# Spintronic Technology For Energy-Efficient In Memory Computing

## Part 2 – Spintronic Fundamentals

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# Lecture Outline


1. Brief Introduction
2. Spintronic Fundamentals: From Electron to GMR
3. Spintronic Fundamentals: Magnetization Dynamics
4. Spintronic Fundamentals: STT and LLGS Equation
5. Spintronic Devices and Applications
6. Summary

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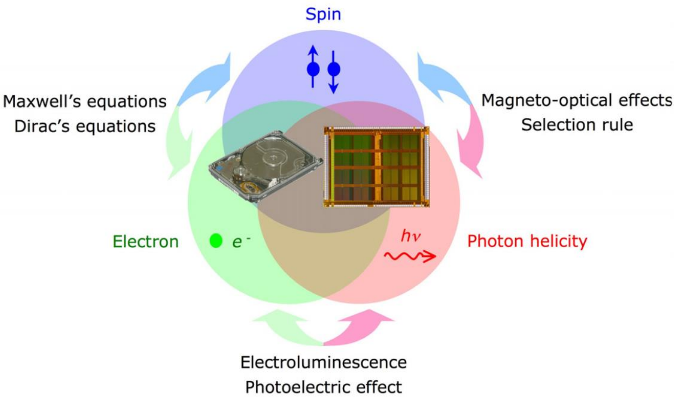
# Spintronics

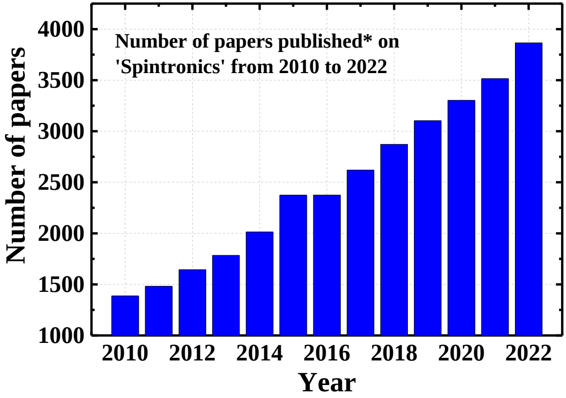
- Spintronics combines three information carriers: electron charge, electron spin, and photon.
- These carriers correspond to the three major fields of information technology:
  1. data processing: it is done through electron transport
  2. data storage: it is achieved through a collection/assembly of electron spins
  3. data transfer: it is accomplished through optical connections




*Source: Hirohata, A., & Takanashi, K. (2014). J. of Physics D: Applied Physics, 47(19), 193001.*

# Spintronics

- **Emerging information technologies require bigger data storage and faster processing**
    - Conventional semiconductor-based memories can not keep with the demand of emerging applications
- Spin-polarized electron transport has emerged as a faster alternative
- The growth of spin transport devices using ferromagnetic and non-magnetic materials has generated a lot of interest among researchers.




*Source: Data obtained from Scopus data base by Esteban Garzón*

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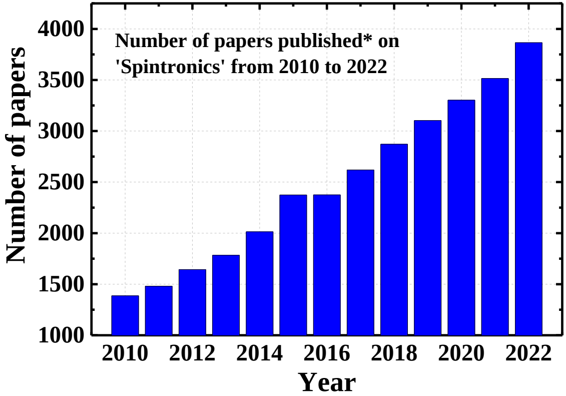


*Source: Data obtained from Scopus data base by Esteban Garzón*

- Building blocks of magnetic memories:
  1. ferromagnetic materials
  2. spin-related phenomena

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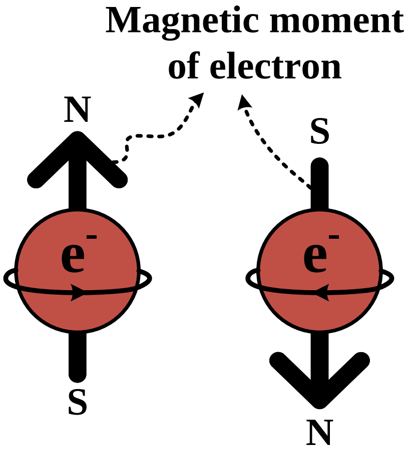
# Electron Spin and Magnetic Moment

- The **electron spin generates** a **magnetic moment** that is opposite to its **spin angular momentum**
  - Spin magnetic moment: $\vec{\mu}$
  - Angular momentum: $\vec{S}$
- Each **electron** can be seen as a **"tiny magnet"** that possesses a small magnetic moment.



