Optical and Electrical Detection of Spin-Orbit Fields

Christian Back

Technische Universität München

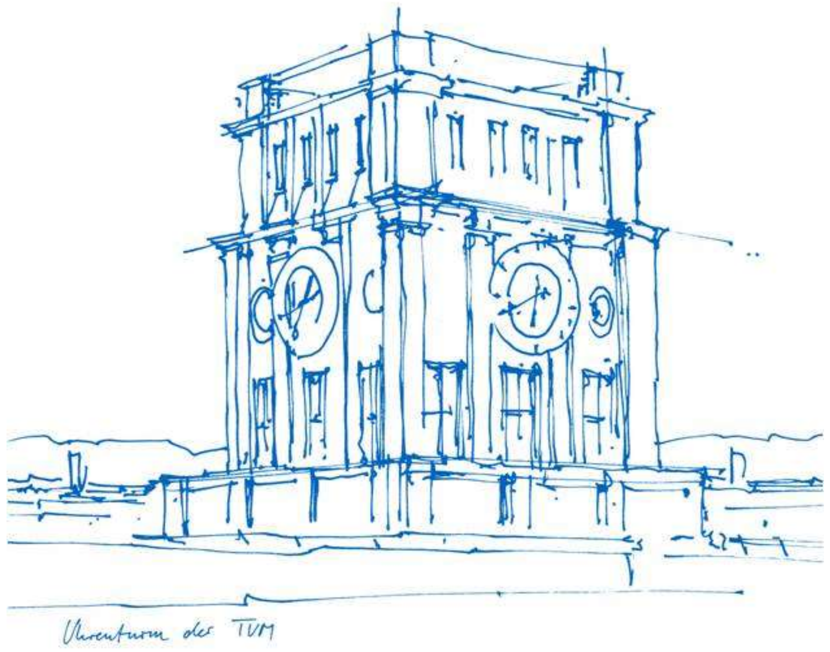
Physik-Department

Fe/GaAs system

Spin Orbit FMR

Voltage control of spin orbit fields

Optical detection of spin orbit fields



Universität Regensburg

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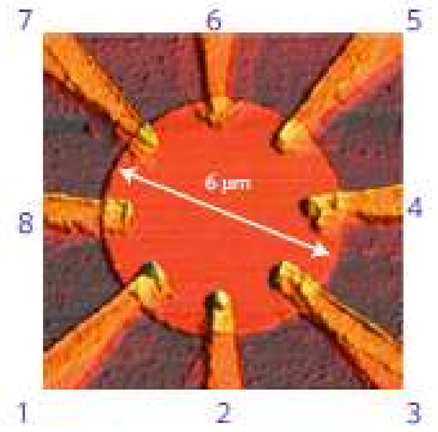
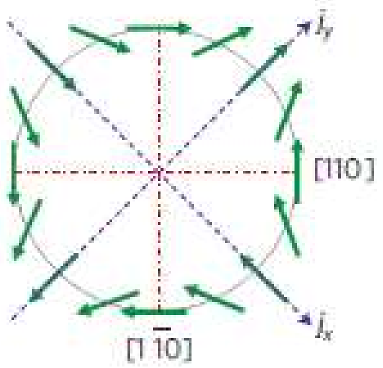
DFG: SFB 689 „Spin Phenomena in Reduced Dimensions“
SFB 1277 „Emergent Relativistic Effects in Condensed Matter“

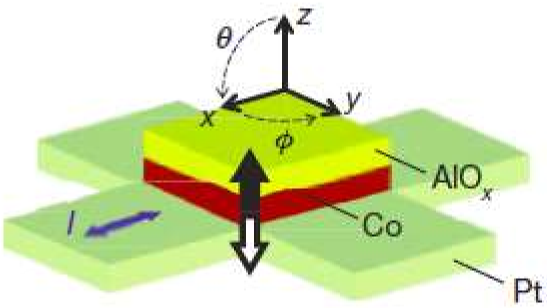
AvH foundation (Lin Chen)

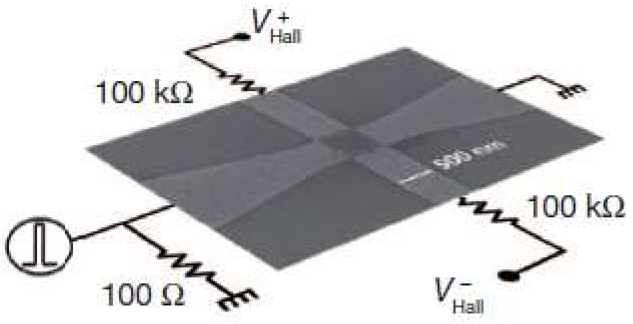
Alexander von Humboldt
Stiftung/Foundation

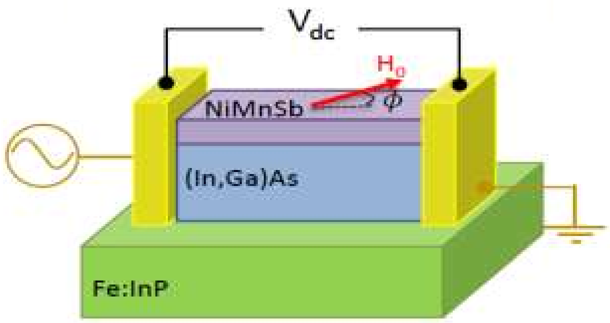
(interfacial) Spin Orbit Torques











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

single crystalline material (GaMnAs)
bulk

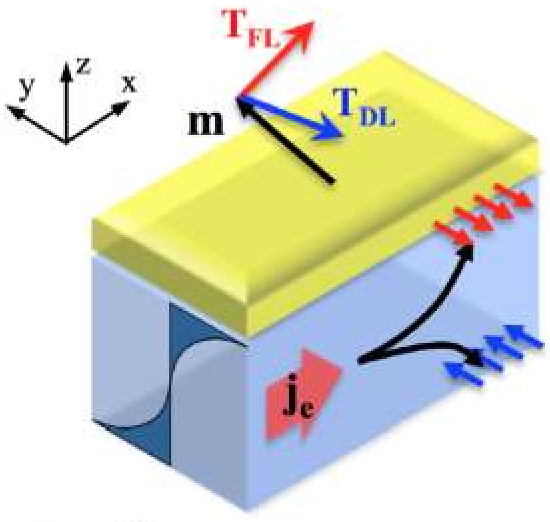
Miron et al., Nature **476**, 189 (2011)

