by dc current amplitude, (frequency modulation, fast switching)
- Fast tuning (ns)
- High quality factor
- Small size (≈ 0.1µm) (on-chip integration)
- Oscillations without applied field

**Remaining challenges:**
- Large Output Power and Small Linewidth
  - Increase of power by synchronization of a large of number N of STO (x N²)

\[ \frac{f}{f \Delta f} \approx 18000 \text{ in point contacts} \]


MgO MTJs with large TMR good candidates
STT experiments without patterned nanopillars

YES: zero bias (equilibrium) torque in continuous MTJ structures with extremely thin barriers

The equilibrium torque determines an effective interfacial exchange coupling (Heisenberg) – $J \cos \theta$

**MTJ: equilibrium (zero bias) torque**

Net charge current \( I = 0 \)
Spin current \( \neq 0 \)

\[
Q_{\alpha\beta}(x,t) = \frac{\hbar}{2im} \left[ \Psi^*(x,t)\sigma_{\beta} \frac{\partial \Psi(x,t)}{\partial x_{\alpha}} - \frac{\partial \Psi^*(x,t)}{\partial x_{\alpha}} \sigma_{\alpha} \Psi(x,t) \right]
\]

\( \alpha = x,y,z \) in spin space and \( \beta = x,y,z \) in real space

\[
\begin{cases}
Q_{xx} = 0 \\
Q_{zz} = 0; Q_{yz} \neq 0
\end{cases}
\]

Vector in the spin space
Direction of \( \mathbf{M}_A \times \mathbf{M}_B \)

The equilibrium torque determines an effective interfacial exchange coupling (Heisenberg) – \( J \cos \theta \)

\( J \) = energy of exchange coupling

Free electrons – asymptotic expression

\[
J = \frac{(U - E_F)}{8\pi^2 d^2} \frac{8k^3}{d^2} \frac{(k^2 - k_\uparrow k_\downarrow)(k_\uparrow - k_\downarrow)^2 (k_\uparrow + k_\downarrow)}{(k^2 + k_\uparrow^2)(k^2 + k_\downarrow^2)} e^{-2kd}
\]

Sign of coupling
AF: \( k^2 < k_\uparrow k_\downarrow \)
F: \( k^2 > k_\uparrow k_\downarrow \)

\[ J.C. \text{ Slonczewski, PRB 39, 6995, (1989).} \]
**MTJ**: equilibrium (zero bias) torque in Fe/MgO/Fe MTJs

Spin current decays exp with $t_{\text{MgO}}$ => **extremely thin MgO required**

**AF Magnetic interactions**

**Heinseberg interfacial coupling**

- **Equilibrium coupling**
  - Signature of torque (nonzero spin current) for zero charge current

Engineering of coupling by interfacial electronic structure (Fe/MgO)

- UHV MBE growth:
  - H applied along easy axis, measured by Kerr and/or VSM

Deposition techniques:
- Fe → Knudsen cell
- MgO → electron gun

Annealed bottom Fe layer
Desposition of Fe islands - variable size (RHEED)
Complete stack

Champ appliqué (Oe)

A. Duluard et al, Oral: EG02
56th Annual MMM, Scottsdale, Arizona
30 Oct-3 Nov 2011
Engineering of coupling by interfacial electronic structure (Fe/MgO)

From SW – modelling => J

- With insulator thickness and coverage

![Graph showing normalized coupling vs Fe on Fe coverage (ML) with different MgO thicknesses.](image)

- Smooth bottom Fe interface (annealed)
- Bottom Fe interface with Fe islands ≠ sizes

A. Duluard et al, Oral: EG02
56th Annual MMM, Scottsdale, Arizona
30 Oct-3 Nov 2011
Main applications of MTJs

**SENSORS**

- Magnetic field, position, Read heads, etc. similar to GMR but...
  
  Tunnel junctions would then offer a superior signal to noise ratio than metal based CIP or CPP sensors.

