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Magnetoelectronic Circuits:
Torque, Pumping, and Noise

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Outline

– Single Ferromagnet Dynamics
– Spin-transfer Torque
– Spin-pumping
– Johnson-Nyquist Noise
– Magnetization Noise
– Conclusions

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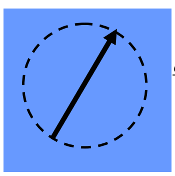
Single Ferromagnet Dynamics



$$\frac{\partial \vec{m}}{\partial t} = -\gamma \vec{m}\times \vec{H}_{\text{eff}} + \alpha^{(0)}\vec{m}\times\frac{\partial\vec{m}}{\partial t} - \gamma\vec{m}\times\vec{h}^{(0)}(t)$$

$\vec{H}_{\text{eff}}$: Effective magnetic field
$\alpha^{(0)}$: Gilbert damping constant
$\vec{h}^{(0)}(t)$: fluctuating magnetic field

Fluctuation-dissipation theorem:

$$\left\langle h_i^{(0)}(t)\, h_j^{(0)}(t')\right\rangle = 2k_B T\,\frac{\alpha^{(0)}}{\gamma M}\,\delta_{ij}\,\delta(t-t')$$

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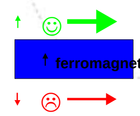
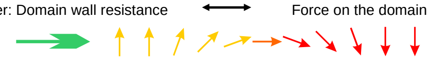
Spin-transfer Torque

Spin-dependent resistance in ferromagnets:

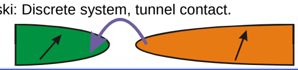


Cause and effect, Newton's third law:

L. Berger: Domain wall resistance ⟷ Force on the domain wall



J. Slonczewski: Discrete system, tunnel contact.



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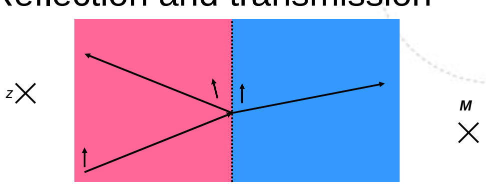
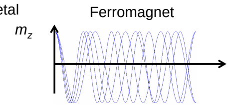
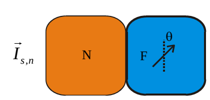
Reflection and transmission





Transverse spin-dephasing length

Spin-transfer Torque



Incoherence in ferromagnet
$\exp(ik_\uparrow^F x) \quad \exp(ik_\downarrow^F x)$
$\vec{I}_{s,f} = \vec{m}\left(\vec{I}_{s,n}\cdot\vec{m}\right)$

Interface: Conservation of angular momentum:

$$\left(\frac{\partial \vec{M}}{\partial t}\right)_T = -\frac{g^*\mu_B}{e}\vec{\tau}$$

Spin-torque transferred to ferromagnet

$$\vec{\tau} = \vec{I}_{s,n} - \vec{m}\left(\vec{I}_{s,n}\cdot\vec{m}\right) = I_{s,n}\vec{m}\times\left(\vec{i}_s\times\vec{m}\right) \qquad \vec{I}_{s,n} = I_{s,n}\vec{i}_s$$

Spin-transfer torque is an interface phenomen.

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Magnetization Dynamics

Single domain ferromagnet:

$$\frac{\partial \vec{m}}{\partial t} = -\gamma \vec{m} \times \vec{H}_{\text{eff}} + \alpha^{(0)} \vec{m} \times \frac{\partial \vec{m}}{\partial t} - \gamma \vec{m} \times \vec{h}^{(0)}(t)$$

Slonczewski

Spin-current driven single domain ferromagnet:

$$\frac{\partial \vec{m}}{\partial t} = -\gamma \vec{m} \times \vec{H}_{\text{eff}} + \alpha^{(0)} \vec{m} \times \frac{\partial \vec{m}}{\partial t} - \gamma \vec{m} \times \vec{h}^{(0)}(t) - \frac{g\mu_B}{Me} \vec{m} \times \left(\vec{I}_s \times \vec{m}\right)$$

Current induced magnetization reversal/precession

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Reflection and Transmission

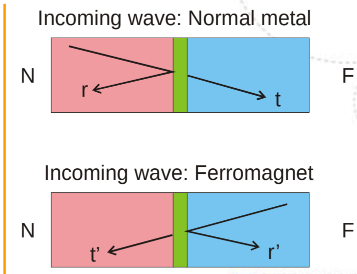
$$\hat{S}_{nm} = \begin{pmatrix} \hat{r}_{nm} & \hat{t}_{nm} \\ \hat{t}_{nm}' & \hat{r}_{nm}' \end{pmatrix}$$

