Anatomy of Spin-Orbit Torques in Topological-Insulator/Ferromagnet Heterostructures

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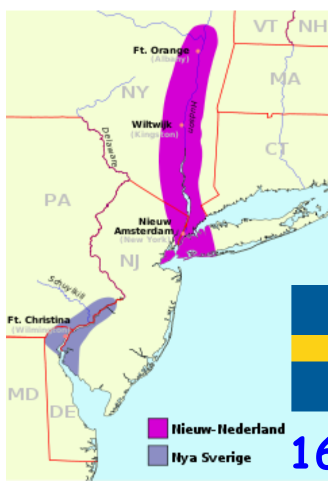
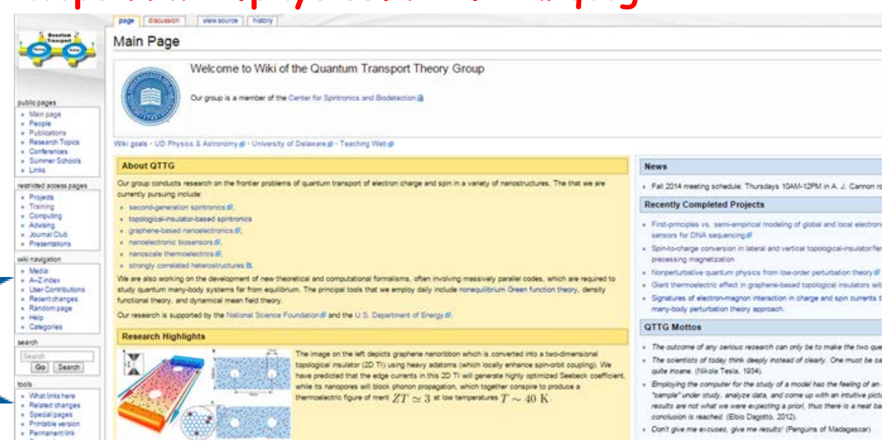
https://wiki.physics.udel.edu/qttg

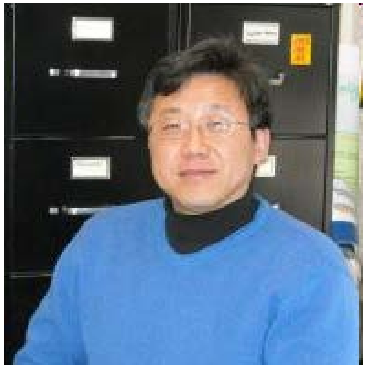


1638–1655



Collaborators

Experiment



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Prof. J.-P. Wang

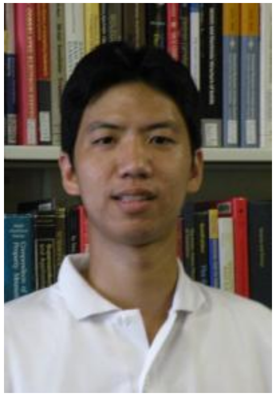
Theory

Dr. Farzad Mahfouzi

Prof. N. Nagaosa

Prof. Nicholas Kioussis

Computation



Dr. Po-Hao Chang

J. M. Marmolejo-Tejada

Dr. Kurt Stokbro

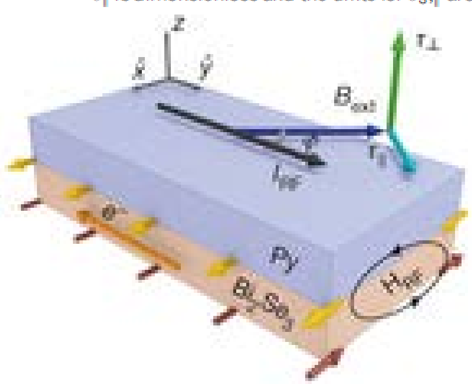
Experiments on SO Torque and Spin-to-Charge Conversion in Lateral TI/F Heterostructures

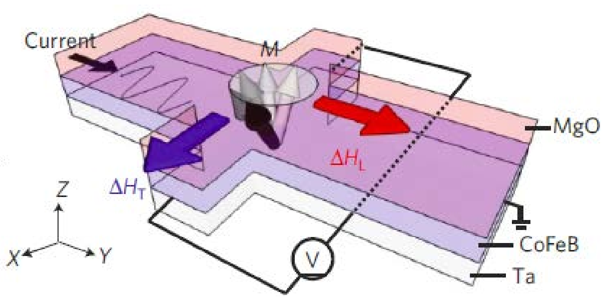
Ralph Lab, Nature **511**, 449 (2014)

Table 1 | Comparison of room-temperature $\sigma_{s,\parallel}$ and $\theta_{s,\parallel}$ for Bi_2Se_3 with other materials

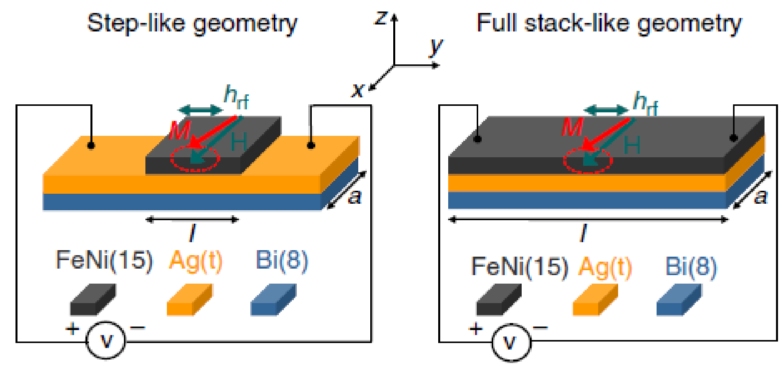
Parameter	Bi_2Se_3 (this work)	Pt (ref. 4)	β-Ta (ref. 6)	Cu(Bi) (ref. 23)	β-W (ref. 24)
$\theta_\parallel$	2.0–3.5	0.08	0.15	0.24	0.3
$\sigma_{S,\parallel}$	1.1–2.0	3.4	0.8	—	1.8

$\theta_\parallel$ is dimensionless and the units for $\sigma_{S,\parallel}$ are $10^5\hbar/2e\ \Omega^{-1}\ m^{-1}$.

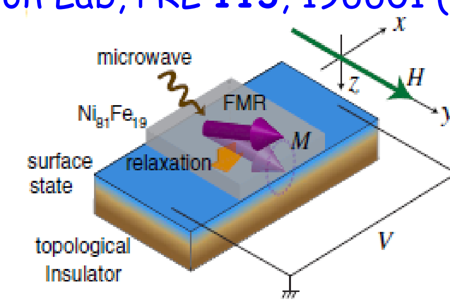




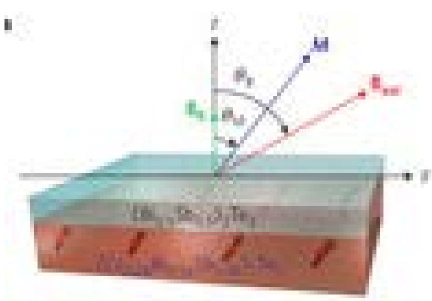
Fert & Vila, Nature Comm. **4**, 2944 (2013)

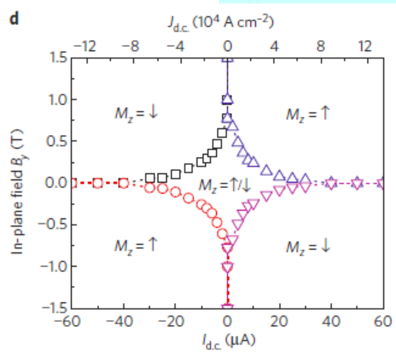


Saitoh Lab, PRL **113**, 196601 (2014)

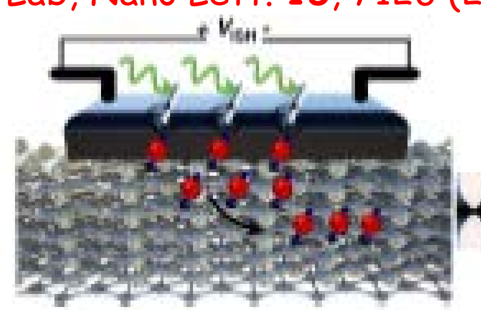


Wang Lab, Nature Mater. **13**, 699 (2014): $\theta_\parallel \simeq 150 - 425$





Wang Lab, Nano Lett. **15**, 7126 (2015)



Yang Lab, PRL **114**, 257202 (2015): $\theta_\parallel \simeq 0.047 \to 0.42$

Current-Driven Nonequilibrium Spin Density on the TI Surface as a Resource for Spintronics

Solid State Communications, Vol. 73, No. 3, pp. 233–235, 1990. 0038–1098/90 $3.00 + .00
Printed in Great Britain. Pergamon Press plc

SPIN POLARIZATION OF CONDUCTION ELECTRONS INDUCED BY ELECTRIC CURRENT IN TWO-DIMENSIONAL ASYMMETRIC ELECTRON SYSTEMS

V.M. Edelstein

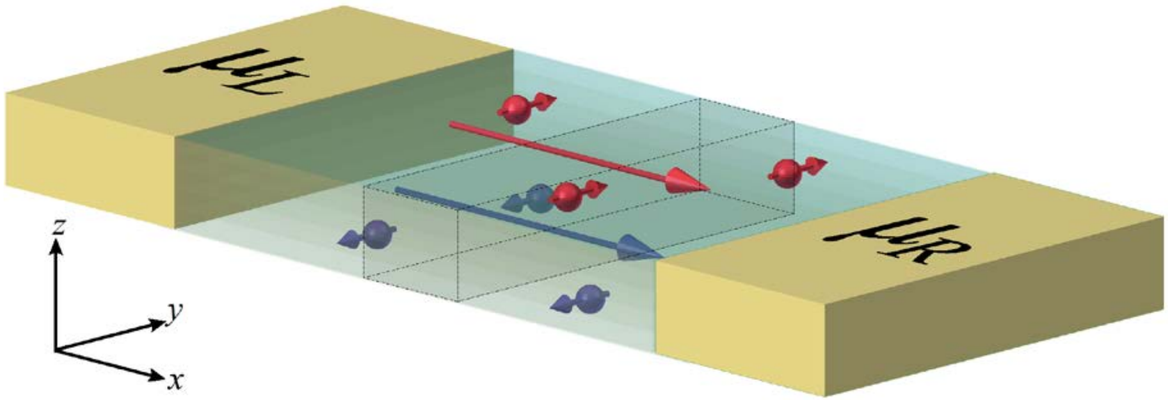
USSR Academy of Sciences, Institute of Solid State Physics, Chernogolovka 142432, USSR

nature materials | INSIGHT | PROGRESS ARTICLE
PUBLISHED ONLINE: 23 APRIL 2012 | DOI: 10.1038/NMAT3305