# Electron Spin and Magnetic Moment (Cont.)

$$\vec{\mu} = -\frac{g_e \, \mu_B}{\hbar}\vec{S}$$

$$\vec{\mu} = \gamma\vec{S}$$

- $\gamma \rightarrow$ gyromagnetic ratio in [Rad $s^{-1}T^{-1}$]
- $\mu_B \rightarrow$ Bohr's Magneton $\approx 9.27 \times 10^{-24}$ $[\mathrm{A} \cdot \mathrm{m}^2]$
- $g_e \rightarrow$ quantum mechanical electron dimensionless factor
  - $g_e = 2$ for electrons,
  - it depends on the material, e.g., $g_e \neq 2$ in semiconductors

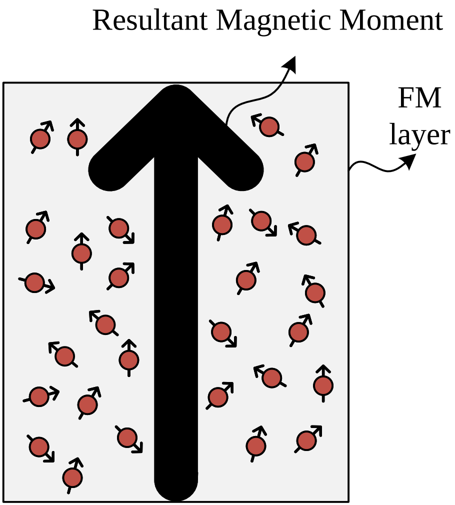
- $\vec{S} = \pm\hbar/2$
  - It quantizes the angular momentum of spin
  - It depends on the orientation of the spin (from clockwise to anticlockwise or vice versa)
  - $\vec{\mu} = -\frac{g_e \, \mu_B}{\hbar}\left(\pm\frac{1}{2}\hbar\right) = \pm\frac{1}{2}g_e \, \mu_B(-1)$

# Magnetization

- Ferromagnetic materials (FM) with incomplete 3d orbitals are widely used in spintronics devices
  - $Mn^{2+}$, $Fe^{3+}$, $Fe^{2+}$, $Co^{3+}$, $Co^{2+}$
- Unpaired orbital electrons have magnetic moments that combine to form a resultant magnetic moment.
- **The net magnetic moment of bounded orbital electrons per unit volume defines the magnetization of an FM layer.**

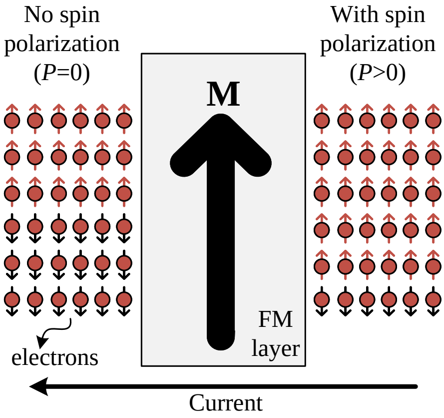
$$\vec{M} = \frac{\sum_{i=1}^{Ne} \vec{\mu_i}}{Volume}$$

  - $\vec{\mu_i}$: individual magnetic moments of bounded electrons
  - $Ne$: total number of orbital electrons



# Magnetization (Cont.)

- Bounded electrons in FM materials exchange magnetic moment with free electrons.
- Spin magnetic moment of free electrons is generated in the direction of bulk magnetization during exchange.
  - Spin filtering
- FM material acts as a filter passing either spin-up or spin-down electrons.
  - The majority of electrons end up with either spin orientation (spin-up in this example)

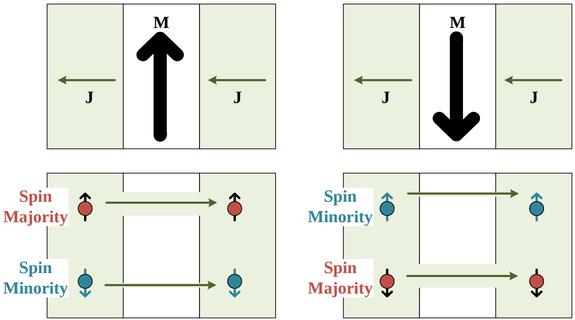


# Spin Polarized Current

- Spin-polarized current ($I_S$) can be defined as:

  $I_S = I_\uparrow - I_\downarrow$
  $I_S = P\, I_C$

  - $I_{\uparrow(\downarrow)}$: current in a material due to electrons with a spin-up (spin-down)
  - $I_C$: electric current resulting from the charge flow through the FM
  - $P$: spin polarization factor of FM
- Note: if $P = 0$, $I_\uparrow = I_\downarrow$
  - non-magnetic (NM) material, which lacks any specific spin orientation among the majority of electrons



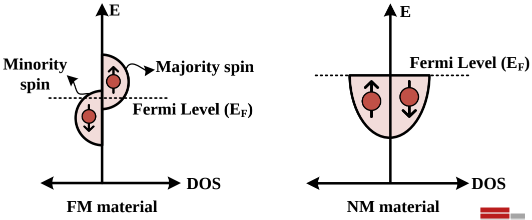
# Energy Bands and Density of States – A Simplified View

- In **FM** the **density of states** (DOS) can exhibit an **asymmetry** due to the spin-splitting of the **energy levels**.
  - larger for one spin direction than the other
  - net magnetic moment ($\vec{M}$) can be attributed to a different population of spin-up and spin-down electrons near Fermi energy level
- In a NM material, the density of states typically exhibits a symmetric distribution around the Fermi level.

- $P$ of a FM can also be written as:

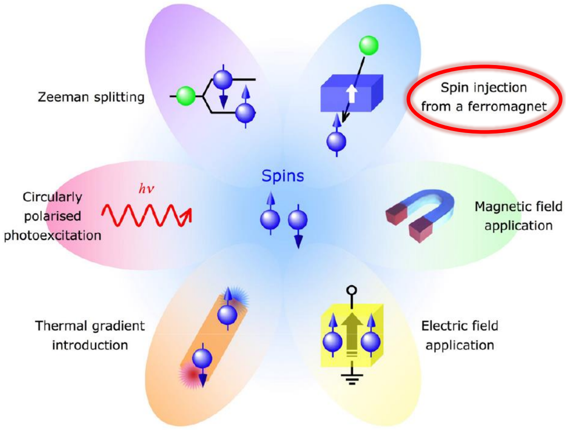
$$P = \frac{N_{\uparrow}(E_F) - N_{\downarrow}(E_F)}{N_{\uparrow}(E_F) + N_{\downarrow}(E_F)}$$

  - $N_{\uparrow}(E_F)$ and $N_{\downarrow}(E_F)$: number of electrons at Fermi energy of spin-up and spin-down orientation, respectively.



# Spin Generation

- Spin-polarized electrons can be generated in non-magnetic materials through various methods including:
  - **Spin injection from a ferromagnet**
  - Magnetic field
  - Electric field
  - Circularly polarized photoexcitation
  - Thermal gradient
  - Zeeman splitting
- **The most common method is spin injection from a ferromagnetic material attached to a non-magnetic metal or semiconductor**

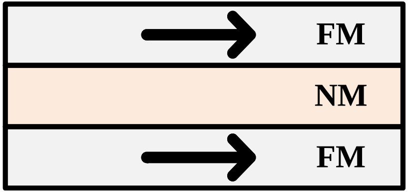



*Source: Hirohata, A., & Takanashi, K. (2014). J. of Physics D: Applied Physics, 47(19), 193001.*

- Spin injection from FM to NM is fundamental for spintronic devices
- Proposed by Aronov in 1976
- Studied by Johnson and Silsbee in 1980s
- Formalisms for spin-dependent injection and transport developed by Valet and Fert in 1993 and Rashba in 2000.

**Albert Fert (Nobel Prize in Physics - 2007)**

- A spin valve is a basic spin-based device that comprises two ferromagnetic (FM) layers and a non-magnetic (NM) spacer layer.
  - The **resistance** of a spin valve can be **changed between** two values by aligning or misaligning the **magnetization orientation of the two FM layers**.
  - The FM layers have different magnetic coercivity levels and are distinguished as a free layer (FL) and a pinned layer (PL).