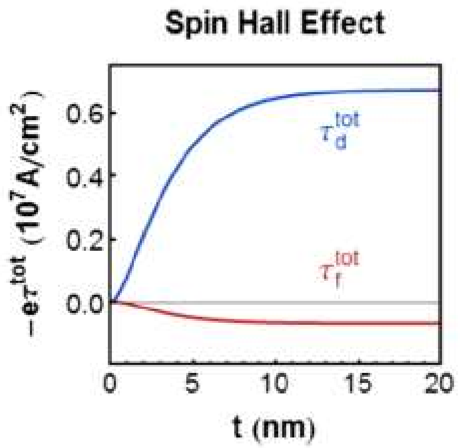
polycrystalline material (Pt/Co/AlO$_x$)
interface

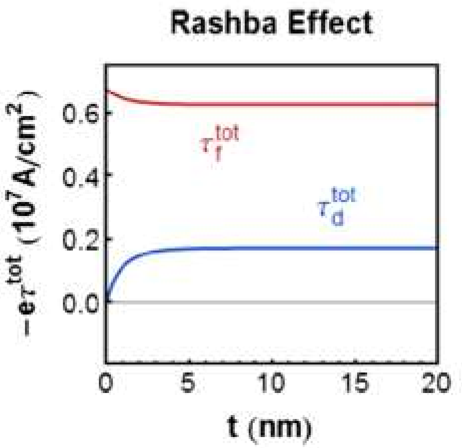
Ciccarelli et al., Nat. Phys. (2016)

single crystalline material (NiMnSb)
room temperature, bulk

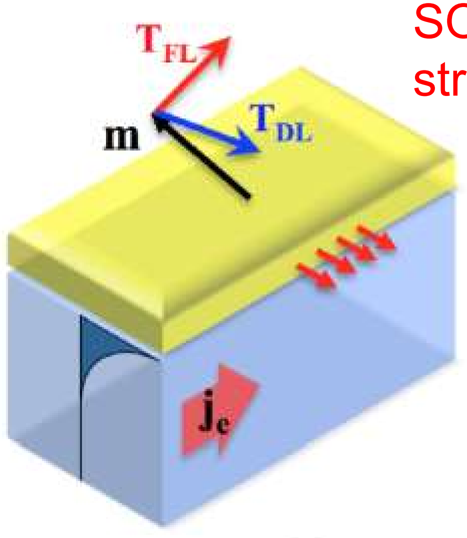
Spin Orbit Torques (Fields) at heavy metal (HM) ferromagnet (FM) interfaces







SO-interaction strength α



Spin Hall Effect (bulk)

Inverse Spin Galvanic Effect (interface)

τ_{FL}: field-like torque

τ_{DL}: (anti-)damping-like torque

$$h_{SOF} \sim \theta_{SH} J_e$$

$$\mathbf{T}_{FL} \sim \mathbf{m} \times (\mathbf{z} \times \mathbf{j}_e)$$
$$\mathbf{T}_{DL} \sim \mathbf{m} \times [(\mathbf{z} \times \mathbf{j}_e) \times \mathbf{m}]$$

$$h_{SOF} \sim \alpha J_e$$

Bychkov-Rashba

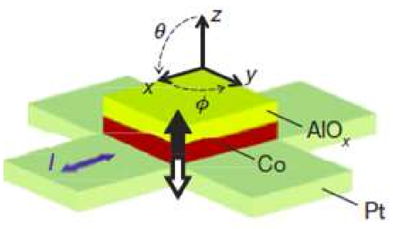
Rashba-Edelstein etc.