No spin-flip:

$$\hat{S} = S^{\uparrow}\hat{u}^{\uparrow} + S^{\downarrow}\hat{u}^{\downarrow}$$

$$\hat{u}^{\uparrow} = (1 + \vec{\sigma} \cdot \vec{m})/2$$

$$\hat{u}^{\downarrow} = (1 - \vec{\sigma} \cdot \vec{m})/2$$



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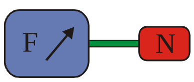
Magnetoelectronic Circuit Theory



V^F $\quad V_c^N$ $\quad \vec{V}_s^N$

Diffusion

$$I_{\uparrow} = G_{\uparrow}\left[\left(V_c^N + \vec{m} \cdot \vec{V}_s^N\right) - V^F\right] \qquad I_{\downarrow} = G_{\downarrow}\left[\left(V_c^N - \vec{m} \cdot \vec{V}_s^N\right) - V^F\right]$$

Particle current

$$eI_0 = \left(I_{\uparrow} + I_{\downarrow}\right)$$

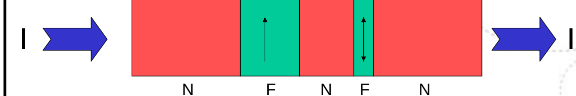
Spin current

Spin-transfer torque

$$\vec{I}_s = e\left(I_{\uparrow} - I_{\downarrow}\right)\vec{m} + 2G_{\uparrow\downarrow}^R\left[\vec{m} \times \left(\vec{m} \times \vec{V}_s^N\right)\right] + 2G_{\uparrow\downarrow}^I\left[\vec{m} \times \vec{V}_s^N\right]$$

Mixing conductance : $G_{\uparrow\downarrow} = \frac{e^2}{h}\sum_{nm}\left[\delta_{nm} - r_{nm}^{\uparrow}\left(r_{nm}^{\downarrow}\right)^*\right]$

Macrospin Excitations



(Mostly) Macrospin Excitations in Spin Valves:

- Cornell: Science 307, 228 (2005), Nature 425, 380 (2003), Science 285, 867 (1999).
- NYU/IBM: PRL 91, 067203 (2003).
- Lausanne: EPL 45, 626 (1999).
- MSU: APL 84, 1516 (2004), PRL 91, 146803 (2003), Nature 406 (2000), PRL 80, 4281 (1998).

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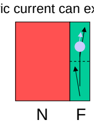
Spin-wave Excitation

- Polianski and Brouwer: PRL 92, 026602 (2004):
  - An unpolarized electric current can excite a spin-wave instability.



- Spin-wave Excitations in Single Ferromagnetic Layers
  - Johns Hopkins: PRL 90, 106601 (2003).
  - NYU/IBM: PRL 93, 176602 (2004).
- **Macrospin and Spin-Wave Excitations in Spin Valves**
  - **NYU/IBM: PRB 71, 140403 (2005), cond-mat/0509034.**
  - **Cornell: PRB 72, 064430 (2005).**

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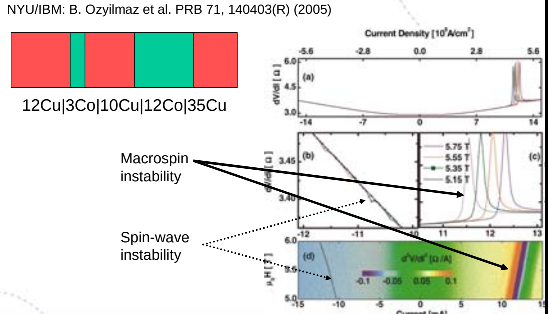
NYU/IBM experiments

NYU/IBM: B. Ozyilmaz et al. PRB 71, 140403(R) (2005)



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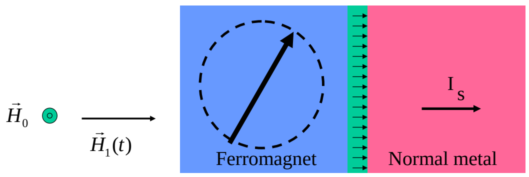
Ferromagnetic Resonance