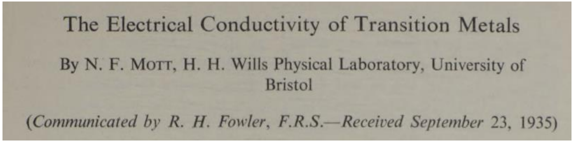


# Understanding the Giant Magnetoresistance Effect in Spin Valves

- **The Giant Magnetoresistance (GMR) effect refers to the phenomenon of resistance change in a spin valve**
  - normalized difference in resistance between parallel ($R_P$) and antiparallel ($R_{AP}$) magnetization configurations of FM layers:

$$GMR = \frac{R_{AP} - R_P}{R_P}$$

- The **GMR effect** is based on the concept of **two-channel theory**, proposed by Mott in 1935-36 (explains the magnetoresistance of a spin valve)



The Electrical Conductivity of Transition Metals

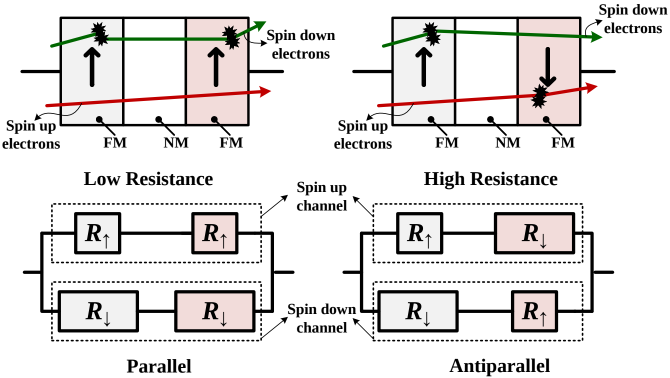
By N. F. Mott, H. H. Wills Physical Laboratory, University of Bristol

(*Communicated by R. H. Fowler, F.R.S.—Received September* 23, 1935)

*Source: N. F. Mott, The Electrical Conductivity of Transition Metals, Proc. Royal Soc. London. A 153, pp. 699-717 (1936)*

# GMR – Two-Channel Theory

- Metal conduction occurs in independent spin-up and spin-down channels
- In FM metal, both channels exhibit different conductivities due to spin-dependent scattering of electrons
- Low probability (high probability) of scattering occurs when electron flowing through FM has spin orientation similar (different) to magnetization orientation of FM

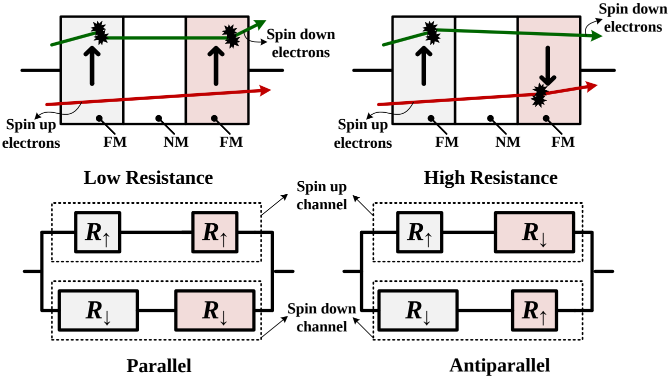


- Resistance is lower when magnetization orientation of two FM layers is parallel.

$$R_P = \frac{2\,R_\uparrow\,R_\downarrow}{R_\uparrow + R_\downarrow}$$

- Resistance is higher when magnetization orientation of two FM layers is in antiparallel.

$$R_{AP} = \frac{R_\uparrow + R_\downarrow}{2}$$



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- The ratio of the spin magnetic moment ($\vec{\mu}_S$) to its spin angular momentum ($\vec{S}$) is referred to as the gyromagnetic ratio

$$\vec{\mu}_S = -\gamma\,\vec{S} \qquad (1)$$

- "The equation for the rotational motion of a rigid body in classical mechanics:"

$$\frac{d\vec{L}}{dt} \rightarrow \frac{d\vec{S}}{dt} = \vec{\tau} \qquad (2)$$

- $\vec{L}$: is the angular momentum of the body
- $\vec{\tau}$: is the torque on an electron
- When an external magnetizing field ($\vec{H}$) is applied:

$$\vec{\tau} = \frac{d\vec{S}}{dt} = \left(\vec{\mu}_S \times \vec{H}\right) \qquad (3)$$

- Using (1) and (3):

$$\frac{d\vec{\mu}_S}{dt} = -\gamma\left(\vec{\mu}_S \times \vec{H}\right) \tag{4}$$

- From a macroscopic point of view, the total magnetization $\vec{M}$ is defined as the sum of the individual magnetic moments per unit volume. Rewriting (4):

$$\sum_{i=1}^{N} \frac{d\vec{\mu}_{S,i}}{dt} = -\gamma\left(\sum_{i=1}^{N} \vec{\mu}_{S,i}\right) \times \vec{H}$$