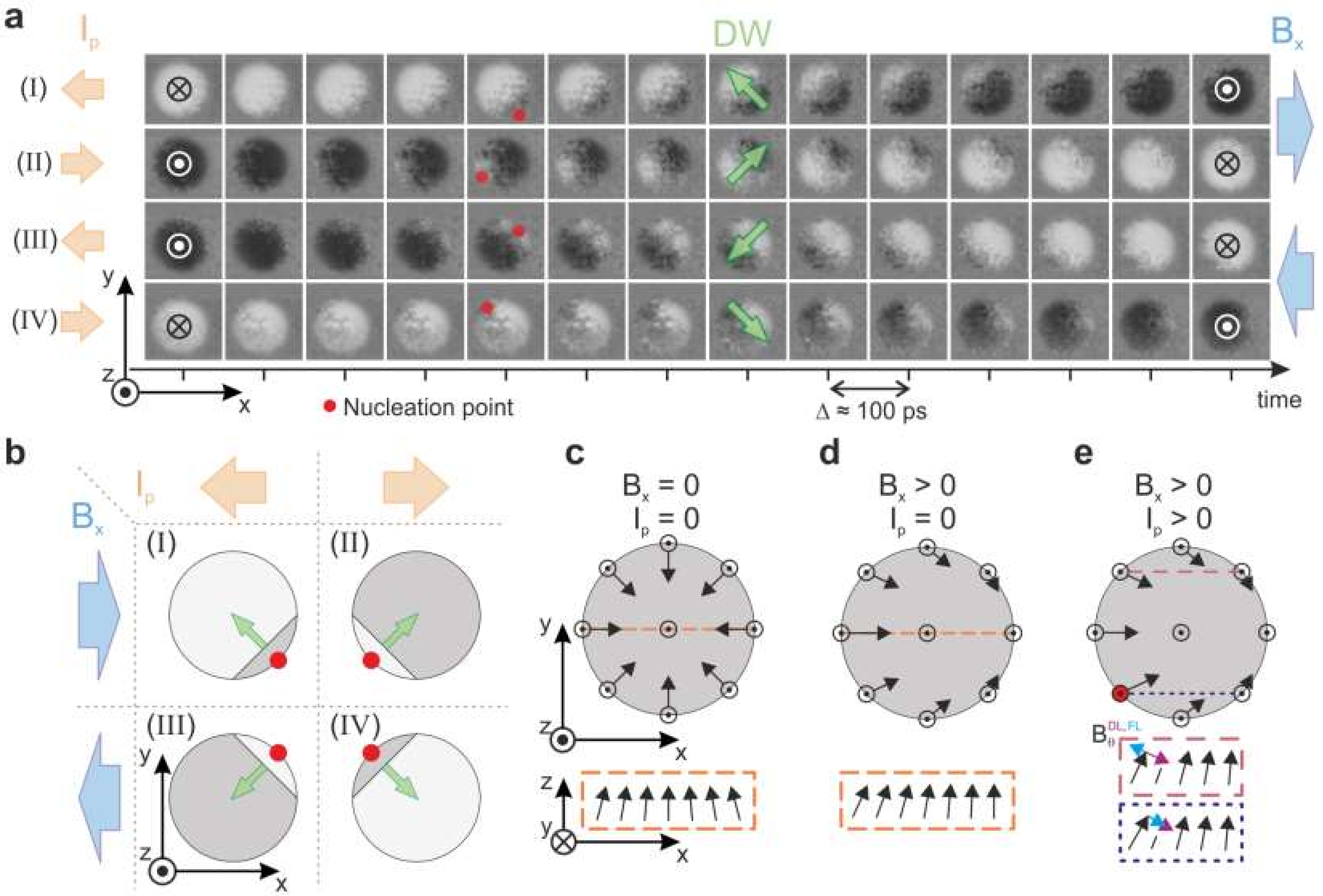
(not bulk Rashba e.g. GeTe)

A. Manchon et al., Rev. Mod. Phys. 91, 035004 (2019)

V.P Amin and M.D. Stiles, Phys. Rev. B 94, 104420 (2016)

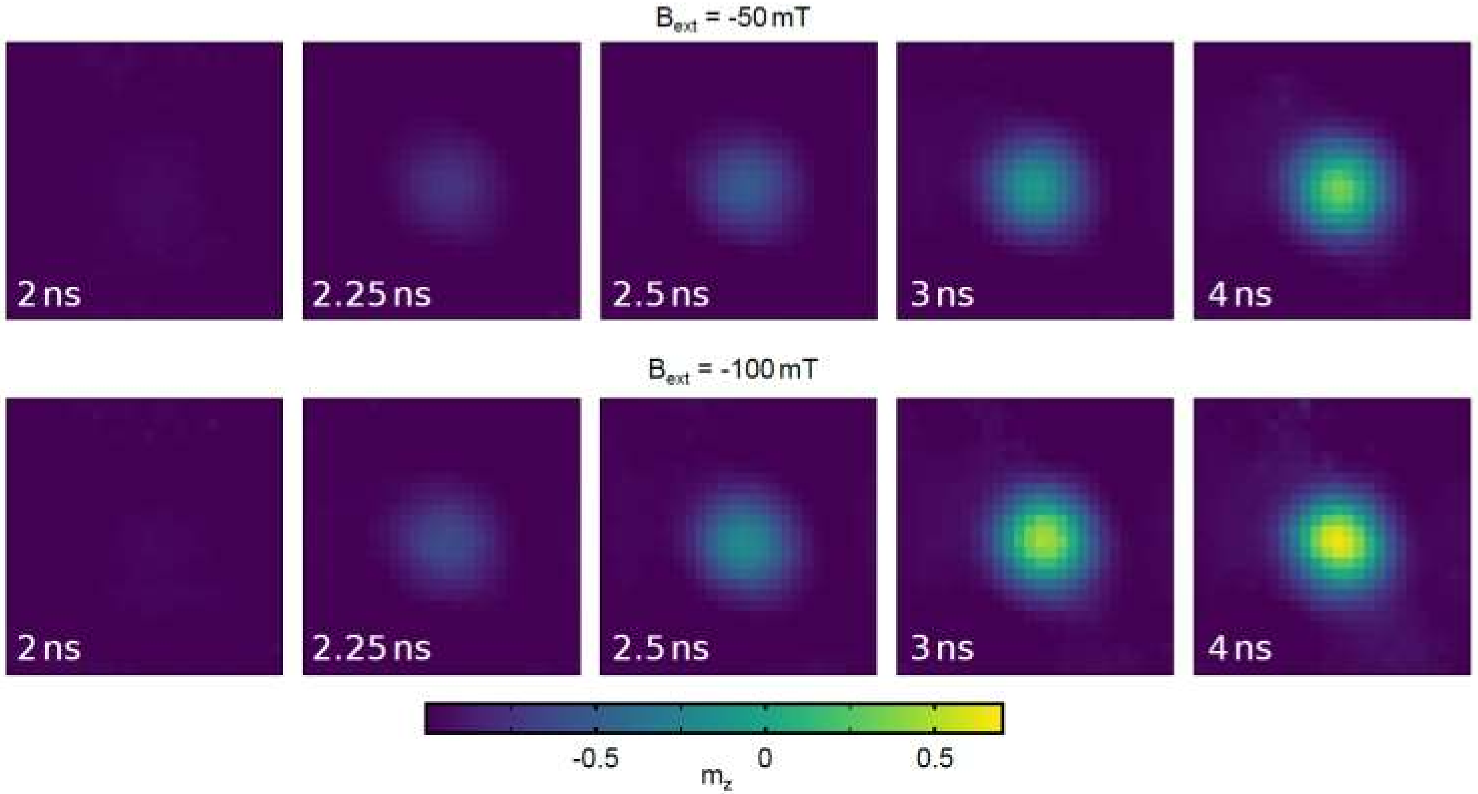
(x,t) resolved detection of SOT induced switching process: Gambardella group