Rotating magnetization direction: $\vec{m}(t)$

Static magnetic field: $\vec{H}_0$ Rotating magnetic field : $\vec{H}_1(t)$



Silsbee, Janossy, Monod, Hurdequint, Berger

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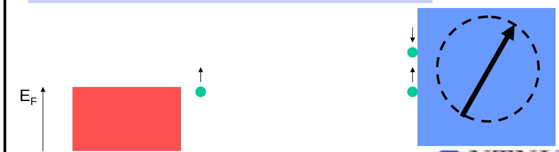
Spin Pumping

$$\vec{I}_s^{\text{pump}} = \frac{\hbar}{4\pi} g_r^{\uparrow\downarrow} \vec{m} \times \frac{\partial \vec{m}}{\partial t}$$

Extreme precession limit $\vec{m} = \hat{x}\cos\omega t + \hat{y}\sin\omega t$ $e\vec{I}_s^{\text{pump}} = \left(\frac{\hbar}{2}\right) N_{\text{trans}} \left(\frac{\hbar\omega}{e}\right)$



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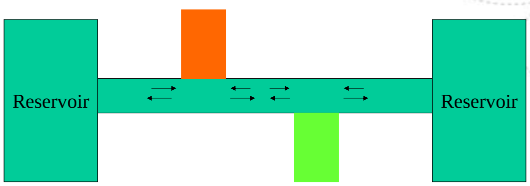
Adiabatic Pumping



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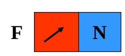
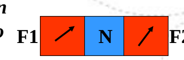
Spin Pumping



Magnetization precession induces spin-current into normal metal



1) No spin-dissipation in N

Spin-battery
Phys. Rev. B 66,060404(R) (2002)

2) Spins relax in N

Enhanced Gilbert damping
Phys. Rev. Lett. 88, 117601 (2002)

3) Spins relax in F2

Angular-dependent Gilbert damping
Phys. Rev. B 67, 140404(R) 2003

4) Spin transfer between F1 and F2

Acoustic and optical modes.
Phys. Rev. Lett. 90, 187601 (2003)

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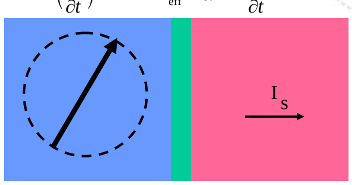
Ferromagnetic Resonance

$$\left(\frac{\partial \vec{m}}{\partial t}\right) = -\vec{m} \times H_{\text{eff}} + \alpha \vec{m} \times \frac{\partial \vec{m}}{\partial t}$$



α is *enhanced* in thin films $\alpha = \alpha^{(0)} + \alpha'$

$$\alpha' = \frac{g_L A_r}{4\pi M}, \qquad A_r = \frac{1}{2}\sum_{nm}\left[\left|r_{nm}^{\uparrow} - r_{nm}^{\downarrow}\right|^2 + \left|t'^{\uparrow}_{nm} - t'^{\downarrow}_{nm}\right|\right]$$

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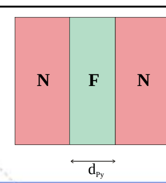
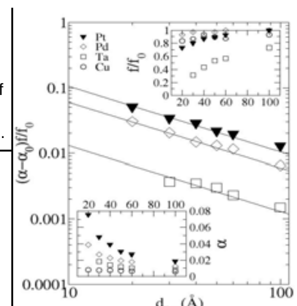
Theory Versus Experiments

- Exp: S. Mizukami, Y. Ando, T. Miyazaki
- Measure Ferromagnetic Resonance Linewidth vs. width of ferromagnet
- Also see exp. by B. Heinrich et al.





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Noise

- Isolated ferromagnet:

$$\frac{\partial \vec{m}}{\partial t} = -\gamma \vec{m} \times \vec{H}_{\text{eff}} + \alpha^{(0)} \vec{m} \times \frac{\partial \vec{m}}{\partial t} - \gamma \vec{m} \times \vec{h}^{(0)}(t)$$

- Ferromagnet in contact with normal metals:
  - ⇨ Spin and charge current fluctuates
  - ⇨ Spin torque fluctuates
  - ⇨ Magnetization fluctuates

$$h(t) = h^{(0)}(t) + h^{(1)}(t)$$
$$h^{(1)}(t) = ?$$

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Thermal Noise

- Described by a new random field

$$\left\langle h_i^{(\text{th})}(t) h_j^{(\text{th})}(t') \right\rangle = 2k_B T \frac{\alpha_{\text{pump}}}{\gamma_0 M} \delta_{ij} \delta(t - t')$$