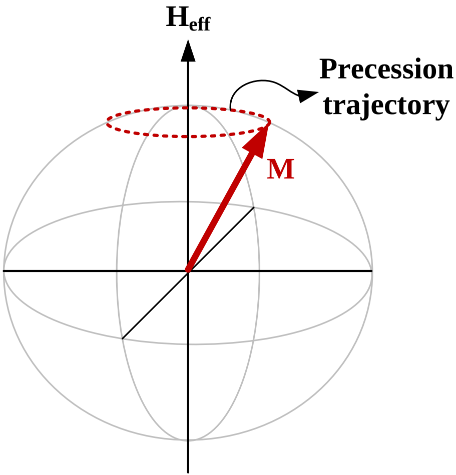
- Now we can define the **precessional motion** (a.k.a **gyromagnetic precession**)

$$\frac{d\vec{M}}{dt} = -\gamma\left(\vec{M} \times \vec{H}\right) \tag{5}$$

- Note: considering all fields (internal and external)

$$\frac{d\vec{M}}{dt} = -\gamma\left(\vec{M} \times \vec{H}_{eff}\right) \tag{6}$$

- Example: simplified (not a complete picture) dynamics of the of the gyromagnetic precession of magnetic moment $\vec{M}$ around the effective magnetic field $\vec{H}_{eff}$



- Previous gyromagnetic pression equation **incomplete in explaining magnetization dynamics**

$$\frac{d\vec{M}}{dt} = -\gamma\left(\vec{M} \times \vec{H}_{eff}\right)$$

- Shown in the 1950s: The magnetization, $\vec{M}$, returns to its equilibrium when no field, $\vec{H}_{eff}$, is applied.
- Precession angle decreases to zero at equilibrium, aligning $\vec{M}$ with $\vec{H}_{eff}$

- To explain this phenomenon, Lev Landau and Evgeny Lifshitz introduced the damping term (DLL):

$$\vec{D}_{LL} = -\frac{\alpha_{LL}}{M_S}\vec{M} \times \left(\vec{M} \times \vec{H}_{eff}\right) \tag{7}$$

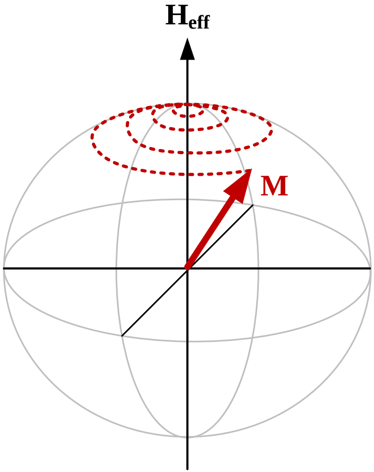
$M_S$: saturation magnetization

$\alpha_{LL}$: Landau-Lifshitz damping coefficient

- We can rewrite the magnetization dynamics including DLL term

$$\frac{d\vec{M}}{dt} = -\gamma_{LL}\left(\vec{M}\times\vec{H}_{eff}\right) - \frac{\alpha_{LL}}{M_S}\vec{M}\times\left(\vec{M}\times\vec{H}_{eff}\right) \quad (8)$$

- This is the Landau–Lifshitz (LL) equation.
- Note: An increased damping should result in a deceleration of magnetization motion



- In 1955, Gilbert introduced an alternative damping term.

$$\vec{D}_G = \frac{\alpha_G}{M_S}\left(\vec{M} \times \frac{d\vec{M}}{dt}\right) \qquad (9)$$

  - $\alpha_G$: Gilbert damping coefficient

- Gilbert equation for magnetization dynamics:

$$\frac{d\vec{M}}{dt} = -\gamma_G\left(\vec{M} \times \vec{H}_{eff}\right) + \frac{\alpha_G}{M_S}\left(\vec{M} \times \frac{d\vec{M}}{dt}\right) \qquad (10)$$

- Two equations:
  - Landau-Lifshitz
  - Gilbert
- Both equations are mathematically equivalent
- **The Gilbert form has been demonstrated to be more precise for a wide number of the damping constants**
  - As a result, the majority of literature considers the Gilbert gyromagnetic ratio