Spintronics and pseudospintronics in graphene and topological insulators

Dmytro Pesin and Allan H. MacDonald

$$S_y = \beta E_x$$

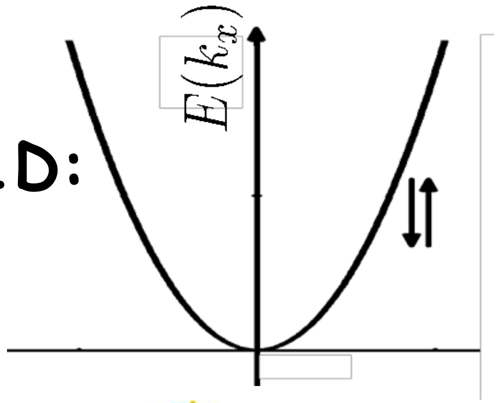


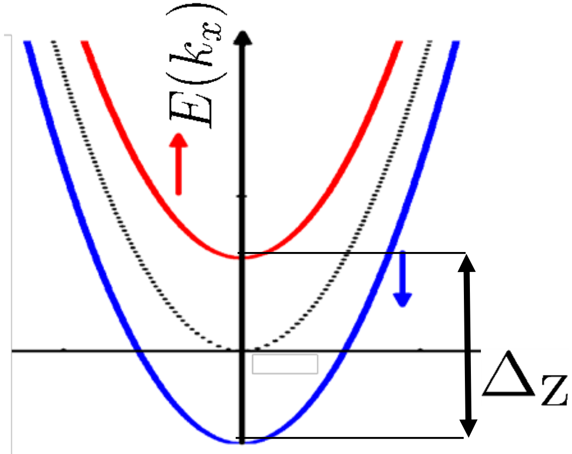
$$\frac{S_y^{\mathrm{Rashba}}}{n} = \frac{e\tau E_x}{p_F}\frac{\alpha}{\hbar v_F} \quad \text{vs.} \quad \frac{S_y^{\mathrm{TI}}}{n} = \frac{e\tau E_x}{p_F}$$

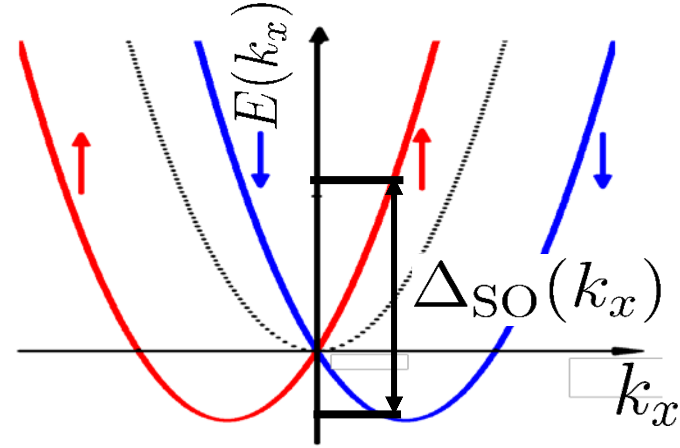
Rashba SO Splitting of Energy Bands

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

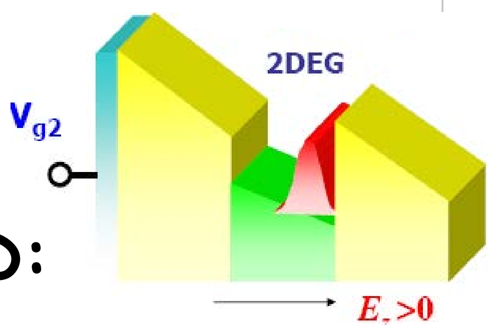
1D:







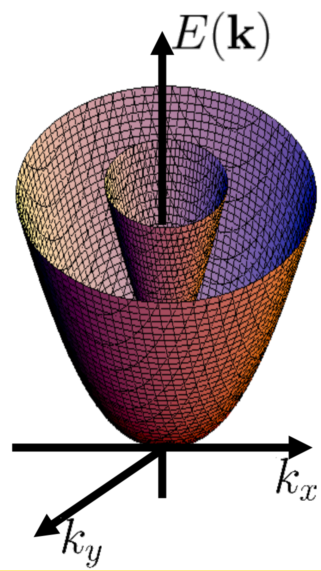
2D:

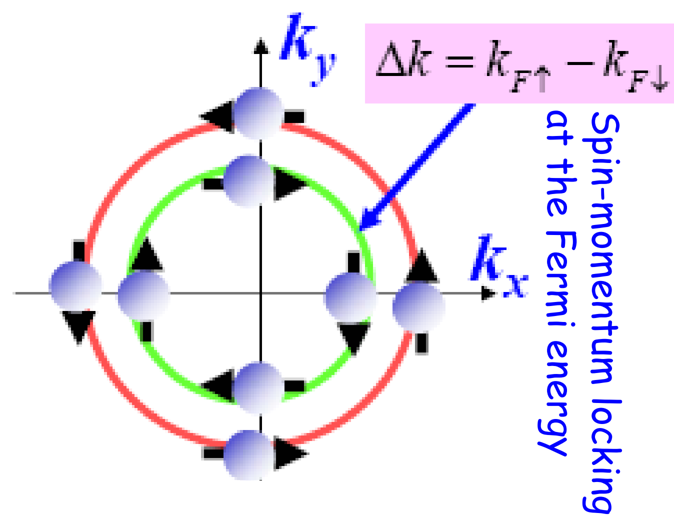


$$\varepsilon(\mathbf{k},\uparrow) = \varepsilon(-\mathbf{k},\downarrow)$$

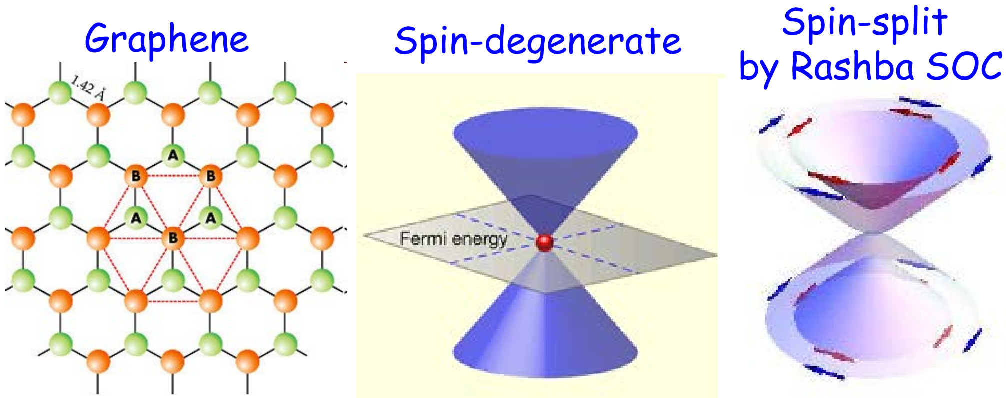
$$\varepsilon(\mathbf{k},\uparrow) \neq \varepsilon(-\mathbf{k},\uparrow)$$

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

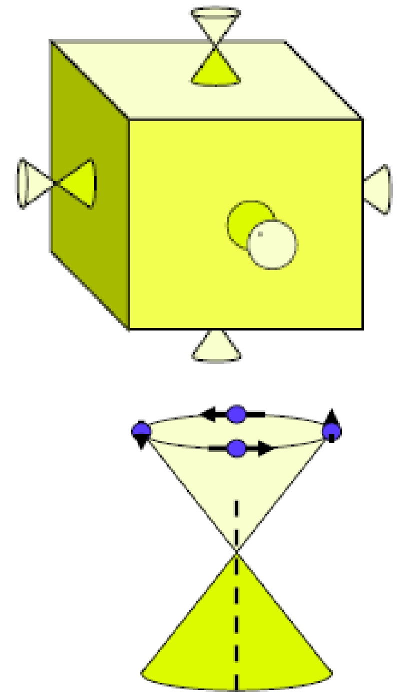




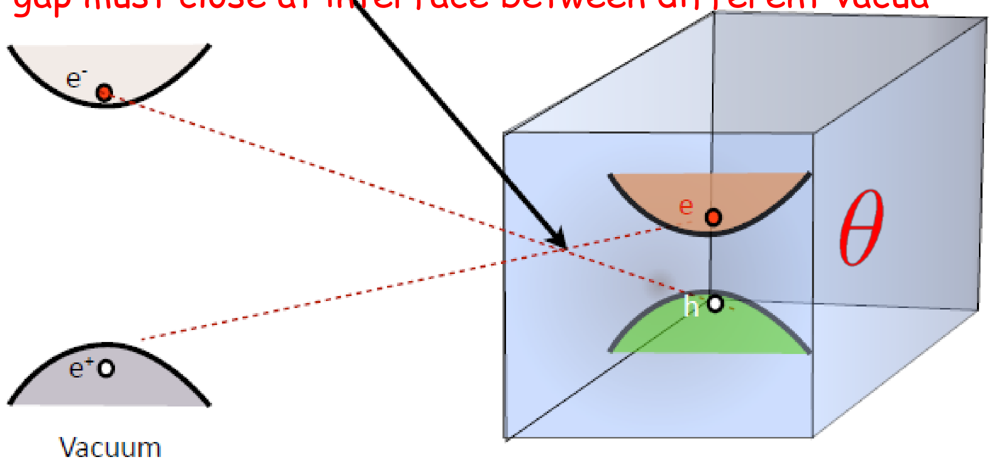
Crash Course on 3D TIs



vs.

