Spin orbit fields at the Fe/GaAs(001) interface

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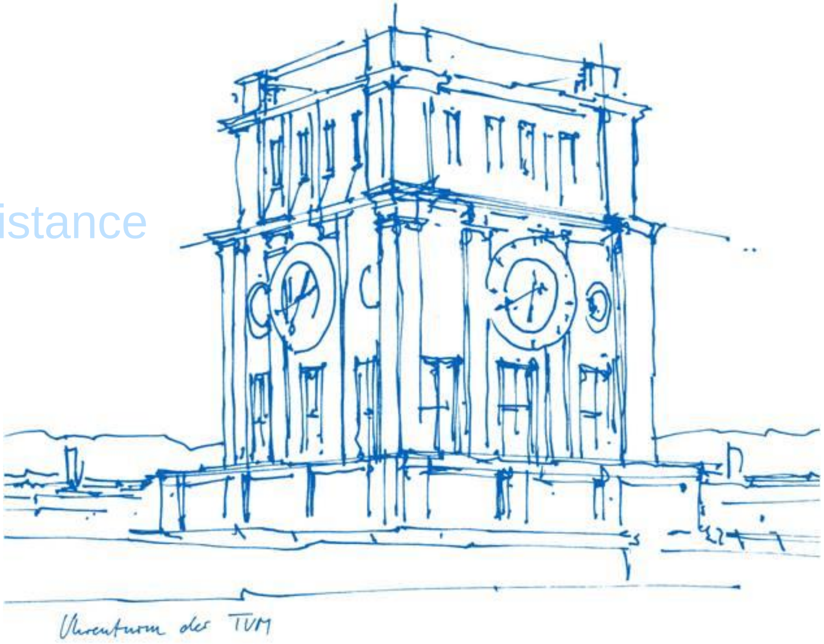
Physik-Department

- Fe/GaAs system
- TAMR & Crystalline anisotropic magneto-resistance
- Spin Orbit FMR
- Anisotropic damping
- Voltage control of spin orbit fields



Universität Regensburg

Lin Chen, M. Decker, M. Buchner, M. Kronseder, R. Islinger, P. Högl, M. Gmitra, D. Schuh, D. Bougeard, J. Fabian, D. Weiss & C. H. Back

Fakultät für Physik, Universität Regensburg, Germany

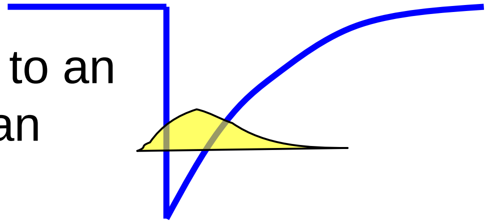
DFG: SFB 689 „Spin Phenomena in Reduced Dimensions“
SFB 1277 „Emergent Relativistic Effects in Condensed Matter“

AvH foundation (Lin Chen)

Alexander von Humboldt
Stiftung/Foundation

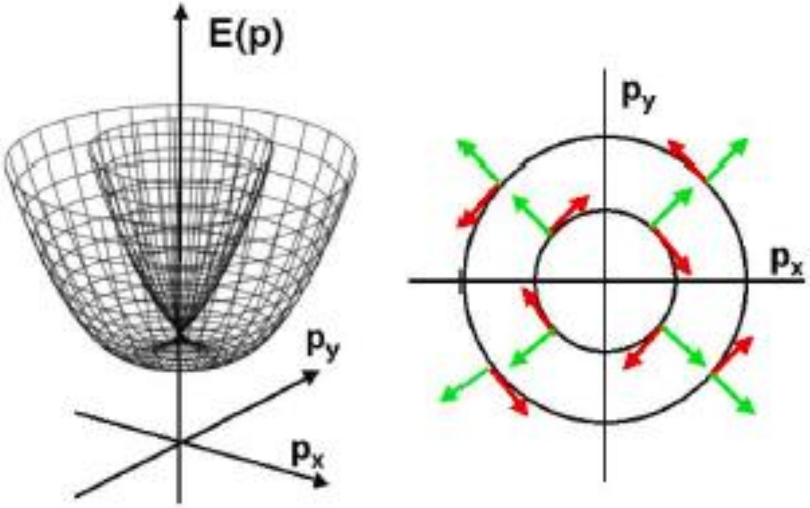
Bychkov-Rashba:

The electric field due in an asymmetric quantum well leads to an additional term in the Hamiltonian. It can be expressed by an effective magnetic field leading to k-linear terms.



$$\boxed{H = \frac{p^2}{2m} - \frac{\lambda}{\hbar}\vec{\sigma}\times\left(\hat{z}\times\vec{p}\right)}$$

λ: Rashba coupling constant



↑ momentum

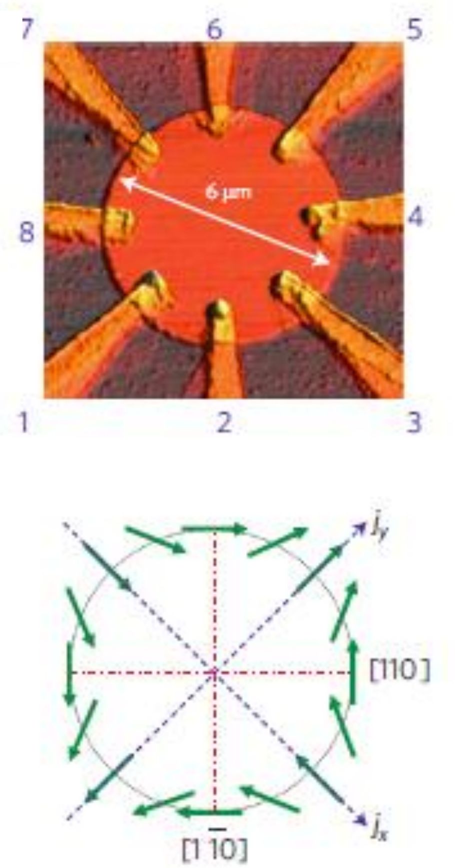
↑ spin

J. Sinova et al., Phys. Rev. Lett. **92**, 126603 (2004)

Bulk inversion asymmetry leads to Dresselhaus terms

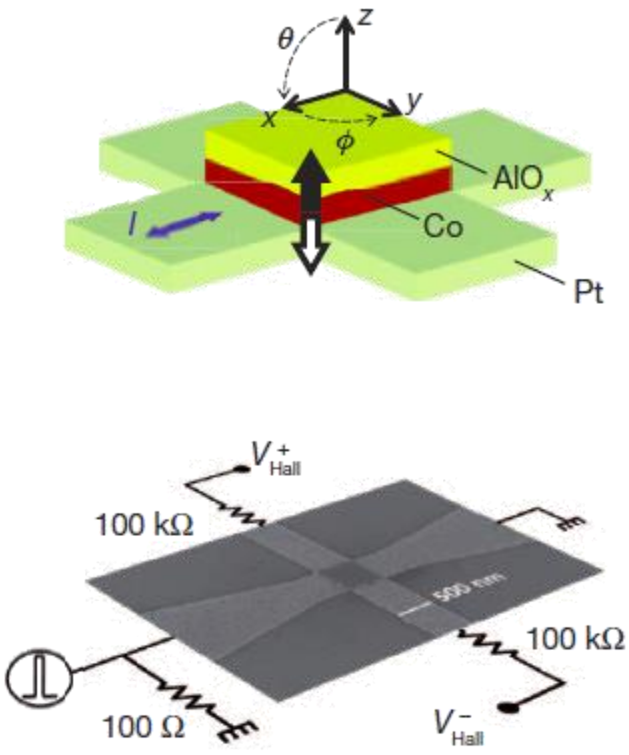
Y. A. Bychkov, E. I. Rashba, *J. Phys. C: Solid State Phys.* **17**, 6039 (1984)

(interfacial) Spin Orbit Torques



Chernyshov et al., Nat. Phys. **5**, 656 (2009)

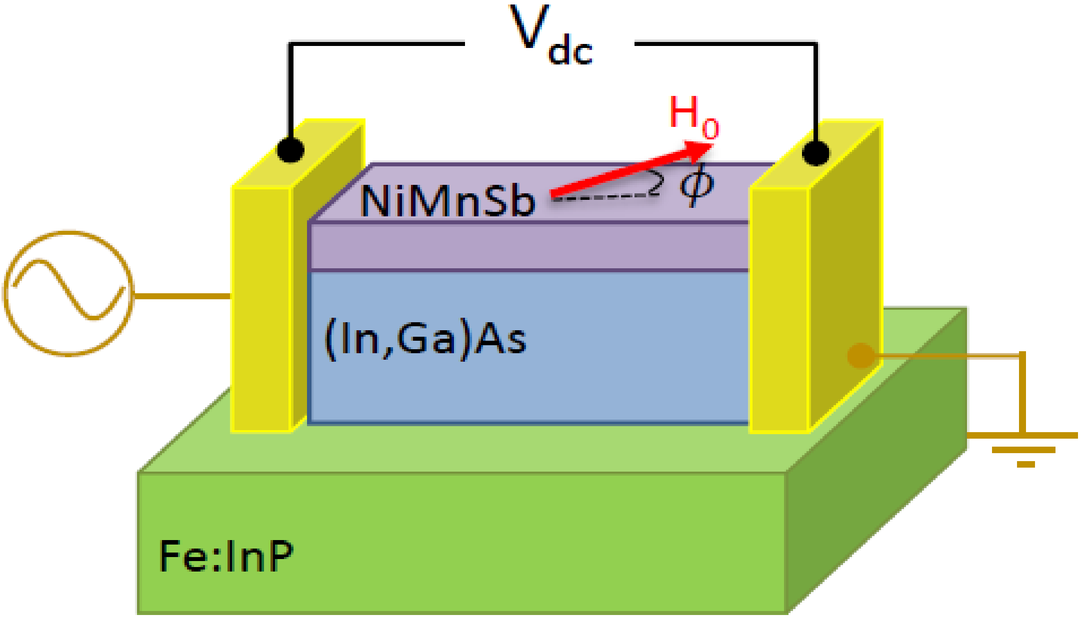
single crystalline material (GaMnAs)
bulk



Miron et al., Nature **476**, 189 (2011)

polycrystalline material (Pt/Co/AlO$_x$)
interface

Spin Orbit Torques



Ciccarelli et al., Nat. Phys. (2016) doi:10.1038/nphys3772

single crystalline material (NiMnSb), room temperature
bulk

Fe/GaAs system

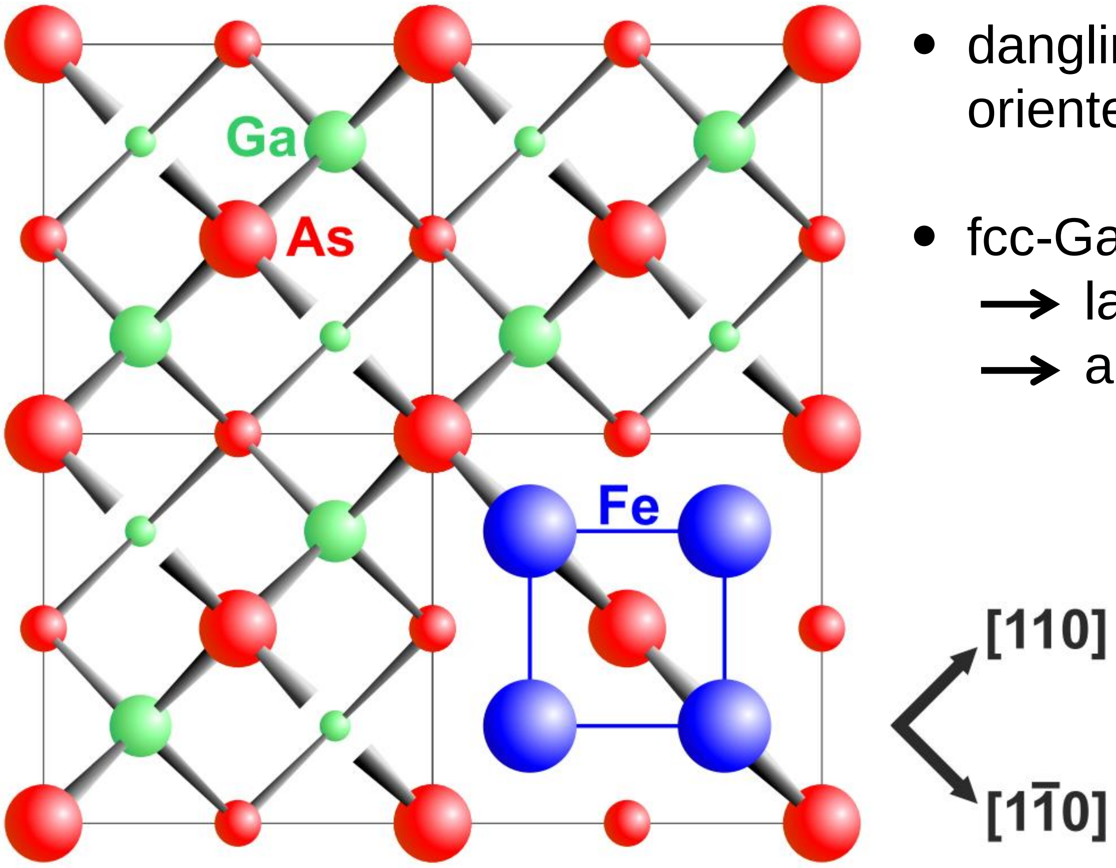
TAMR & Crystalline anisotropic magneto-resistance