- After some math (cross product of both sides of equation with $\vec{M}$) and simplifications ($\vec{M} \cdot \frac{d\vec{M}}{dt} = 0$), we can obtain:

$$\frac{d\vec{M}}{dt} = - \mid \gamma_{LL} \mid \left( \vec{M} \times \vec{H}_{eff} \right) - \frac{\mid \gamma_{LL} \mid \alpha}{M_S} \vec{M} \times \left( \vec{M} \times \vec{H}_{eff} \right)$$

  - where: $\gamma_{LL} = \gamma / (1 + \alpha^2)$

$$\frac{d\vec{M}}{dt} = - \mid \gamma \mid \left( \vec{M} \times \vec{H}_{eff} \right) + \frac{\alpha}{M_S} \left( \vec{M} \times \frac{d\vec{M}}{dt} \right)$$

- **The simplified magnetization equations of a magnetic moment $\vec{m}$ in presence of torque generating by an external field and damping:**

$$\frac{d\vec{m}}{dt} = -\gamma_{LL}\left(\vec{m} \times \vec{H}_{eff}\right) - \alpha\gamma_{LL}\vec{m} \times \left(\vec{m} \times \vec{H}_{eff}\right) \quad (11)$$

$$\frac{d\vec{m}}{dt} = -\gamma\left(\vec{m} \times \vec{H}_{eff}\right) + \alpha\left(\vec{m} \times \frac{d\vec{m}}{dt}\right) \quad (12)$$

- Note:
  $\vec{M} = \vec{m}\, M_S$
  - $\vec{m}$: unit vector of $\vec{M}$

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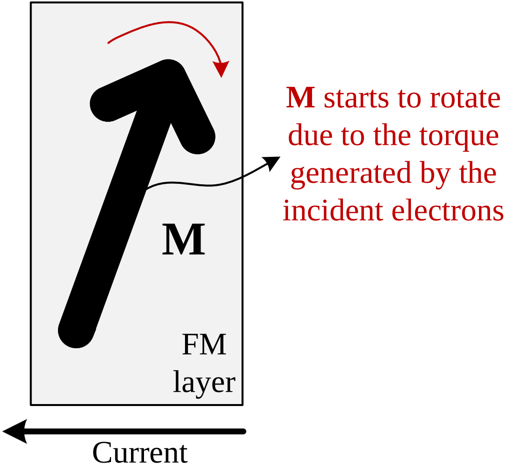
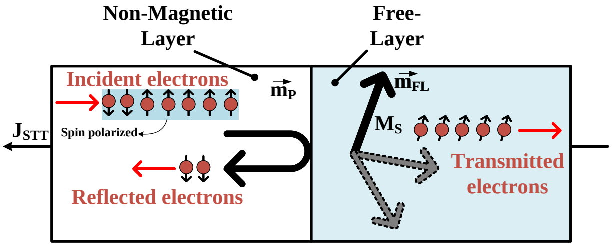
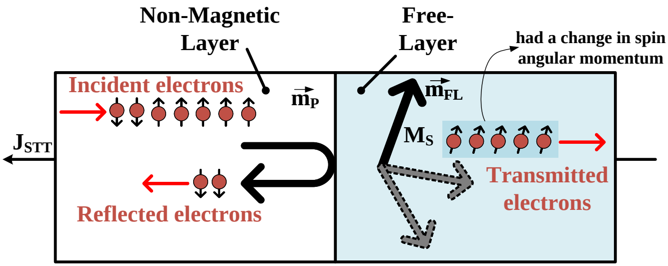
- FM layer serves as a spin filter while also absorbing the spin angular momentum of incident electrons.
- The change in spin angular momentum of the incident electrons $\Rightarrow$ change in spin angular momentum of orbital electrons in an FM.
- Therefore, this change in the orbital electrons acts as a **torque** on the magnetization $\vec{M}$ of the FM layer



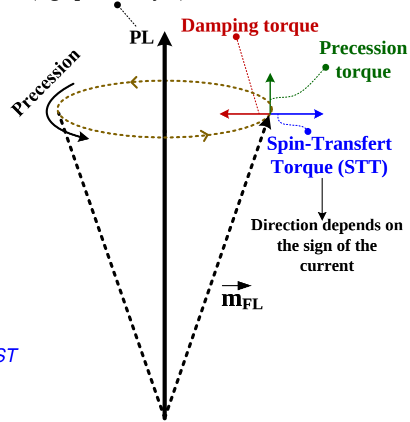
- Consider a single ferromagnetic layer:
  - Free-Layer (FL): can change its magnetization direction under the influence of spin-polarized current.
  - The FL has a saturation magnetization $M_S$ and a unit vector $\vec{m}_{FL}$ that points toward its magnetization direction
- A current density $J_{STT}$ is applied
  - Spin-polarization unit vector of the current represented as $\vec{m}_P$
- **"Scattering"** at the interface of the non-magnetic (NM) layer and FL.