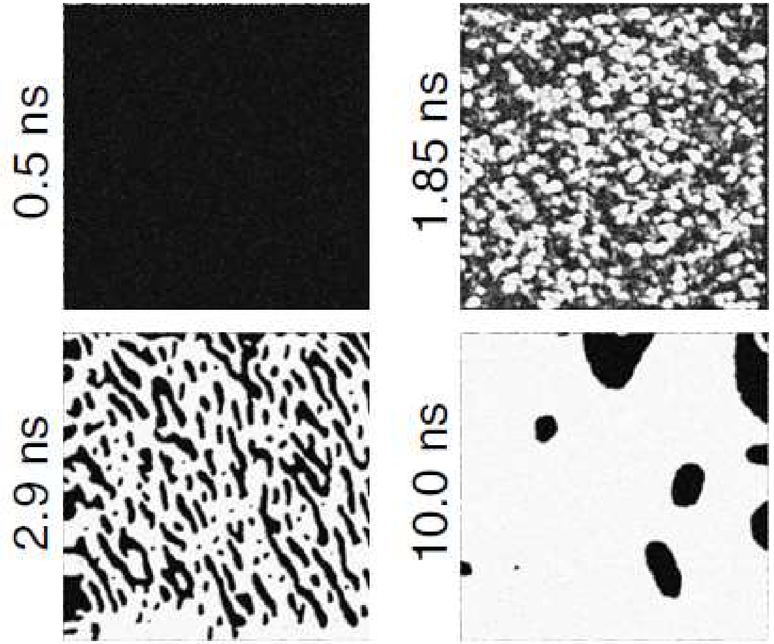




M. Baumgartner et al., Nat. Nanotech. **12**, 980 (2017)

Experiments and micromagnetic simulations





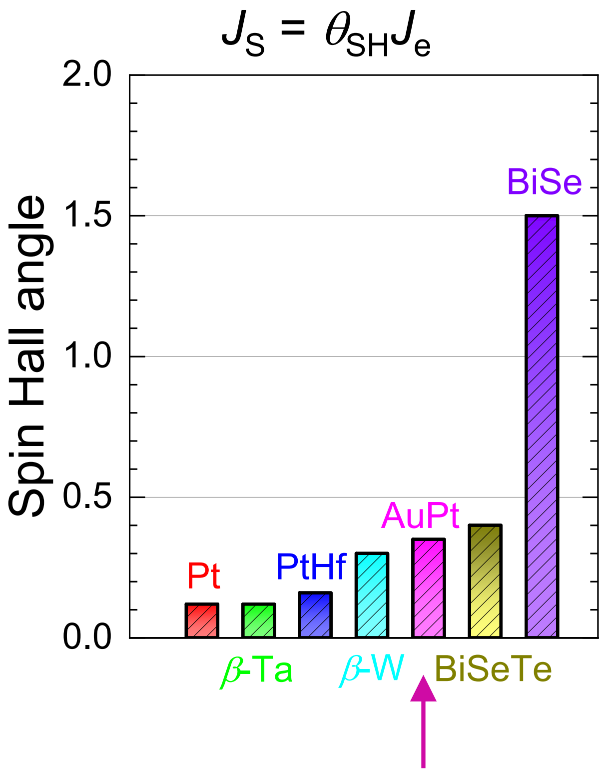
To reproduce response by micromagnetic simulations, anti-damping like torque, field like torque, temperature and DMI must be taken into account

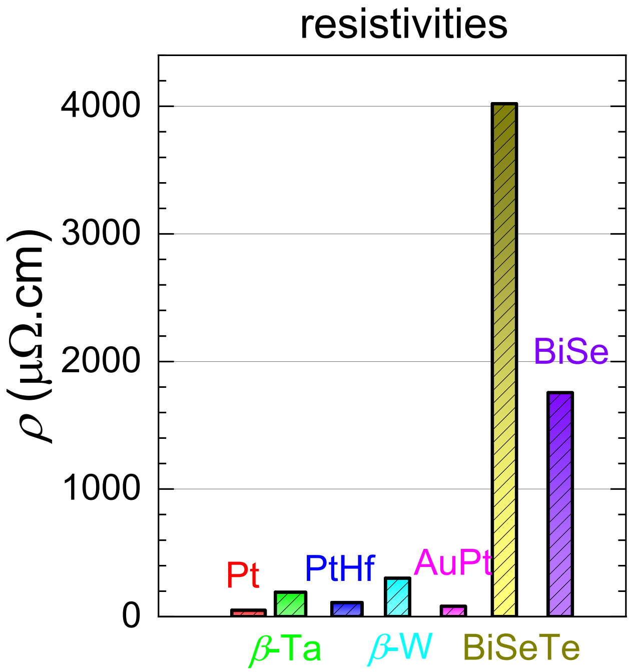
At low temperatures: deterministic domain wall nucleation from edges (and propagation)
see Gambardella group