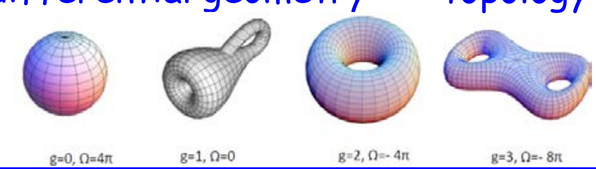


TIs are adiabatically disconnected from vacuum, so the gap must close at interface between different vacua

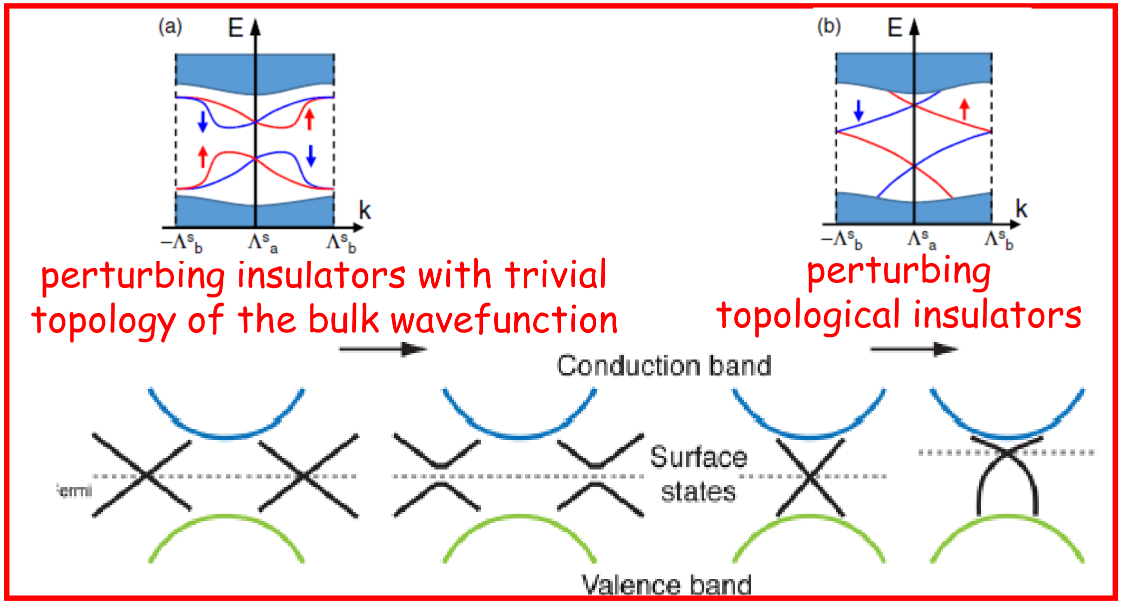


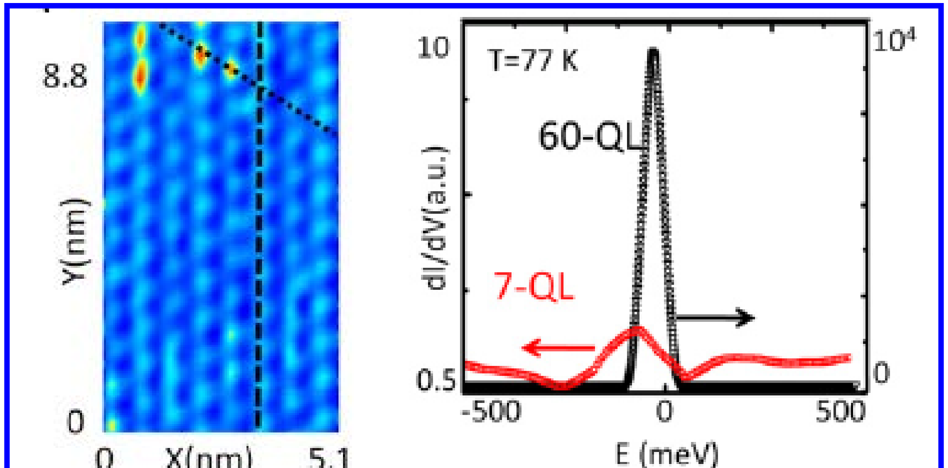
$$\theta = \frac{1}{4\pi}\int_{BZ} d^3k\,\varepsilon^{ijk}\,\mathrm{Tr}\left[\mathcal{A}_i\partial_j\mathcal{A}_k - i\frac{2}{3}\mathcal{A}_i\mathcal{A}_j\mathcal{A}_k\right] = \pi$$

$$\underbrace{\frac{1}{4\pi}\int \kappa dA}_{\text{differential geometry}} = \frac{\Omega}{4\pi} = \underbrace{(1-g)}_{\text{topology}}$$

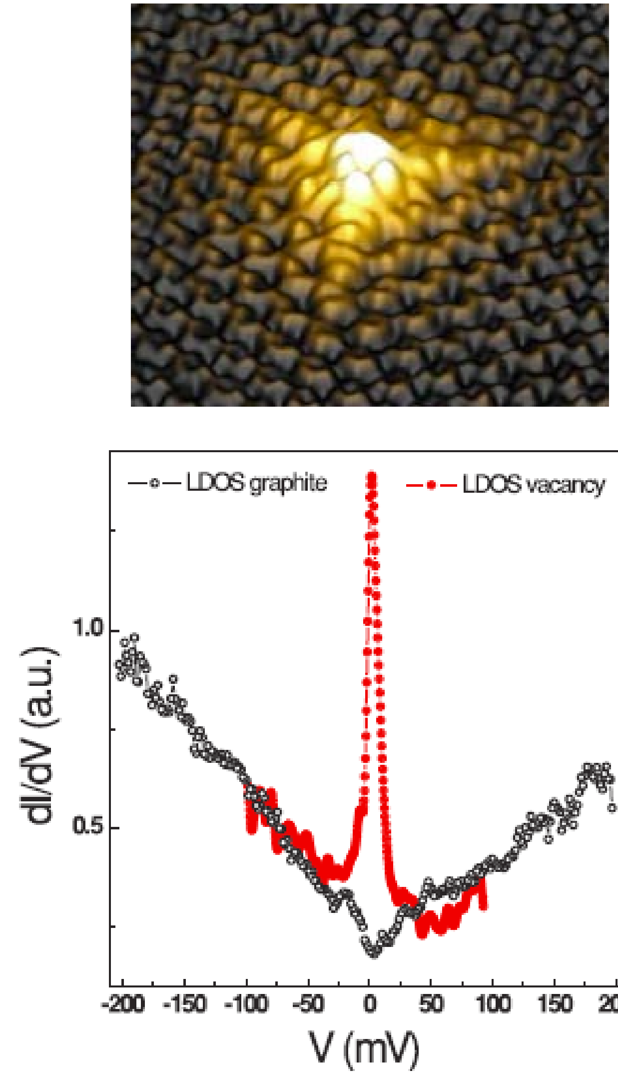


Physical Meaning of Topological Protection



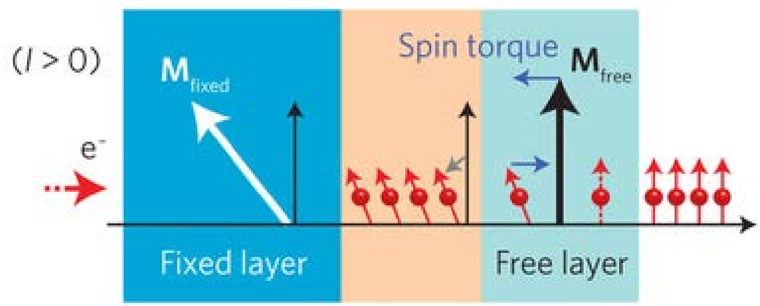


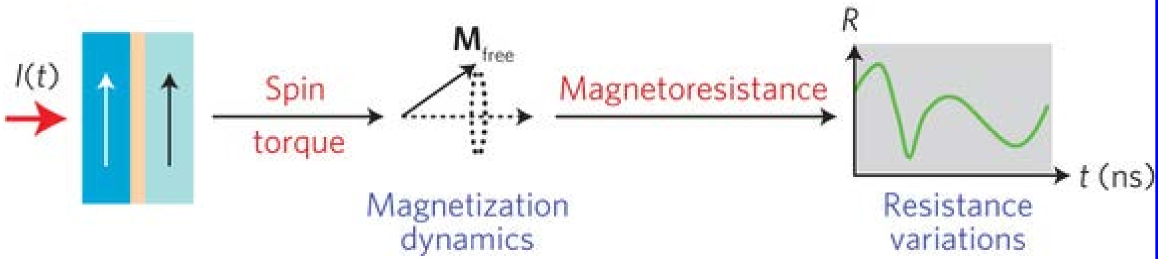
Bi$_2$Se$_3$ surface + impurity: SSC **152**, 747 (2012)

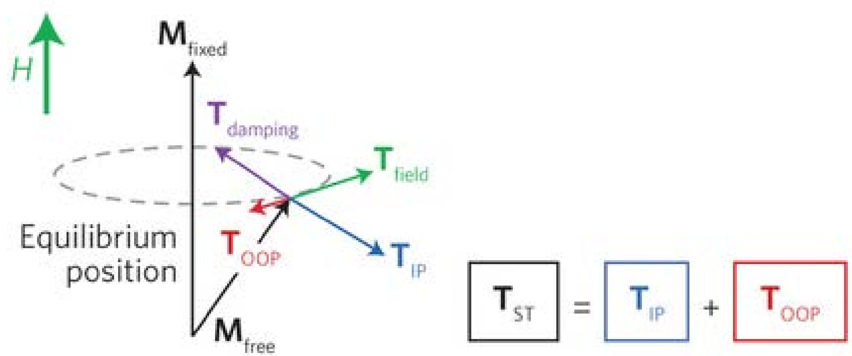


graphene + vacancy: PRL **104**, 096804 (2010)

Crash Course on Spin-Transfer Torque







Learn more about STT from:

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

Current Perspectives

Spin transfer torques

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

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
Vol. 3, No. 2 (2013) 1330002 (17 pages)
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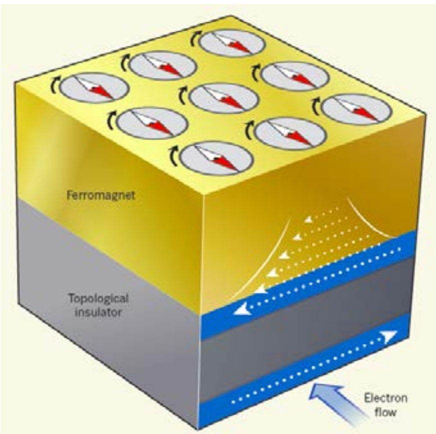
DOI: 10.1142/S2010324713300028
World Scientific www.worldscientific.com

HOW TO CONSTRUCT THE PROPER GAUGE-INVARIANT DENSITY MATRIX IN STEADY-STATE NONEQUILIBRIUM: APPLICATIONS TO SPIN-TRANSFER AND SPIN-ORBIT TORQUES