Spin Orbit FMR

Anisotropic damping

Voltage control of spin orbit fields

Fe/GaAs(001): crystal structure



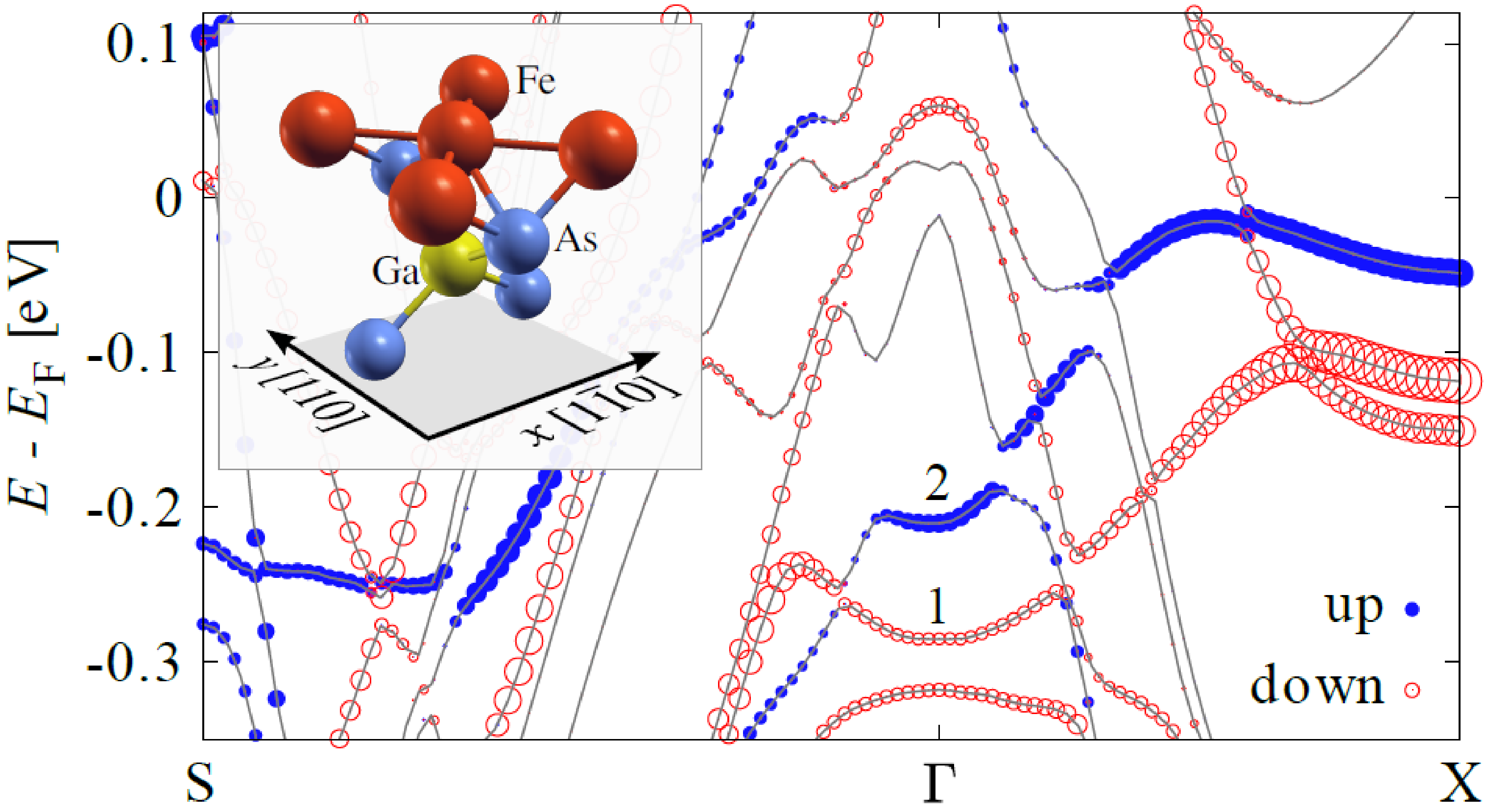
- dangling bonds of As-atoms oriented along $[1\underline{1}0]$

- fcc-GaAs and bcc-Fe:
  ⟶ lattice mismatch of 1.4 %
  ⟶ almost perfect epitaxial growth

- [110] and $[1\underline{1}0]$ directions **not** equivalent

- **C_{2v} symmetry**

Fe/GaAs(001): electronic band structure

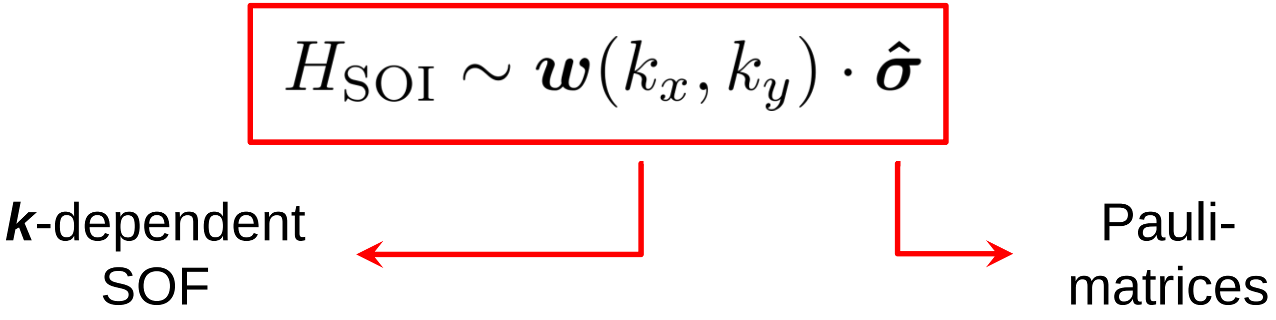


- band structure calculated for 3 ML Fe / 9 ML GaAs(001)
- interface atoms determine spin character of bands
- Magnetization along [1$\underline{1}$0] direction

M. Gmitra, A. Matos-Abiague, C. Draxl, and J. Fabian, PRL **111**, 036603 (2013)

SOFs at the Fe/GaAs interface

- C_{2v} symmetry accounts for both, bulk inversion asymmetry and structure inversion asymmetry
- C_{2v} spin-orbit field lies in the plane of the slab, perpendicular to the growth direction.
- Effective magnetic field, direction and magnitude depend on the electron momentum:



$$\boxed{H_{\mathrm{SOI}} \sim \boldsymbol{w}(k_x, k_y) \cdot \hat{\boldsymbol{\sigma}}}$$

***k*-dependent SOF**

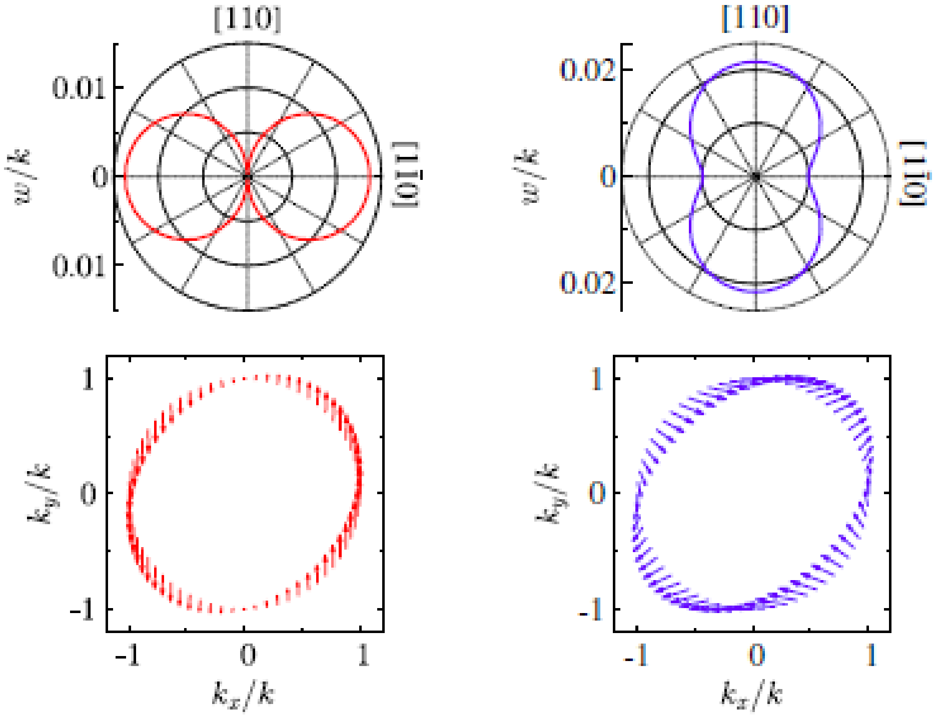
Pauli-matrices

e.g. well-known Dresselhaus SOF for zinc blende semiconductors and Rashba SOF in asymmetric quantum wells

SOFs at the Fe/GaAs interface

Spin orbit coupling strength

Vector field **w(k)**



Magnetization along: $[1\underline{1}0]$ [110]

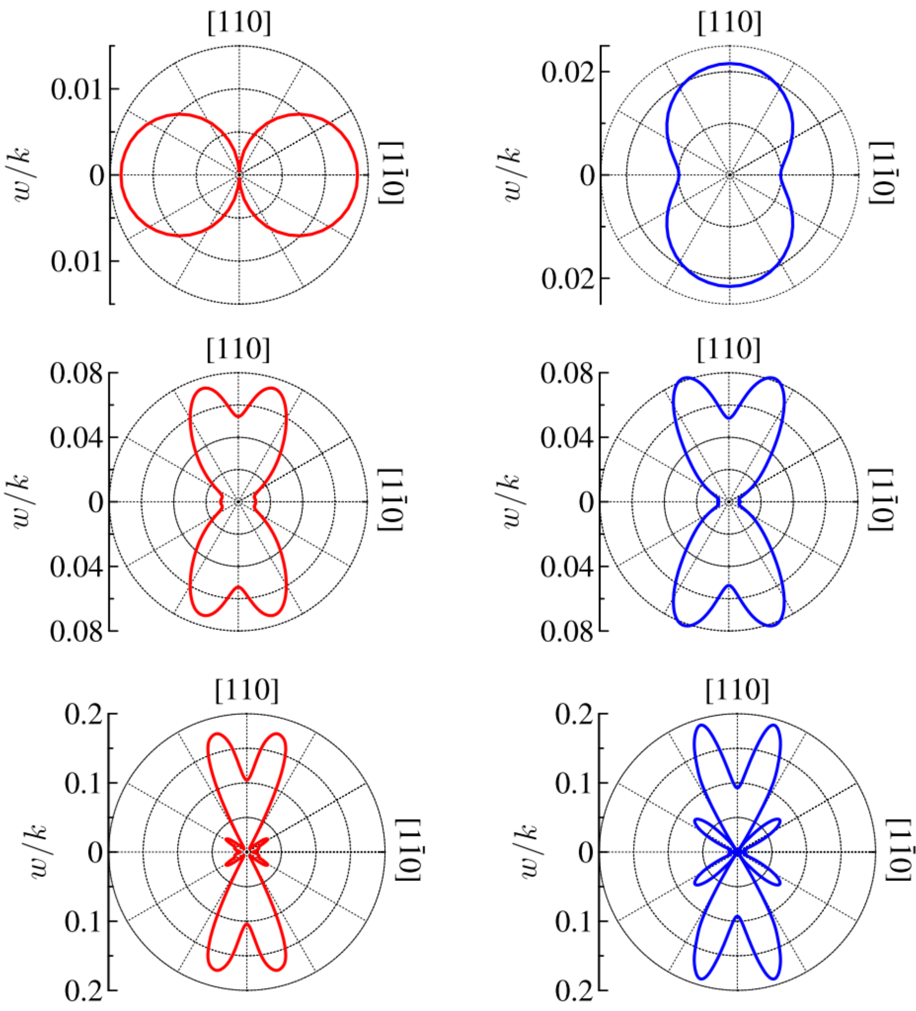
M. Gmitra, A. Matos-Abiague, C. Draxl, and J. Fabian, PRL **111**, 036603 (2013)

SOFs at the Fe/GaAs interface

- Calculated SO coupling strengths for different energies and magnetization directions

- **C_{2v} symmetry** preserved for all energies

- Higher order contributions for higher energies



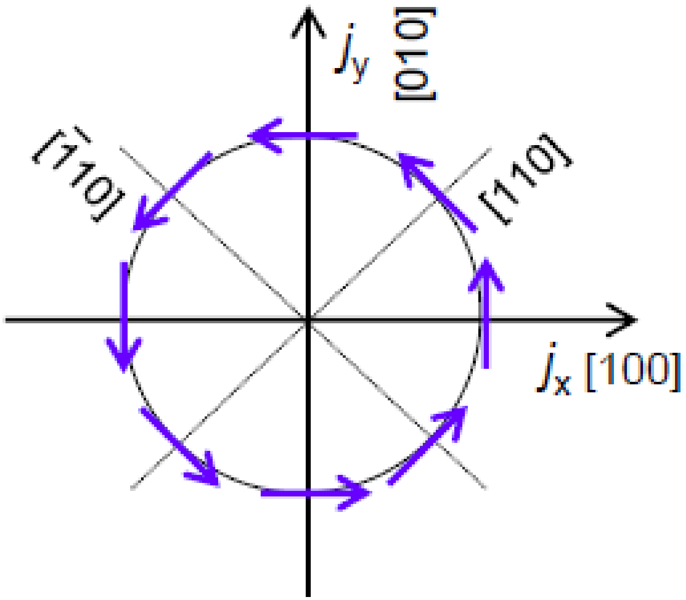
Magnetization along: $[1\underline{1}0]$ [110]

M. Gmitra, A. Matos-Abiague, C. Draxl, and J. Fabian, PRL **111**, 036603 (2013)

SOFs at the Fe/GaAs interface

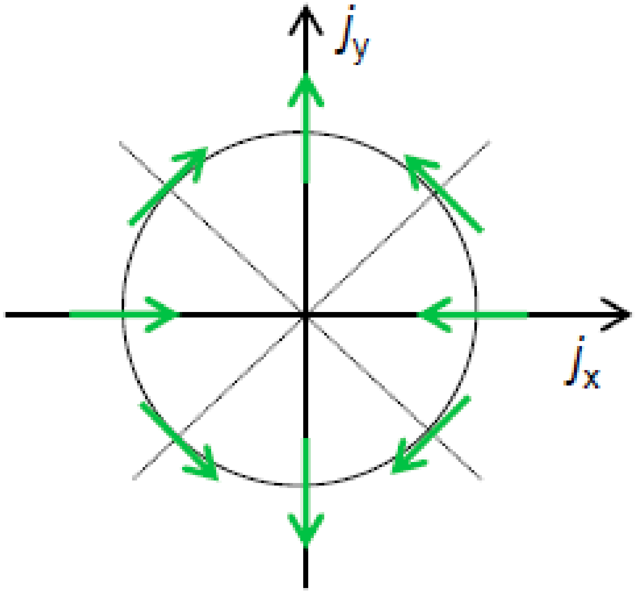
Bychkov-Rashba (like) and Dresselhaus (like)

„due to structure inversion asymmetry (SIA) at the Fe/GaAs interface“



$$H_R = \alpha_{BR}(\sigma_x k_y - \sigma_y k_x)$$

„due to bulk inversion asymmetry (BIA) in the bulk-GaAs“



$$H_D = \beta_D(\sigma_x k_x - \sigma_y k_y)$$

Fe/GaAs system

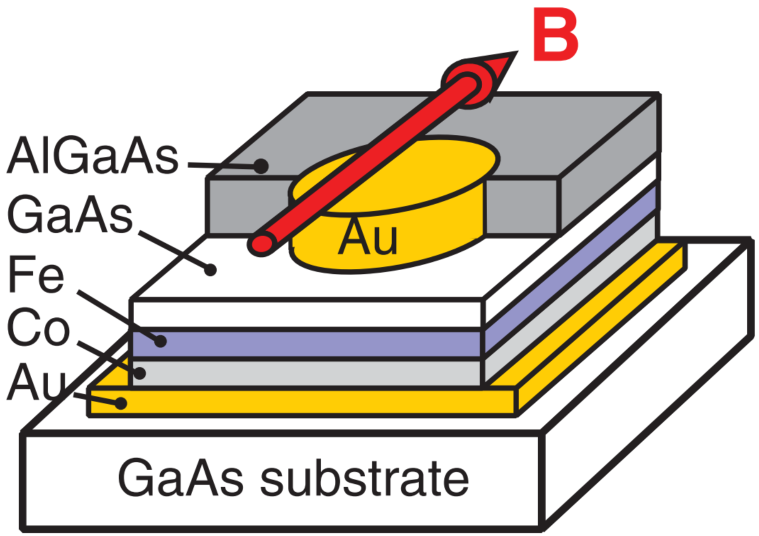
TAMR & Crystalline anisotropic magneto-resistance