**DATA STORAGE**

- Unit in magnetic random access memories (MRAM)
  

- Basic element of reprogrammable logic gates
  
  *Johnson IEEE Spectrum 33, (2000).*

- Magnetoresistive sensor for CPP read-heads
  
  *Nakashio J.Appl.Phys.89, 7356 (2001).*

**MICROWAVE APPLICATIONS**

- Microwave detection by Spin-torque diode effect
  
  (DC voltage induced by AC flowing current)
  
  *Tulapurkar A A et al Nature 438, 339, (2005).*

- Microwave emission
  
  negative damping STT in pillars produces M steady precession
  
  *Kiselev S I et al Nature 425 380 (2003).*

*The requirements of the properties, especially the product of resistance and area (R.A) are different for these various applications.*
1. MAGNETIC TUNNEL JUNCTION – Magnetic sensing technologies

Schematics of four generations of magnetic sensing technology

Comparison of Magnetic Sensing Technology Parameters

<table>
<thead>
<tr>
<th>Technology</th>
<th>Hall Effect (mA)</th>
<th>AMR (mA)</th>
<th>GMR (Ω)</th>
<th>TMR (Ω)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Power Consumption (mA)</td>
<td>5 – 20</td>
<td>1 – 10</td>
<td>1 – 10</td>
<td>0.001 – 0.01</td>
</tr>
<tr>
<td>Die Size (mm²)</td>
<td>1 x 1</td>
<td>1 x 1</td>
<td>1 x 2</td>
<td>0.5 x 0.5</td>
</tr>
<tr>
<td>Field Sensitivity (mV/V/Oe)</td>
<td>-0.05</td>
<td>-1</td>
<td>-3</td>
<td>-100</td>
</tr>
<tr>
<td>Dynamic Range (Oe)</td>
<td>~ 10000</td>
<td>~ 10</td>
<td>~ 100</td>
<td>~ 1000</td>
</tr>
<tr>
<td>Resolution (nT/Hz)</td>
<td>&gt;100</td>
<td>0.1 – 10</td>
<td>1 – 10</td>
<td>0.1 – 10</td>
</tr>
<tr>
<td>Temperature Performance (°C)</td>
<td>&lt; 150</td>
<td>&lt; 150</td>
<td>&lt; 150</td>
<td>&lt; 200</td>
</tr>
</tbody>
</table>
2. MAGNETIC TUNNEL JUNCTION – Read Head in HDD

Conventional magnetic storage media – magnetized magnetic grains

Tracks of recording support

B = 25 nm, W = 150 nm, t = 14 nm
Data reading/writing speed: GHz

Inductive element writing

TMR reading element

Conventional magnetic storage media – magnetized magnetic grains

Disk moving direction

>250 Gb/inch$^2$
Future of HDD read heads?

- Areal density above 500 Gbit/inch²
- Areal density above 250 Gbit/inch²

Graph showing MR ratio at RT vs. RA (Ω·µm²) with different regions for CPP-GMR, MgO MTJs, and MTJs with Al-O or Ti-O barrier for HDD read head.
MgO-TMR head for ultrahigh-density HDD

- Commercialized in 2007.
- Density > 250 Gbit/inch<sup>2</sup> achieved.
- Applicable up to 1 Tbit/inch<sup>2</sup>.
3. MAGNETIC TUNNEL JUNCTION — elementary cell of magnetic random access memories (MRAM)

Ferromagnetic electrodes

“Word” lines

“Bit” lines

Tunnel barriers

Low resistance state

High resistance state

R

H

« 0 »

« 1 »

Everspin (Freescale 2006)

2011
Magnetic random access memories (MRAM)

Electric characteristics
- High resistance $\Rightarrow$ low power consumption
- Large $\Delta R \Rightarrow$ high signal/noise
- Perpendicular transport, low mean free path $\Rightarrow$ high integration potential
- Exponential variation of current with voltage, barrier thickness

Magnetic characteristics
- non volatile

Other characteristics
- no mechanic pieces
- stable against radiations

TMR MRAM Promises
- High density of DRAM
- High speed of SRAM
- Low cost memory
- Non destructive read-out
- Radiation Hard
Perpendicular MTJs, basis for STT-MRAM

