Spin Torque in Spin Valve Nanopillars, Magnetic Tunnel Junctions and Spin-Orbit-Coupled Heterostructures

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http://wiki.physics.udel.edu/phys824

References

Journal of Magnetism and Magnetic Materials 320 (2008) 1190–1216

Current Perspectives

Spin transfer torques

D.C. Ralph[a,*], M.D. Stiles[b]

Abstract

This tutorial article introduces the physics of spin transfer torques in magnetic devices. We provide an elementary discussion of the mechanism of spin transfer torque, and review the theoretical and experimental progress in this field. Our intention is to be accessible to beginning graduate students. This is the introductory paper for a cluster of "Current Perspectives" articles on spin transfer torques published in volume **320** of the *Journal of Magnetism and Magnetic Materials*. This article is meant to set the stage for the others which follow it in this cluster; they focus in more depth on particularly interesting aspects of spin-torque physics and highlight unanswered questions that might be productive topics for future research.

REVIEW ARTICLES | INSIGHT nature materials
PUBLISHED ONLINE: 23 APRIL 2012 | DOI: 10.1038/NMAT3311

Current-induced torques in magnetic materials

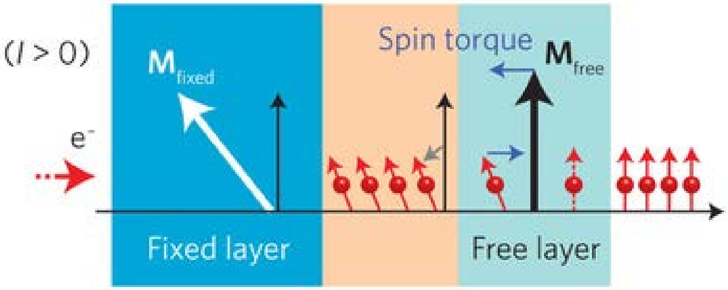
Arne Brataas[1*], Andrew D. Kent[2] and Hideo Ohno[3,4]

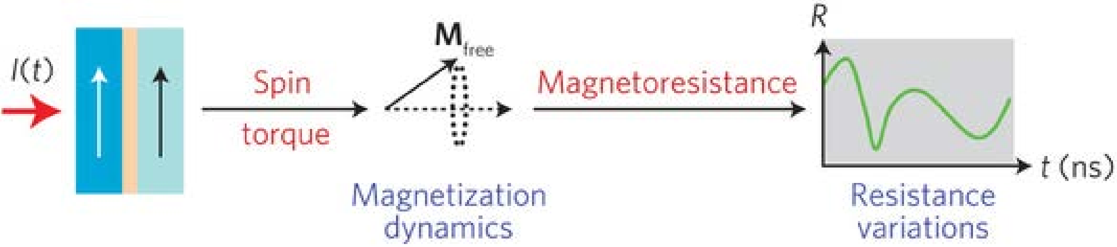
nature materials PROGRESS ARTICLE
PUBLISHED ONLINE: 17 DECEMBER 2013 | DOI: 10.1038/NMAT3823

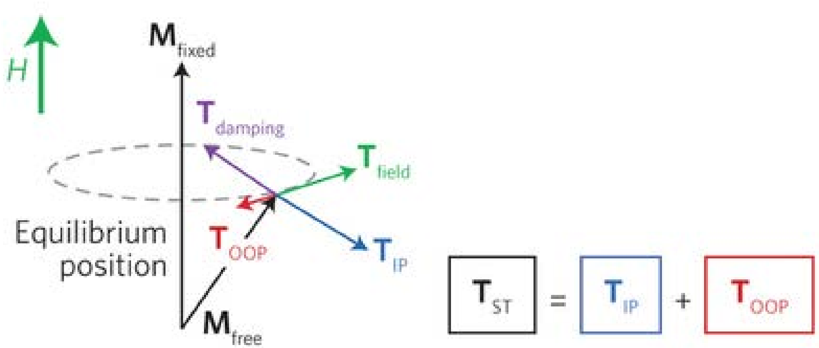
Spin-torque building blocks

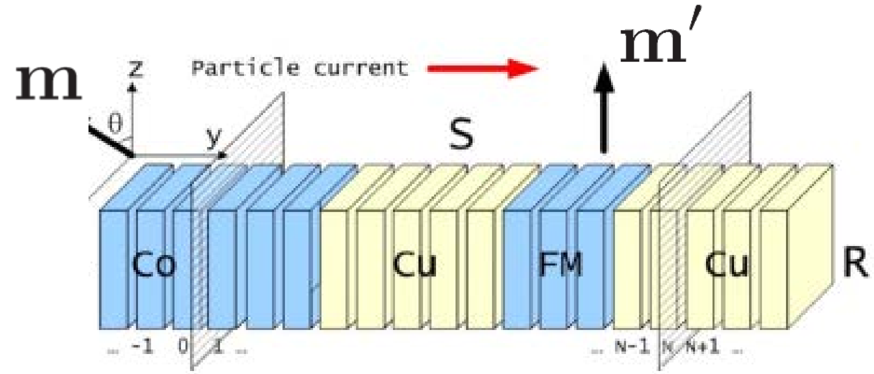
N. Locatelli, V. Cros and J. Grollier*

Spin-Transfer Torque in Pictures and Basic Terminology









$$\mathbf{T} = \mathbf{T}_{\|} + \mathbf{T}_{\perp}$$

$$\mathbf{T}_{\|} = \tau_{\|}\mathbf{m} \times (\mathbf{m} \times \mathbf{m}')$$

$$\mathbf{T}_{\perp} = \tau_{\perp}\mathbf{m} \times \mathbf{m}'$$

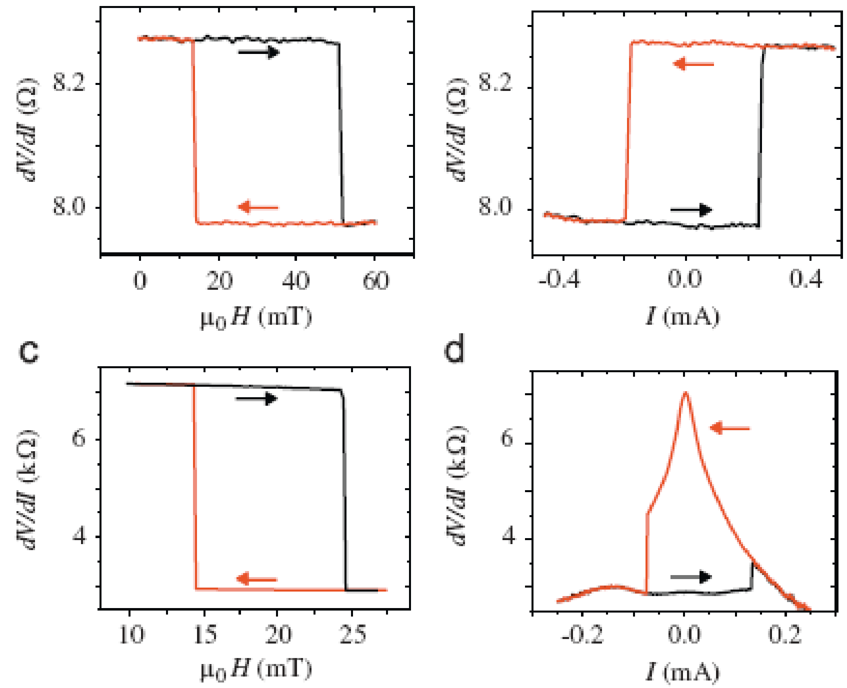
Terminology:

- In-plane or (anti) damping torque
- Parallel or field-like torque

What Are Experimental Manifestations of STT?

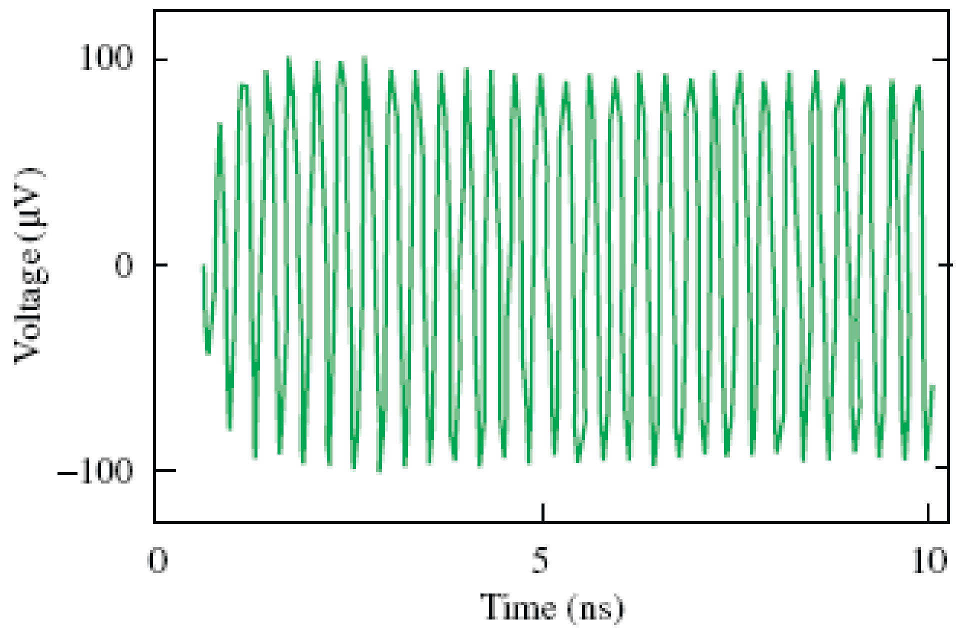
Magnetization Switching:

20 nm $Ni_{81}Fe_{19}$ / 12 nm Cu / 4.5 nm $Ni_{81}Fe_{19}$,

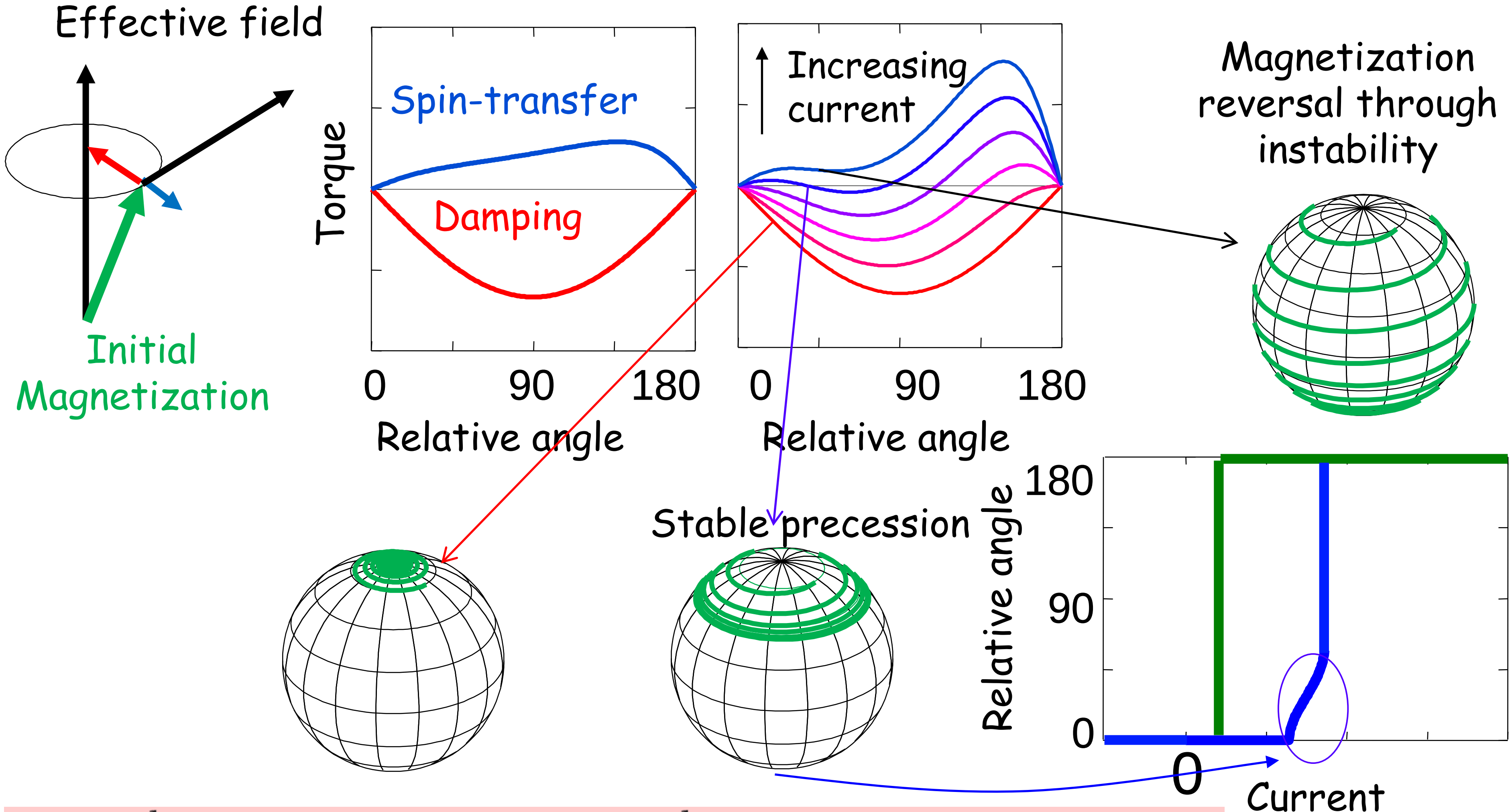


junction nanopillar sample consisting of the layers 15 nm PtMn / 2.5 nm $Co_{70}Fe_{30}$ / 0.85 nm Ru / 3 nm $Co_{60}Fe_{20}B_{20}$ / 1.25 nm MgO / 2.5 nm $Co_{60}Fe_{20}B_{20}$, as the 2.5-nm $Co_{60}Fe_{20}B_{20}$ free layer is re-