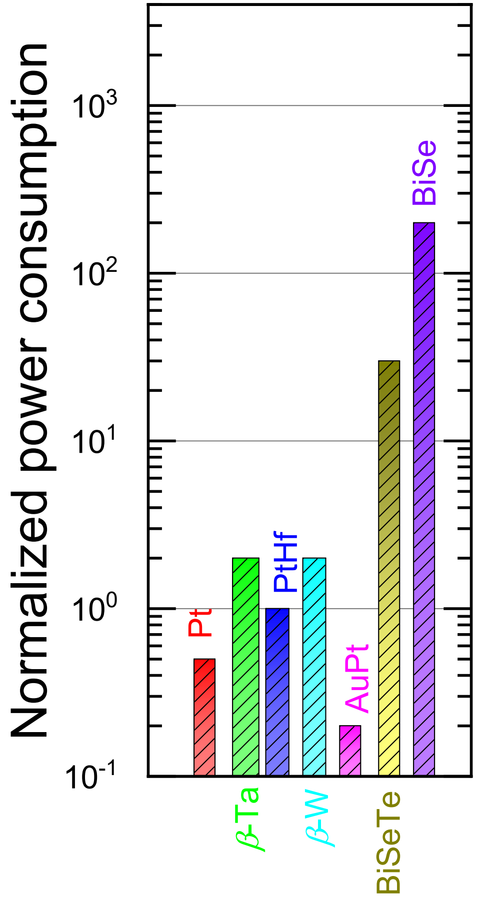
M. Decker et al., Phys. Rev. Lett. **118**, 257201 (2017)

For current induced switching via Spin Orbit Torques, one would like to reduce the required current density J_e

metals more suitable ?



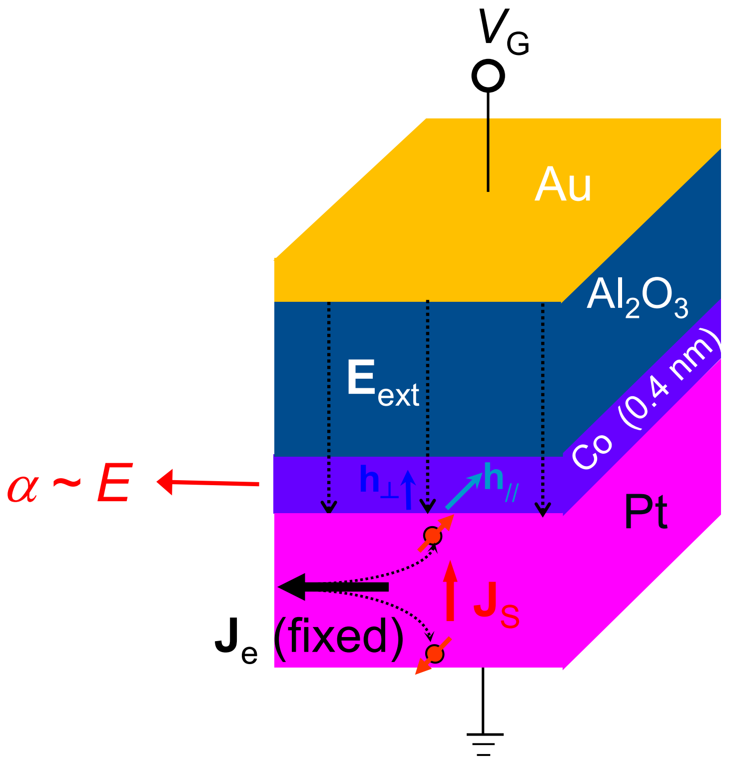




Tuning Spin Hall Angles by Alloying,
Phys. Rev. Lett. **117**, 167204 (2016)

L. J. Zhu *et al*. Phys. Rev. Appl. **10**, 031001 (2018)

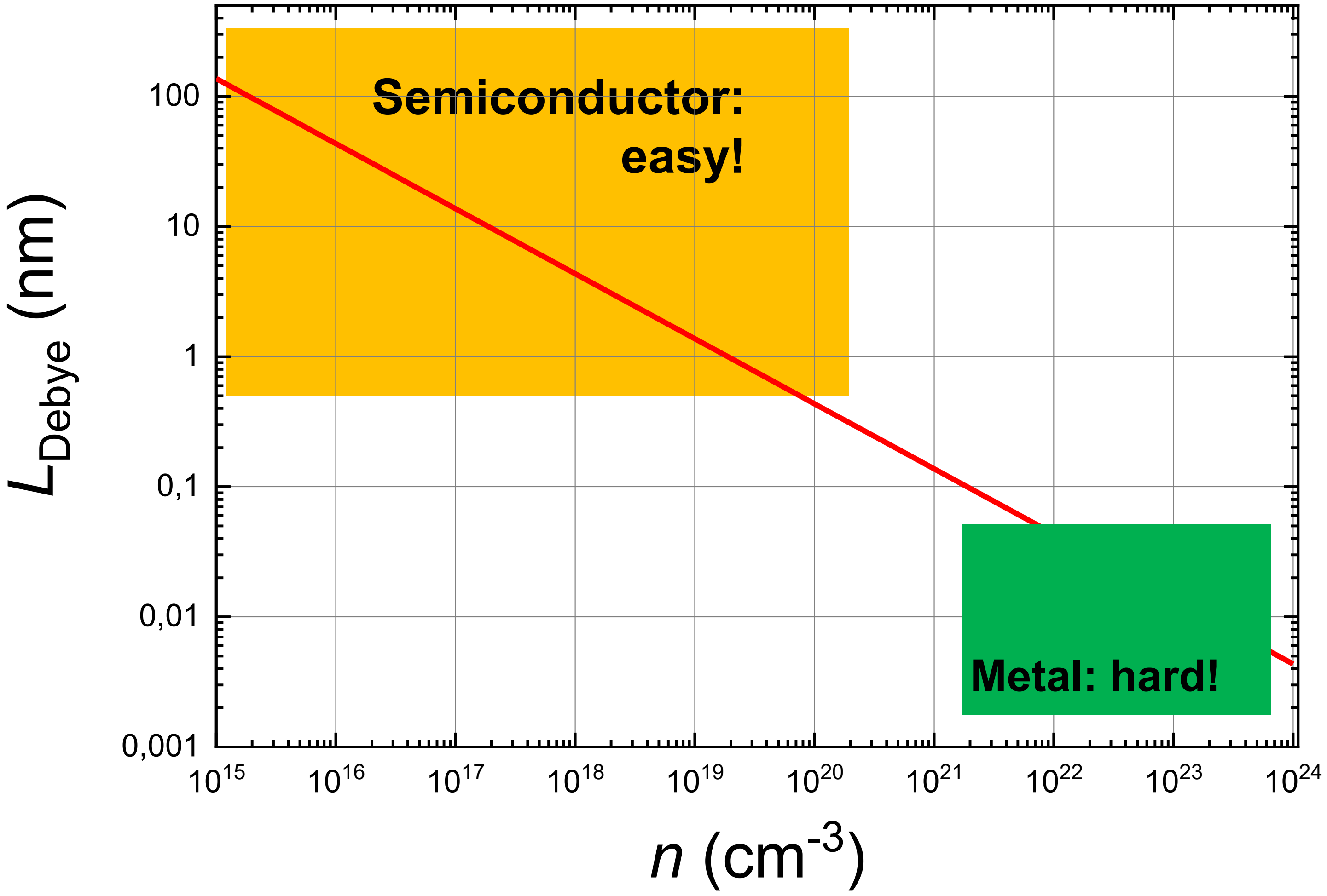
Possible modulation of SOI strength: electric field control