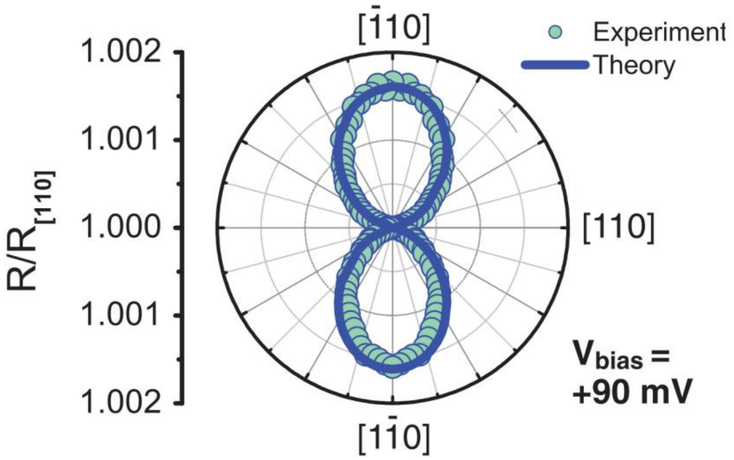
Spin Orbit FMR

Anisotropic damping

Voltage control of spin orbit fields

Tunneling Anisotropic Magneto-Resistance (TAMR)



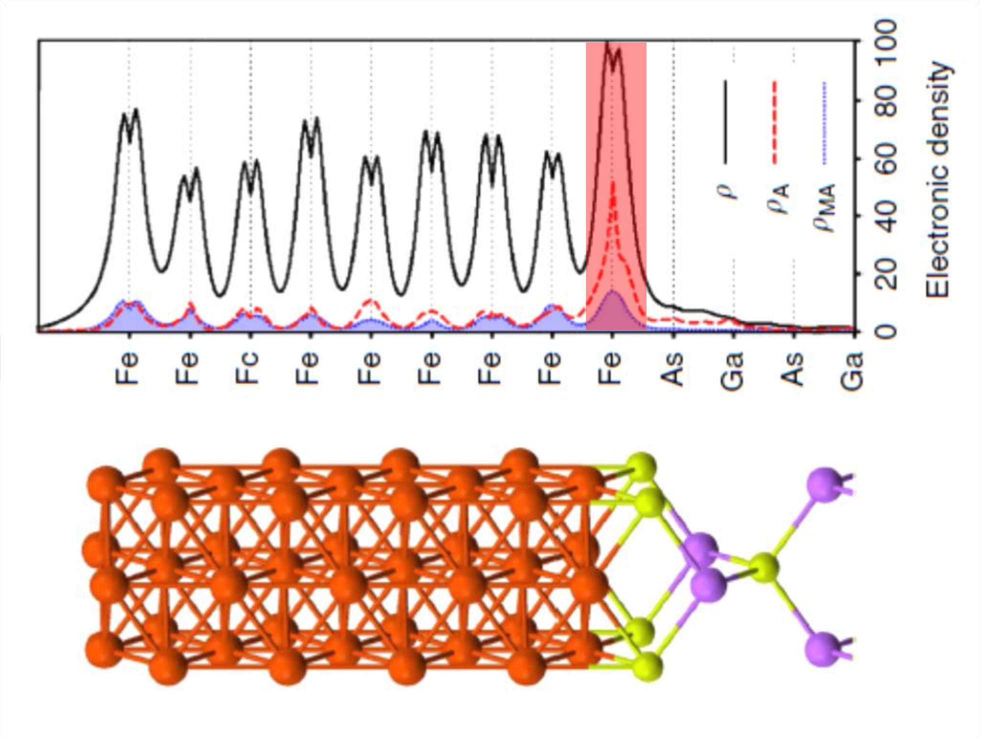


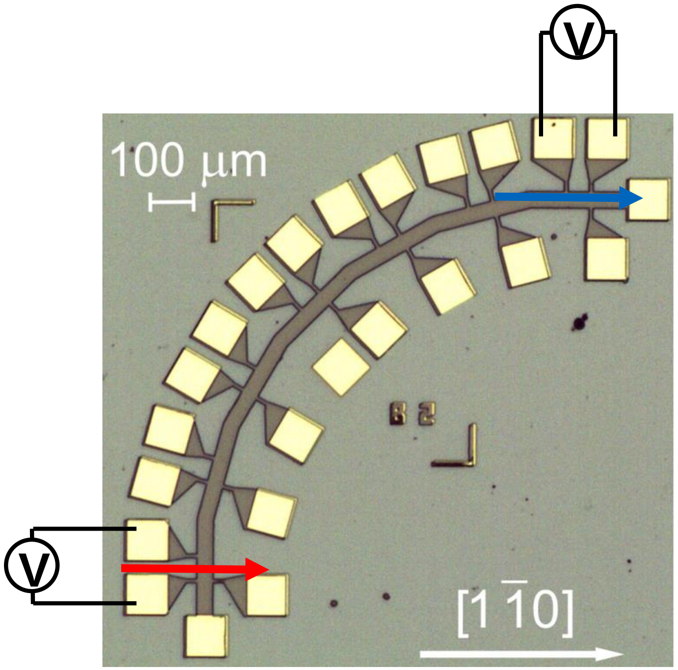
- Tunneling through Fe/GaAs/Au junction (only one ferromagnetic electrode)
- Tunneling anisotropic magnetoresistance (TAMR)
- Anisotropy can be switched by reversing the bias voltage
- Tunneling resistance shows pronounced C_{2v} symmetry

$$\boxed{\mathrm{TAMR}(\phi) = R(\phi)/R_{[110]} - 1 \sim \alpha_{\mathrm{BR}}\beta_{\mathrm{D}}[\cos(2\phi) - 1]}$$

J. Moser *et al.*, Phys. Rev. Lett. **99**, 056601 (2007)

Crystalline Anisotropic Magneto-Resistance (CAMR)

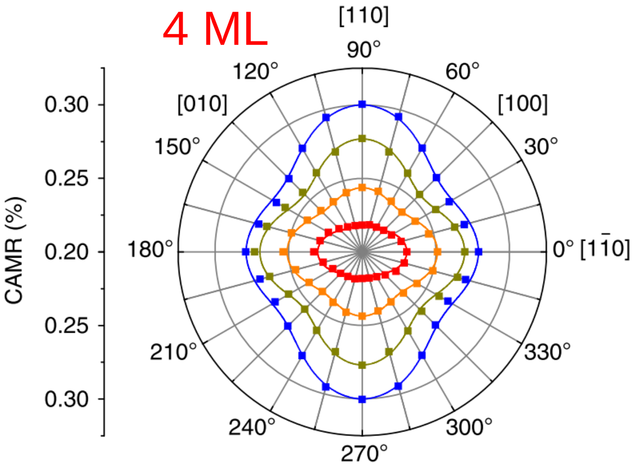


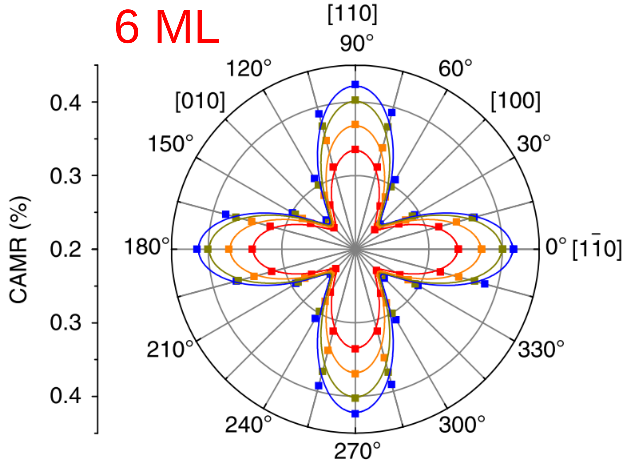


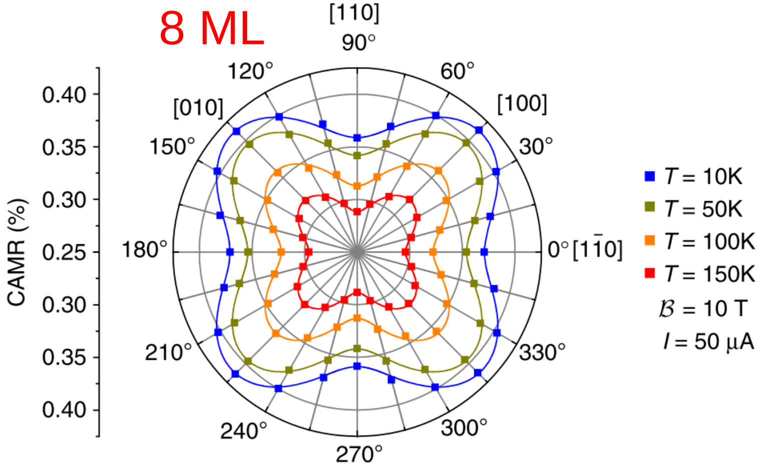
- Lateral transport through the Fe layer
- Measurement of resistivity and in-plane AMR (rotate B-field)

T. Hupfauer *et al.*, Nat. Commun. **6**, 7374 (2015)

Crystalline Anisotropic Magneto-Resistance (CAMR)







- Crystalline AMR exhibits a pronounced **C_{2v} symmetry**

- CAMR reflects interfacial Spin Orbit Fields (solid line fits)

T. Hupfauer *et al.*, Nat. Commun. **6**, 7374 (2015)

- Fe/GaAs system
- TAMR & Crystalline anisotropic magneto-resistance
- Spin Orbit FMR
- Anisotropic damping
- Voltage control of spin orbit fields

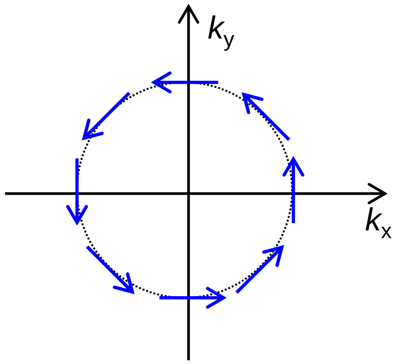
SOFs at the Fe/GaAs(001) interface

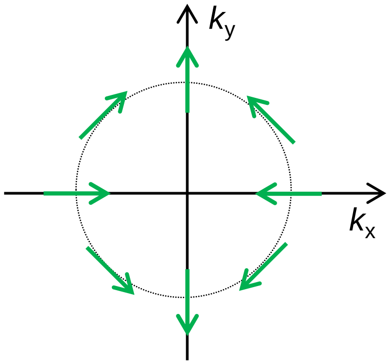
Rashba

due to structure inversion asymmetry (SIA) at the Fe/GaAs interface

Dresselhaus

due to bulk inversion asymmetry (BIA) in the bulk-GaAs





$$H_\mathrm{R} = \alpha_{BR}(\sigma_x k_y - \sigma_y k_x)$$

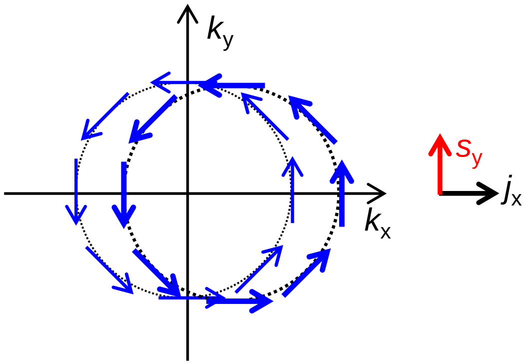
$$H_\mathrm{D} = \beta_D(\sigma_x k_x - \sigma_y k_y)$$

No net spin accumulation

SOFs at the Fe/GaAs(001) interface

Rashba

due to structure inversion asymmetry
(SIA) at the Fe/GaAs interface

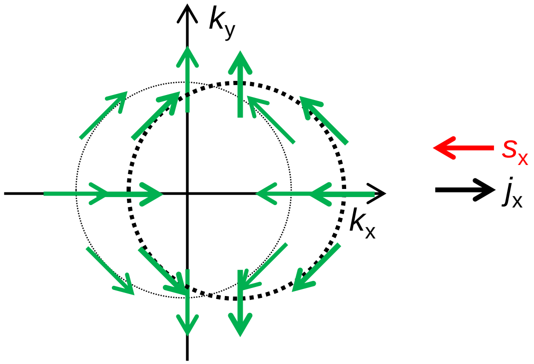


$$H_R = \alpha_{BR}(\sigma_x k_y - \sigma_y k_x)$$

$$\boxed{\langle s_y \rangle \sim \alpha_{BR} j_x}$$

Dresselhaus

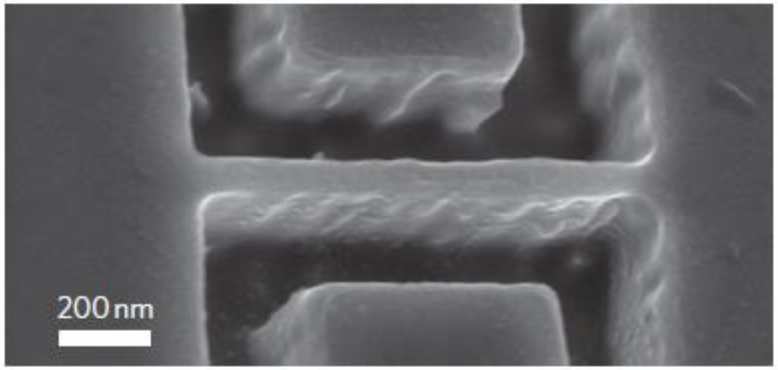
due to bulk inversion asymmetry (BIA)
in the bulk-GaAs



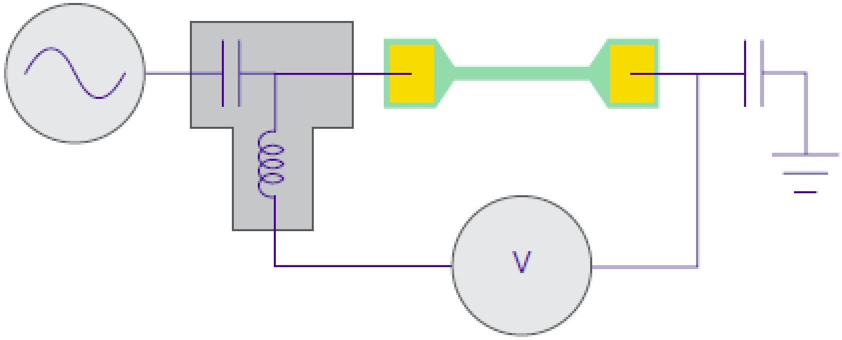
$$H_D = \beta_D(\sigma_x k_x - \sigma_y k_y)$$