Magnetization Precession:



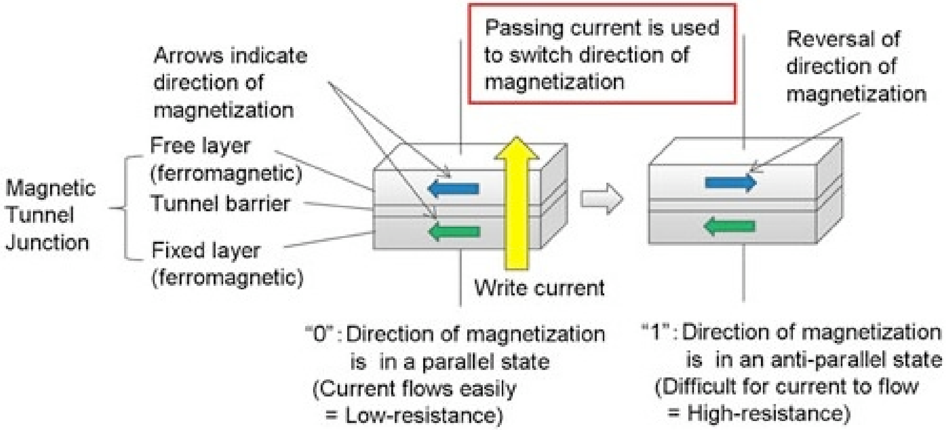
Fast Quantum Electrons Interact with Slow Classical Magnetization Governed by LLG Equation

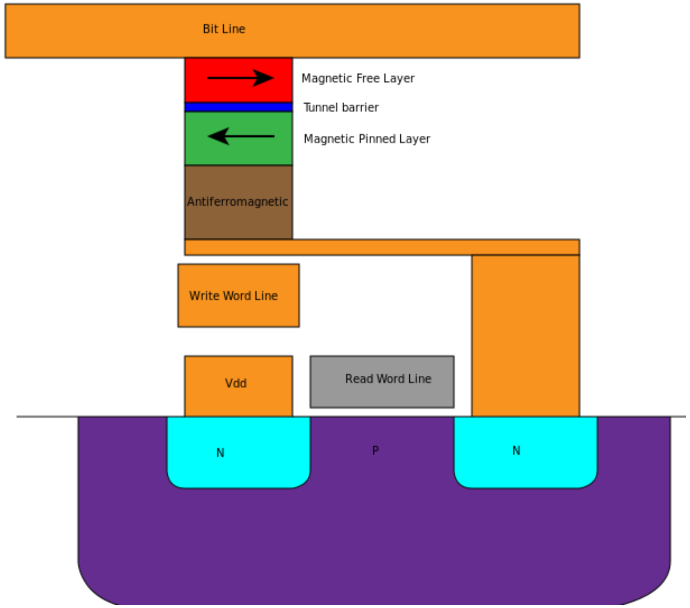


$$\mathrm{LLG}: \frac{d\mathbf{m}}{dt} = -\gamma \mathbf{m} \times \mathbf{H}_{\mathrm{eff}} + \alpha \mathbf{m} \times \frac{d\mathbf{m}}{dt} + a_J \mathbf{m} \times (\mathbf{m} \times \mathbf{m}_{\mathrm{polarizer}})$$

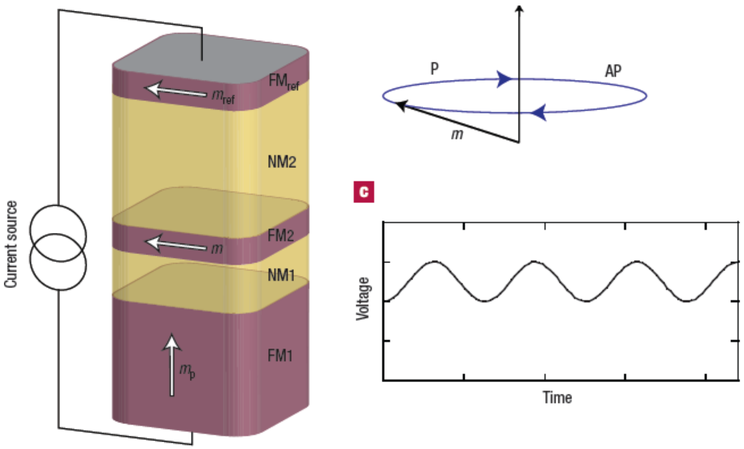
Principal Applications of STT: STT-MRAM and STT-Nano-oscillators

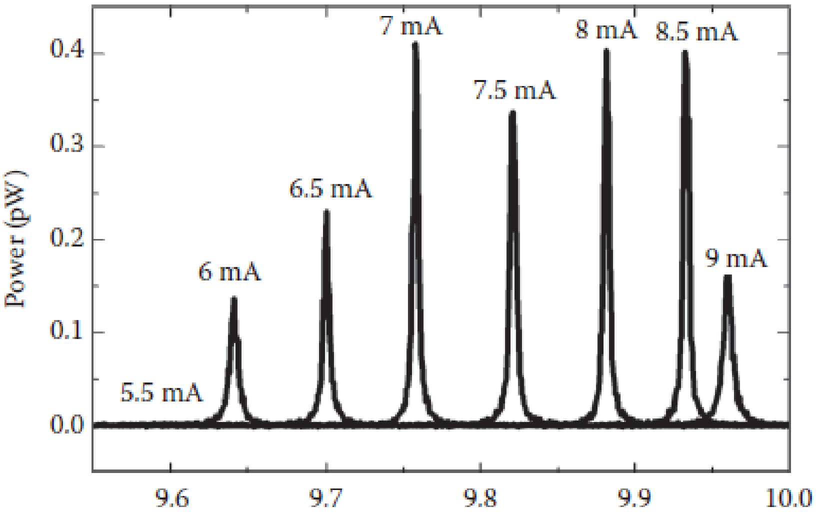
Non-volatile Memory:





Microwave Nano-Oscillators:

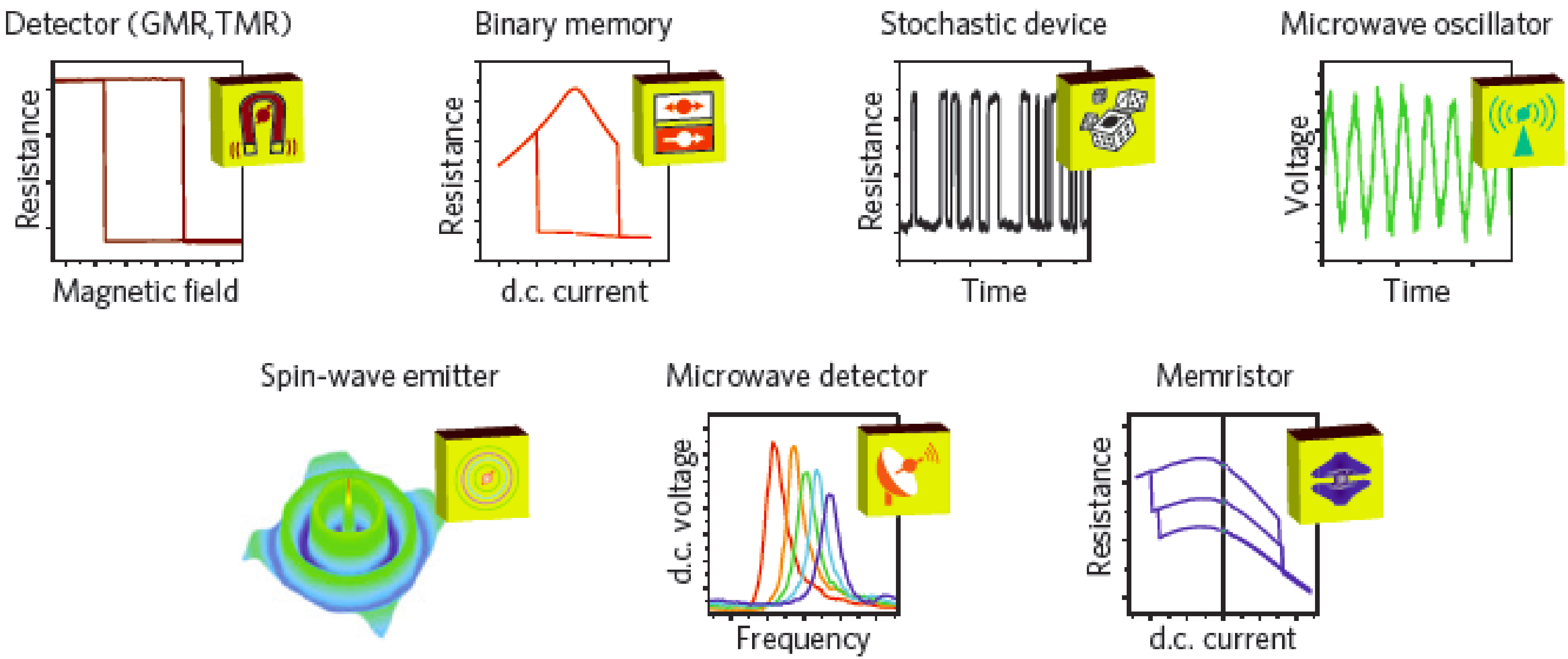




(b)

Nature Mater. 6, 447 (2007)

Other Anticipated Technologies Based on STT



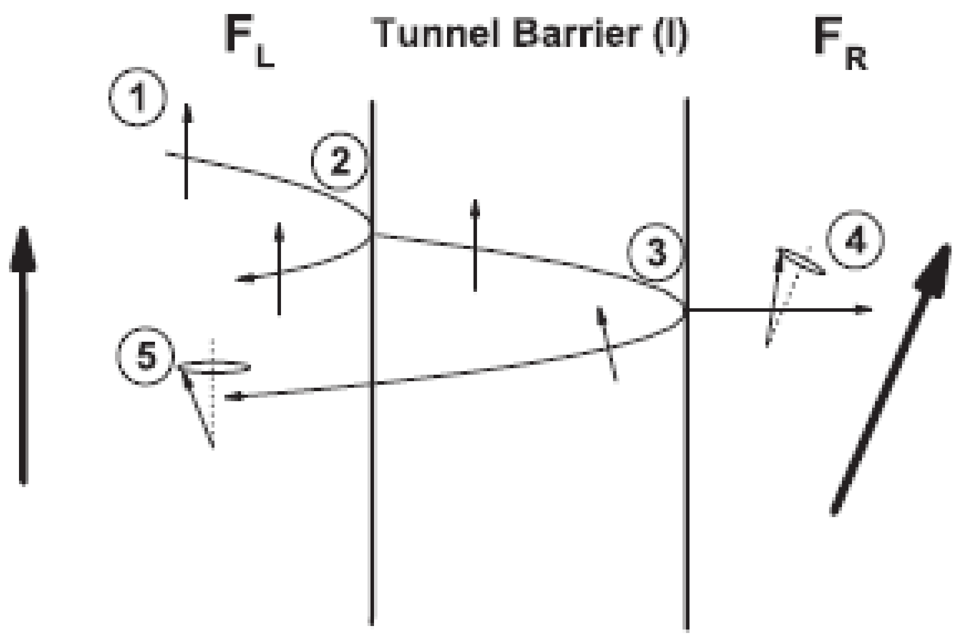
nature materials
PROGRESS ARTICLE
PUBLISHED ONLINE: 17 DECEMBER 2013 | DOI: 10.1038/NMAT3823

Spin-torque building blocks

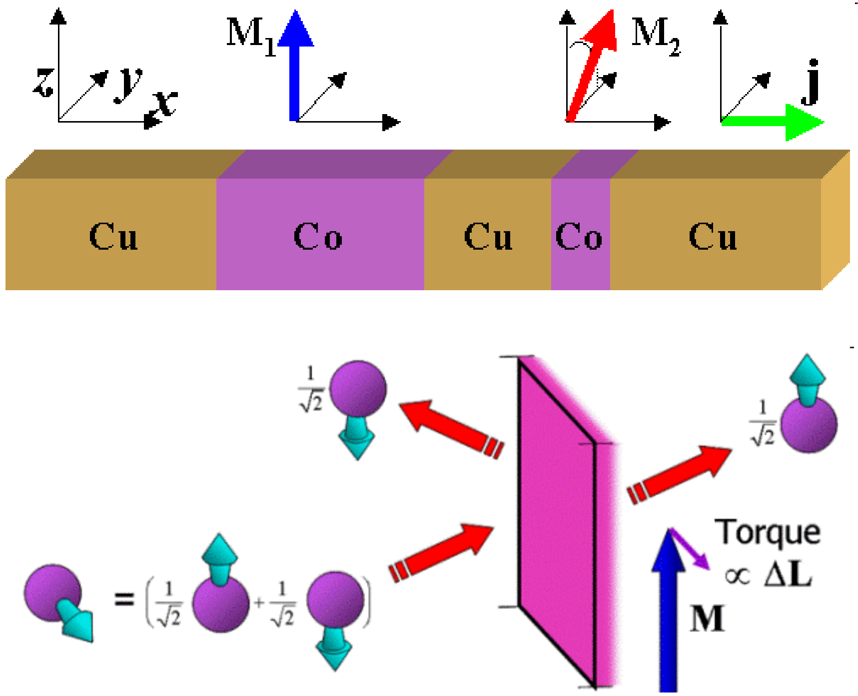
N. Locatelli, V. Cros and J. Grollier*

Physical Explanation of the Origin of STT

Semiclassical:



Fully Quantum:



Undergrad Quantum-Mechanical Theory of STT: One-Dimensional Toy Model #1

$$\psi = \frac{e^{ikx}}{\sqrt{\Omega}}\left(a\left|\uparrow\right\rangle + b\left|\downarrow\right\rangle\right)$$

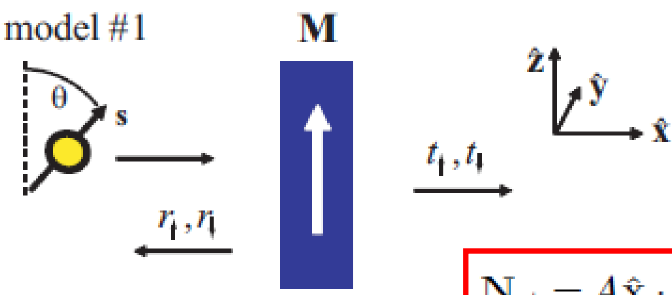
$$\mathbf{Q} = \frac{\hbar^2}{2m}\mathrm{Im}(\psi^* \boldsymbol{\sigma} \otimes \boldsymbol{\nabla}\psi)$$

$$Q_{xx} = \frac{\hbar^2 k}{2m\Omega} 2\mathrm{Re}(ab^*)$$

$$Q_{xy} = \frac{\hbar^2 k}{2m\Omega} 2\mathrm{Im}(ab^*)$$

$$Q_{xz} = \frac{\hbar^2 k}{2m\Omega}(|a|^2 - |b|^2)$$

Toy model #1



$$\mathbf{N}_{\rm st} = -\int_{\text{pillbox surfaces}} d^2R\,\hat{\mathbf{n}}\cdot\mathbf{Q}$$
$$= -\int_{\text{pillbox volume}} d^3r\,\nabla\cdot\mathbf{Q},$$

$$\mathbf{N}_{\rm st} = A\hat{\mathbf{x}}\cdot(\mathbf{Q}_{\rm in} + \mathbf{Q}_{\rm refl} - \mathbf{Q}_{\rm trans})$$
$$= \frac{A}{\Omega}\frac{\hbar^2 k}{2m}\sin(\theta)\left[1 - \mathrm{Re}(t_\uparrow t_\downarrow^* + r_\uparrow r_\downarrow^*)\right]\hat{\mathbf{x}}$$
$$-\frac{A}{\Omega}\frac{\hbar^2 k}{2m}\sin(\theta)\mathrm{Im}(t_\uparrow t_\downarrow^* + r_\uparrow r_\downarrow^*)\hat{\mathbf{y}}.$$

$$\psi_{\rm in} = \frac{e^{ikx}}{\sqrt{\Omega}}\left(\cos(\theta/2)\left|\uparrow\right\rangle + \sin(\theta/2)\left|\downarrow\right\rangle\right)$$

$$\psi_{\rm trans} = \frac{e^{ikx}}{\sqrt{\Omega}}\left(t_\uparrow\cos(\theta/2)\left|\uparrow\right\rangle + t_\downarrow\sin(\theta/2)\left|\downarrow\right\rangle\right)$$

$$\psi_{\rm refl} = \frac{e^{-ikx}}{\sqrt{\Omega}}\left(r_\uparrow\cos(\theta/2)\left|\uparrow\right\rangle + r_\downarrow\sin(\theta/2)\left|\downarrow\right\rangle\right)$$

$$\mathbf{Q}_{\rm in} = \frac{\hbar^2 k}{2m\Omega}\left[\sin(\theta)\hat{\mathbf{x}} + \cos(\theta)\hat{\mathbf{z}}\right]$$

$$\mathbf{Q}_{\rm trans} = \frac{\hbar^2 k}{2m\Omega}\sin(\theta)\mathrm{Re}(t_\uparrow t_\downarrow^*)\hat{\mathbf{x}}$$
$$+\frac{\hbar^2 k}{2m\Omega}\sin(\theta)\mathrm{Im}(t_\uparrow t_\downarrow^*)\hat{\mathbf{y}}$$
$$+\frac{\hbar^2 k}{2m\Omega}\left[|t_\uparrow|^2\cos^2(\theta/2) - |t_\downarrow|^2\sin^2(\theta/2)\right]\hat{\mathbf{z}}$$

$$\mathbf{Q}_{\rm refl} = -\frac{\hbar^2 k}{2m\Omega}\sin(\theta)\mathrm{Re}(r_\uparrow r_\downarrow^*)\hat{\mathbf{x}}$$
$$-\frac{\hbar^2 k}{2m\Omega}\sin(\theta)\mathrm{Im}(r_\uparrow r_\downarrow^*)\hat{\mathbf{y}}$$
$$-\frac{\hbar^2 k}{2m\Omega}\left[|r_\uparrow|^2\cos^2(\theta/2) - |r_\downarrow|^2\sin^2(\theta/2)\right]\hat{\mathbf{z}}$$

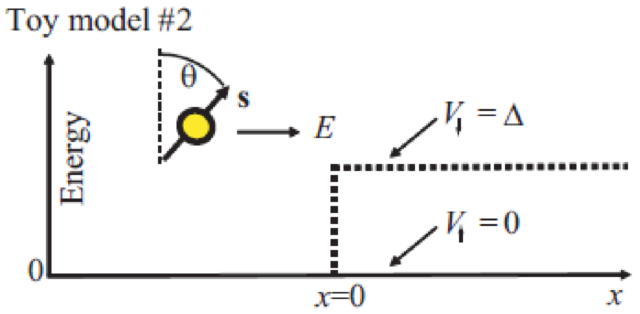
JMMM 320, 1190 (2008)

Undergrad Quantum-Mechanical Theory of STT: One-Dimensional Toy Model #2

$$\psi_{\rm trans} = \frac{e^{ik_\uparrow x}}{\sqrt{\Omega}} \cos(\theta/2)\,|\uparrow\rangle + \frac{e^{ik_\downarrow x}}{\sqrt{\Omega}} \frac{2k}{k+k_\downarrow} \sin(\theta/2)\,|\downarrow\rangle$$

$$\psi_{\rm refl} = \frac{e^{-ikx}}{\sqrt{\Omega}} \frac{k-k_\downarrow}{k+k_\downarrow} \sin(\theta/2)\,|\downarrow\rangle\,,$$

$$k_\uparrow = k \text{ and } k_\downarrow = [2m(E-\Delta)]^{1/2}/\hbar < k$$



$$\mathbf{Q} = \frac{\hbar^2}{2m} {\rm Im}(\psi^* \boldsymbol{\sigma} \otimes \boldsymbol{\nabla}\psi)$$

$$\mathbf{Q}_{\rm in} = \frac{\hbar^2}{2m\Omega}\left(k\sin(\theta)\hat{\mathbf{x}} + k\cos(\theta)\hat{\mathbf{z}}\right)$$

$$\mathbf{Q}_{\rm trans} = \frac{\hbar^2}{2m\Omega}\sin(\theta)k\cos[(k_\uparrow - k_\downarrow)x]\hat{\mathbf{x}} - \frac{\hbar^2}{2m\Omega}\sin(\theta)k\sin[(k_\uparrow - k_\downarrow)x]\hat{\mathbf{y}} + \frac{\hbar^2}{2m\Omega}\left[k\cos^2(\theta/2) - k_\downarrow\left(\frac{2k}{k+k_\downarrow}\right)^2\sin^2(\theta/2)\right]\hat{\mathbf{z}}$$

$$\mathbf{Q}_{\rm refl} = \frac{\hbar^2}{2m\Omega}k\left(\frac{k-k_\downarrow}{k+k_\downarrow}\right)^2\sin^2(\theta/2)\hat{\mathbf{z}}.$$

$$\mathbf{N}_{\rm st} = A\hat{\mathbf{x}}\cdot(\mathbf{Q}_{\rm in} + \mathbf{Q}_{\rm refl} - \mathbf{Q}_{\rm trans}) \approx A\hat{\mathbf{x}}\cdot\mathbf{Q}_{\rm in\perp}$$

$$\mathbf{N}_{\rm st} \approx \frac{A}{\Omega}\frac{\hbar^2 k}{2m}\sin(\theta)\hat{\mathbf{x}}$$

when summing or averaging over all contributions from around the Fermi surface, dephasing leads to Q_{refl}≈0, Q_{trans}≈0 (to a good approximation valid for typical metallic interfaces), so that STT acting on the magnet per unit area being equal to the full component of incident spin current that is transverse to magnetization of a ferromagnet

JMMM **320**, 1190 (2008)

Nonequilibrium Density Matrix for Steady-State Quantum Transport

- Equilibrium density matrix is universal (fixed by Boltzmann and Gibbs):

$$\hat{\rho}_{\rm eq} = \frac{e^{-\beta \hat{H}}}{{\rm Tr}\, e^{-\beta \hat{H}}} \Rightarrow \langle \hat{A} \rangle = {\rm Tr}\,[\hat{\rho}_{\rm eq} \hat{A}]$$

- Applied to non-interacting fermions in equilibrium:

$$\hat{\rho}_{\rm eq} = \sum_\alpha f(E_\alpha) |E_\alpha\rangle\langle E_\alpha| \Leftrightarrow \hat{\rho}_{\rm eq} = -\frac{1}{\pi} \int dE\, {\rm Im}[\hat{G}_0^r(E)] f(E)$$

$$\hat{G}_0^r = [E - \hat{H} + i\eta]^{-1} \text{ or } \hat{G}_0^r = [E - \hat{H} - \hat{\Sigma}_L - \hat{\Sigma}_R]^{-1}$$

- Equilibrium-like density matrix for stead-state transport of interacting fermions:

$$\hat{\rho}_{\rm neq} \propto e^{-\beta(\hat{H} - \hat{Y})}$$

- Nonequilibrium density matrix in terms of NEGFs:

$$\hat{\rho}_{\rm neq} = \frac{1}{2\pi i} \int dE\, \hat{G}^<(E) - \frac{1}{\pi} \int dE\, {\rm Im}[\hat{G}_0^r(E)] f(E)$$

How to Remove Equilibrium Expectation Values in Gauge Invariant Fashion

❑Density matrix often split into "equilibrium" + "nonequilibrium" contributions for purely computational purposes:

$$\hat{\rho} = -\frac{1}{\pi}\int_{-\infty}^{+\infty} dE\, \mathrm{Im}\hat{G}^r(E) f(E-eV_R) + \frac{1}{2\pi}\int_{-\infty}^{+\infty} dE\, \hat{G}^r(E)\cdot\hat{\Gamma}_L(E-eV_L)\cdot\hat{G}^a(E)\,[f(E-eV_L) - f(E-eV_R)]$$

❑The proper gauge-invariant nonequilibrium density matrix is defined by:

$$\hat{\rho}_{\mathrm{neq}} = \hat{\rho} - \hat{\rho}_{\mathrm{eq}} = \hat{\rho} + \frac{1}{\pi}\int_{-\infty}^{+\infty} dE\, \mathrm{Im}\left[\hat{G}^r_0(E)\right] f(E)$$

❑First two terms below remove any equilibrium contribution to physical quantity whose non-zero value is compatible with time-reversal invariance (zero T limit):

$$\begin{aligned}\hat{\rho}_{\mathrm{neq}} \;=\; & -\frac{eV_R}{\pi}\mathrm{Im}\left[G^r_0(E_F)\right] - \frac{1}{\pi}\int_{-\infty}^{E_F} dE\, \mathrm{Im}\left[\hat{G}^r_0\left(eU - eV_L\frac{\partial\hat{\Sigma}_L}{\partial E} - eV_R\frac{\partial\hat{\Sigma}_R}{\partial E}\right)\hat{G}^r_0\right] f(E) \\ & + \frac{eV_b}{2\pi}\hat{G}^r_0(E_F)\cdot\hat{\Gamma}_L(E_F)\cdot\hat{G}^a_0(E_F),\end{aligned}$$

SPIN **3**, 1330002 (2013)

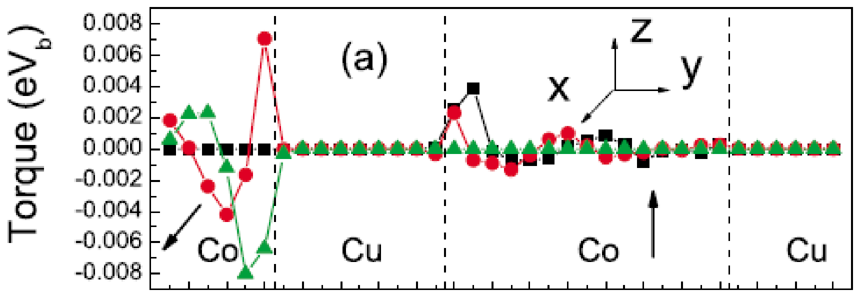
Graduate Quantum-Mechanical Theory of STT using Torque Operator and NEGF Formulas