Charging energy << Joule heating

Problem: it is hard to control metals by electric field!

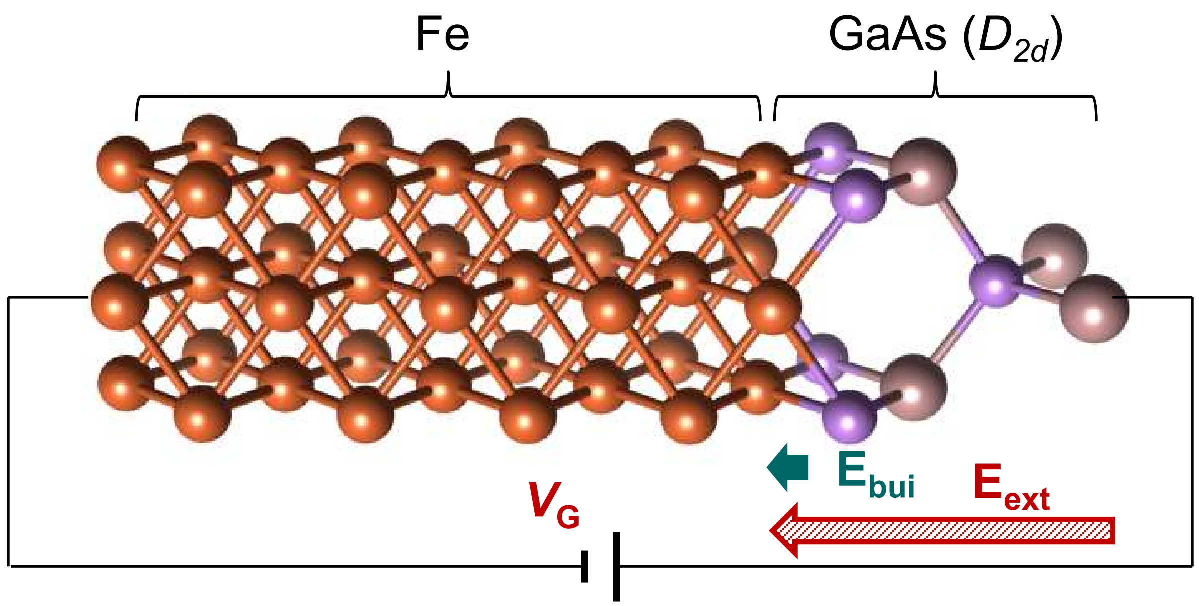
Thomas-Fermi screening length



$$L_D = \sqrt{\frac{\varepsilon_S k_B T}{e^2 n}}$$

Open question: can we use SCs to control a metal?

Electric-field control of interfacial SOFs



- C_{2V} symmetry ⇒ Interfacial Bychkov-Rashba-like and Dresselhaus-like SOI
- SOI ~ $\mathbf{E}_{in} = \mathbf{E}_{bui} + \mathbf{E}_{ext}$
- **Allows electric-field control!**