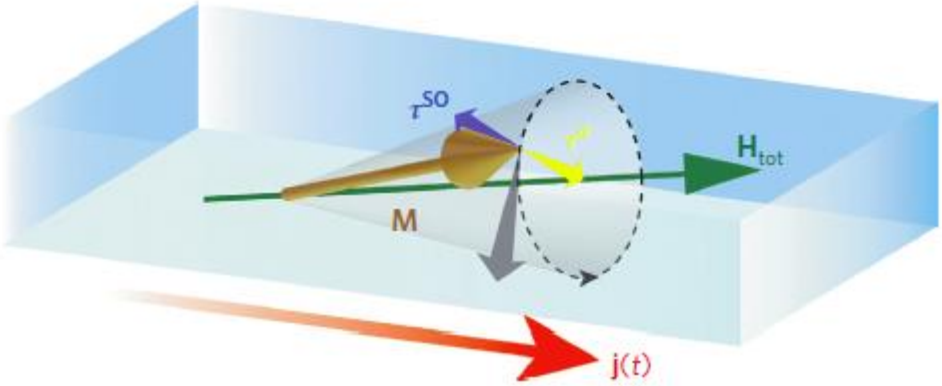
$$\boxed{\langle s_x \rangle \sim -\beta_D j_x}$$

Spin Orbit FMR



GaMnAs bar

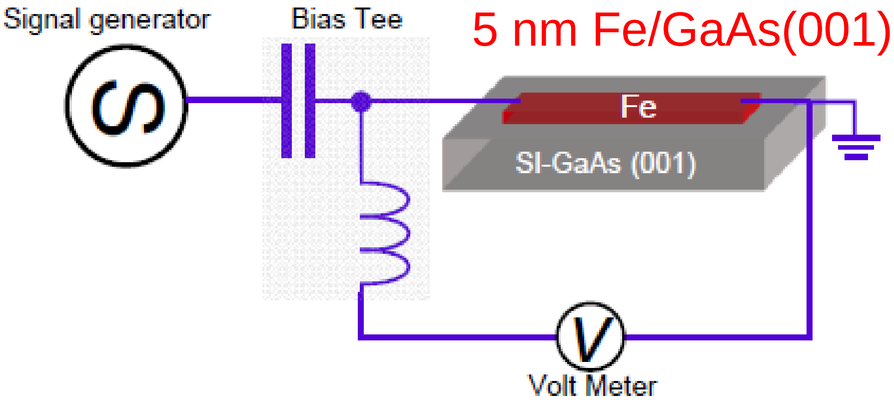




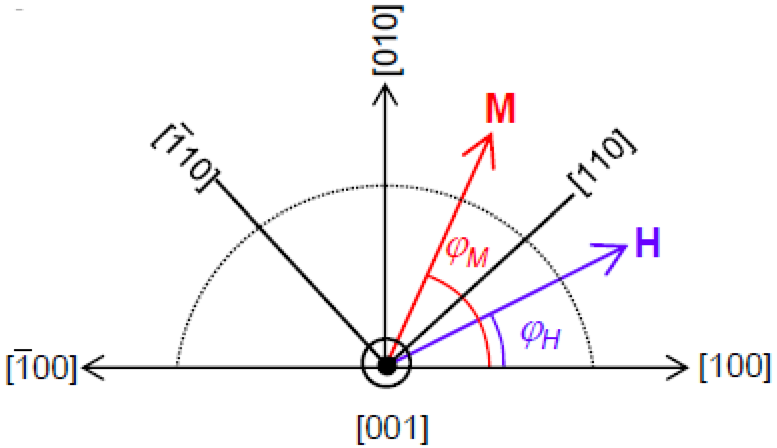
- $\mathbf{j}(t) \Rightarrow \mathbf{h}(t)$
- $\mathbf{h}(t) \Rightarrow \mathbf{M}(t) \Rightarrow \mathrm{R}(t)$
- $V \sim \overline{\mathbf{j}(t)\,\mathrm{R}(t)}$

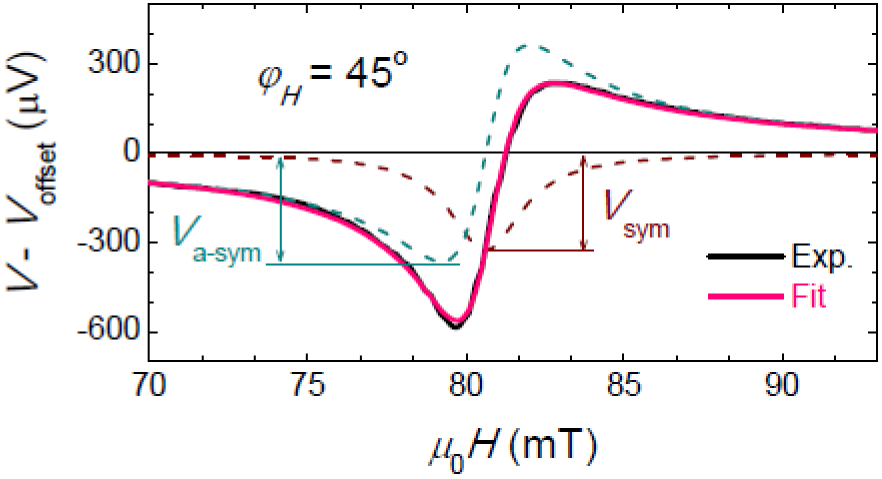
D. Fang et al., Nat. Nano. **6**, 413 (2011), H. Kurebayashi, Nat. Nano. **9**, 211 (2014)

Spin Orbit FMR at the Fe/GaAs interface



5 nm Fe/GaAs(001)





We obtain:

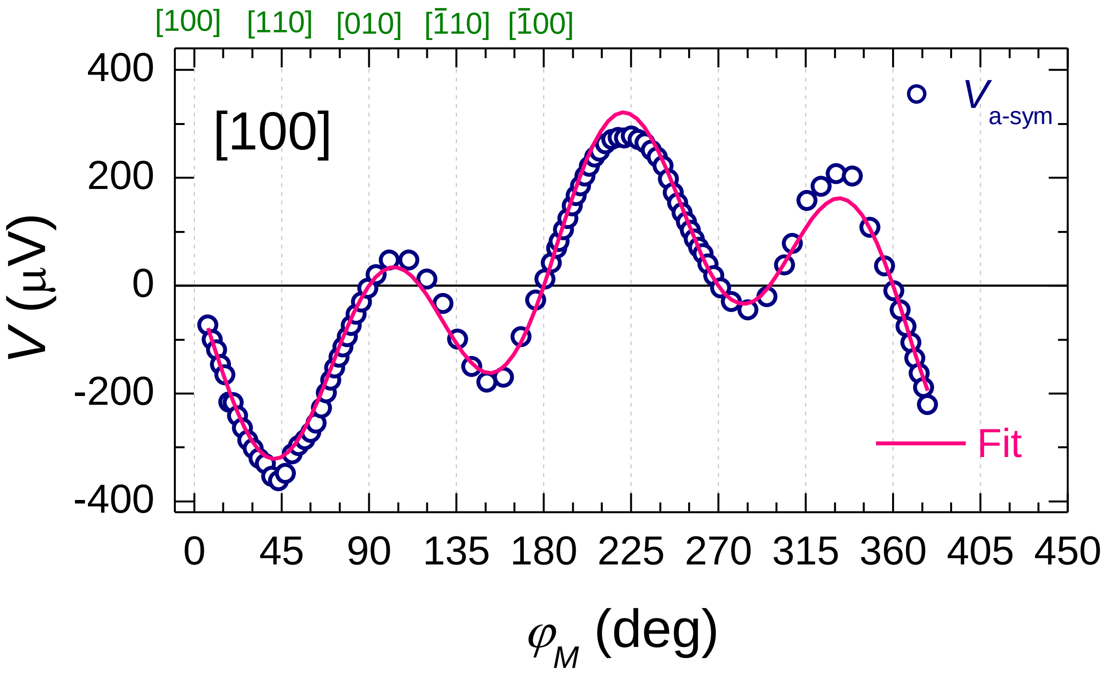
- H_R, $\Delta H \Rightarrow$ FMR
- $V_{a\text{-}sym} \Rightarrow$ in-plane SO fields
- $V_{sym} \Rightarrow$ out-of-plane SO fields

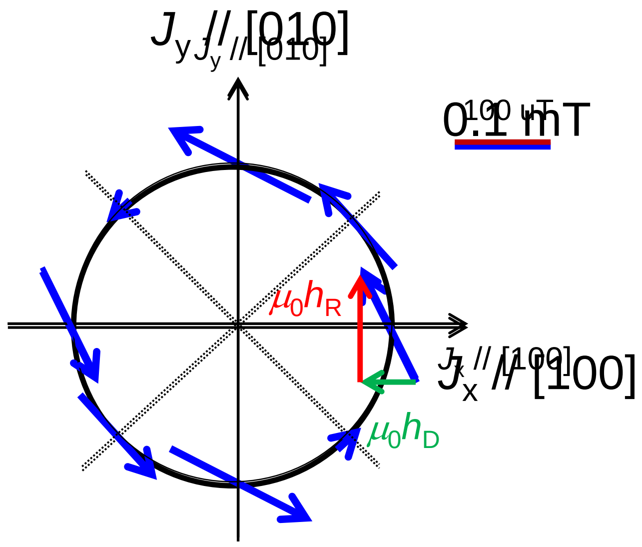
$$V(H)-V_{offset}=V_{sym}\frac{\Delta H^2}{4(H-H_R)^2+\Delta H^2}+V_{a-sym}\frac{-4\Delta H(H-H_R)}{4(H-H_R)^2+\Delta H^2}$$

D. Fang et al., Nat. Nano. **6**, 413 (2011)

Spin Orbit FMR: results

One devic long different directions





$$V^{[100]}_{a-sym} = -\frac{\Delta\rho j l}{2M}\left(-\boxed{h^{[100]}}\sin\varphi_M + \boxed{h^{[010]}}\cos\varphi_M\right)\mathrm{Re}\left(\chi^I\right)\sin 2\varphi_M$$

Dresselhaus and Bychkov-Rashba contributions

$\mu_0 h^{[100]} = -0.15$ mT $\mu_0 h^{[010]} = 0.28$ mT

Comparison

Interfacial SOT in FM/NM bi-layers

Polycrystalline

FM/NM	t_{FM} (nm)	h(mT)	j(10^{11}Am^{-2})	$h*t_{FM}/j$ (mT.nm/10^{11}Am^{-2})	Ref.
CoFeB/Pt	0.5-5.7	0.6-0.06	0.2	**1.5**	1
Co/Pt	0.6	5	1	**3.0**	2
CoFeB/Ta	0.9	3	1	**2.7**	2
CoNi/PtMn	2.1	7.8	1	**16.4**	3
Fe/(Ga,Mn)As	2	0.05	0.1	**1**	4
Fe/GaAs	5	0.35	1	**1.8**	Our results

1. X. Fan *et al*. Nature Commun. **5**, 3042 (2014)
2. K. Garello *et al*. Nature Nanotech. **8**, 587 (2013)
3. S. Fukami *et al*., Nature Mater. doi:10.1038/nmat4566 (2016)
4. T. D. Skinner *et al*., Nature Commun. **6**, 6730 (2015)

L. Chen *et al*. Nat. Commun. **7**, 13802 (2016)

- Fe/GaAs system
- TAMR & Crystalline anisotropic magneto-resistance
- Spin Orbit FMR
- **Anisotropic damping**
- Voltage control of spin orbit fields

Equation of motion

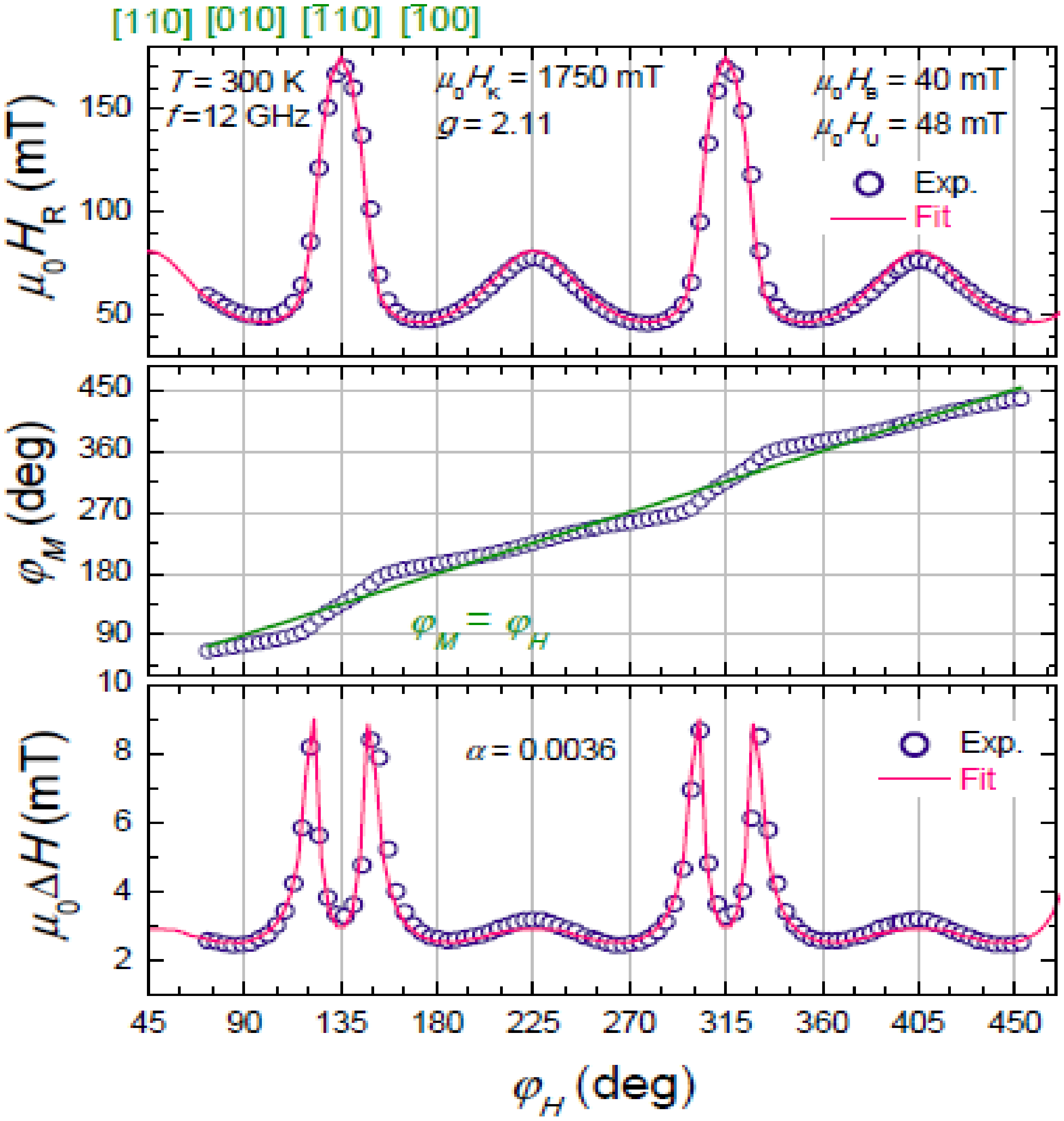
Landau-Lifshitz-Gilbert (LLG) equation

$$\dot{\vec{m}} = \underbrace{-|\gamma|\mu_0 \vec{m} \times \vec{H}_{\text{eff}}}_{\text{precession}} \underbrace{+\alpha \vec{m} \times \dot{\vec{m}}}_{\text{damping}}$$