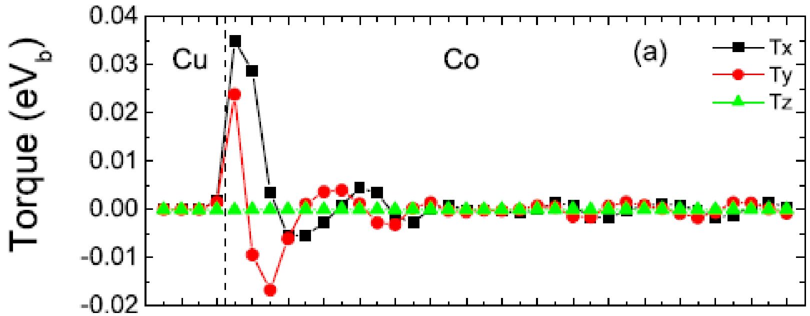
$$\hat H = \hat H_0 + \Delta(\mathbf{m}\cdot\boldsymbol{\sigma}) \Rightarrow \hat{\mathbf{T}} = \Delta(\mathbf{m}\times\boldsymbol{\sigma}) \Rightarrow \mathbf{T} = \mathrm{Tr}[\hat\rho_{\rm neq}\hat{\mathbf{T}}]$$

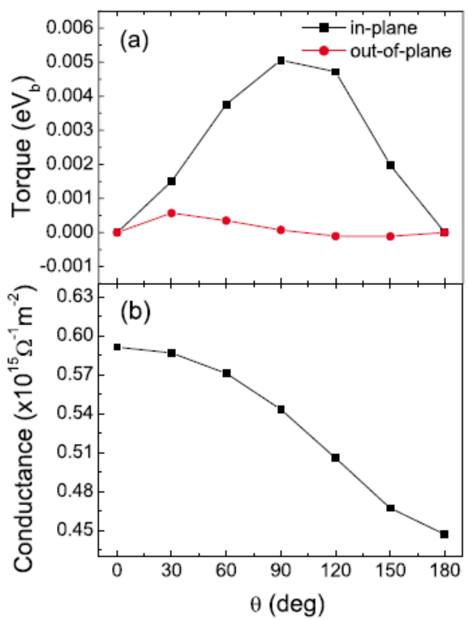
$$\hat\rho_{\rm neq} = -\frac{eV_R}{\pi}\mathrm{Im}\left[G_0^r(E_F)\right] - \frac{1}{\pi}\int_{-\infty}^{E_F} dE\,\mathrm{Im}\left[\hat G_0^r\left(eU - eV_L\frac{\partial\hat\Sigma_L}{\partial E} - eV_R\frac{\partial\hat\Sigma_R}{\partial E}\right)\hat G_0^r\right] f(E) + \frac{eV_b}{2\pi}\hat G_0^r(E_F)\cdot\hat\Gamma_L(E_F)\cdot\hat G_0^a(E_F)$$

$$\begin{aligned}
\hat{\mathbf{T}} &= \frac{d\hat{\mathbf{S}}}{dt} = -\frac{i}{\hbar}\left[\frac{\hbar}{2}\boldsymbol{\sigma}, \hat H\right] \\
(\boldsymbol{\sigma}\cdot\mathbf{p})(\boldsymbol{\sigma}\cdot\mathbf{q}) &= \mathbf{p}\cdot\mathbf{q} + i(\mathbf{p}\times\mathbf{q})\cdot\boldsymbol{\sigma} \\
(\boldsymbol{\sigma}\cdot\mathbf{p})\boldsymbol{\sigma} &= \mathbf{p} + i\boldsymbol{\sigma}\times\mathbf{p} \\
\boldsymbol{\sigma}(\boldsymbol{\sigma}\cdot\mathbf{q}) &= \mathbf{q} + i\mathbf{q}\times\boldsymbol{\sigma}
\end{aligned}$$

$$\begin{aligned}
\hat\rho_{\rm neq} &= \frac{1}{2\pi i}\int dE[\hat G^<(E,V_b) - \hat G^<(E,V_b=0)] \\
\hat G^r &= [E - \hat H - \hat\Sigma_L^r - \hat\Sigma_R^r]^{-1} \\
\hat\Sigma^< &= if_L\hat\Gamma_L + if_R\hat\Gamma_R \ \text{(for elastic transport)} \\
\hat G^< &= \hat G^r\hat\Sigma^<\hat G^a
\end{aligned}$$

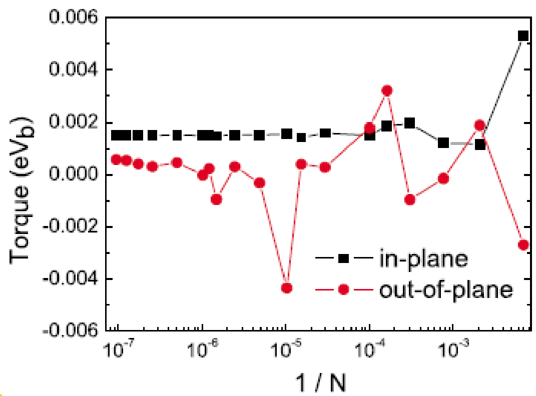




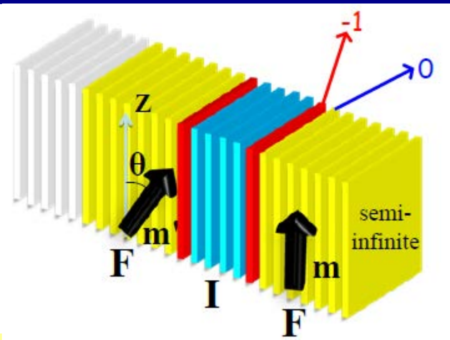


$\mathrm{Co}(\theta)|\mathrm{Cu}(9\ \mathrm{ML})\ |\mathrm{Co}(15\ \mathrm{ML})\ |\mathrm{Cu}$

PRB **77**, 184430 (2008)



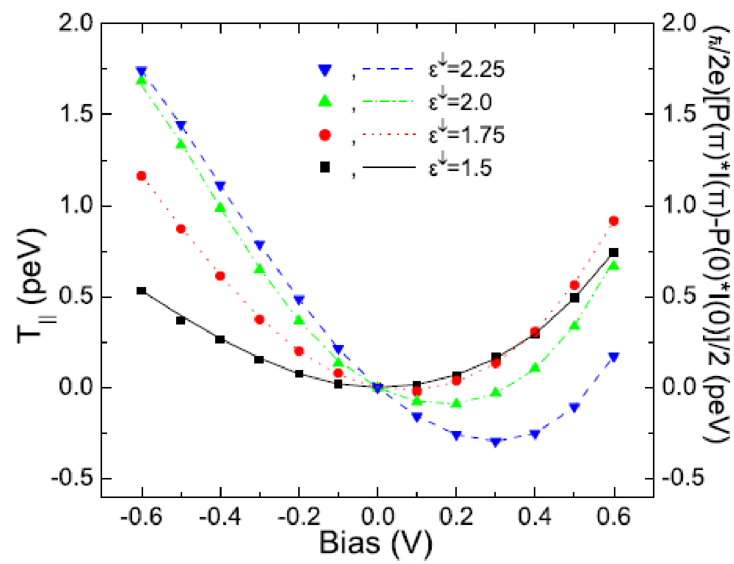
NEGF Formulas for STT in the Absence of Spin Flips Using Interfacial Spin Current



$$\mathbf{I}^S_{n,n+1} = \frac{\gamma}{4\pi}\int dE d\mathbf{k}_\parallel \, \mathrm{Tr}_\sigma \left[\boldsymbol{\sigma}(G^{<\sigma,\sigma}_{n+1,n} - G^{<\sigma,\sigma'}_{n,n+1})\right]$$

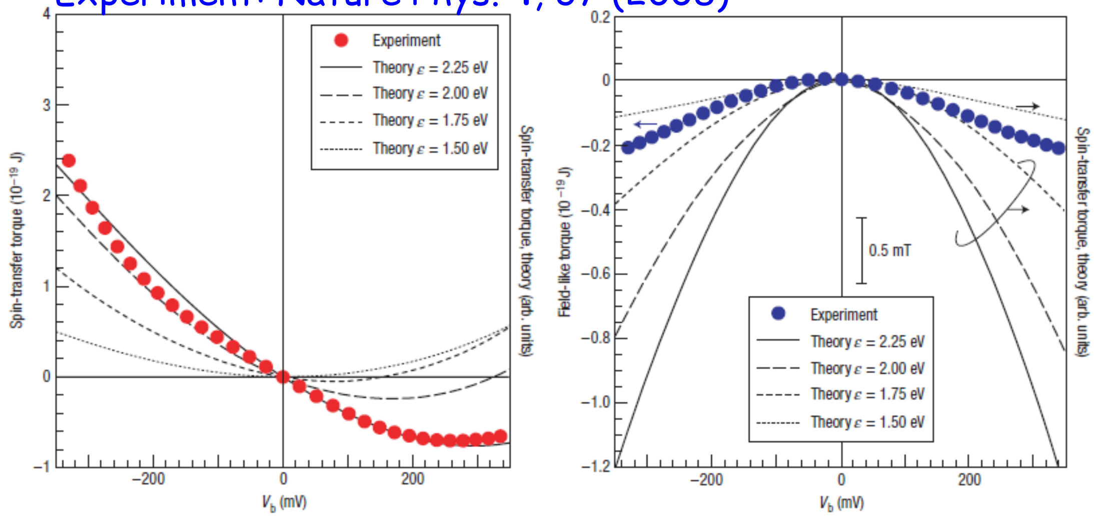
$$\mathbf{T}_n = -\nabla \cdot \mathbf{I}^S = \mathbf{I}^S_{n-1,n} - \mathbf{I}^S_{n,n+1}$$

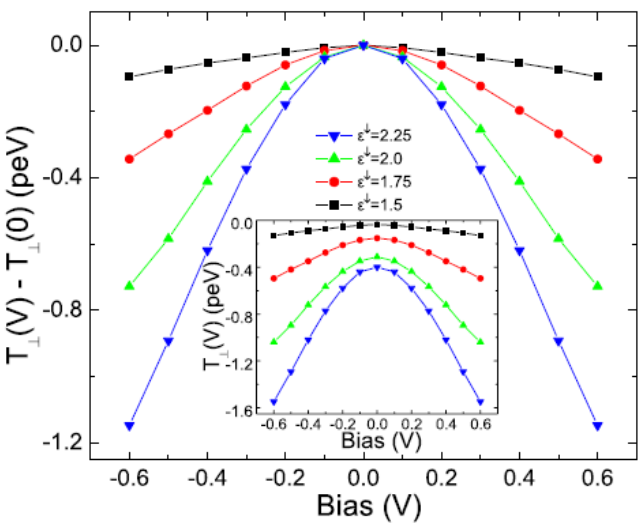
$$\mathbf{T} = \sum_{\lambda'=0}^{\infty} (\mathbf{I}^S_{n-1,n} - \mathbf{I}^S_{n,n+1}) = \mathbf{I}^S_{-1,0} - \mathbf{I}^S_{\infty,\infty} = \mathbf{I}^S_{-1,0}$$



Theory: PRL 97, 237205 (2006)

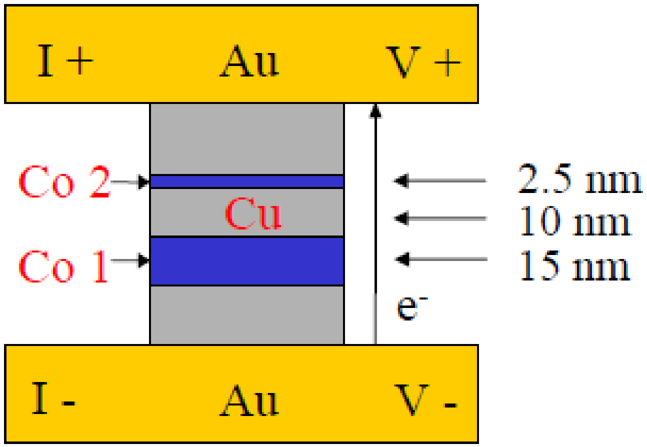
Experiment: Nature Phys. **4**, 37 (2008)