FARZAD MAHFOUZI and BRANISLAV K. NIKOLIĆ*

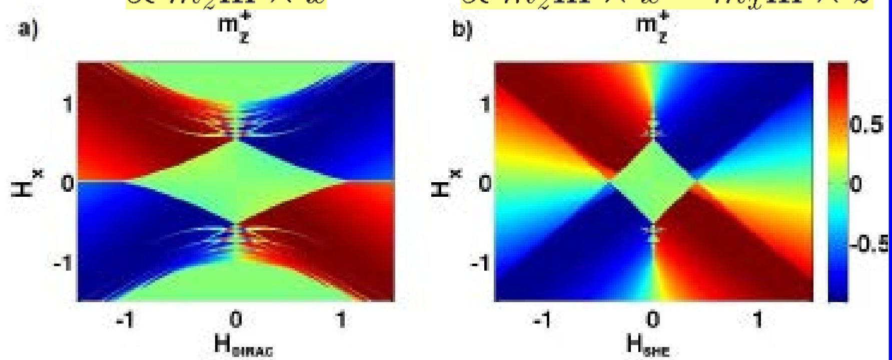
What Can Theory Do for Topological Spintronics: Understand, Control and Design Antidamping SOT



Nature **511**, 449 (2014)
PRB **93**, 125303 (2016)

Berry curvature antidamping torque
$\propto m_z \mathbf{m} \times \hat{x}$

SHE antidamping torque
$\propto m_z \mathbf{m} \times \hat{x} - m_x \mathbf{m} \times \hat{z}$



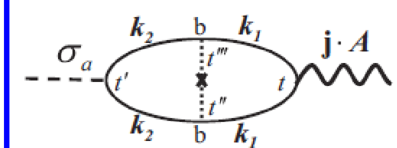
arXiv:1509.06929

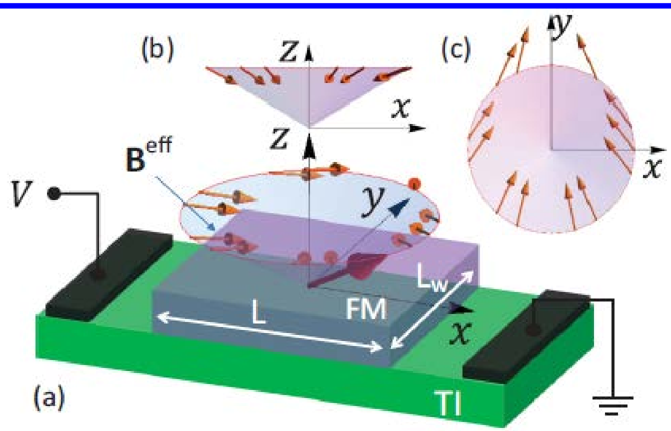
PRB **91**, 134402 (2015)
Nature Nanotech. **9**, 211 (2014)

spin-dependent scattering
PRB **86**, 014416 (2012)

$$\hat{U}_{\rm dis} = \sum_i \delta(\mathbf{r} - \mathbf{r}_i)(u_\downarrow P_+^0 + u_\uparrow P_-^0)$$

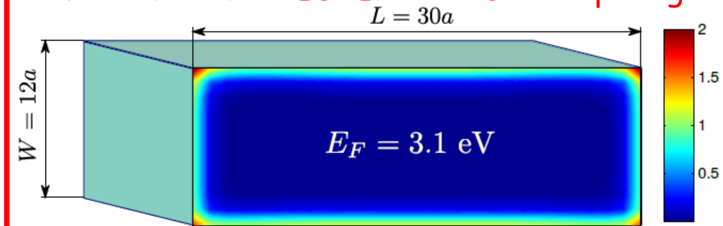
vertex corrections
PRB **92**, 014402 (2015)

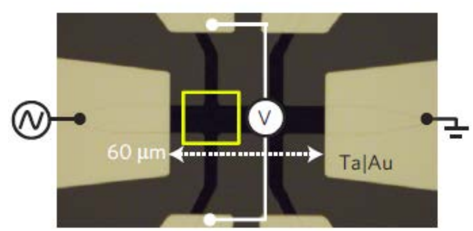


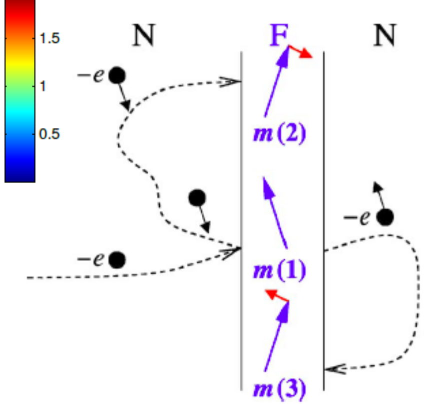


PRB **84**, 113407 (2011)
PRB **86**, 161406(R) (2012)

MISSING INGREDIENTS: 3D transport geometry and N/TI contact







PRL **92**, 026602 (2004)

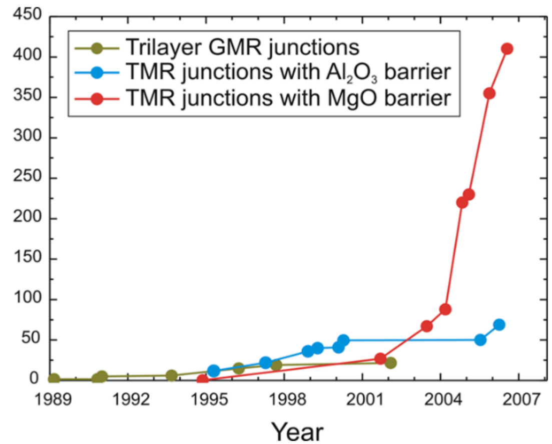
What Can Computation Do for Topological Spintronics: Find Optimal Materials Combinations

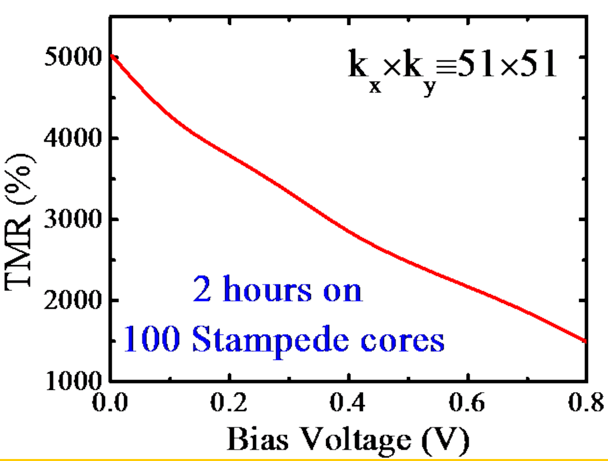
PHYSICAL REVIEW B, VOLUME 63, 054416

Spin-dependent tunneling conductance of Fe|MgO|Fe sandwiches

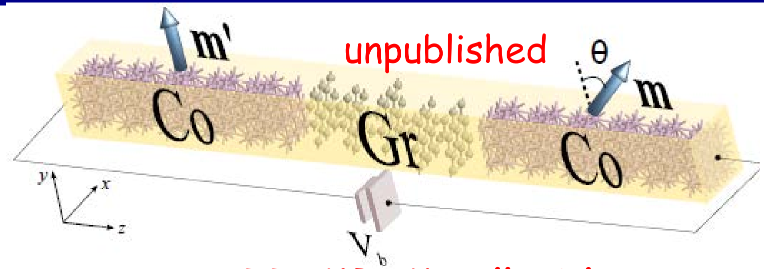
W. H. Butler, X.-G. Zhang, and T. C. Schulthess
Oak Ridge National Laboratory, Oak Ridge, Tennessee 37831-6114

J. M. MacLaren
Department of Physics, Tulane University, New Orleans, Louisiana 70018

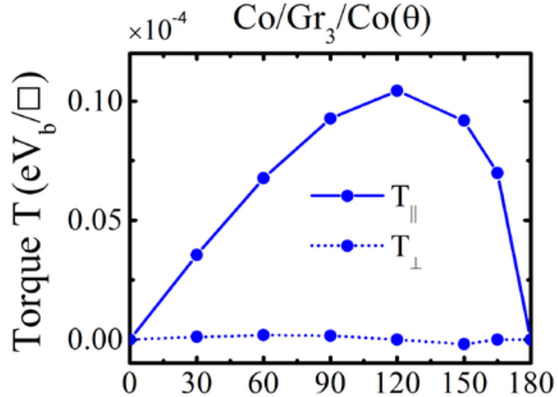


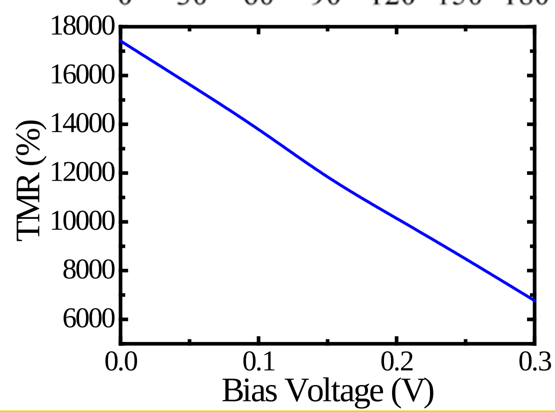


unpublished

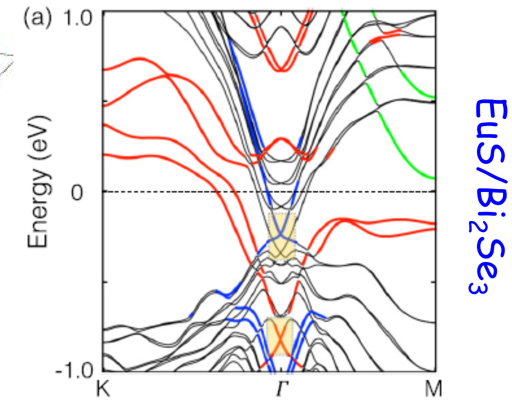


STT-MRAM cell with high TMR and low RA

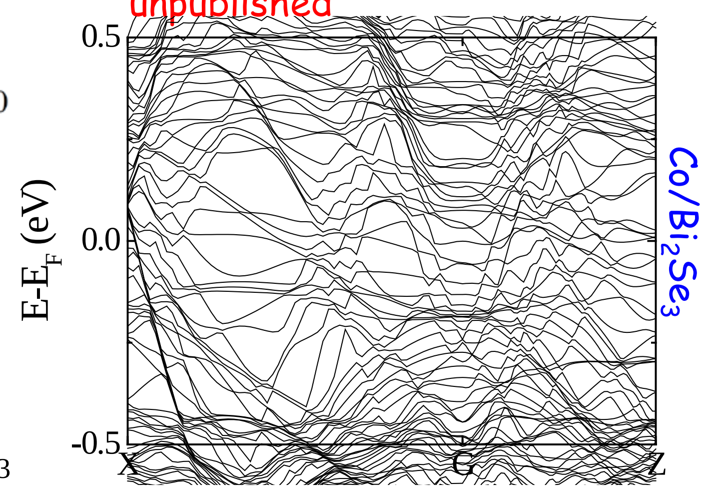




PRB **90**, 115103 (2014)



unpublished



Spin Density and STT from NEGF Formalism

❑Fundamental quantities of NEGF formalism:

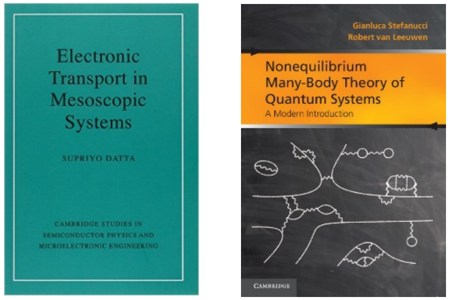
density of available quantum states:

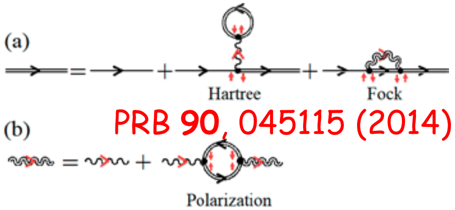
$$G^r_{\sigma\sigma'}(t,t') = -\frac{i}{\hbar}\Theta(t-t')\langle\{\hat{c}_{\mathbf{r}\sigma}(t),\hat{c}^\dagger_{\mathbf{r}'\sigma'}(t')\}\rangle$$

how are those states occupied:

$$G^<_{\sigma\sigma'}(t,t') = \frac{i}{\hbar}\langle\hat{c}^\dagger_{\mathbf{r}'\sigma'}(t')\hat{c}_{\mathbf{r}\sigma}(t)\rangle$$

Learn more about NEGF from:





PRB **90**, 045115 (2014)

❑NEGF for steady-state transport:

$$G^r(t,t') \rightarrow G^r(t-t') \xrightarrow{\text{FT}} G^r(E)$$

$$G^<(t,t') \rightarrow G^<(t-t') \xrightarrow{\text{FT}} G^<(E)$$

$$\boldsymbol{\rho}_{\text{eq}} = -\frac{1}{\pi}\int_{-\infty}^{+\infty} dE\, \text{Im}\,\mathbf{G}^r(E) f(E-E_F)$$

$$\boldsymbol{\rho}_{\text{neq}} = \frac{1}{2\pi i}\int_{-\infty}^{+\infty} dE\, \mathbf{G}^<(E)$$

❑NEGF-based expression for spin-transfer torque:

SPIN **3**, 1330002 (2013)

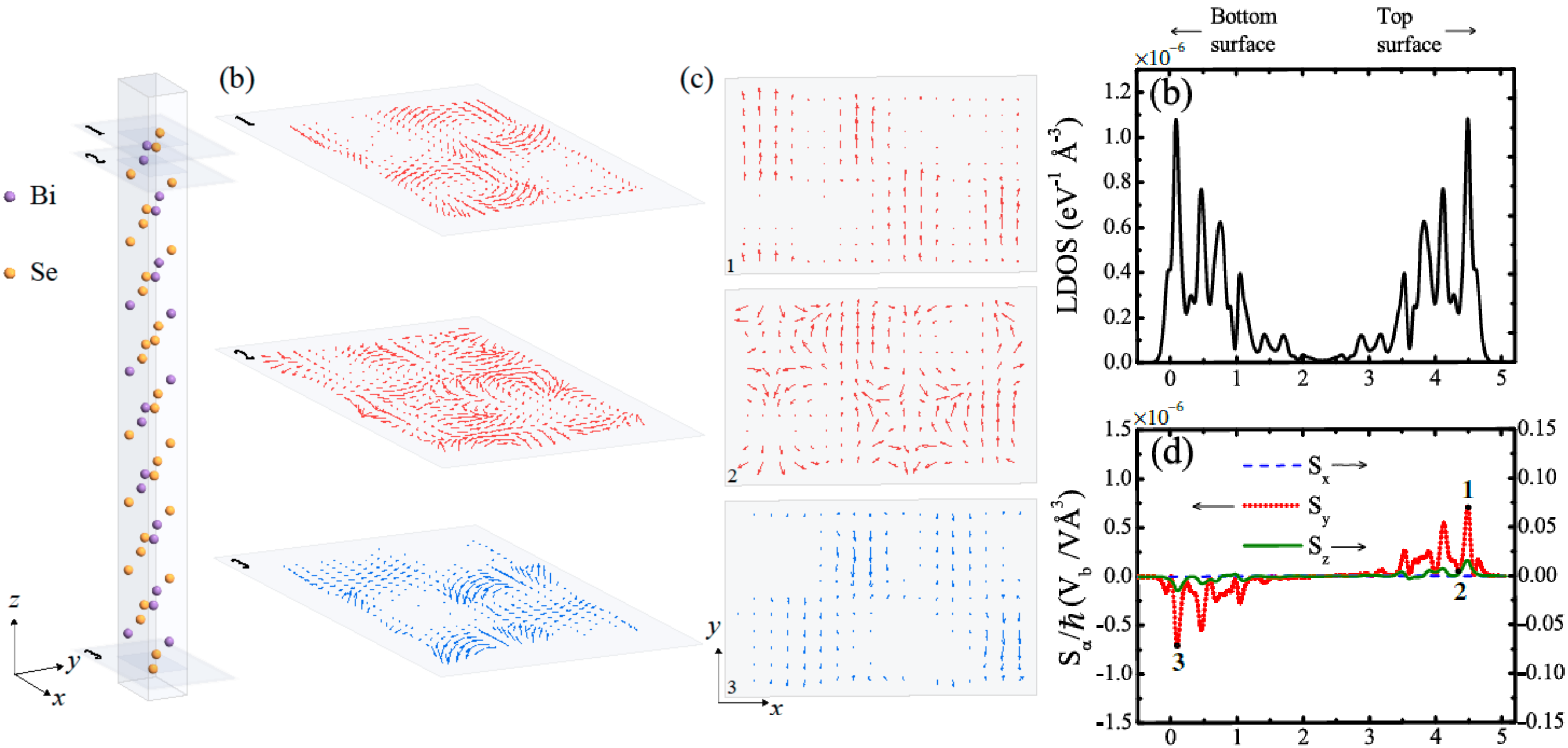
$$\hat{H} = -\frac{\hbar^2\nabla^2}{2m} + V_{\text{H}}(\mathbf{r}) + V_{\text{XC}}(\mathbf{r}) + V_{\text{ext}}(\mathbf{r}) - \boldsymbol{\sigma}\cdot\mathbf{B}_{\text{XC}}(\mathbf{r}) \Rightarrow \hat{\mathbf{T}} = \frac{d\hat{\mathbf{S}}}{dt} = \frac{1}{2i}[\hat{\boldsymbol{\sigma}},\hat{H}]$$

$$\mathbf{T} = \text{Tr}\,[\hat{\rho}_{\text{neq}}\hat{\mathbf{T}}] \Leftrightarrow \mathbf{T} = \int_F d^3r\, \mathbf{m}_{\text{neq}}(\mathbf{r}) \times \mathbf{B}_{\text{XC}}(\mathbf{r})$$

Most general torque formula valid in the presence of SOC and other spin-nonconserving processes

Current-Driven Nonequilibrium Spin Texture on the Surface and in the Bulk of Bi_2Se_3

PRB **92**, 201406(R) (2015)



Adiabatic Expansion of NEGFs in Derivatives of Slow Magnetization

$$\mathbf{G}(E,t) \simeq \mathbf{G}_t + i(\partial \mathbf{G}_t/\partial E)(\partial \mathbf{U}_t/\partial t)\mathbf{G}_t$$

$$\mathbf{G}^<(t,t) \simeq \int \frac{dE}{2\pi}[\mathbf{G}(E,t) - \mathbf{G}^\dagger(E,t)]f + i\sum_{\alpha=L,R} f' e V_\alpha \mathbf{G}_t \mathbf{\Gamma}_\alpha \mathbf{G}_t^\dagger + i f' \mathbf{G}_t \frac{\partial \mathbf{U}_t}{\partial t}\mathbf{G}_t^\dagger$$

$$\boldsymbol{\rho}(t) = \frac{1}{i}\mathbf{G}^<(t,t)$$

$$T^{\alpha\beta}(E) = \mathrm{Tr}\left[\mathbf{\Gamma}_\alpha \mathbf{G}_t \mathbf{\Gamma}_\beta \mathbf{G}_t^\dagger\right]$$ charge current

$$T^{\alpha i}(E) = \mathrm{Tr}\left[\mathbf{1}_m \boldsymbol{\sigma}_i \mathbf{G}_t^\dagger \mathbf{\Gamma}_\alpha \mathbf{G}_t\right]$$ spin torque

$$T^{i\alpha}(E) = \mathrm{Tr}\left[\mathbf{1}_m \boldsymbol{\sigma}_i \mathbf{G}_t \mathbf{\Gamma}_\alpha \mathbf{G}_t^\dagger\right]$$ charge pumping

Gilbert damping

$$T^{ij}(E) = \mathrm{Tr}\left[\mathbf{1}_m \boldsymbol{\sigma}_i (\mathbf{G}_t^\dagger - \mathbf{G}_t)\mathbf{1}_m \boldsymbol{\sigma}_j (\mathbf{G}_t - \mathbf{G}_t^\dagger)\right]$$

$\boldsymbol{\rho}$ =

$$\boldsymbol{\rho}_{\rm oo} = \int dE (f_L - f_R)[\mathbf{G}\mathbf{\Gamma}_L\mathbf{G}^\dagger - \mathbf{G}^\dagger\mathbf{\Gamma}_L\mathbf{G} - \mathbf{G}\mathbf{\Gamma}_R\mathbf{G}^\dagger + \mathbf{G}^\dagger\mathbf{\Gamma}_R\mathbf{G}]/8\pi$$ gives field-like torque

+

$$\boldsymbol{\rho}_{\rm oe} = \int dE (f_L - f_R)[\mathbf{G}\mathbf{\Gamma}_L\mathbf{G}^\dagger + \mathbf{G}^\dagger\mathbf{\Gamma}_L\mathbf{G} - \mathbf{G}\mathbf{\Gamma}_R\mathbf{G}^\dagger - \mathbf{G}^\dagger\mathbf{\Gamma}_R\mathbf{G}]/8\pi$$ gives antidamping torque

+

$$\boldsymbol{\rho}_{\rm ee} = \int dE (f_L + f_R)[-\mathrm{Im}\mathbf{G}]/2\pi$$