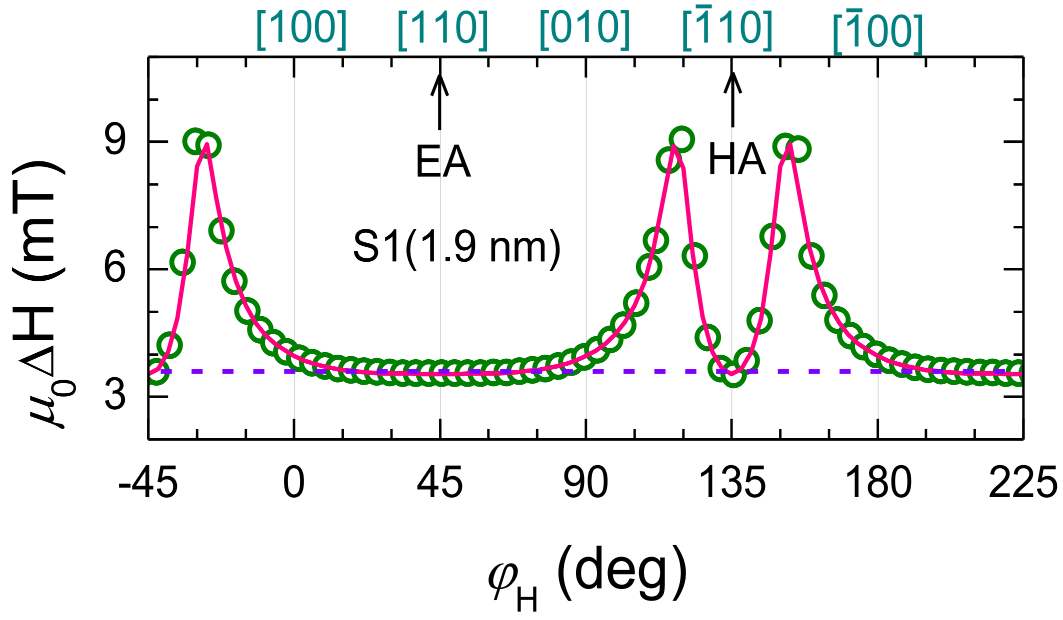
T. L. Gilbert, IEEE Trans. Mag. **40**, 3443 (2004)

- Fundamental parameter in magnetism
- Isotropic *α* for most ferromagnetic materials
- Open question: Could *α* be anisotropic?

Spin Orbit FMR: results



Spin Orbit FMR: damping



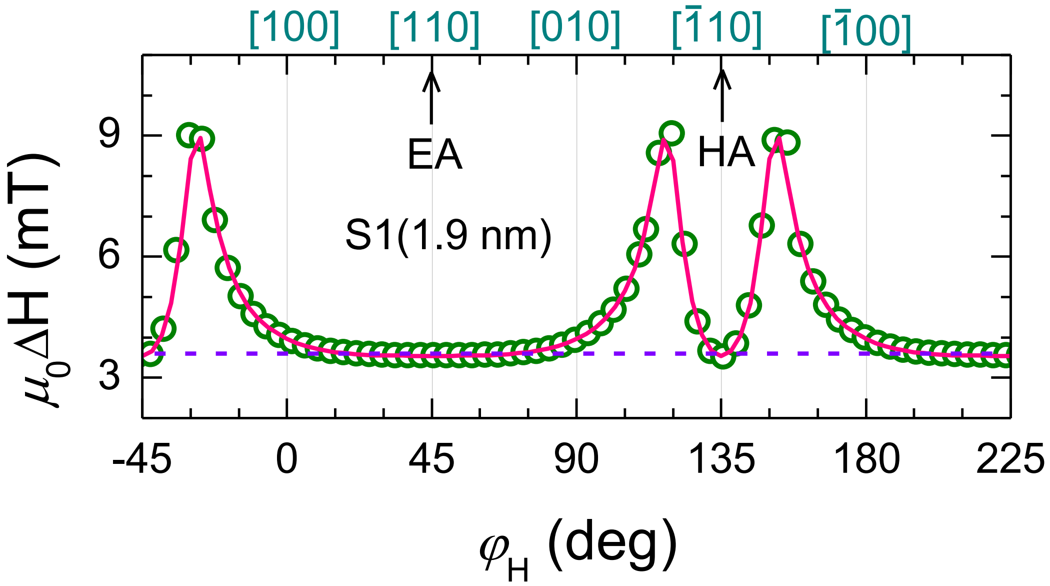
α = 0.0044

Fitting method: imaginary part of susceptibility with in-plane anisotropy

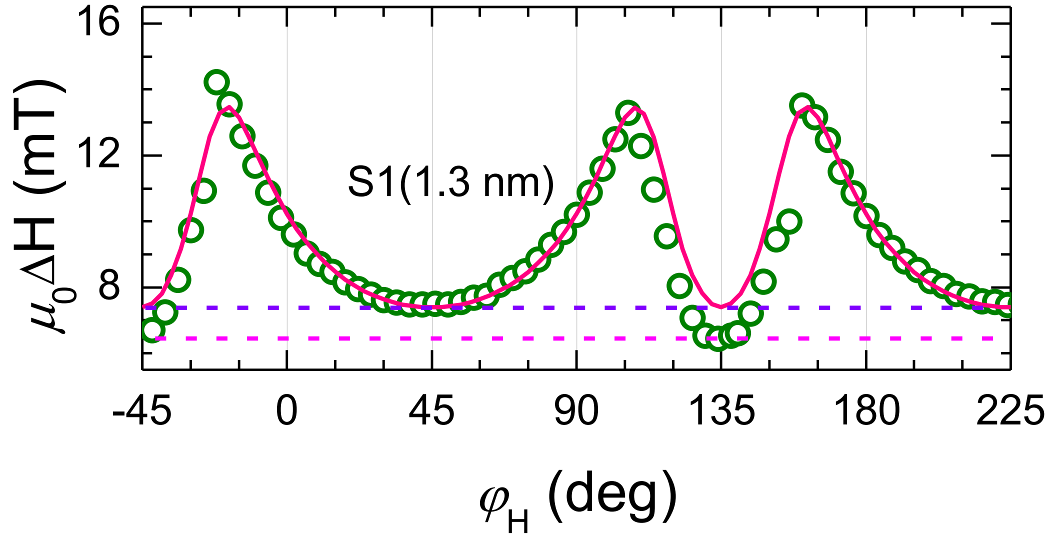
$$\chi'' = \frac{\alpha\sqrt{H_1^R H_2^R}\,[H_1(H_1+H_2)+(H_1^R H_2^R - H_1 H_2)]}{(H_1 H_2 - H_1^R H_2^R)^2 + \alpha^2 H_1^R H_2^R (H_1+H_2)^2} M$$

L. Chen, F. Matsukura, and H. Ohno, Nat. Commun. **4,** 2055 (2013)

Spin Orbit FMR: anisotropic damping



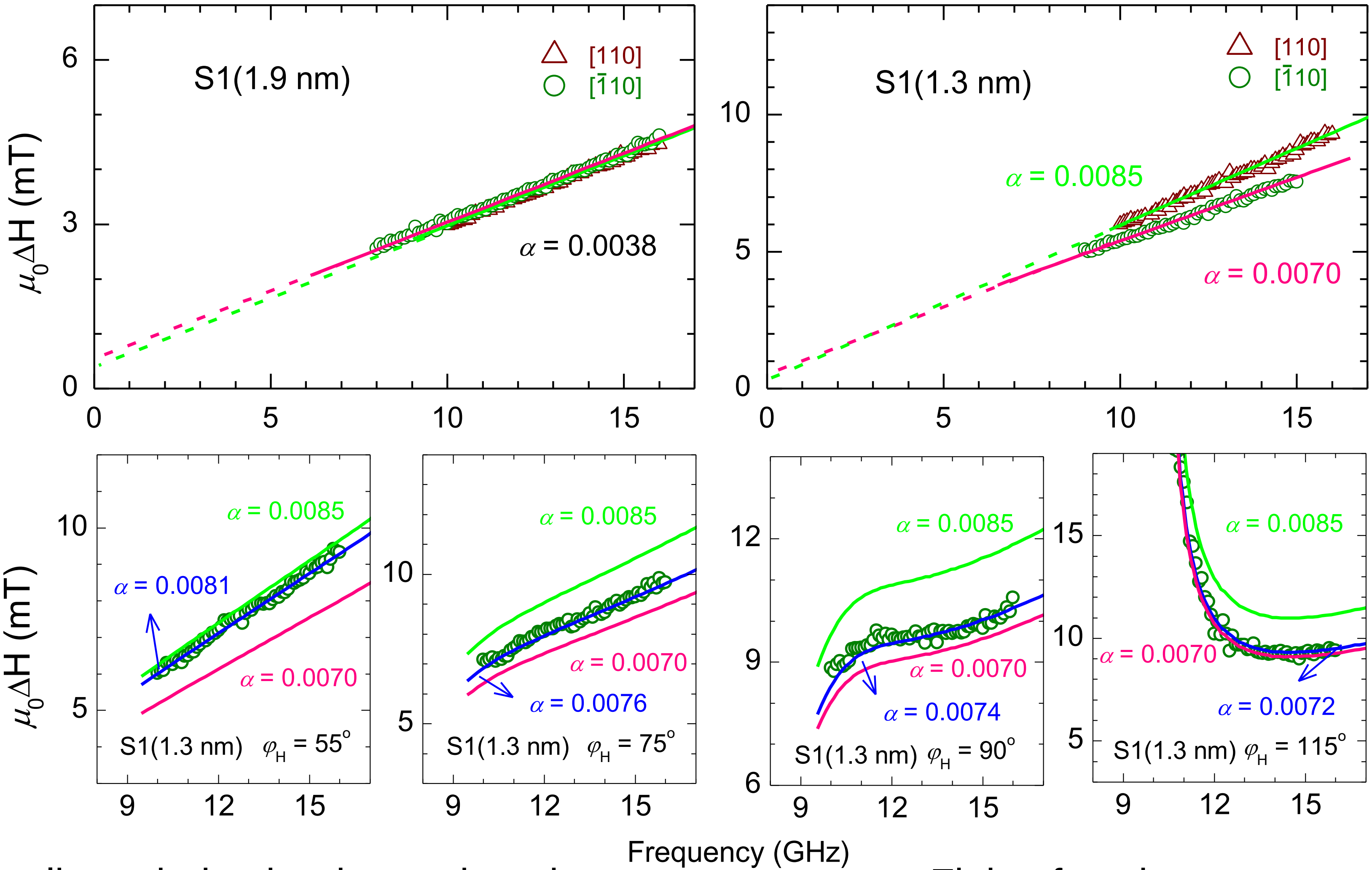
α = 0.0044



α = 0.0086

Lin Chen et al., Nat. Phys. (2018) doi:10.1038/s41567-018-0053-8

Spin Orbit FMR: anisotropic damping

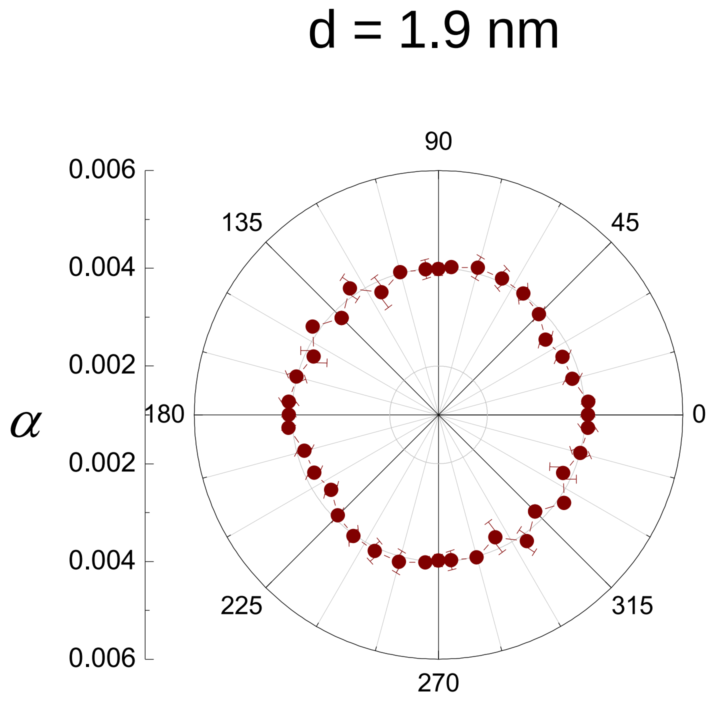


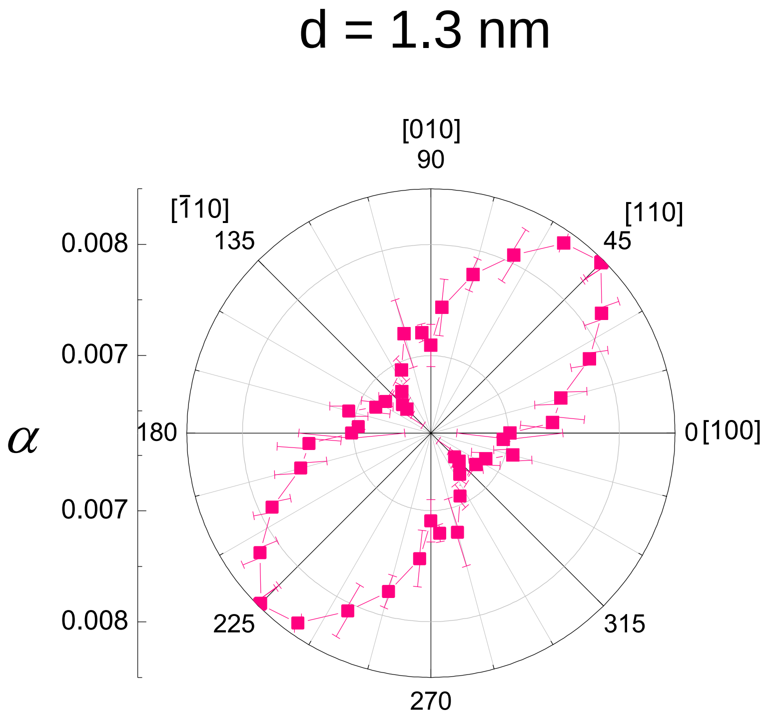
Non-linear behavior due to dragging

Fitting function:

$$\mu_0\Delta H = \mu_0\Delta\left[\mathrm{Im}(\chi)\right] + \mu_0\Delta H_0$$

Spin Orbit FMR: anisotropic damping





- C_{2v} symmetry

s-*d* model:

$$\alpha = \frac{\mu_0 \mu_B^2}{\gamma M} N(E_F) \frac{\langle \xi \rangle^2}{\Delta^2} \frac{1}{\tau}$$