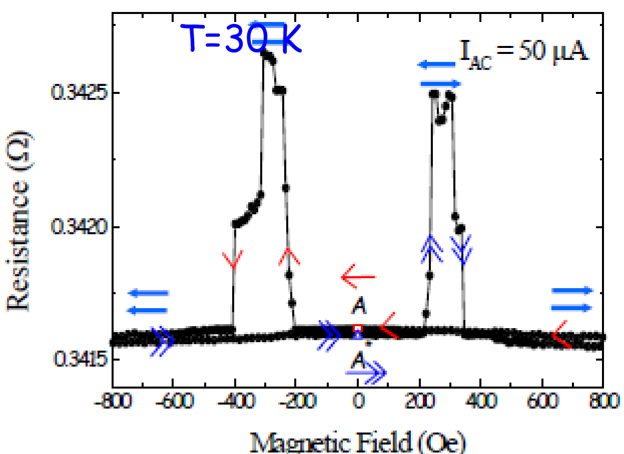


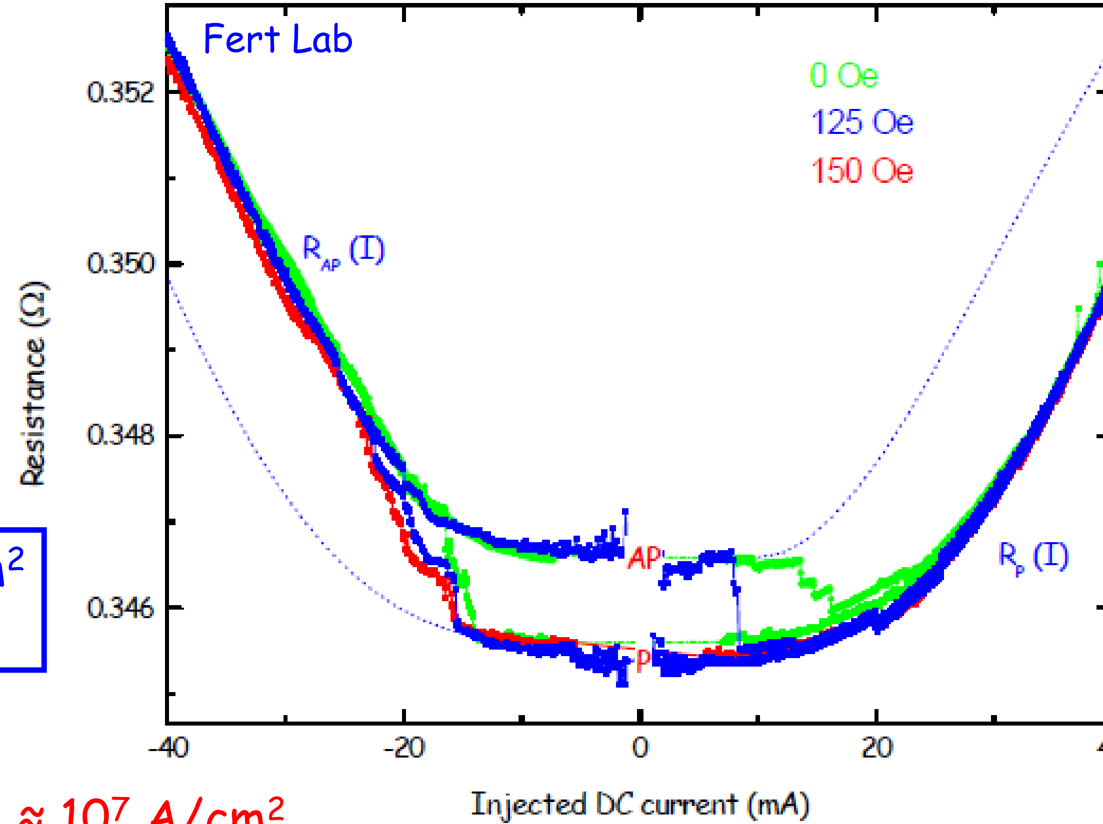
Experiments on STT in Spin Valves

nanopillar geometry



Low-impedance (RA) ~ 0.01 $\Omega\mu m^2$
GMR ~ 10-20%





$|J_c| \approx 10^7\ A/cm^2$

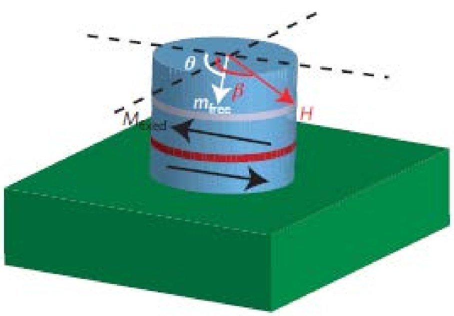
- ❑Critical current densities quite similar in good spin valves and MTJs (high polarization of MTJs may give ~ 2x advantage)
- ❑Conventional ferromagnet spin transfer devices require lateral dimensions ≤ 250 nm to avoid significant self-field effects from required current levels

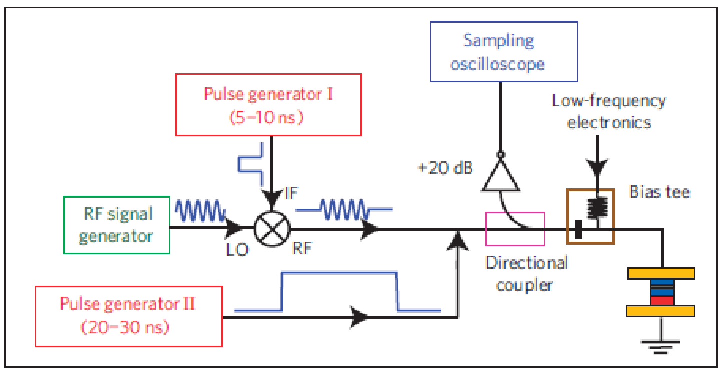
Experiments on STT in Magnetic Tunnel Junctions

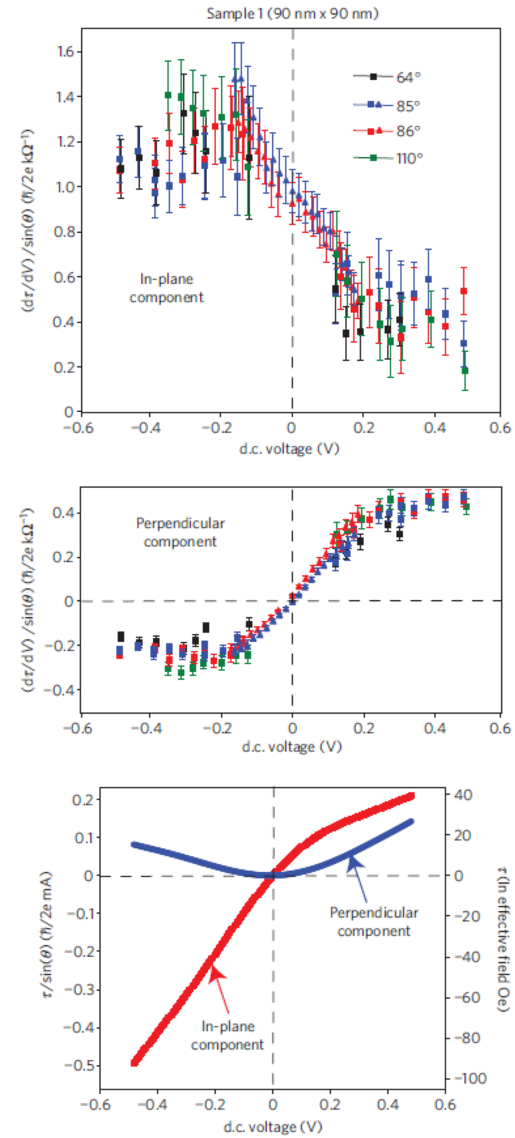
ARTICLES
PUBLISHED ONLINE: 27 FEBRUARY 2011 | DOI: 10.1038/NPHYS1928
nature physics

Time-resolved measurement of spin-transfer-driven ferromagnetic resonance and spin torque in magnetic tunnel junctions

Chen Wang[1], Yong-Tao Cui[1], Jordan A. Katine[2], Robert A. Buhrman[1] and Daniel C. Ralph[1,3]*







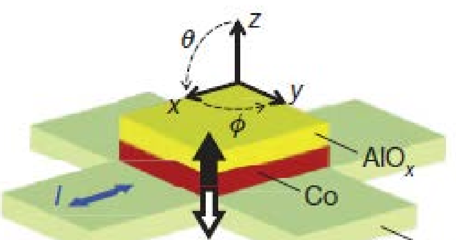
High-impedance (RA) ~ 1-100 Ωμm²
TMR ~ 100%

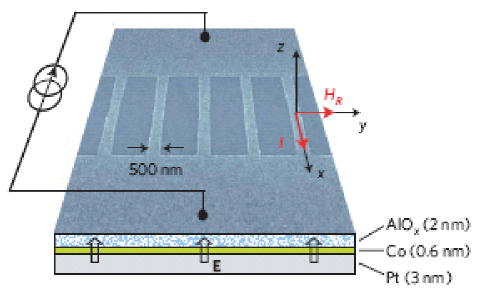
New Frontier: Spin-Orbit Coupling-Driven STT on **Single** Ferromagnetic Layer

LETTERS
PUBLISHED ONLINE: 10 JANUARY 2010 | DOI: 10.1038/NMAT2613
nature materials

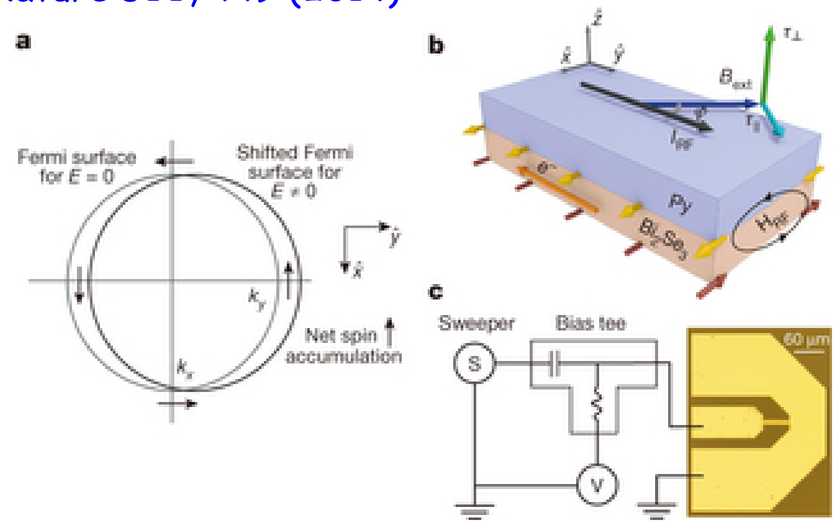
Current-driven spin torque induced by the Rashba effect in a ferromagnetic metal layer

Ioan Mihai Miron[1]*, Gilles Gaudin[2], Stéphane Auffret[2], Bernard Rodmacq[2], Alain Schuhl[2], Stefania Pizzini[3], Jan Vogel[3] and Pietro Gambardella[1,4]





Nature **511**, 449 (2014)



EW LETTERS
week ending 31 AUGUST 2012

Current-Induced Switching of Perpendicularly Magnetized Magnetic Layers Using Spin Torque from the Spin Hall Effect

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[1]Cornell University, Ithaca, New York 14853, USA
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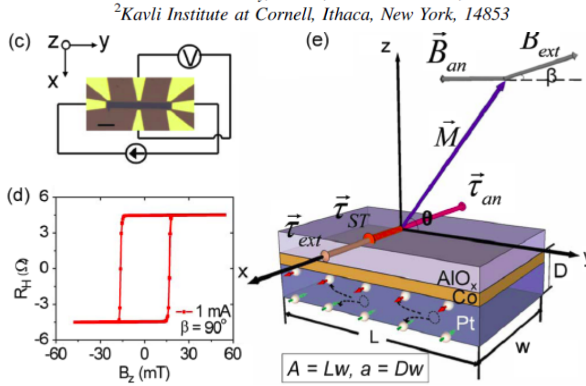
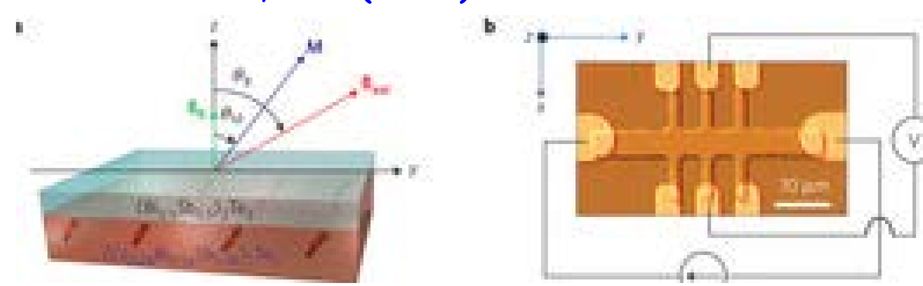
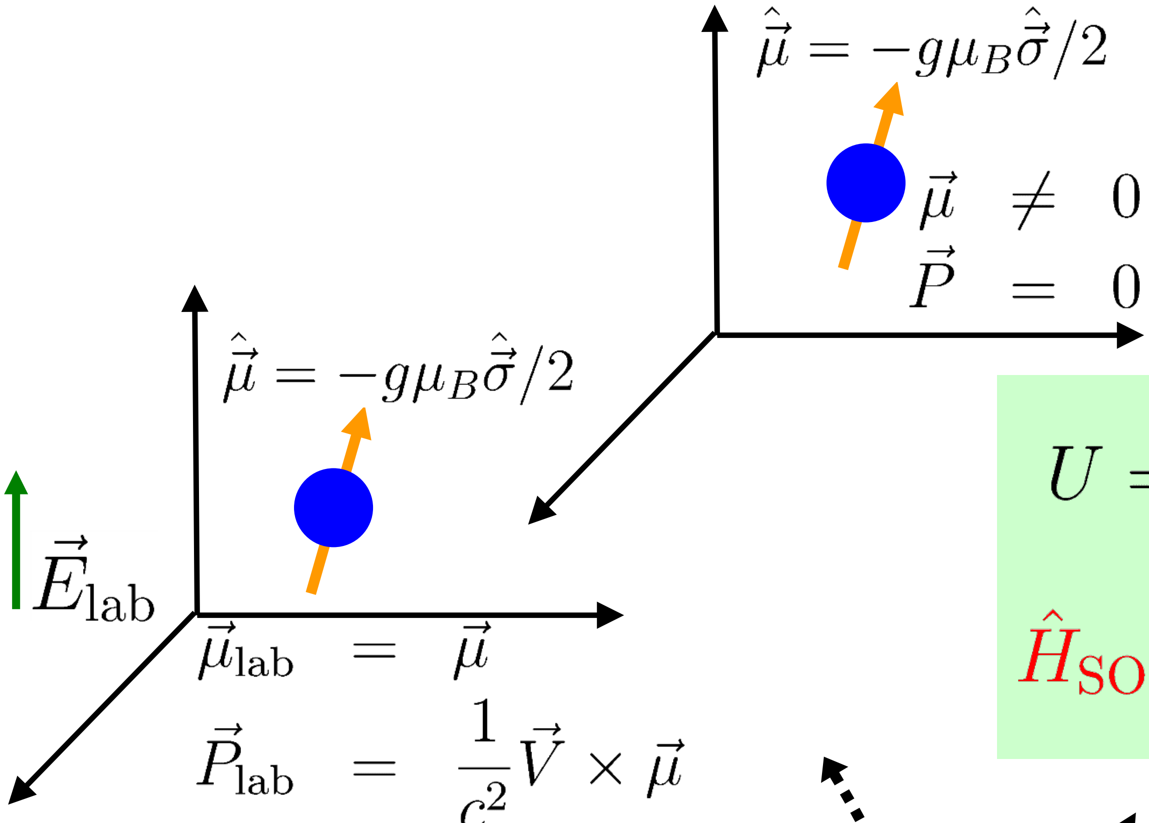


