SPINTRONICS RESEARCH - Report #2

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Topics discussed in previous session & Potential topics for next session

Previously Discussed Topics:

Spin Orbit Torque, Spin Hall Effect, Timeline of Spin Orbit Torque, Torque Vectors involved in Spin Transfer Torque

Potential Topics for next session: *Half Ferromagnetic Material Band Phenomena, Easy and Hard Axis (Magnetic Anisotropy), Spin Hall Effect, Rashba Effect, Mathematics behind SHE, NHE and other relevant phenomena, Fitting Parameters.*

Session Date: 30th October 2024
Topics in this Report: *Spin Polarization, Spin Filtering, Spin Accumulation, Spin Relaxation, Critical Current, Switching Regimes*

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1. SPIN POLARIZATION

The concept of spin polarization (P) talks about the imbalance between the number of up-spin (N_1) and down-spin (N_2) electrons in a system. The different kinds of polarized systems are as follows:

- In a **completely unpolarized** system, where N1=N2, the polarization is zero, meaning the electron spins are equally distributed between up and down orientations. P is always zero for unpolarized systems.
- In a **polarized** system, N1≠N2, and this difference gives a finite value of P, indicating a preferential spin orientation.
- For a **fully polarized** system, all the electrons have the same spin, either all up-spin (N1=N, N2=0) or all down-spin (N1=0, N2=N), resulting in P=100%.

The same can be represented using the following equation:

$$P = \frac{N_1 - N_2}{N_1 + N_2}\%, \ \text{where } N_1 + N_2 = N$$

[1.01] Spin Polarization in Ferromagnetic and Half Ferromagnetic Materials:

In ferromagnetic materials (like iron Fe, cobalt Co, and nickel Ni), the electron spins are not perfectly aligned. Some electrons have up-spin, and some have down-spin, but there's still a majority of one spin type over the other. This results in partial spin polarization. For example:
• In iron (Fe), around 44% of the spins are aligned, so P=0.44 or 44%.
• In cobalt (Co), P=0.34 or 34%.
• In nickel (Ni), P=0.11 or 11%.
Half-Metallic Ferromagnets (e.g., CrO_2, Fe_3O_4) In special materials called half-metallic ferromagnets, something unique happens. These materials have two distinct energy bands for electrons: one for up-spin and one for down-spin. In half-metals, one of these bands is completely empty, while the other (up-spin) is full. This makes them behave like a metal for one spin type (the one with the full band) and an insulator for the other spin type (the empty band). As a result, the material becomes fully spin-polarized because only electrons of one spin type are available to move.

2. SPIN FILTERING

Spin filtering is the process of separating particles based on their spin states. By applying specific techniques, we can allow electrons with one spin orientation to pass through while blocking those with the opposite spin. This separation is useful for creating spin-polarized currents, which are essential for spintronic devices, needed for switching spin states with the help of this current.
It has been found that majority spin electrons are more easily transmitted through ferromagnet than minority spin electrons. This phenomenon is known as the spin filter effect and is characterized by a parameter called spin asymmetry 'A'.
Spin filtering effect or spin asymmetry arises due to this spin-dependent scattering and is defined as:

$$A = (I^{\uparrow} - I^{\downarrow})/(I^{\uparrow} + I^{\downarrow})$$

Here, A is the spin asymmetry, I up arrow is the current contributed by up spin electrons and I down arrow is the current contribution of down spin electrons.

3. SPIN ACCUMULATION

Spin accumulation occurs at the interface between a ferromagnetic (FM) and non-magnetic (NM) material when a specific spin type builds up in the NM layer due to spin injection from the FM layer.

Mechanism:
- In FM materials the majority spin (up-spin) electrons dominate, carrying most of the current into the NM layer.
- This results in an excess of up-spin electrons near the FM/NM interface, creating a net magnetic moment in the NM layer.

Non-Equilibrium Phenomenon:
- Spin accumulation is temporary and decays due to spin-flip scattering.
- Over distance, spins reach equilibrium in the NM layer, balancing up-spin and down-spin populations.

Spin Accumulation Length:
- Defined as the distance over which the accumulated spin decays to 1/e of its initial magnitude at the interface.
- Typically characterized by exponential decay

$$e^{-x/\lambda_{sd}}$$

Above is the equation for decay of spin accumulation. Here is the λsd spin accumulation length, x is the distance from spin injection point

Forces at work:
- Drift: Movement of spins under an applied electric field.
- Diffusion: Spread of spins from high to low concentration areas.
- Spin-Flip Scattering: Conversion of spins, driving the system toward equilibrium.

Steady State:
- Spin accumulation reaches a steady state when spin diffusion balances spin relaxation (loss of spin identity).

4. SPIN RELAXATION

Spin relaxation is the process by which electron spin polarization loses its alignment over time due to stochastic processes (random phenomena), leading to depolarization. This is critical in spintronics as it impacts data reliability.

Causes of Spin Relaxation:
Environmental Magnetic Fields: Effective magnetic fields in a solid can affect electron spin.

Sources:
- 1. Spins of nearby electrons or holes.
- 2. Nuclear spins within the material.
- 3. Phonons or atomic vibrations, creating fluctuating magnetic fields.
- 4. Spin-Orbit Interaction: Interactions between an electron’s spin and its orbital motion within the solid.