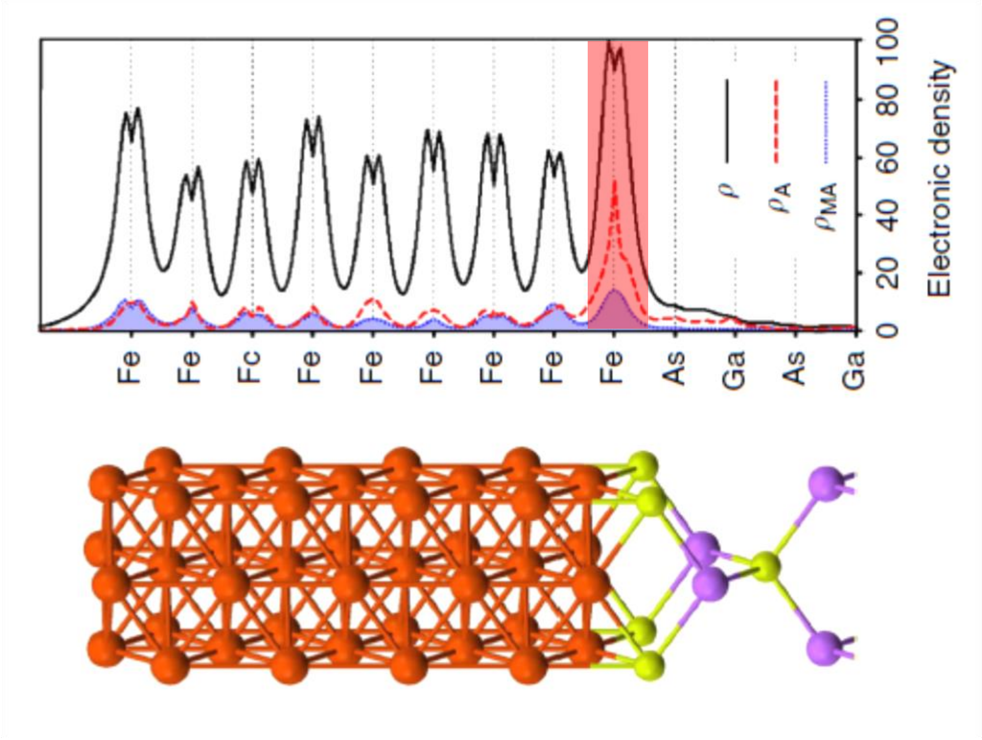
α is related to:

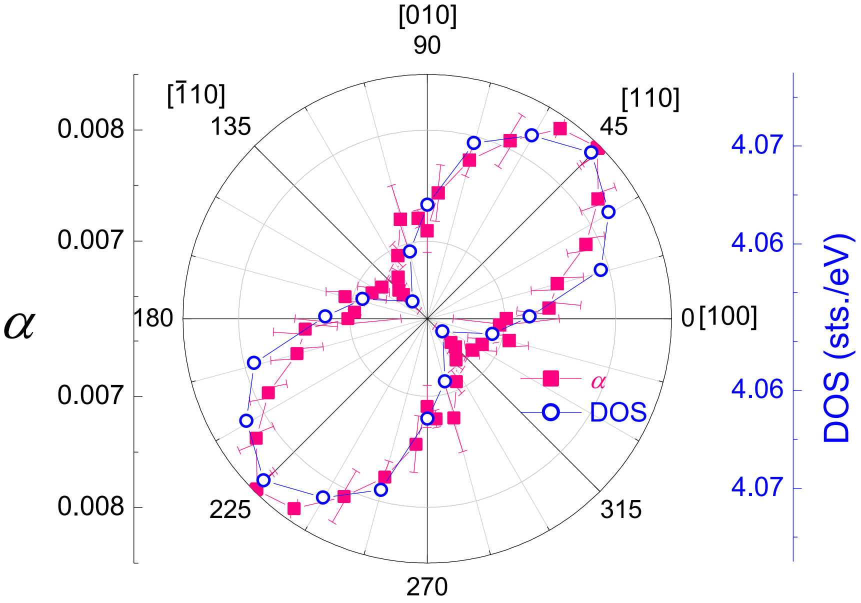
N(E_F): density of states at E_F

<ξ>: magnitude of SOI

τ : momentum relaxation time

Spin Orbit FMR: anisotropic damping





anisotropic DOS at the Fe/GaAs interface

Lin Chen et al., Nat. Phys. (2018) doi:10.1038/s41567-018-0053-8

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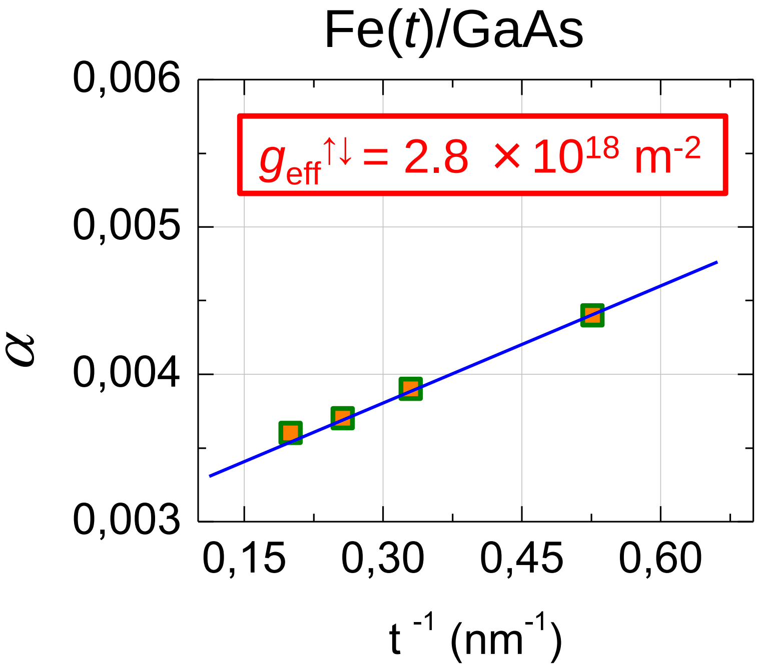
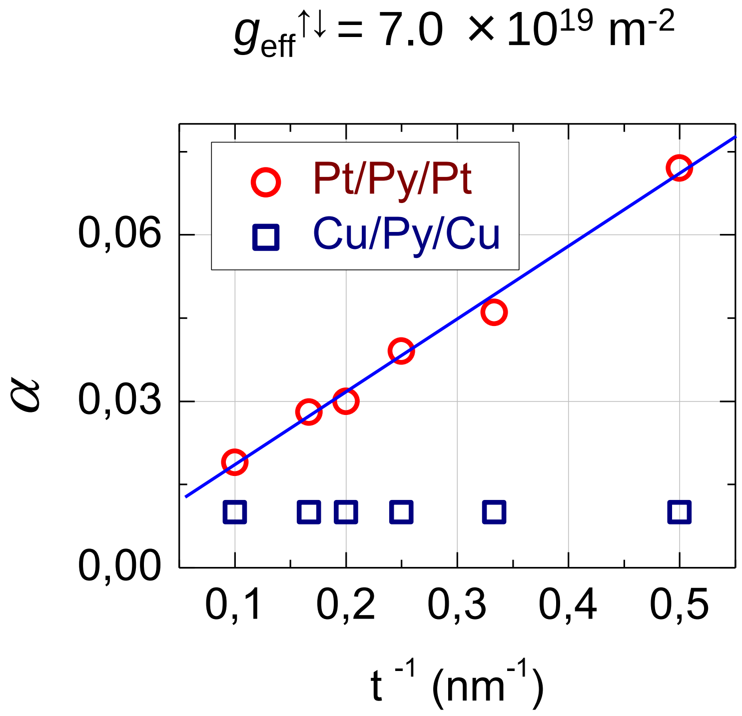
Side note: Spin pumping in Fe/GaAs





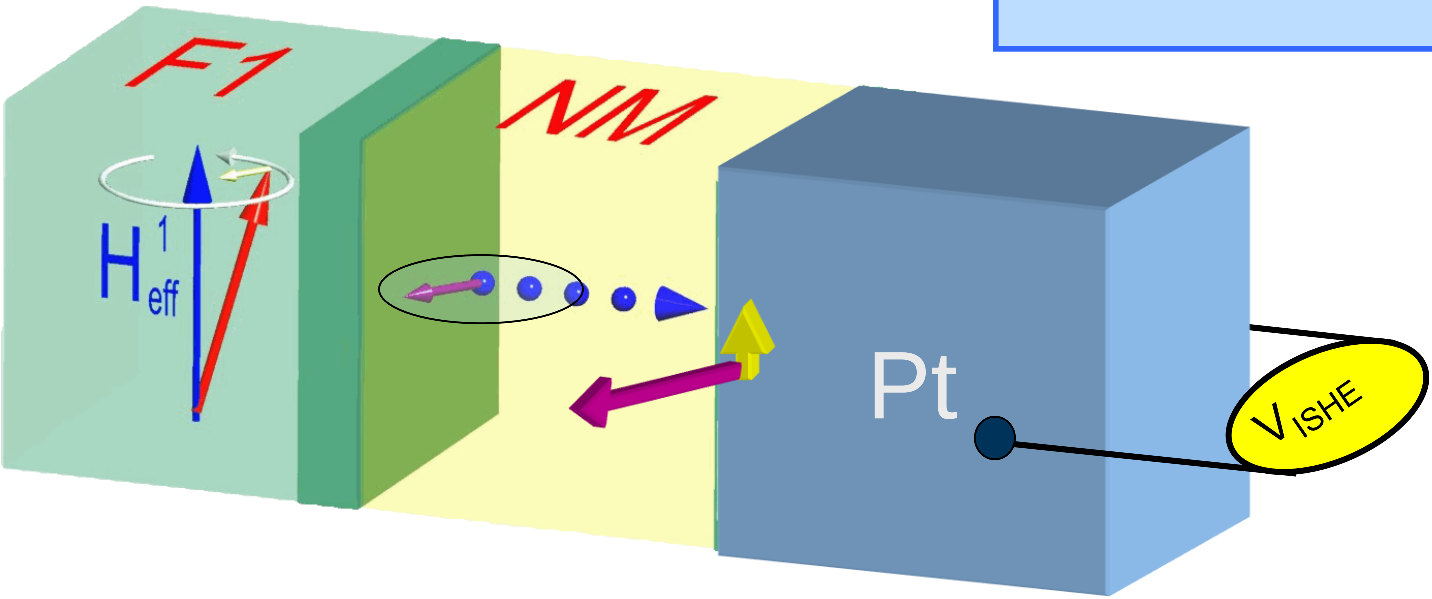
from spin pumping theory:

$$\boxed{\alpha_{\substack{spin\\pump}} = \frac{g\mu_B}{4\pi M_S} g_{\uparrow\downarrow} \frac{1}{t_F}}$$

data from S. Mizukami *et al*. Jpn. J. Appl. Phys. **40**, 580 (2001), Y. Tserkovnyak *et al*. PRB **66**, 224403 (2002)

Spin Pumping and ISHE, SGE etc.

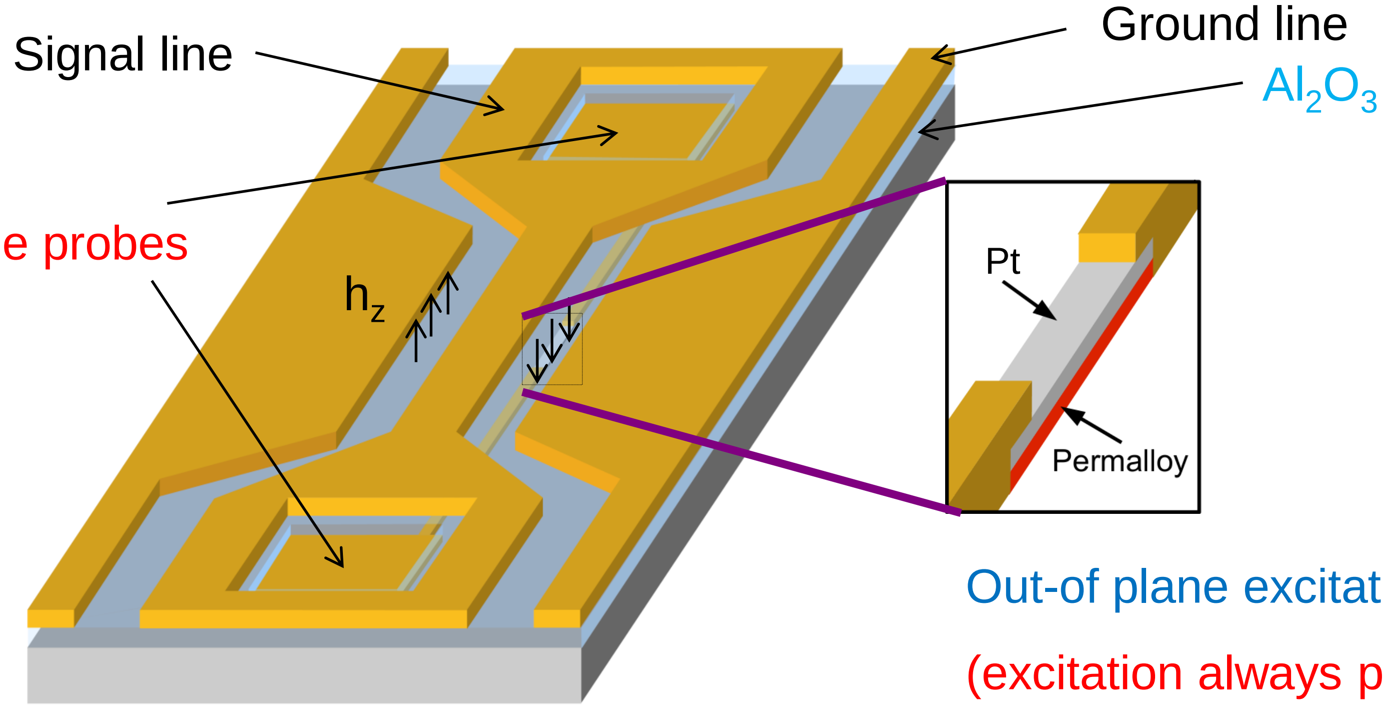
$$\vec{j}_s(t) = \frac{\hbar}{4\pi}\mathrm{Re}(g_{\uparrow\downarrow})\left(\vec{m}\times\frac{d\vec{m}}{dt}\right)$$



E. Saitoh et al. APL **88**, 182509 (2006)
K. Ando *et al.* PRL **101**, 036601 (2008)
E. Saitoh et al., APL **88**, 182509 (2006)
O. Mosendz et al., PRL **104**, 046601 (2010)
F. Czeschka et al. PRL **106**, (2011)

$$j_{s,dc} = \frac{\hbar\omega}{4\pi}\mathrm{Re}(g_{\uparrow\downarrow})\sin^2\theta$$

Spin Pumping and ISHE, SGE etc.