Nature **511**, 449 (2014)

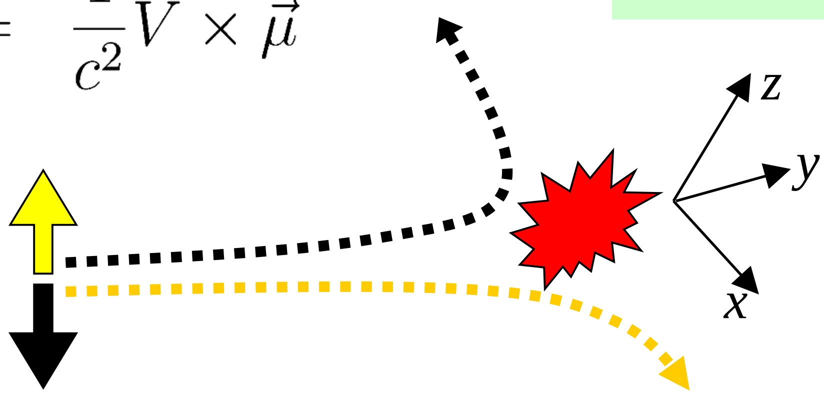


What is Spin-Orbit Coupling?



$$U = -\frac{1}{2}\vec{P}_{\rm lab} \cdot \vec{E}$$

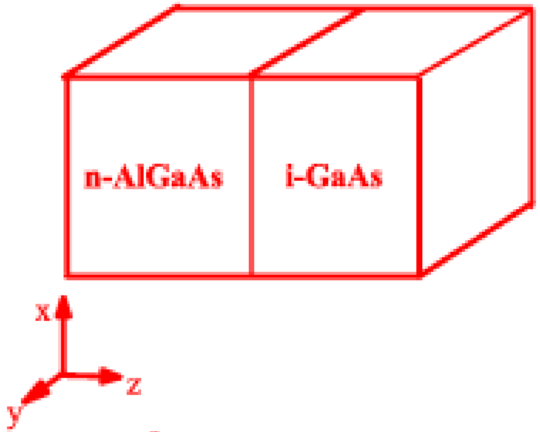
$$\hat{H}_{\rm SO} = \frac{e\hbar^2}{4m_0^2c^2}(\hat{\vec{\sigma}} \times \hat{\vec{p}}) \cdot \vec{E}$$

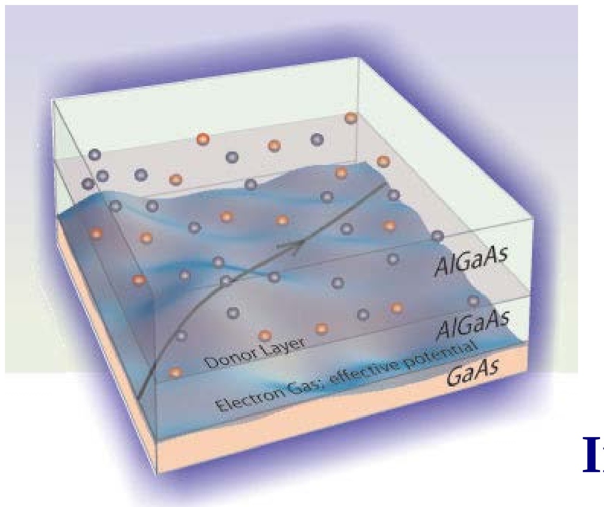


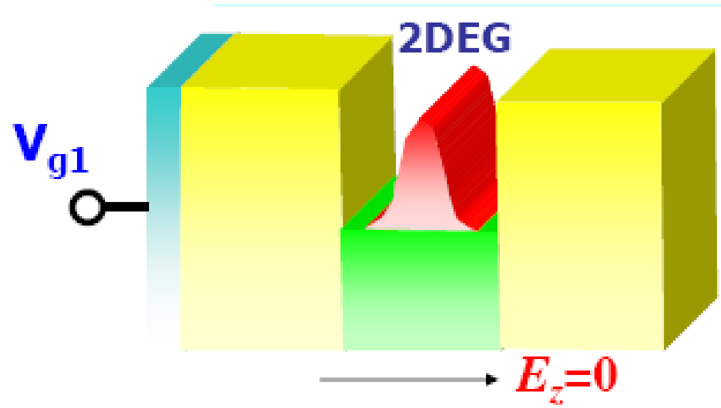
SO deflection force:

$$F_{\rm SO} = \pm P_{\rm lab} \nabla E_x$$

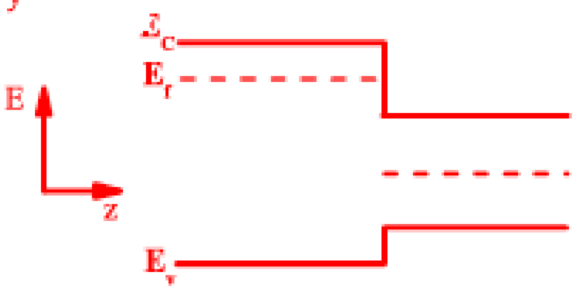
Structural Inversion Asymmetry of 2DEGs in Semiconductor Heterostructures



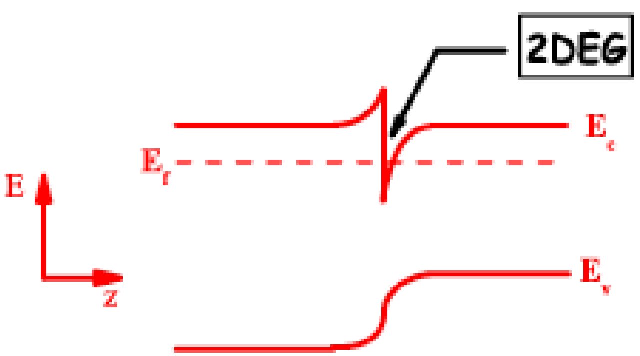


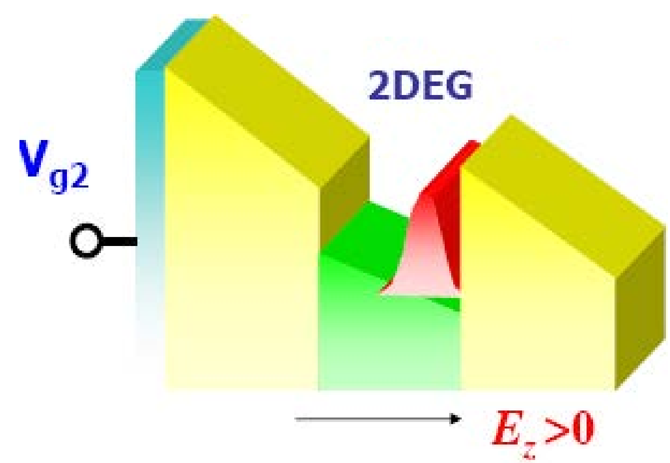


Inversion symmetry ⇒ no R-SO



$$\varepsilon(\mathbf{k},\uparrow) = \varepsilon(-\mathbf{k},\downarrow)$$
$$\varepsilon(\mathbf{k},\uparrow) \neq \varepsilon(-\mathbf{k},\uparrow)$$
$$\varepsilon(\mathbf{k},\uparrow) \neq \varepsilon(\mathbf{k},\downarrow)$$





Broken inversion symmetry ⇒ R-SO

Vacuum vs. Crystalline SO Coupling Strength

$$\hat{H}_{\text{Dirac}} = \beta m_0 c^2 + eV + c\boldsymbol{\alpha}\cdot(\hat{\mathbf{p}} - e\mathbf{A})$$

On the v^2/c^2 expansion of the Dirac equation with external potentials

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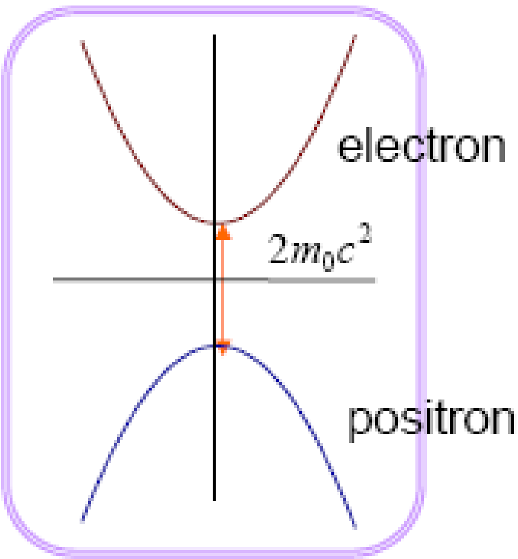
(Received 13 January 2005; accepted 8 April 2005)

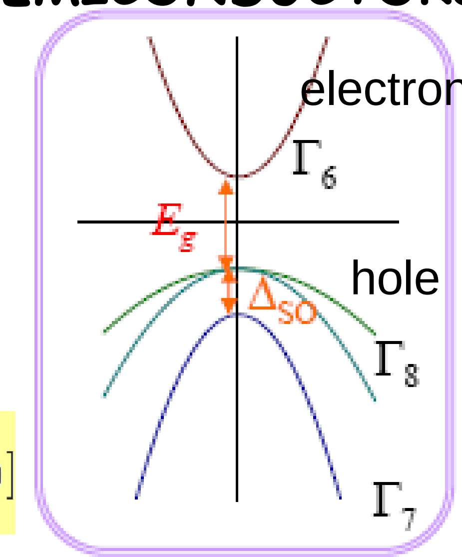
The v^2/c^2 expansion of the Dirac equation with external potentials is reexamined. A complete, gauge invariant form of the expansion to order $(1/c)^2$ is established that contains two additional terms, in contrast to various published results. It is shown that the additional terms describe the relativistic decrease of the electron spin magnetic moment with increasing electron energy.

VACUUM



Nonrelativistic expansion of the Dirac equation can be seen as a method of systematically including the effects of the negative energy solutions on the states of positive energy starting from their nonrelativistic limit

SEMICONDUCTORS



$$\hat{H}_{\text{SO}} = \frac{\hbar^2}{4m_0^2c^2}\hat{\vec{\sigma}}\cdot[\hat{\vec{k}}\times\nabla(V_{\text{nucleus}} + V_{\text{interface}})]$$

$$\lambda_{\text{vac}} = \hbar^2/4m_0^2c^2$$

$$\lambda_{\text{Sm}} = (P^2/3)[1/E_g^2 - 1/(E_g + \Delta_{\text{SO}})^2$$

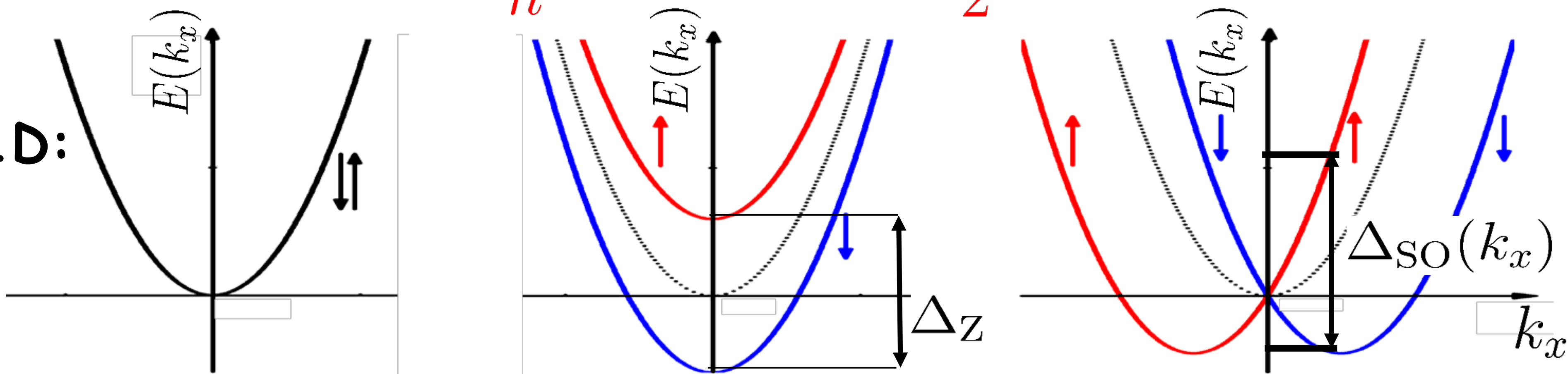
$$\lambda_{\text{vac}} = 3.7\times 10^{-6}\,\text{Å}^2$$

$$\lambda_{\text{GaAs}} = 5.3\,\text{Å}^2$$

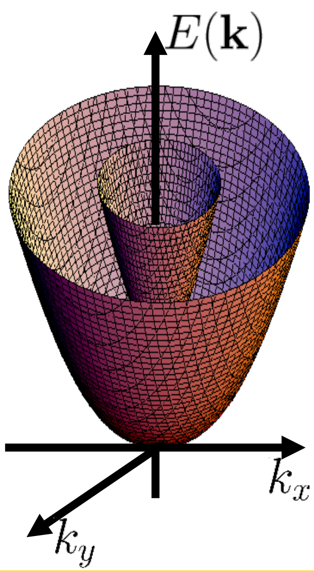
Rashba SO Splitting of Energy Bands in 2DEGs