Mechanism:
If an electron's spin isn’t aligned with the effective magnetic field Beff, it precesses around Beff at a frequency:

$$\Omega_{eff} = g.\mu_B.B_{eff}$$

This process is known as Larmor precession. With time, the spin orientation changes due to precession.

Randomization of Effective Magnetic Field:
As electrons move, they encounter varying effective magnetic fields due to changes in velocity. This causes random shifts in precession axis and frequency, leading to gradual and unpredictable spin changes over time in a process termed spin relaxation.

Spin Flip: When an electron’s spin flips between "up" and "down" states due to a strong magnetic interaction, this shift is called a spin flip. A scatterer with an internal magnetic field couples the up-spin and down-spin states, facilitating the spin flip.

5. CRITICAL CURRENT – Mathematical Overview

This equation calculates the critical current, IC0, which is the minimum amount of current required to switch the magnetic state of a magnetic layer in an STT-based memory device. It tells us how much current is needed to "push" the magnetization enough to flip its direction.

• **α** - Damping Constant: This term represents energy loss in the magnetic material. Higher alpha means more "friction" in the magnetic motion, making it harder to switch the magnetization, which means a higher critical current is required.

• **γe/μBg**- Combined Constants Related to Spin and Magnetism.

• γ: Gyromagnetic ratio. This tells us how fast magnetization responds to an applied magnetic field.
• e: Charge of an electron. It's a fundamental constant.
• μB: Bohr magneton, which is a unit of magnetic moment for an electron.
• g: Lande factor: This value represents how effectively the current's spin aligns with the magnetization direction.

• **Ms** - Saturation Magnetization: This term represents the maximum magnetic strength of the material. Higher Ms means the material has a stronger magnetization, which generally requires more current to switch.

• **Hk** - Anisotropy Field: This is the internal "locking" magnetic field that keeps the magnetization in a specific direction. If this field is strong, it means the magnetization is more stable and harder to switch, so more current is required.

• **V**- Volume of the Free Layer: This represents the size of the magnetic layer being switched. A larger volume requires a larger current to switch the magnetization because more magnetic material needs to be influenced.

In simple terms, this equation shows that the critical current, IC0 depends on:
• The damping (α): More damping means higher current is needed to overcome magnetic "friction".
• Material Properties (Ms and Hk): Stronger magnetic properties or a more stable magnetic state requires more current.
• Layer Size (V): Bigger layers need more current to be switched.

6. SWITCHING REGIMES – Mathematical Explanation to Magnetization Dynamics Torques

There are 3 Switching Regimes which can help us understand the behavior of DT (damping torque), FLT (Field Like Torque), STT (Spin Transfer Torque) from a mathematical perspective, which are as follows:

1. **PS – Precessional Switching**
   • Condition: $\tau < 3$ns
   • Indicated by equation 17.
   • PS occurs when current density J exceeds Jc0, leading to fast magnetization reversal

2. **DR – Dynamic Reversal**
   • Condition: 3ns $< \tau <$ 10ns
   • Indicated by equation 19.
   • DR is a transition state/regime between PS and TA

3. **TA – Thermal Activation**
   • Condition: $\tau >$ 10ns
   • Indicated by equation 18.
   • If J<Jc0, thermal activation can still induce reversal but it is slower switching process

$$J_{c,PS}(\tau) = J_{c0} + \frac{Cln\left(\frac{\pi}{2\theta}\right)}{\tau} \quad \text{for } (\tau < 3ns), \qquad (17)$$

$$J_{c,TA}(\tau) = J_{c0}\left(1 - \frac{k_B T}{E_b}\ln\left(\frac{\tau}{\tau_0}\right)\right) \quad \text{for } (\tau > 10ns), \qquad (18)$$

$$J_{c,DR}(\tau) = \frac{J_{c,TA}(\tau) + J_{c,PS}(\tau)\exp(-A(\tau - \tau_c))}{1 + \exp(-A(\tau - \tau_c))} \quad \text{for } (3\,ns < \tau < 10\,ns). \qquad (19)$$

KEY PARAMETERS:
• Jc0: Baseline critical current density required for switching.
• τ: Width of the write current pulse.
• θ: Angle between FL and RL, which impacts STT effectiveness.
• kBT: Thermal energy component; more significant in the TA regime.
• A, C, τc : Fitting parameters used to model the transition between PS and TA.

Switching Regimes and their torque vectors:

1. *PS - Precessional Switching* (STT Dominates)
   • In the PS regime, as J> JC0, spin-transfer torque (STT) dominates. STT is responsible for transferring spin angular momentum from the current to the magnetic layer, causing magnetization reversal. When current density J exceeds a critical current density Jc0, STT is greater than DT and provides the energy needed to switch the magnetization quickly, within a few nanoseconds.
2. *DR - Dynamic Reversal*
   • DR is a transitional regime where both STT and DT contribute to magnetization reversal, with field-like torque (FLT) helping stabilize the intermediate switching. DR uses a combination of PS and TA effects. The equation is a combination of both PS and TA equations.
3. *TA - Thermal Activation* (DT Dominates)
   • In the TA regime, damping torque (DT) primarily affects magnetization. DT aligns the magnetization in the direction of an external field or the reference layer. If the current density J is below Jc0, DT causes magnetization reversal through thermal fluctuations rather than by direct STT.