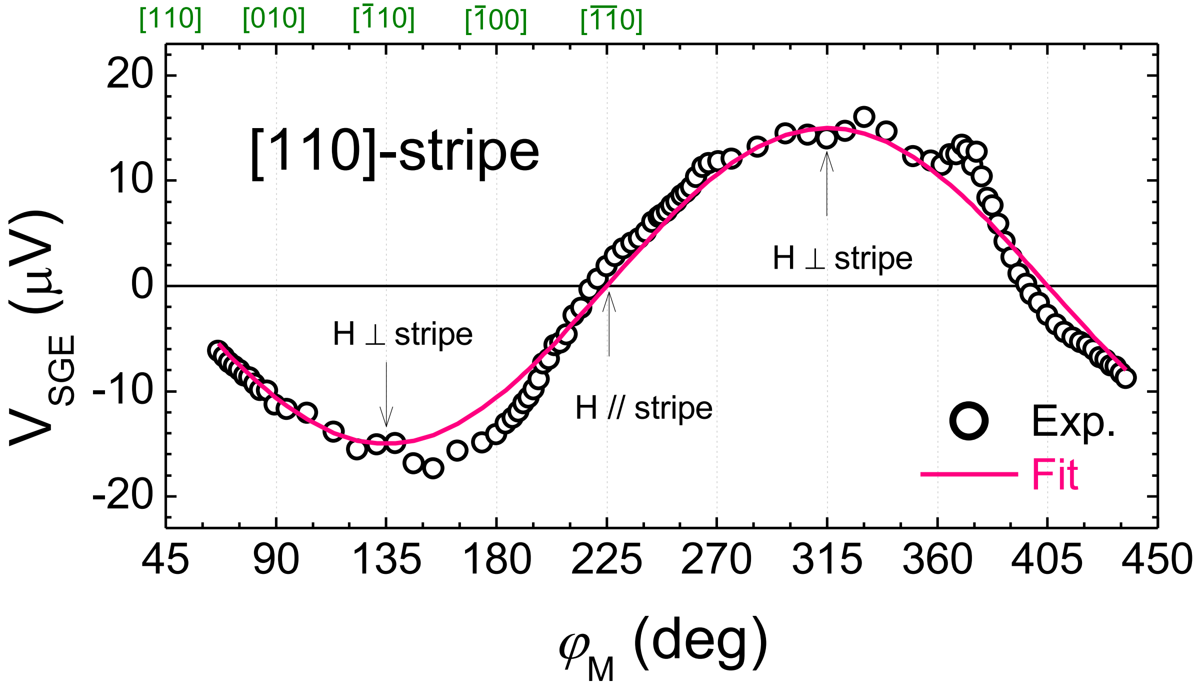


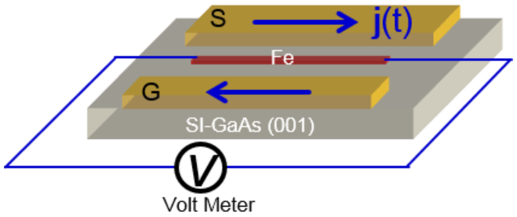
Out-of plane excitation

(excitation always possible)

M. Obstbaum *et al*. Phys. Rev. B **89**, 060407(R) (2014)

Spin-to-Charge conversion at the Fe/GaAs interface





Angular dependence expected: $\mathbf{J}_C \sim \mathbf{n} \times \boldsymbol{\sigma}$

Spin galvanic effect (SGE): no NM conducting layer

S. Ganichev *et al*. Nature **417**, 153-156 (2002)

L. Chen *et al*. Nat. Commun. **7**, 13802 (2016)

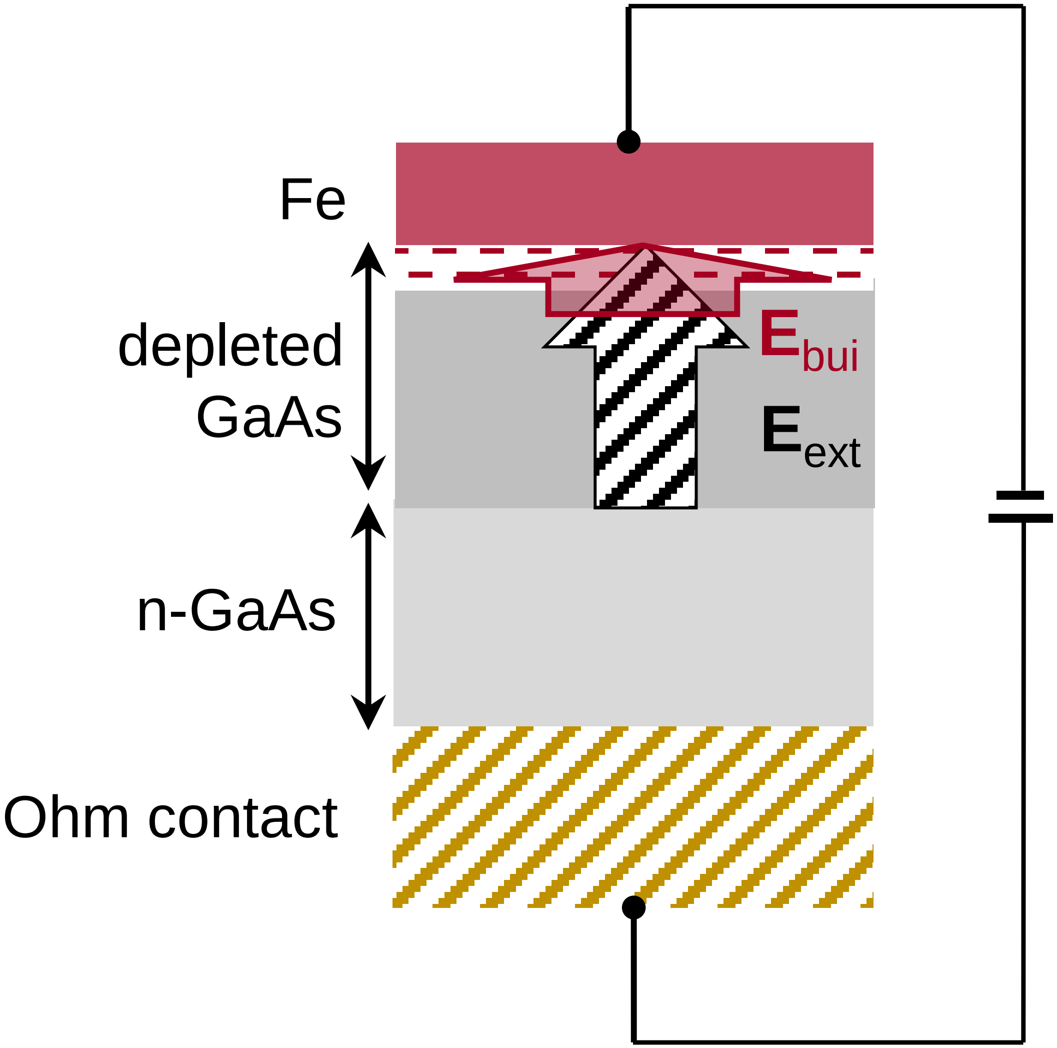
Spin-to-Charge conversion efficiency

Spin-to-charge conversion efficiency

Material	Mechanism	$(\theta_{SHE}*\lambda_{sf})$ or (λ_{2D}) (nm)	Ref.
$LaAlO_3/SrTiO_3$	Rashba	6.4	1
Bi/Ag	Rashba	0.1-0.4	2
α-Sn	TI	2.1	3
Fe/GaAs	Rashba	0.3	our results
Pt	SHE	0.2	1

1. E. Lesne *et al*. Nat. Mater. **15**, 1261 (2016)
2. J. C. Rojas Sánchez *et al*. Nat. Commun. **4**, 2944 (2013)
3. J. C. Rojas Sánchez *et al*. PRL **116**, 096602 (2016)

Electric field control of SOFs



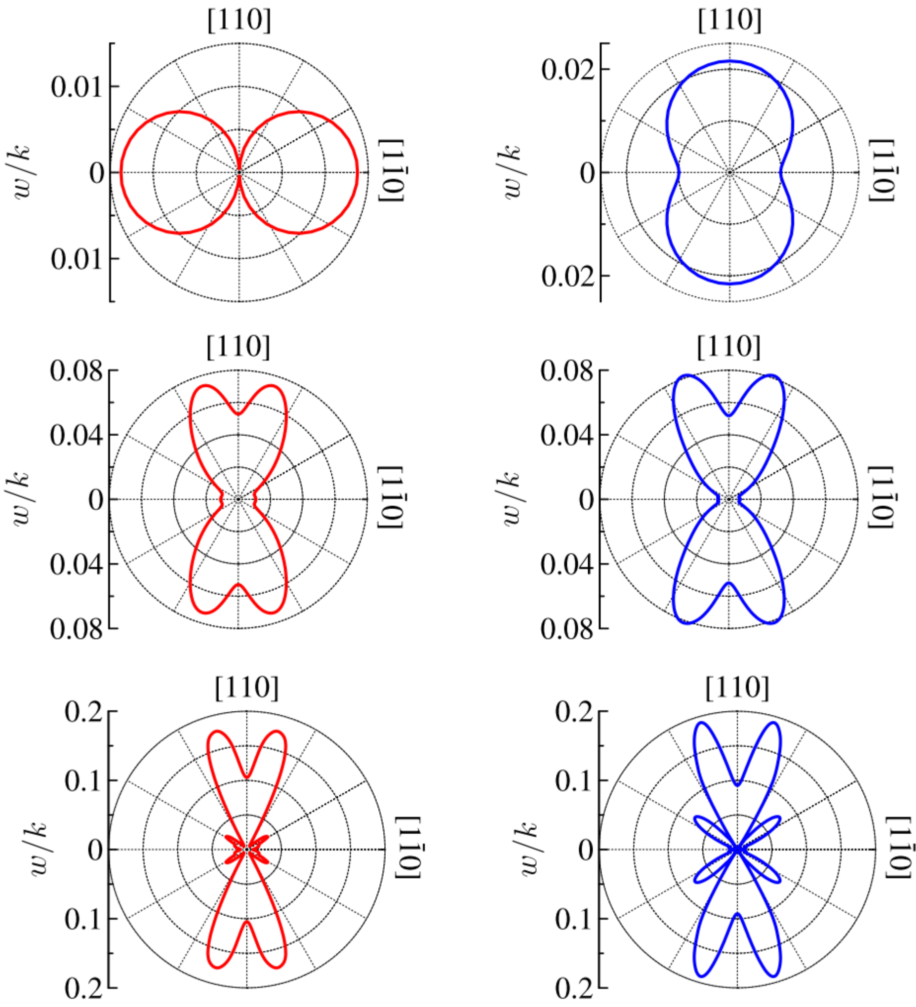
Lin Chen *et al.*, Arxiv 1803.01656

SOFs at the Fe/GaAs interface

- Calculated SO coupling strengths for different energies and magnetization directions

- **C_{2v} symmetry** preserved for all energies

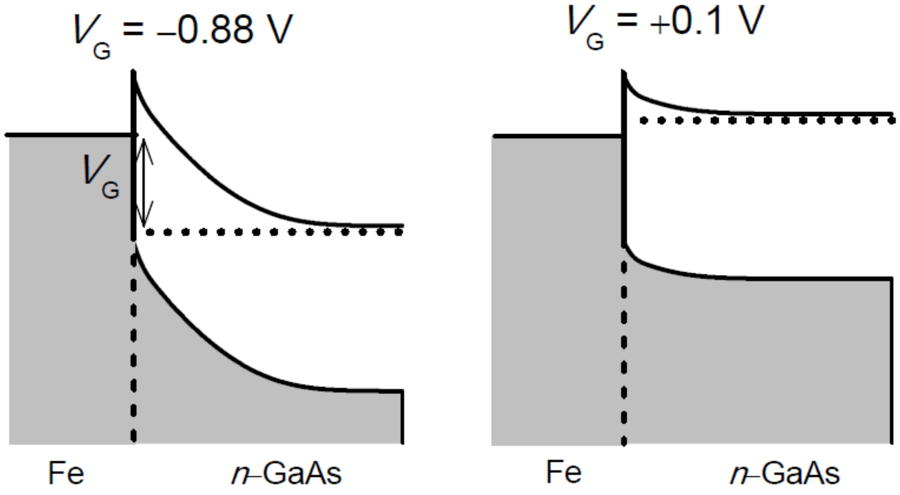
- Higher order contributions for higher energies

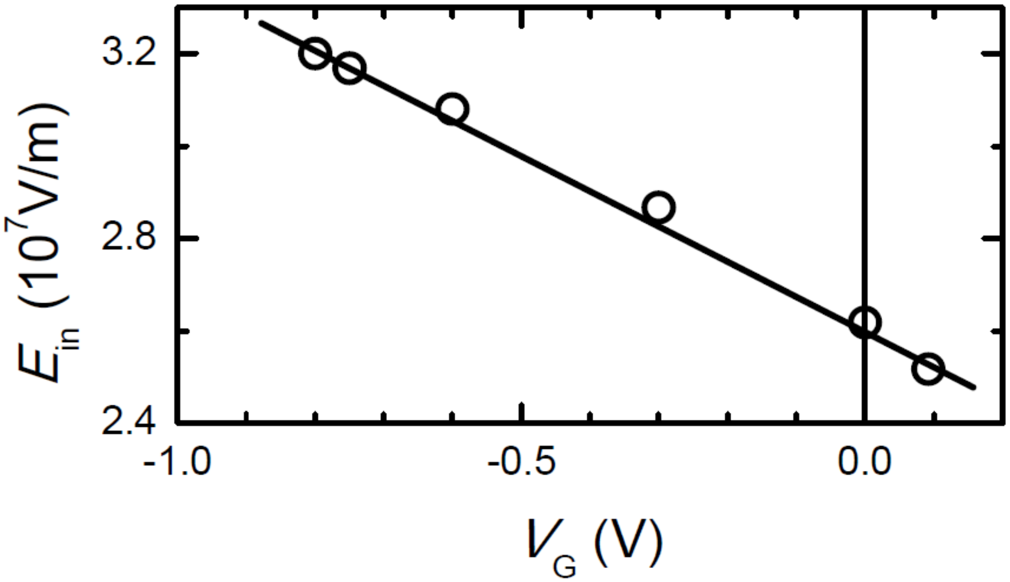


Magnetization along: [1$\underline{1}$0] [110]