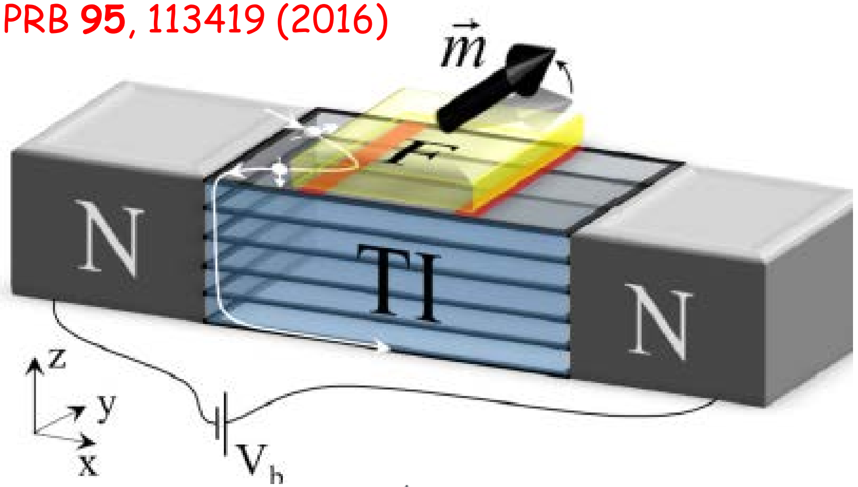
+

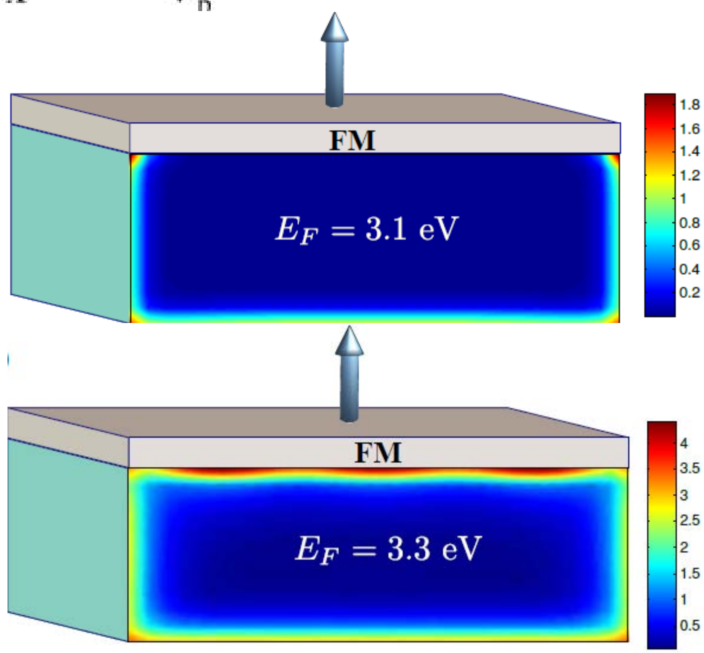
$$\boldsymbol{\rho}_{\rm eo} \equiv 0$$

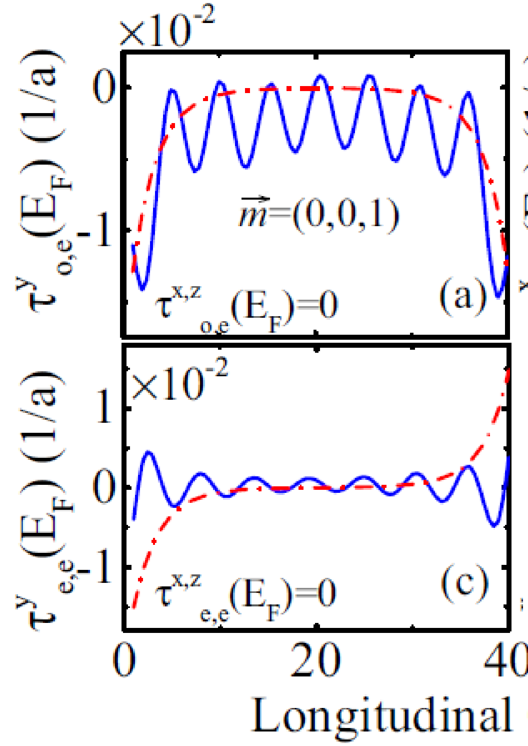
PRB **95**, 113419 (2016)

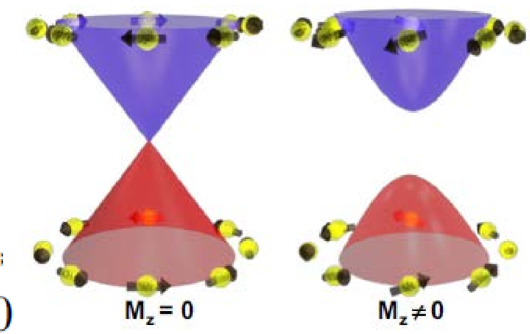
Spatial Profile of Antidamping SO Torque and the Role of Evanescent Wavefunctions

PRB **95**, 113419 (2016)

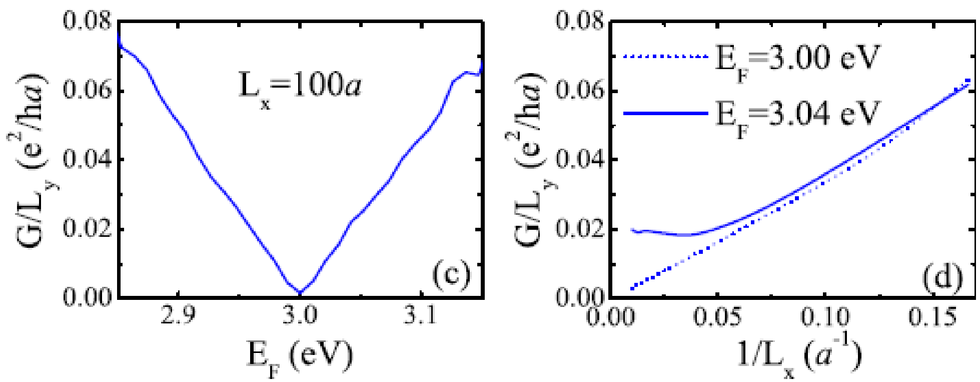






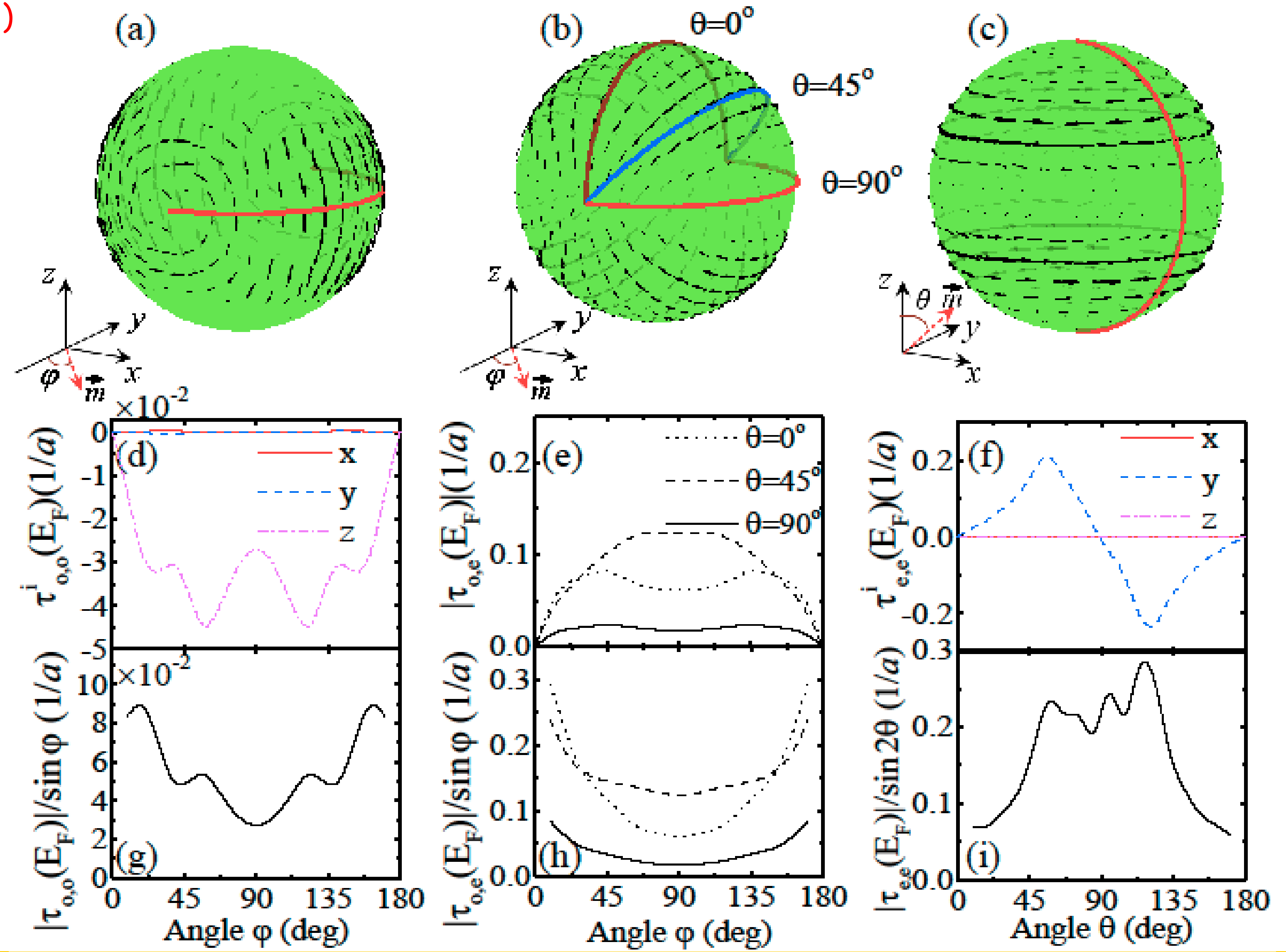


PRB **89**, 195418 (2014)