- Effective field

$$h(t) = h^{(0)}(t) + h^{(\text{th})}(t)$$

- Enhanced noise associated with enhanced damping

$$\alpha = \alpha_0 + \alpha_{\text{pump}}$$

- Fluctuation-dissipation theorem satisfied

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Spin Shot Noise

- New random field

$$\left\langle h_i^{(sh)}(t) h_j^{(sh)}(t') \right\rangle = \frac{\hbar}{4\pi} \frac{e|V|}{M^2} [Tr(r_\uparrow r_\uparrow^\dagger t_\downarrow^{'} t_\downarrow^{'\dagger}) + Tr(r_\downarrow^{'} r_\downarrow^{'\dagger} t_\uparrow t_\uparrow^\dagger)] \delta_{ij} \delta(t - t')$$

- Shot noise vs. thermal noise:

  Crossover at $T \sim 10$ K

- Violation of fluctuation-dissipation theorem

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Conclusions

- Magnetoelectronic Circuit Theory
  - PRL 84, 2481 (2000).
- Spin-transfer Torque
  - Cond-mat/0602151, to be published in Physics Reports
  - PRB RC 65, 220401 (2002).
- Spin-pumping
  - Rev. Mod. Phys. 77, 1375 (2005).
  - PRL 90, 187601 (2003),.
  - PRL 88, 117601 (2002);
- Magnetization 2003Noise
  - PRL 95, 016601 (2005).
- Spin-waves:
  - cond-mat/0501672

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Adiabatic Spin Pump

2x2 current due to adiabatic change of parameter *X(t)*

$$\hat{I}^{\text{pump}}(t) = e \frac{\partial \hat{n}}{\partial X} \frac{dX(t)}{dt}$$

The emissitivy is

$$\frac{\partial \hat{n}}{\partial X} = \frac{1}{4\pi i} \sum_{mn,J} \left(\frac{\partial \hat{S}_{mn,NJ}}{\partial X} \hat{S}_{mn,NJ} - \hat{S}_{mn,NJ} \frac{\partial \hat{S}_{mn,NJ}}{\partial X} \right)$$

There is no pumping of charge. The spin-current is

$$\vec{I}_s^{\text{pump}} = \frac{\hbar}{4\pi} (A_r + A_i \vec{m} \times) \left(\vec{m} \times \frac{d\vec{m}}{dt} \right)$$

$$A_r = \frac{1}{2} \sum_{nm} \left[\left| r_{nm}^\uparrow - r_{nm}^\downarrow \right|^2 + \left| t'^\uparrow_{nm} - t'^\downarrow_{nm} \right|^2 \right]$$

$$A_i = \text{Im} \sum_{nm} \left[r_{nm}^\uparrow \left(r_{nm}^\downarrow \right)^* + t'^\uparrow_{nm} \left(t'^\downarrow_{nm} \right)^* \right]$$

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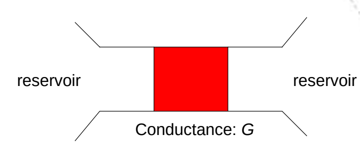
Current Fluctuations



Thermal fluctuations in reservoirs: Equilibrium current fluctuations

$$S^{(c)}(t - t') = \left\langle \Delta I^{(c)}(t) \Delta I^{(c)}(t') \right\rangle$$

Johnson-Nyquist, fluctuation-dissipation theorem

$$S^{(c)}(\omega) = 2k_B TG$$

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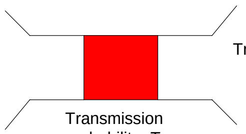
Shot noise

- Reflection



$$S^{(c)}(t-t') = \left\langle \Delta I^{(c)}(t) \Delta I^{(c)}(t') \right\rangle$$

Determinism when *T=0* or *T=1*. ***No shot noise.***

In general (Lesovik, Buttiker)

$$S^{(c)}(\omega) \propto T(1-T)$$

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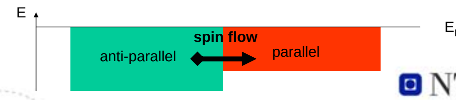
Spin Pumping

Population of spin-up and spin-down bands in equilibrium:

Abruptly reverse the magnetization direction:



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