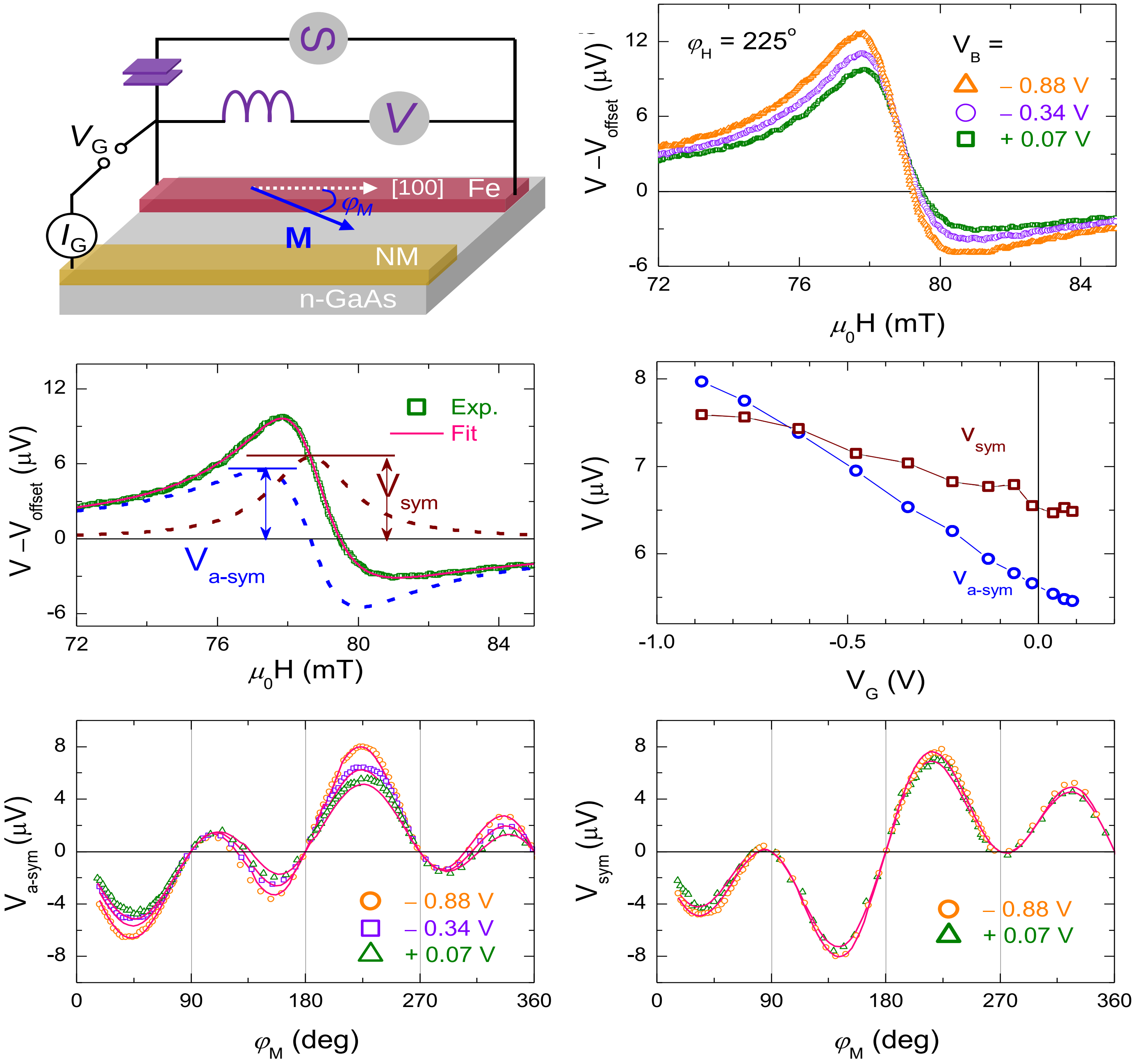
M. Gmitra, A. Matos-Abiague, C. Draxl, and J. Fabian, PRL **111**, 036603 (2013)

Electric field control of SOFs: Schottky barrier





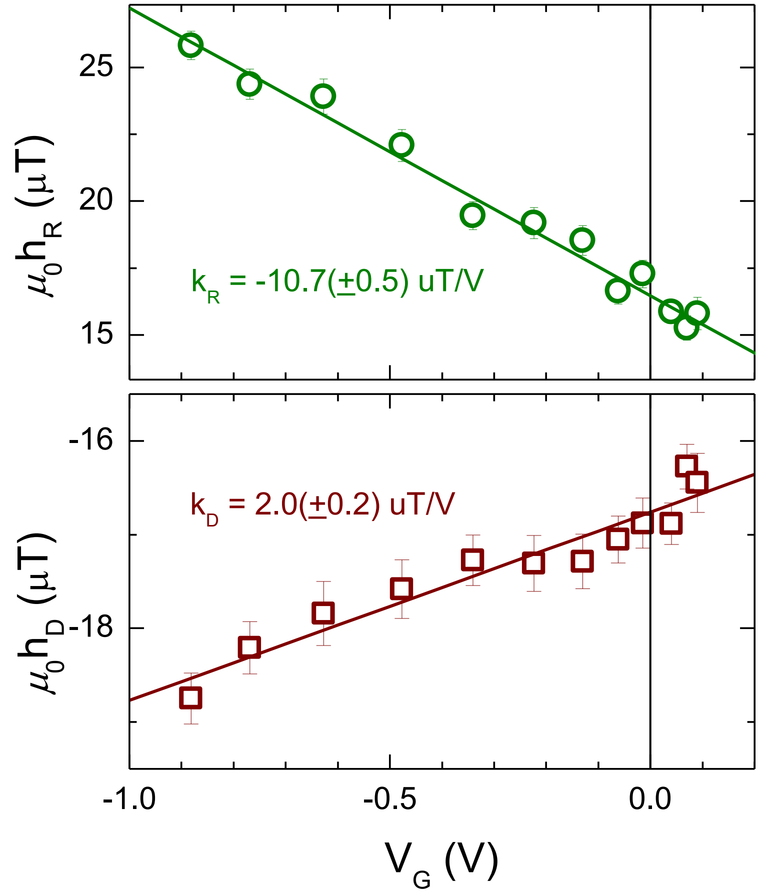
Electric field control of SOFs

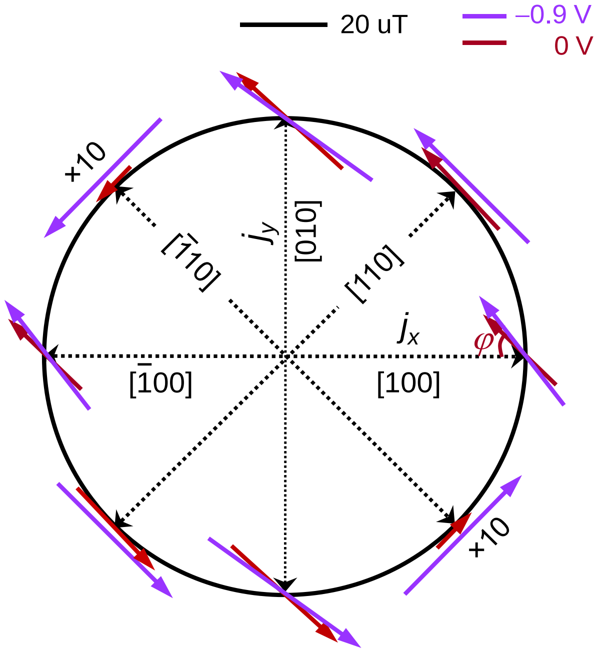


Electric field control of SOFs

Rashba vs. Dresselhaus in-plane SOFs

[100]-oriented device



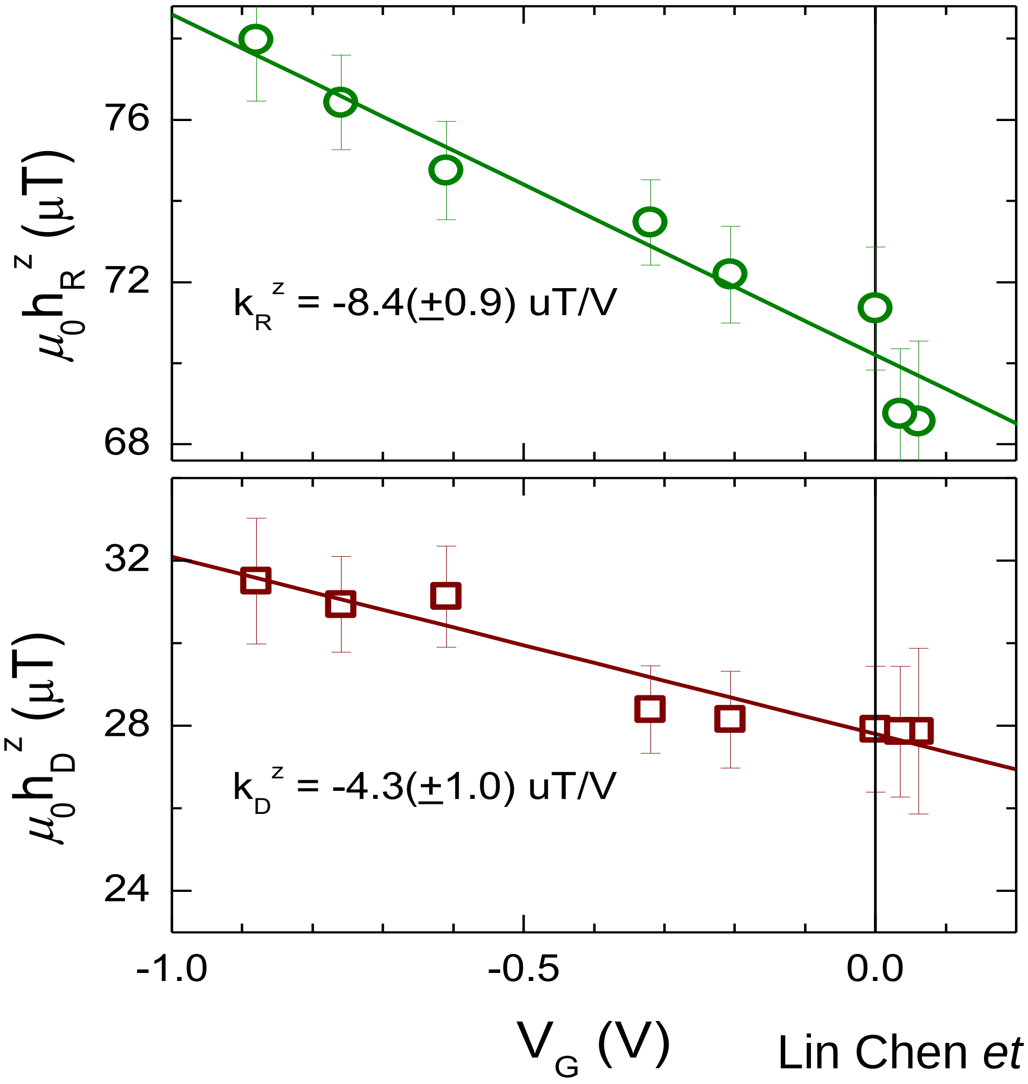


Lin Chen *et al.*, Arxiv 1803.01656

Electric field control of SOFs

Rashba vs. Dresselhaus out-of-plane SOFs

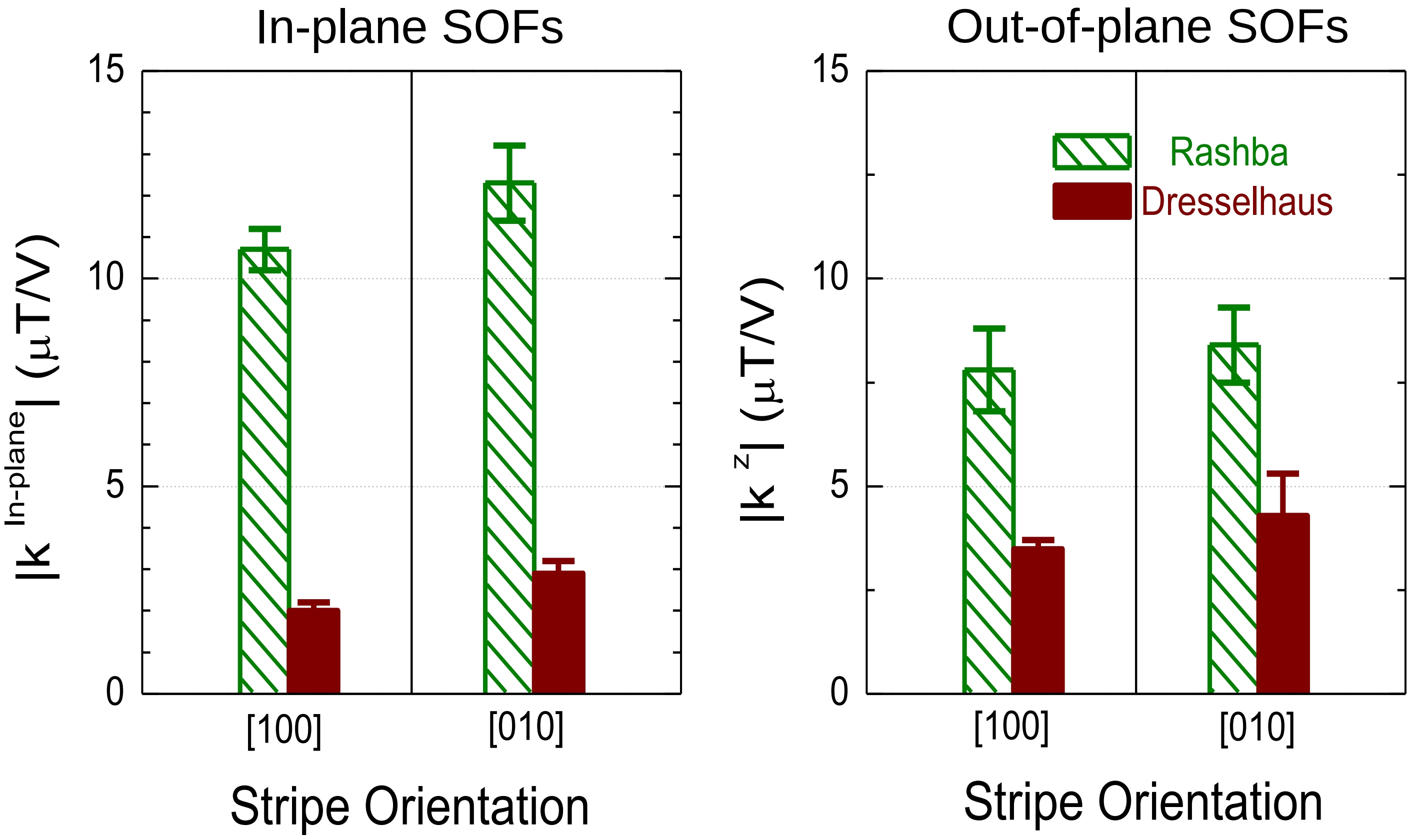
[100]-oriented device



Lin Chen *et al*., Arxiv 1803.01656

Electric field control of SOFs

Modulation Amplitude



In-plane SOFs

Out-of-plane SOFs

Lin Chen *et al.*, Arxiv 1803.01656

- electronic properties of Fe/GaAs(001) interface are dominated by C_{2v} symmetry

- CAMR expresses C_{2v} symmetry (and can be used to quantify SOFs)

- Mutual conversion of spin and charge currents at Fe/GaAs(001) interface

- Voltage control of SOFs demonstrated

- Sizeable effects at a simple interface!