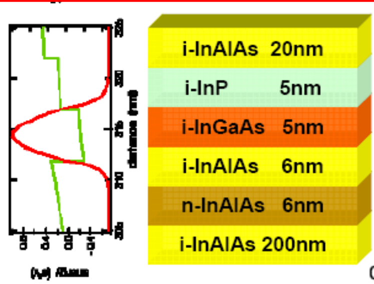
$$\hat{H}^{\mathrm{R}}_{\mathrm{SO}} = \frac{\alpha}{\hbar}(\hat{\boldsymbol{\sigma}} \times \hat{\mathbf{p}})_z \equiv -\frac{g\mu_B}{2}\hat{\boldsymbol{\sigma}} \cdot \mathbf{B}_{\mathrm{R}}(\hat{\mathbf{p}})$$

1D:



2D:



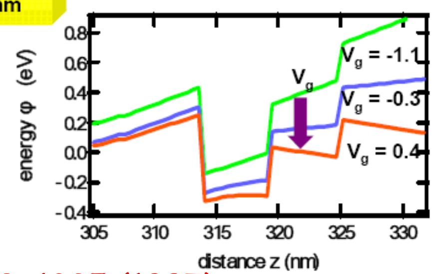


SOI depends on Vg

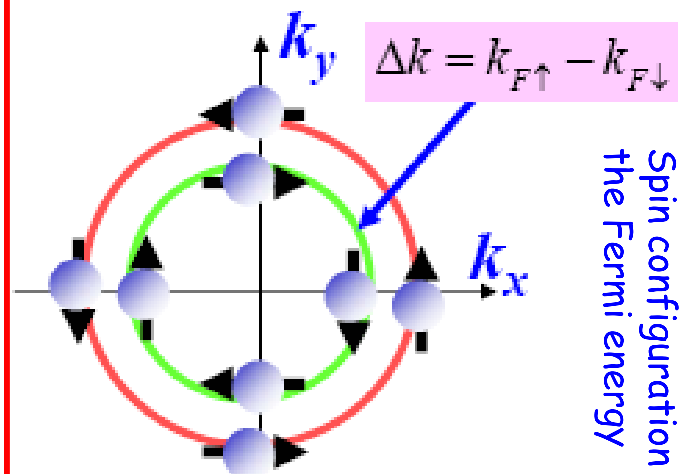
V_g	< E >	α
-1.1	large	large
-0.3	medium	medium
0.4	small	small

SOI is proportional to E

$$\alpha \propto \langle E \rangle = -\frac{\partial \phi(z)}{\partial z}$$



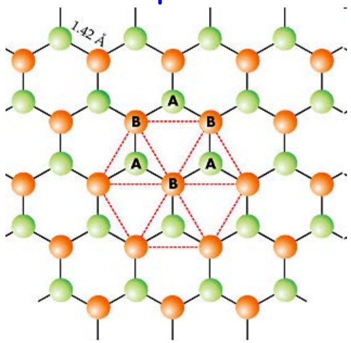
J. Nitta *et al.*, PRL **78**, 1335 (1997)



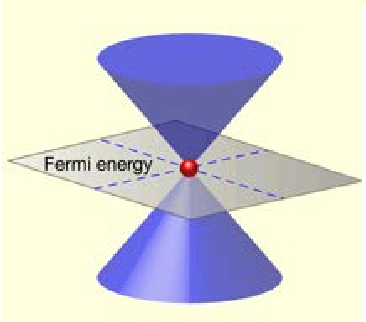
Spin configuration at the Fermi energy

Crash Course on 3D Topological Insulators

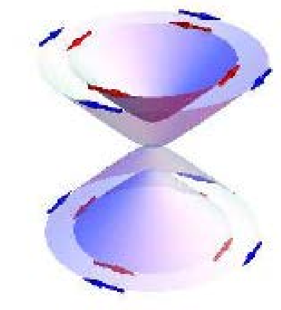
Graphene



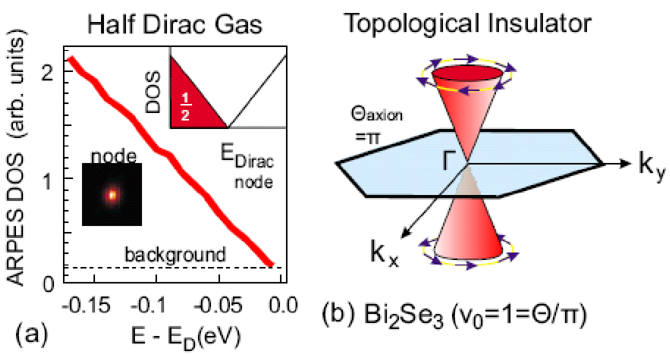
Spin-degenerate

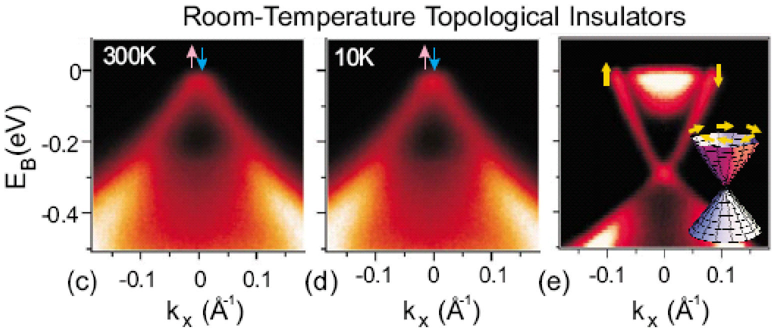


Spin-split by Rashba SOC

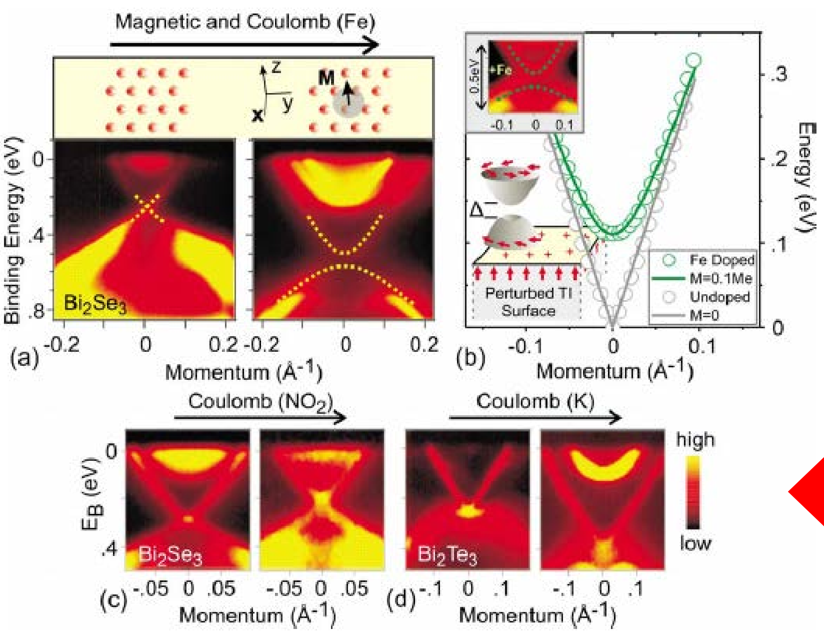


Helical liquid on the surface of strong 3D TI





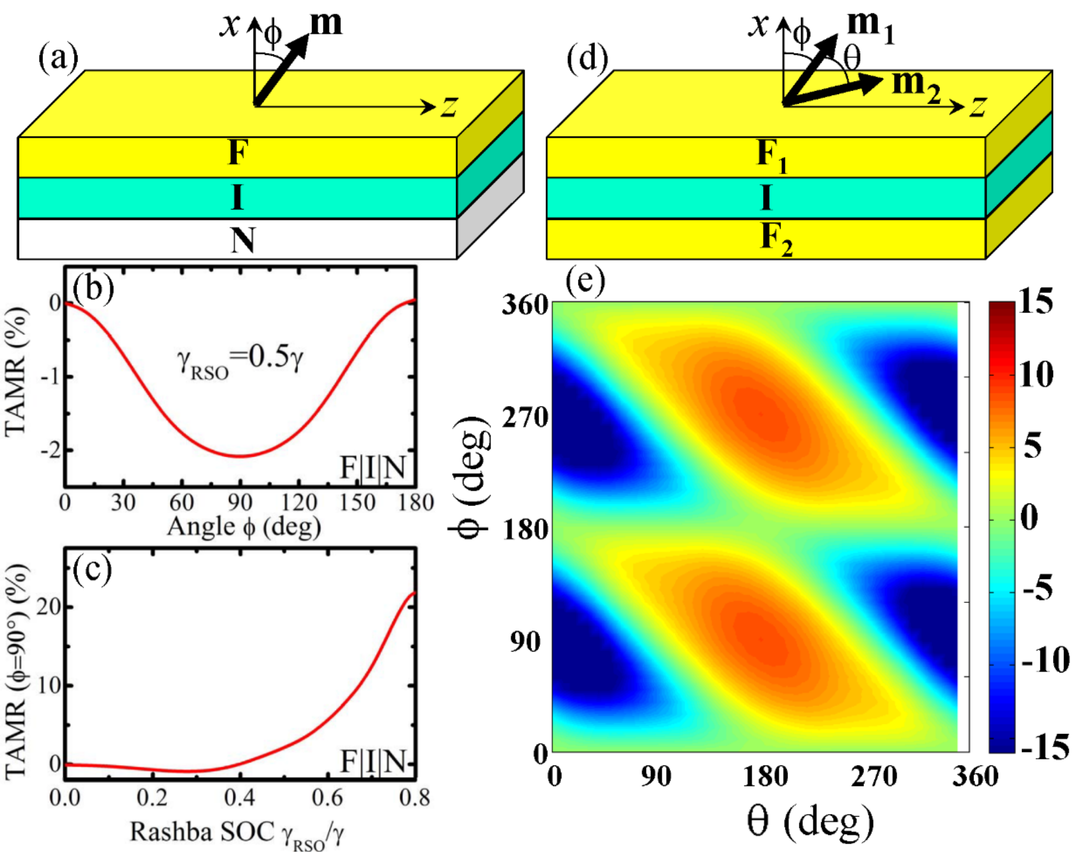
Hasan Lab, Science 323, 919 (2009)



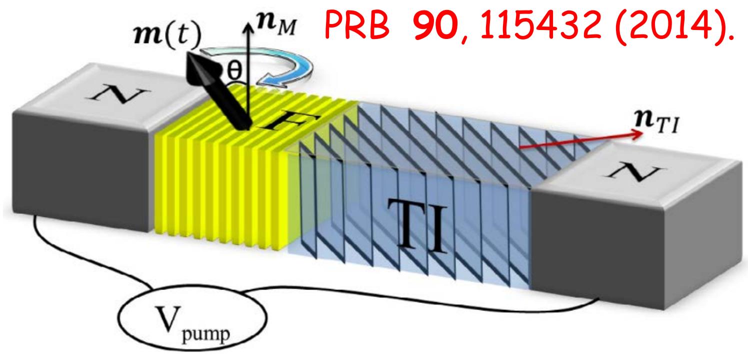
Why is this interesting: Protection by time-reversal invariance against scattering off non-magnetic impurities

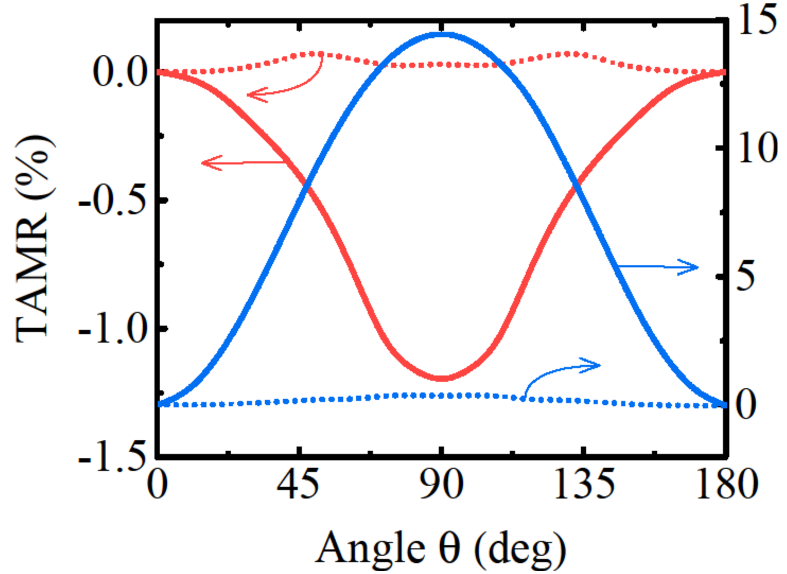
Detecting Interfacial SOC via Tunneling Anisotropic Magnetoresistance

PRB **85**, 054406 (2012)

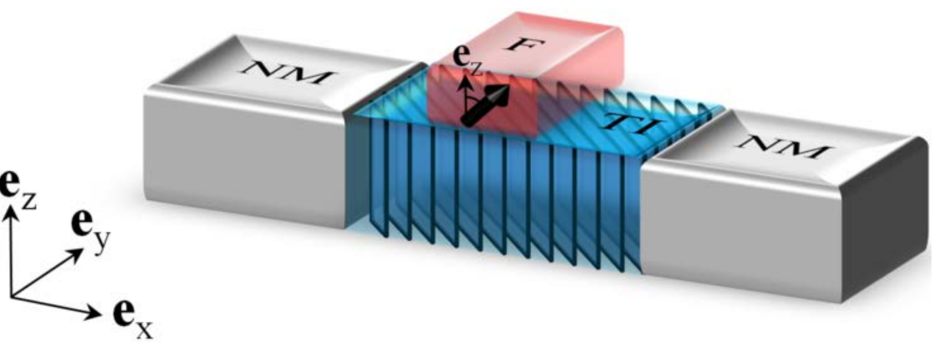


PRB **90**, 115432 (2014).