- Transmitted electrons had a change in spin angular momentum
  - During this stage, there is a **transfer of spin angular momentum** between the FL and the incident electrons
- The **change of magnetization direction of the FL** takes place only if there is enough **torque** by the incident electrons.



- The torque acting on the FL is known as **Slonczewski's torque**
  - Slonczewski's torque aids or opposes damping torque to decide FM free layer's magnetization
  - Along with STT torque we have the precession torque, which acts of the precessional motion of the $\vec{m}_{FL}$
  - The torques **only exhibit their effect** when the **magnetization** of the system is in a **non-equilibrium position**.



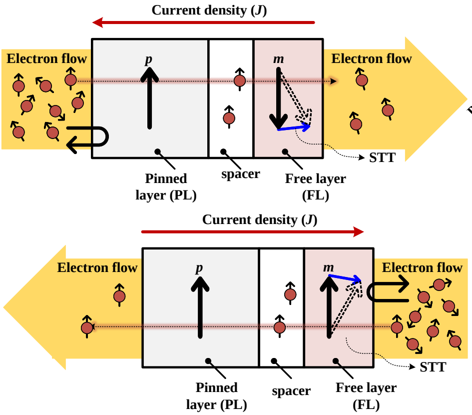

$$\frac{d\vec{m}_{FL}}{dt} = -\gamma_{LL}\left(\vec{m}_{FL} \times \vec{H}_{eff}\right) - \alpha\gamma_{LL}\vec{m}_{FL} \times \left(\vec{m}_{FL} \times \vec{H}_{eff}\right) + \vec{\tau}_{ST}$$

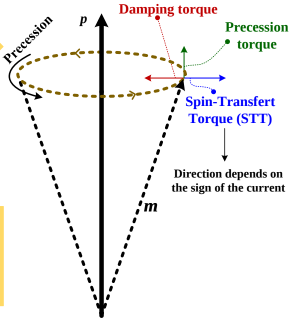
$\vec{\tau}_{ST}$ is the STT term defined as:
$\sigma\, I\, \vec{m}_{FL} \times \left(\vec{m}_{FL} \times \vec{m}_{PL}\right)$

Example of FL magnetization switching: Here

# STT in Multilayers

- Two switching transitions
  - Anti-Parallel (AP) to Parallel (P) – top fig
  - P to AP – bottom fig
- AP→P
  - Current (electron) flow from FL (PL) to PL (FL)
  - "easier" to switch (need less current than P→AP)
- P→AP
  - Current (electron) flow from PL (FL) to FL (PL)
  - "harder" to switch (need more current than AP→P)



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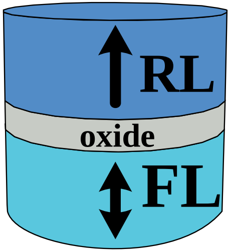
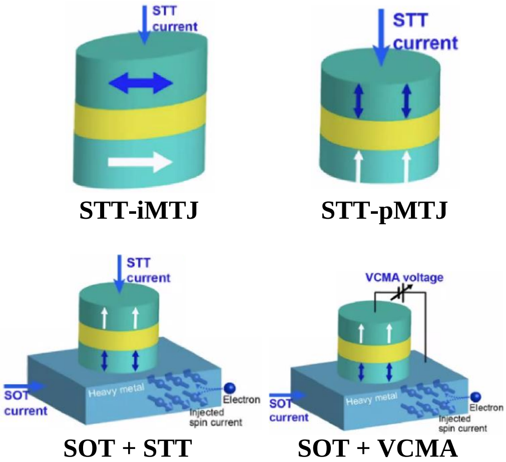
- Magnetic tunnel junction (MTJ): two FMs (RL and FL) separated by an oxide barrier
- Two stable states: parallel (low-resistance) and antiparallel (high resistance)



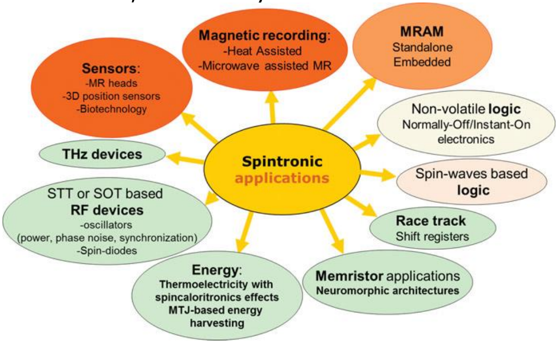




*Source: W. Zhao, "Roadmap for the future MTJs", Beihang Spintronics Interdisciplinary Center. 2021*