Thermal stability factor
\[ \frac{E_a}{k_B T} > 40 \] for non volatility

PMA provides
- Large \( H_k \) which ensures thermal stability for scaling below 20nm
- Micromagnetic switching features non dependent on pilar shape/aspect ratio => reproducibility
- Smaller intrinsic threshold current \( I_{c0} \) for current-induced switching proportional to \( E \):

\[
I_{c0} = \alpha \frac{\gamma e}{\mu_B g} M_s H_K V = 2\alpha \frac{\gamma e}{\mu_B g} E
\]

smaller in PMA-MTJ (\( E=E_a \)) than in IPA-MTJ (\( E=E_a+E_{demag}=E_a+4\pi M_s^2 \) = large)
MTJs with FM having PMA

next-generation of high-density non-volatile memory and logic chips with high thermal stability and low critical current for current-induced magnetization switching

Requests for MTJ integration with CMOS in MRAM

- high tunnel magnetoresistance (TMR) ratio over 100%,
- switching current lower than the corresponding transistor drive current
- high thermal stability for sufficient retention time,
- annealing treatment stability at 350–400°C for back end process.

Ta/CoFeB/MgO/CoFeB/Ta p-MTJs with the smallest feature size of 17 nm

Feature size 40nm

TMR=120% RT

Other modern issues

- Electric field effect on anisotropy
  E assisted switching

4. MAGNETIC TUNNEL JUNCTION – Reading sensor in Domain wall devices

- No mechanical moving parts
- Domain walls moved by STT effects
- MTJ reads (0) and (1) by TMR effect

Image: Domain wall devices

Magnetic Race Track Memory

From 2D to 3D memories
Racetrack Memory!

Very compact, low power and low cost
Horizontal racetrack $\rightarrow$ density of Flash memory but much faster and no wear-out
Vertical racetrack $\rightarrow$ density of magnetic hard disk drive but much faster

Magnetic RaceTrack: *A hard disk drive on a chip!*

$\rightarrow$ The future of digital data storage!

$\rightarrow$ An innately three-dimensional technology!
Heusler alloys
- half-metals: large spin polarization (100%)
- low Gilbert damping, important for STT based applications (switching, HFO)

\[
P = \frac{D_\uparrow(E_F) - D_\downarrow(E_F)}{D_\uparrow(E_F) + D_\downarrow(E_F)} = 100\%
\]

TMR in Heusler based MTJs, both AlOx and MgO barriers

Development of the TMR ratio for MTJs with Heusler electrodes

![Graph showing TMR ratio for MTJs with different Heusler electrodes and barriers]

*ZHAOQIANG BAI et al, SPIN 02, 1230006 (2012)*

**However**

small damping = easy M manipulation by STT by large mag-noise
=> necessity to tune damping (i.e. by spin Hall effect)
Modulation of effective damping constant using spin Hall effect

Permalloy/Pt bilayer

FIG. 1. Schematic illustration of SHE-induced EDM. \(J_s\) denotes spin current (density) due to dc inside Pt layer through SHE, which exerts spin transfer torque on magnetization inside FM layer and effectively reduces damping torque. The FMR spectrum can be detected as a dc voltage spectrum with applying an ac through the mixing of the ac and oscillatory change of anisotropic magnetoresistance.

FIG. 2. (a)ST-FMR spectra for various dc’s applied to Py (1.9 nm)/Pt (3.5 nm) sample with \(\theta = 45^\circ\). (b) \(J_{Pt}\) dependence of \(\zeta_{eff}\) and \(\Delta\).

S. Kasai et al, APPLIED PHYSICS LETTERS 104, 092408 (2014)
MTJs with M manipulated by STT of spin currents generated by spin-orbitronic effects

**Spin-Torque Switching with the Giant Spin Hall Effect of Tantalum**


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**Figure A**

- MTJ device schematic
- CoFeB (2.4 nm) / Ta (0.6 nm) / CoFeB (1.8 nm)
- 100 x 350 nm
- 0.1 μm

---

**Figure B**

- Graph showing dV/dl vs. B_{ext} (mT)
- B_{ext} = -3.5 mT

---

**Figure C**

- Graph showing dV/dl vs. I_{DC} (mA)
- I_{DC} range from -1.5 to 1.5 mA

---

**Figure D**

- Graph showing Switching Current vs. Ramp Rate (mA/s)
- Data points for I_{C, AP to P} and I_{C, P to AP}

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Buhrman and Ralph groups, Cornell Univ. Work performed at Cornell NanoScale Facility

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MTJ devices
Thank you !