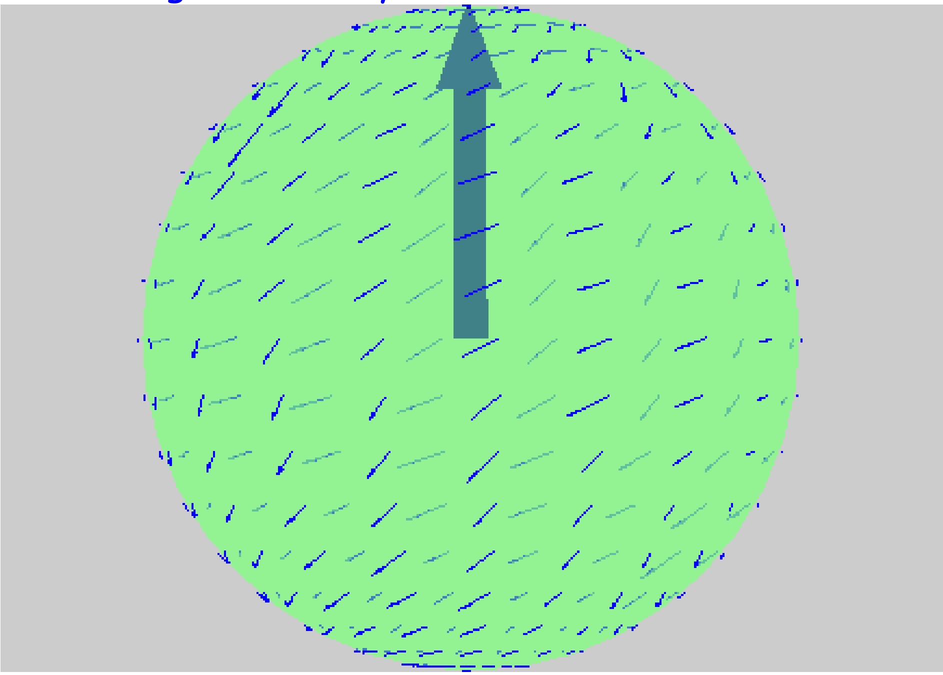




STT in Lateral TI/FM Heterostructures

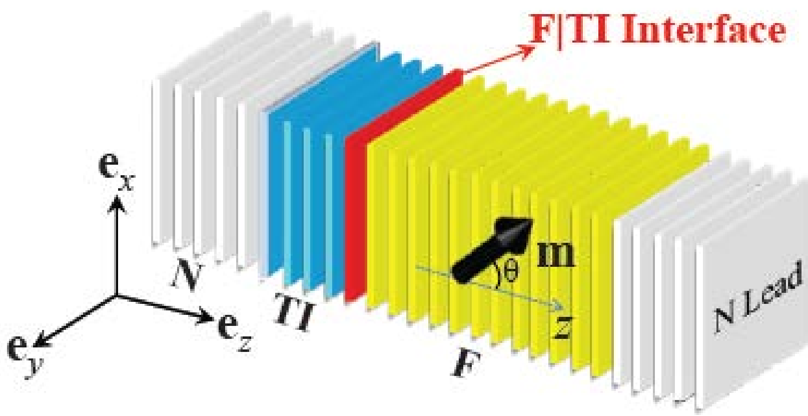


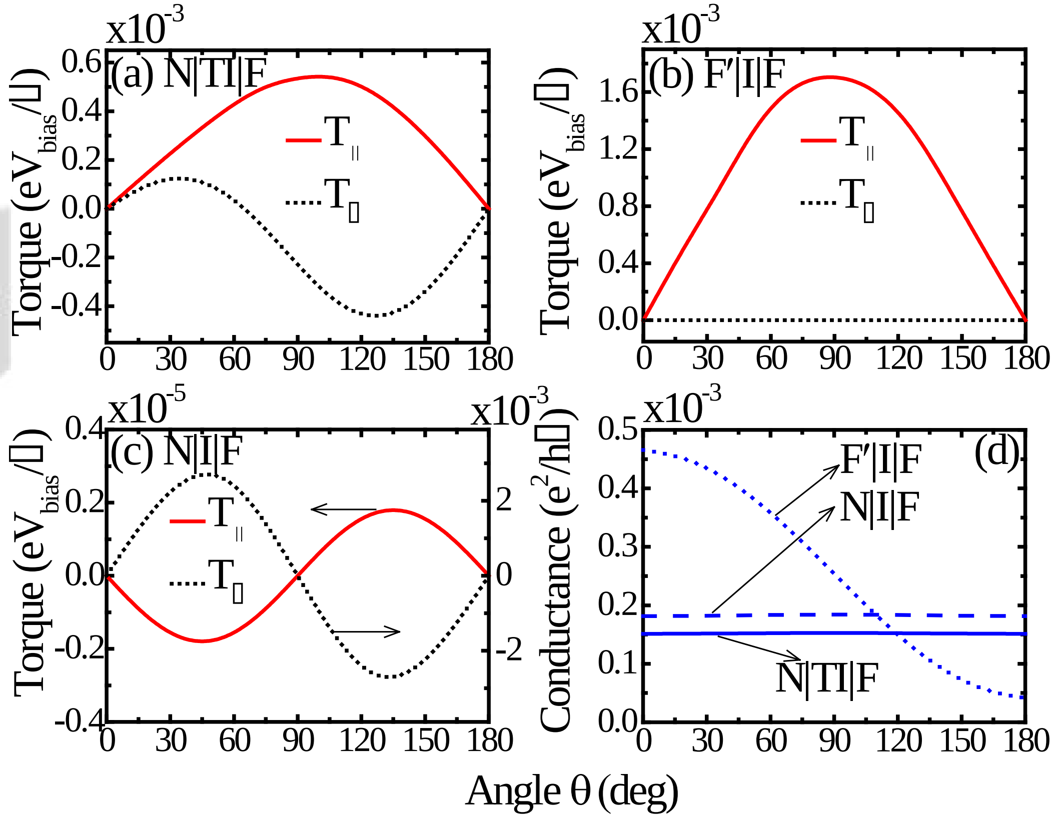
Solving LLG equation with torque field generated by the surface of 3D TI



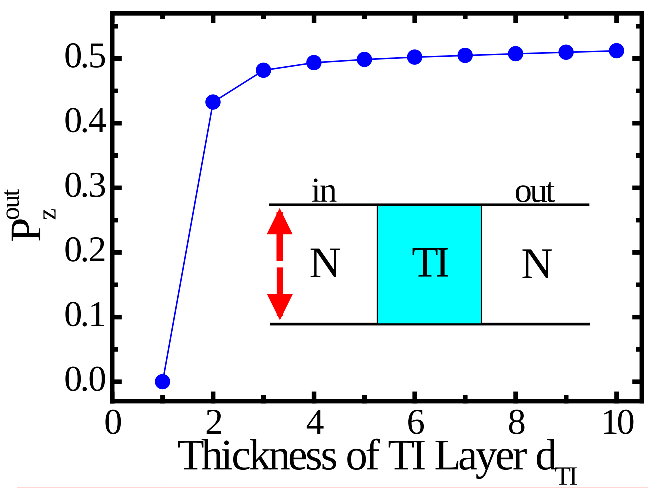
unpublished

STT in Vertical TI/FM Heterostructures





PRL **109**, 166602 (2012)



$$\mathbf{T} = \mathbf{T}_{\|} + \mathbf{T}_{\perp} = \tau_{\|}\mathbf{m} \times (\mathbf{m} \times \mathbf{e}_z) + \tau_{\perp}\mathbf{m} \times \mathbf{e}_z$$

PRB **71**, 195328 (2005)

$$\hat{\rho}^{\mathrm{out}} = \frac{1}{2}(1 + \mathbf{P}^{\mathrm{out}} \cdot \boldsymbol{\sigma})$$

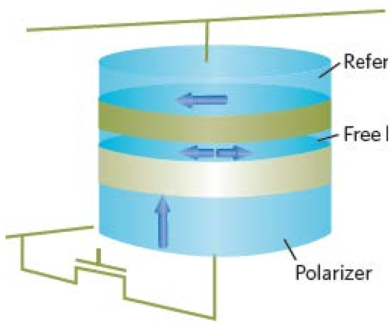
$$\hat{\rho}^{\mathrm{out}} = \frac{e^2/h}{n_\uparrow(G^{\uparrow\uparrow} + G^{\downarrow\uparrow}) + n_\downarrow(G^{\uparrow\downarrow} + G^{\downarrow\downarrow})} \sum_{n',n=1}^{M} \begin{pmatrix} |\mathbf{t}_{n'n,\uparrow\uparrow}|^2 + |\mathbf{t}_{n'n,\uparrow\downarrow}|^2 & \mathbf{t}_{n'n,\uparrow\uparrow}\mathbf{t}^*_{n'n,\downarrow\uparrow} + \mathbf{t}_{n'n,\uparrow\downarrow}\mathbf{t}^*_{n'n,\downarrow\downarrow} \\ \mathbf{t}^*_{n'n,\uparrow\uparrow}\mathbf{t}_{n'n,\downarrow\uparrow} + \mathbf{t}^*_{n'n,\uparrow\downarrow}\mathbf{t}_{n'n,\downarrow\downarrow} & |\mathbf{t}_{n'n,\downarrow\uparrow}|^2 + |\mathbf{t}_{n'n,\downarrow\downarrow}|^2 \end{pmatrix}$$

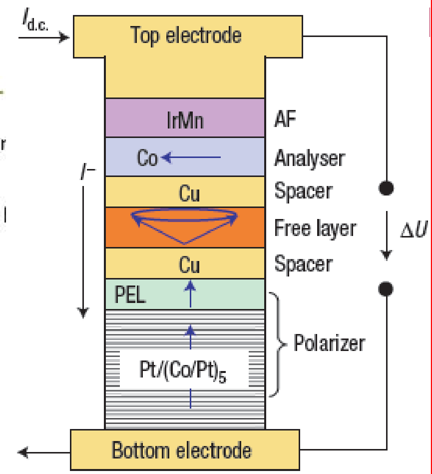
Applications: OSTT-MRAM and STT-nanooscillators using TI Capped MTJs

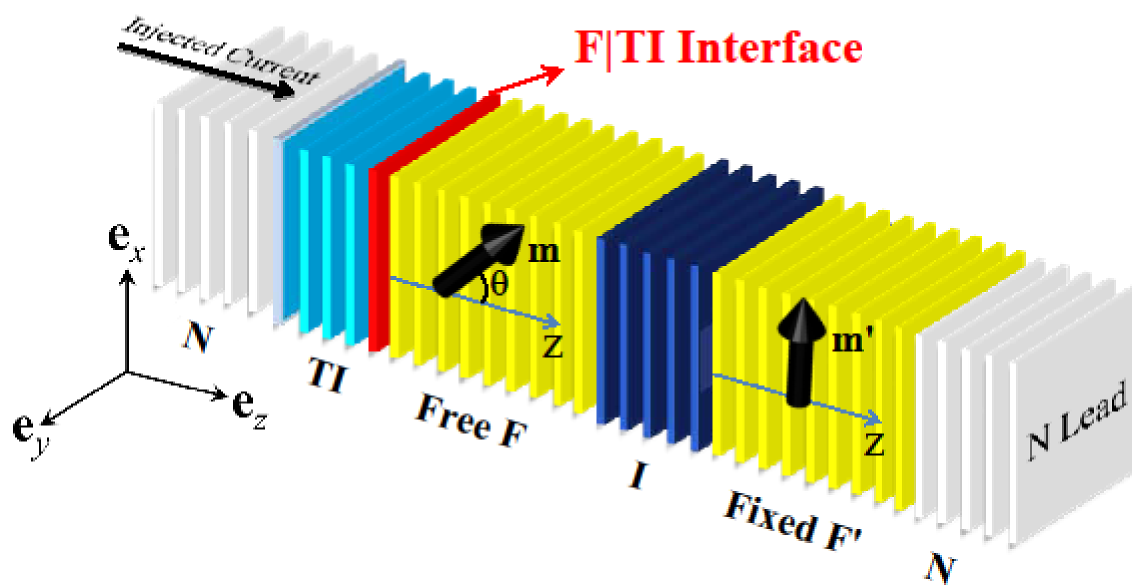
MTJs for STT-MRAM applications

- compromise between large current density (requiring low junction resistance to avoid damage) and readability (requiring large magnetoresistance)

- optimization of the spin polarization across the junction, stabilization of the 'fixed' layer magnetization, and minimization of stray fields often result in complex stacking structures involving more than 10 different layers.







Supplemental Materials to PRL **109**, 166602 (2012)