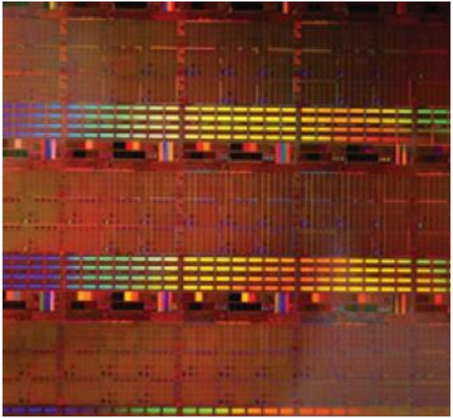
# Spintronic Applications

- Two spintronics roadmaps presented in 2019 and 2020
  - J1. Dieny, Bernard, et al. "The SpinTronicFactory roadmap: A European community view." (2019).
  - J2. Dieny, Bernard, et al. "Opportunities and challenges for spintronics in the microelectronics industry." Nature Electronics 3.8 (2020): 446-459.

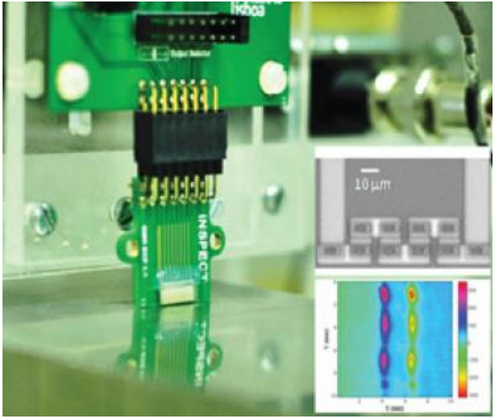
- Spintronics applications:
  - Logic Devices,
  - RF devices,
  - Magnetic Sensors,
  - MRAM, and many more...




*Source: imec, "The SpinTronicFactory roadmap", 2019*

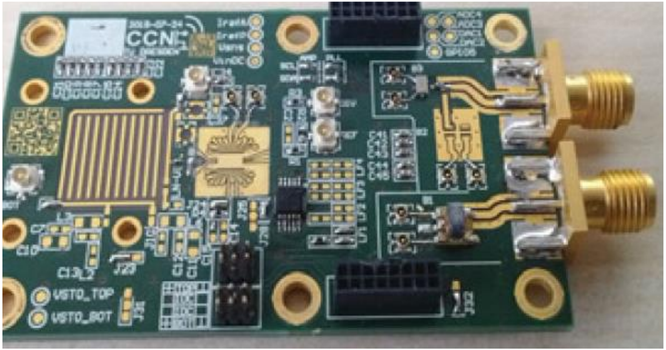


**Integrated circuit exploiting hybrid CMOS/Magnetic technology**

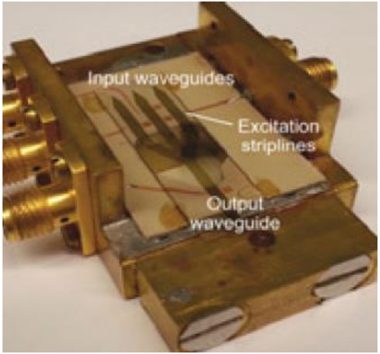



**Array of MTJ sensors for non-destructive testing**

*Source: imec, "The SpinTronicFactory roadmap", 2019*




**PCB board for STT RF emmitters**




**Spin wave majority gate**

*Source: imec, "The SpinTronicFactory roadmap", 2019*

pillars, motivation to MRAM a big phase that states we are focusing to focus on memories!
Four main pillars according to the Spintronics European community view (Here)

**Memories**

Magnetic Sensors

Radio-frequency and microwaves devices

**Logic and non-Boolean devices**

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# Summary

- This Lecture covered the basics of STT and magnetization dynamics.
- Spin-polarized transport through NM materials is explained, including spin polarization, filtering, and injection.
- The mathematical formalism of magnetization dynamics was also introduced
- The LLG equation, magnetization damping, magnetization precession, and STT are explained
- It provides an overview on spintronic devices and applications.
- **Overall, this part provides an overview of the Spintronic fundamentals that serves as a foundation for understanding the remaining of this course.**