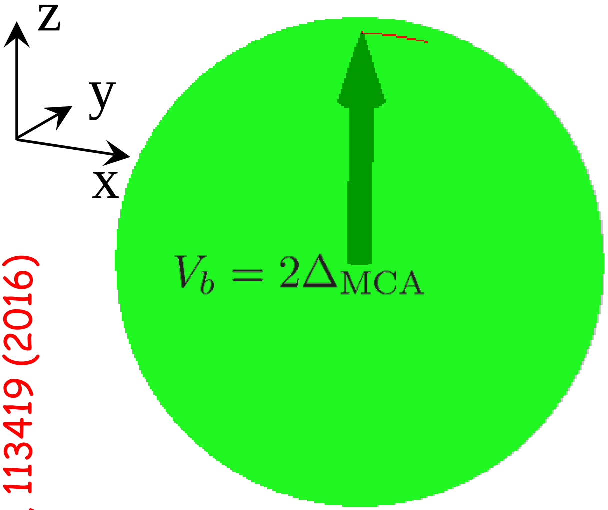


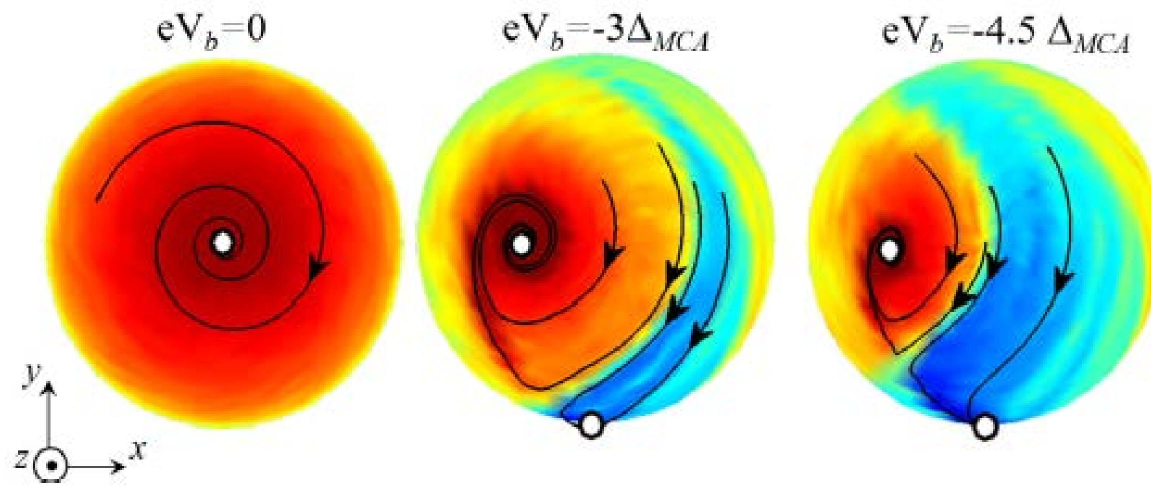
Angular Dependence of SO Torque in Lateral TI/F Heterostructures

PRB **95**, 113419 (2016)

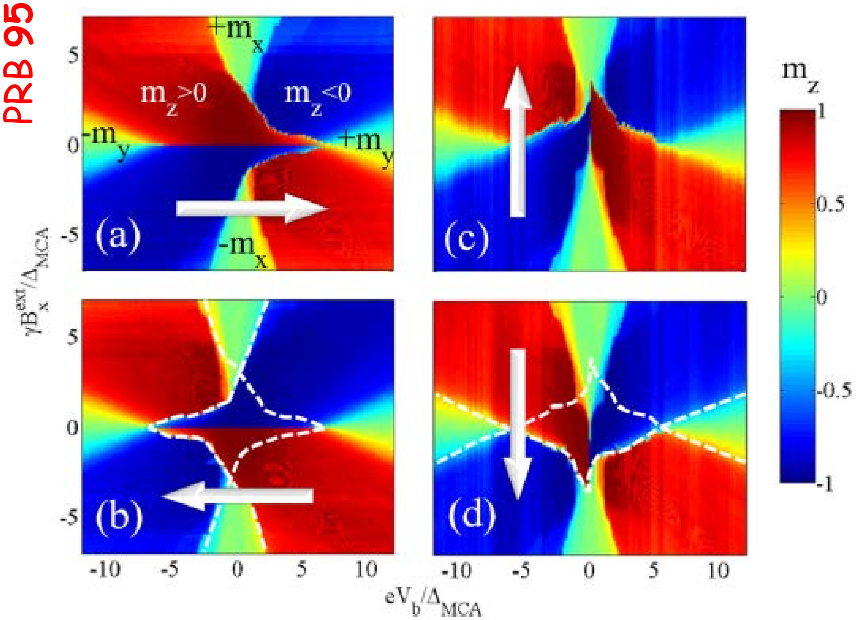


LLG Simulations of Magnetization Reversal and Switching Phase Diagram for TI/F Bilayer

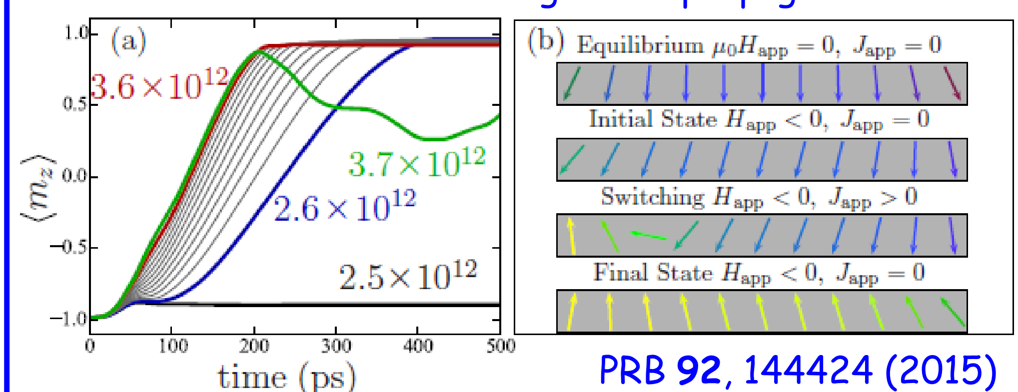




PRB **95**, 113419 (2016)

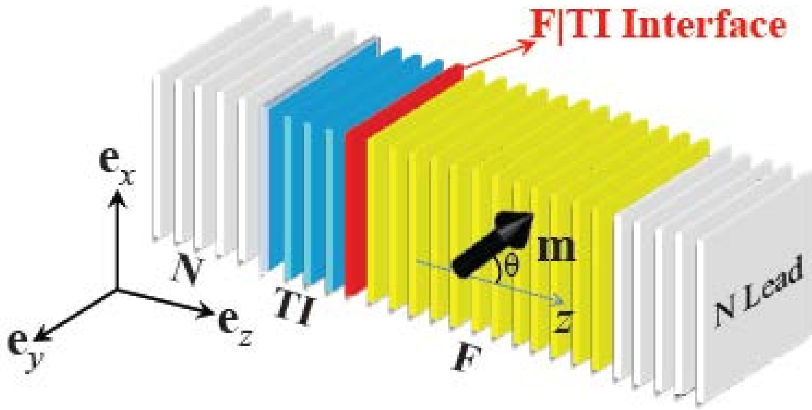


SOT induced magnetization reversal by domain nucleation at the edges and propagation

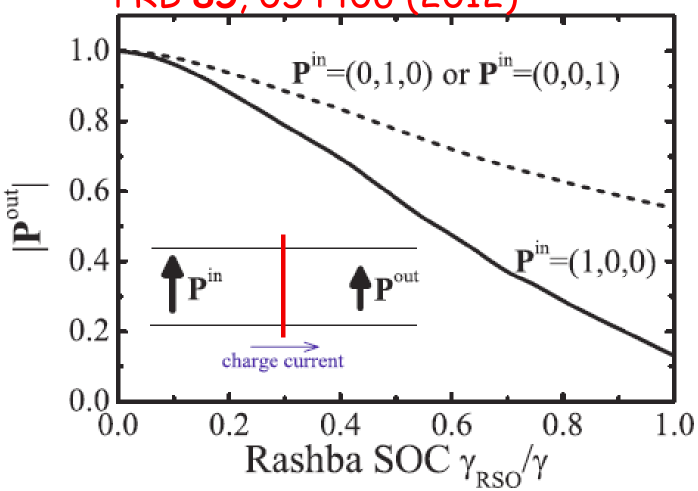


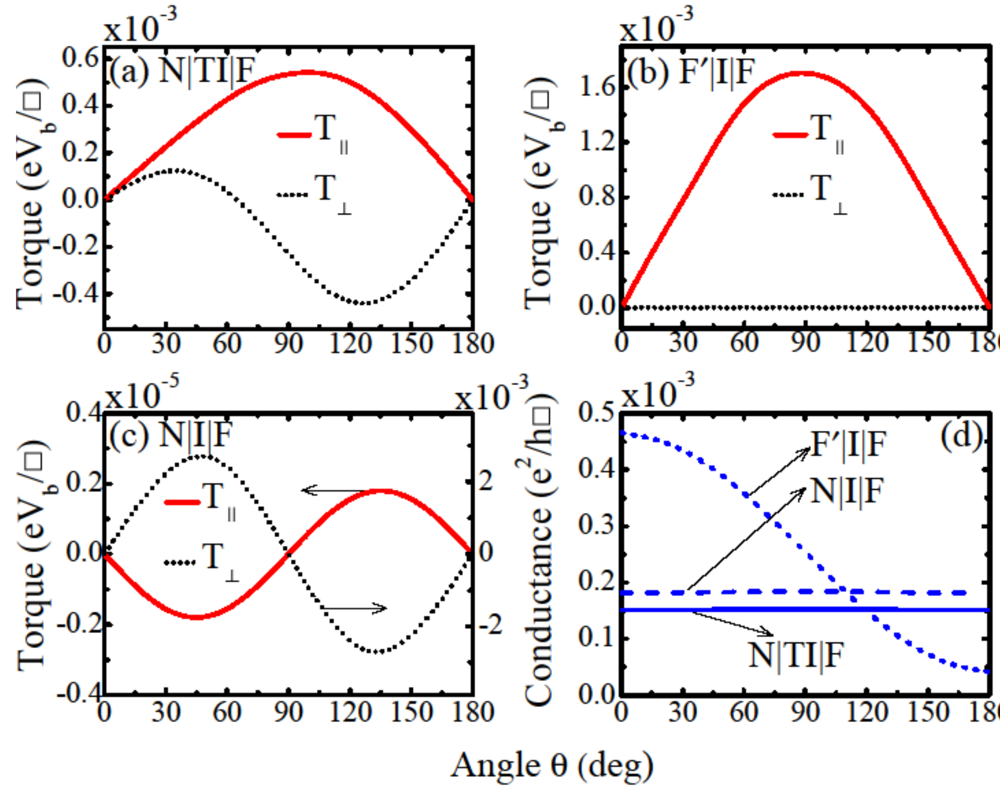
PRB **92**, 144424 (2015)
APL **105**, 212402 (2014)

SO Torque in Vertical TI/F Heterostructures



PRB **85**, 054406 (2012)





PRL 109, 166602 (2012)

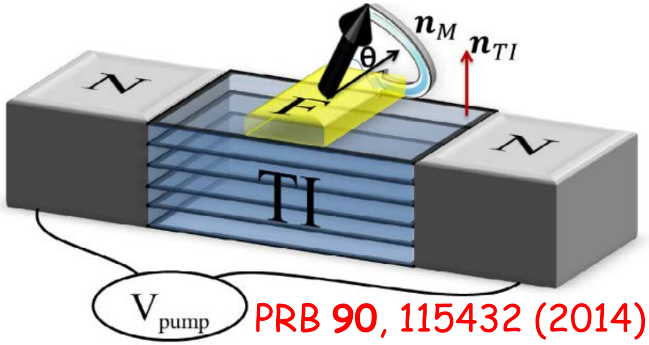
$$\mathbf{T} = \mathbf{T}_\parallel + \mathbf{T}_\perp = \tau_\parallel \mathbf{m} \times (\mathbf{m} \times \mathbf{e}_z) + \tau_\perp \mathbf{m} \times \mathbf{e}_z$$

PRB **71**, 195328 (2005)

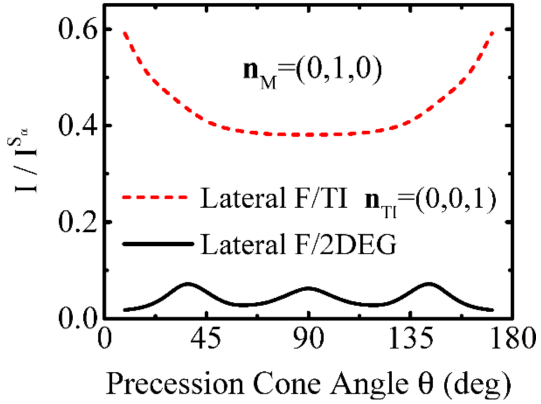
$$\hat{\rho}^{out} = \frac{1}{2}(1 + \mathbf{P}^{out} \cdot \boldsymbol{\sigma})$$

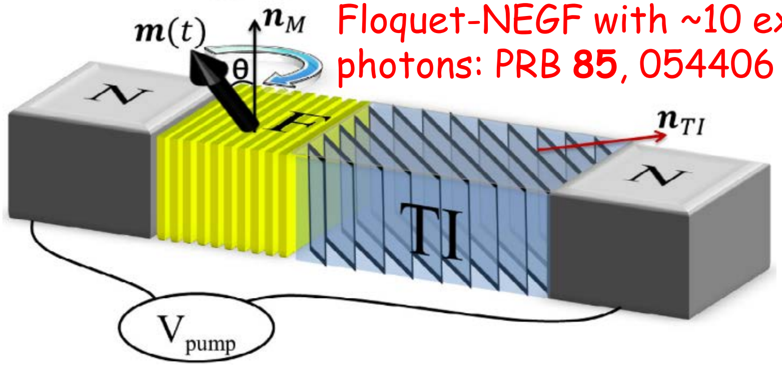
$$\hat{\rho}^{out} = \frac{e^2/h}{n_\uparrow(G^{\uparrow\uparrow} + G^{\downarrow\uparrow}) + n_\downarrow(G^{\uparrow\downarrow} + G^{\downarrow\downarrow})} \sum_{n',n=1}^{M} \begin{pmatrix} |\mathbf{t}_{n'n,\uparrow\uparrow}|^2 + |\mathbf{t}_{n'n,\uparrow\downarrow}|^2 & \mathbf{t}_{n'n,\uparrow\uparrow}\mathbf{t}^*_{n'n,\downarrow\uparrow}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

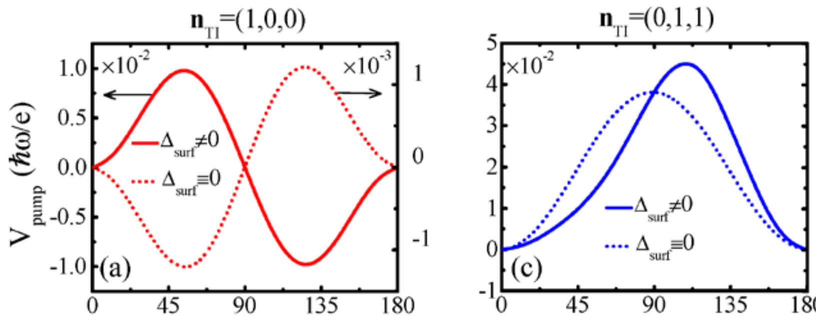
Spin Pumping-to-Charge Conversion in Lateral and Vertical TI/F Heterostructures



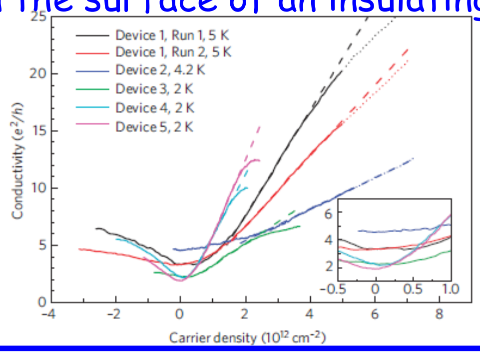
PRB **90**, 115432 (2014)
Floquet-NEGF with ~10 exchanged photons: PRB **85**, 054406 (2012)





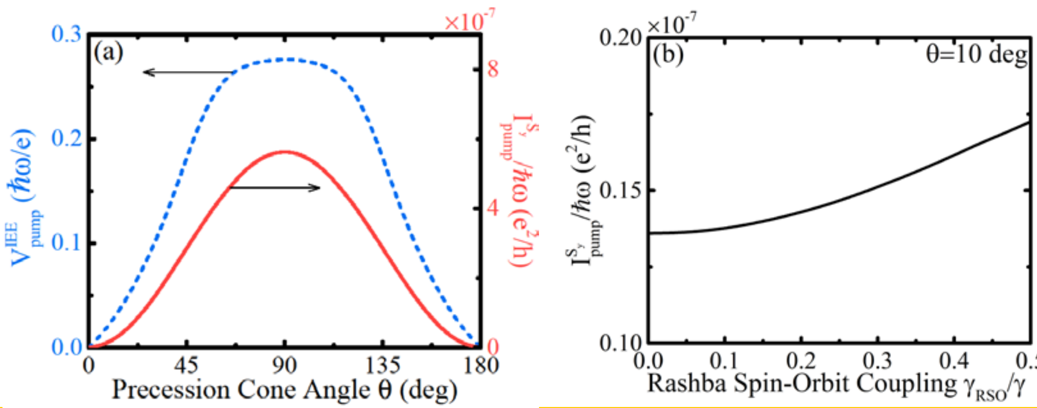


Ambipolar electronic transport on the surface of an insulating bulk

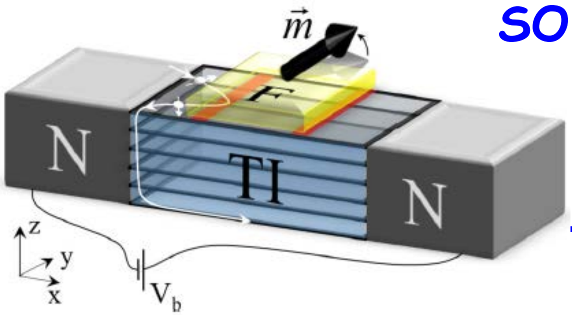


Nature Phys. **8**, 459 (2012)

Nano Lett. **15**, 7126 (2015)



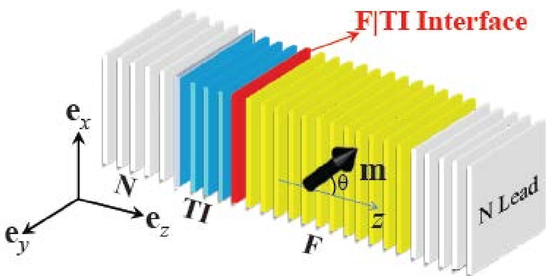
Conclusions and Open Questions in Pictures

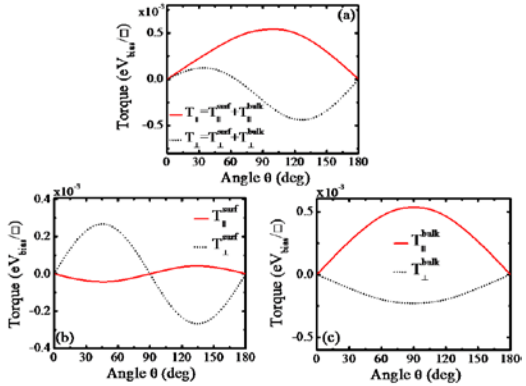


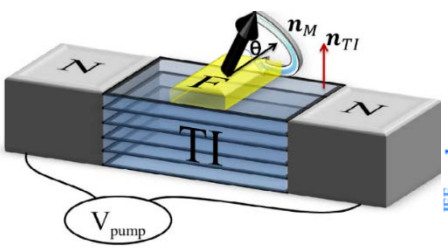
SO torque

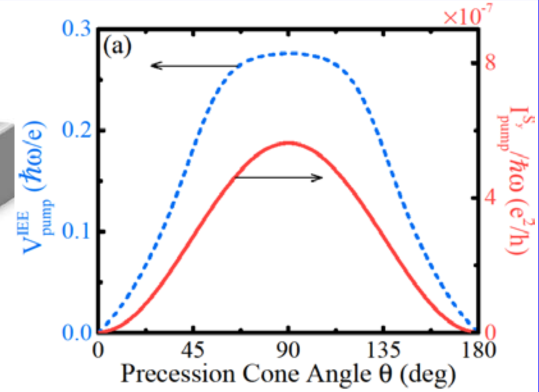
Open questions:

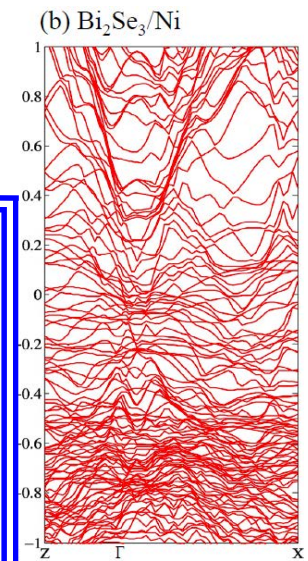
- hybridization between TI and F states
- SO torque from first principles











Spin-to-charge conversion