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

Fe/GaAs system

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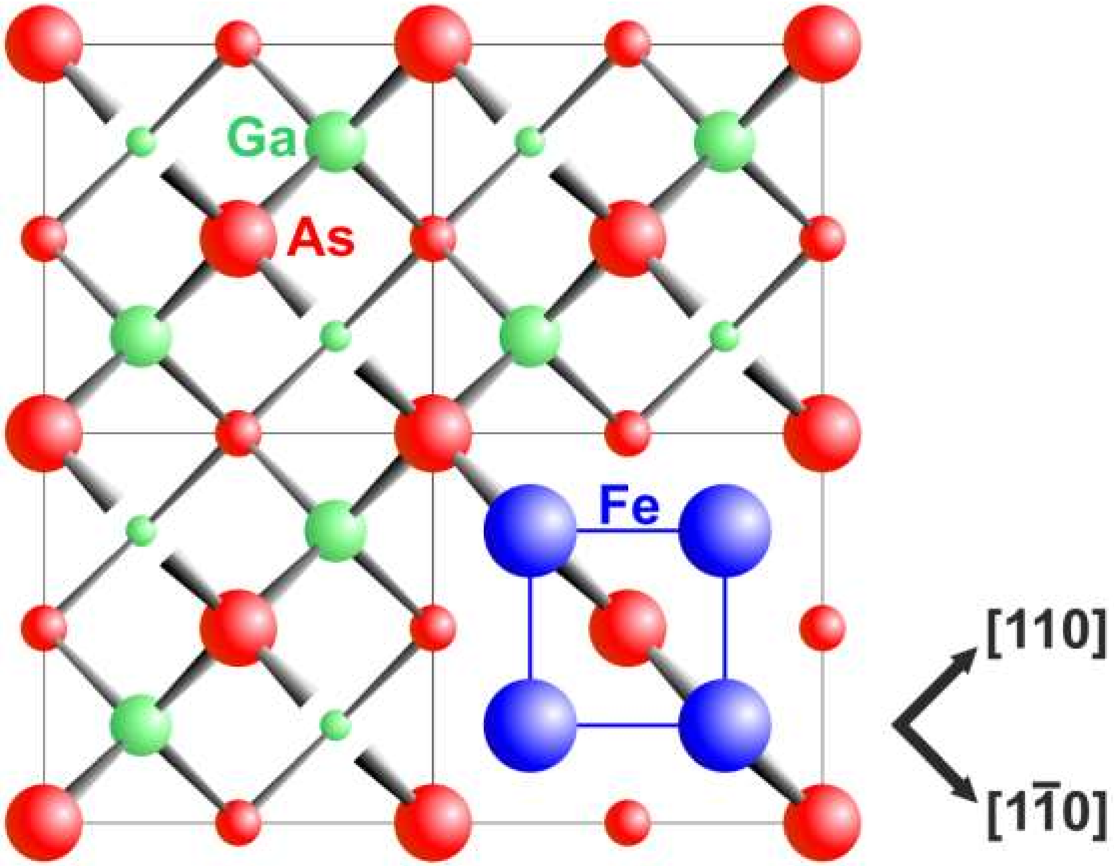
Voltage control of spin orbit fields

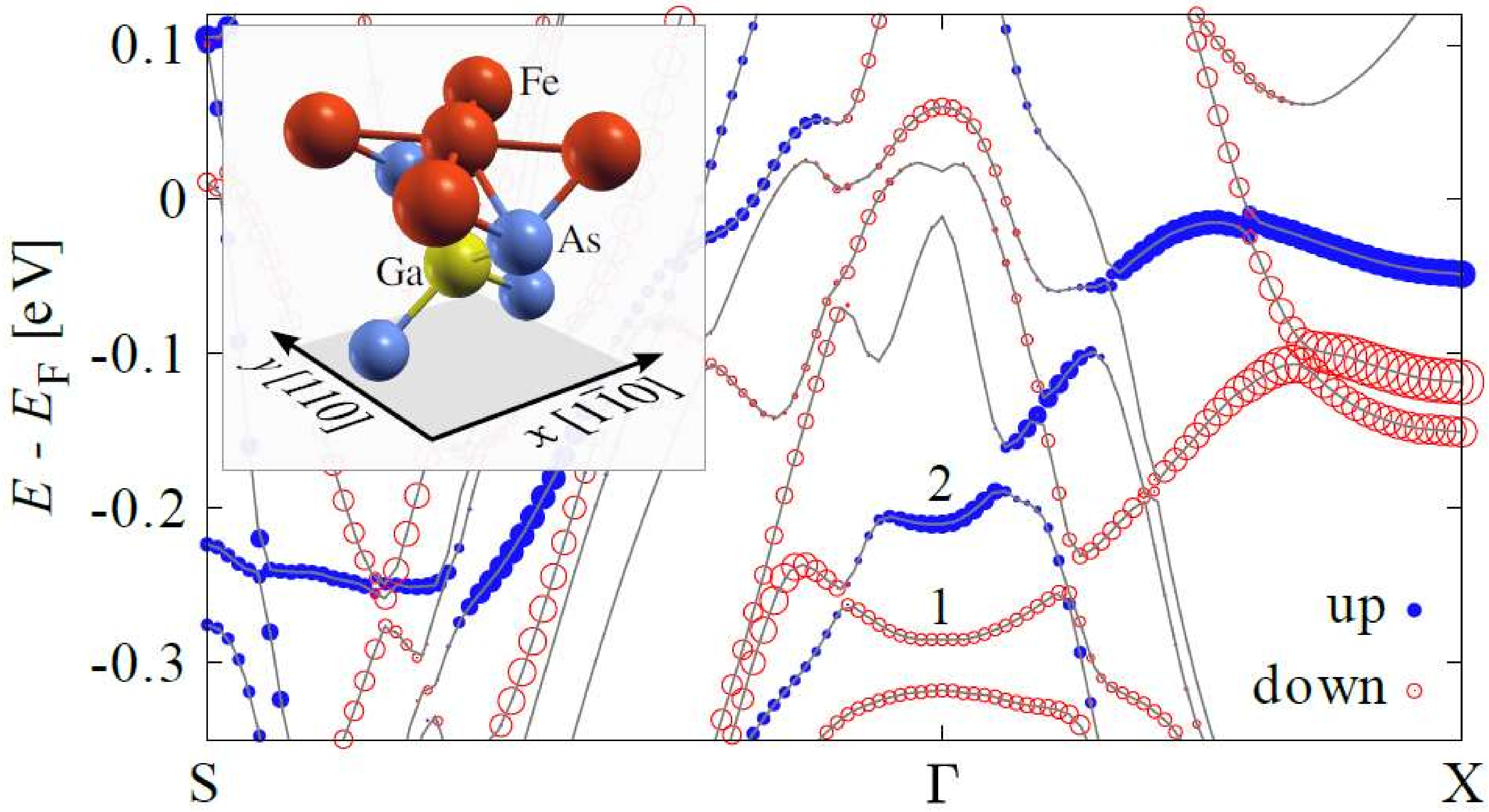
Optical detection of spin orbit fields

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_10] 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:

[redacted]

***k*-dependent SOF**

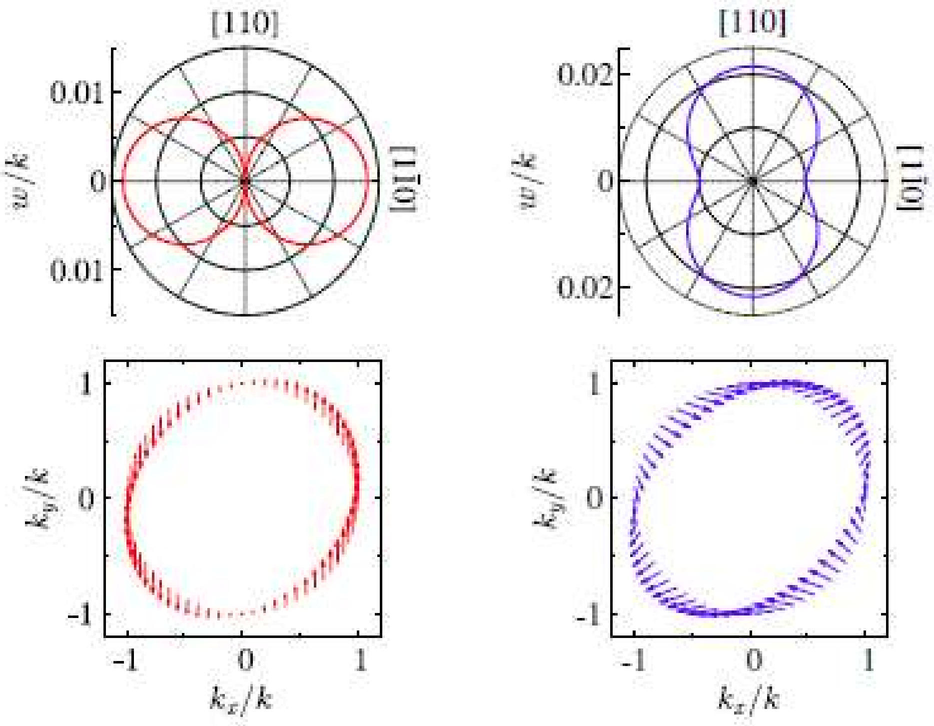
Pauli-matrices

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$\bar{1}$0] [110]

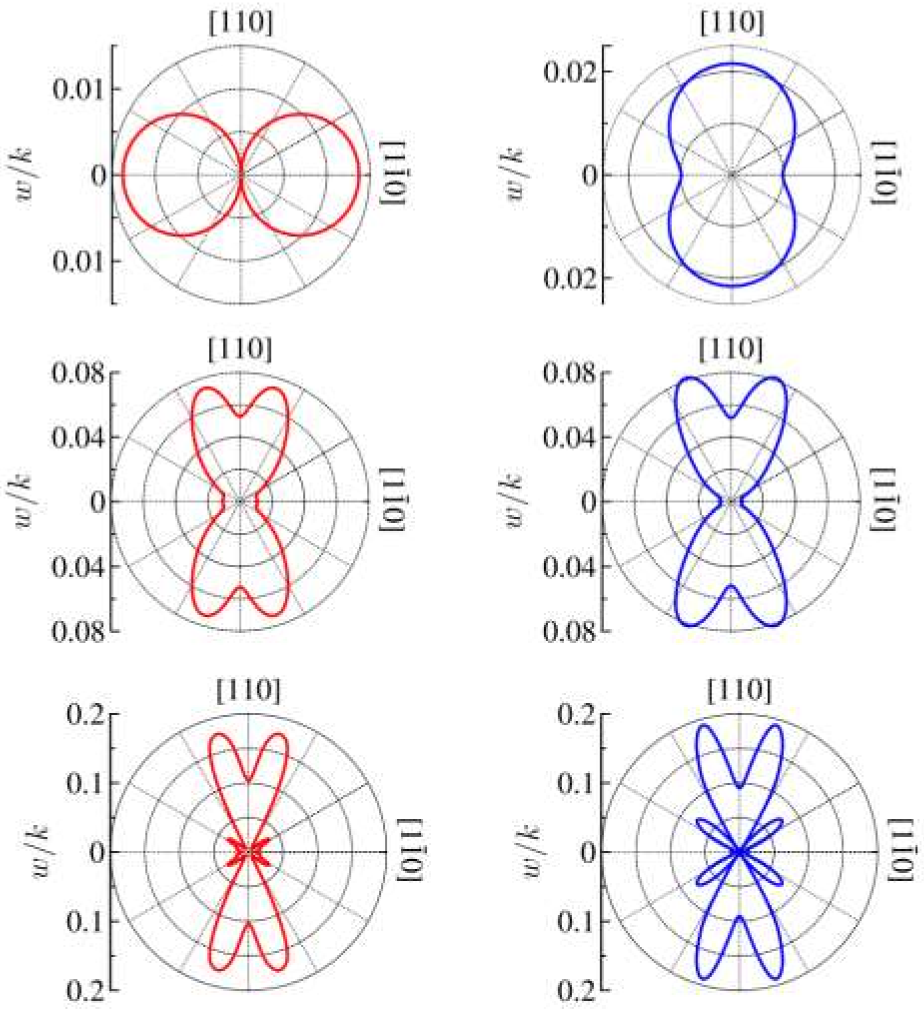
M. Gmitra, A. Matos-Abiague, C. Draxl, and J. Fabian, PRL **111**, 036603 (2013)

SOFs at the Fe/GaAs interface

- Calculated SO coupling strengths for different energies and magnetization directions

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

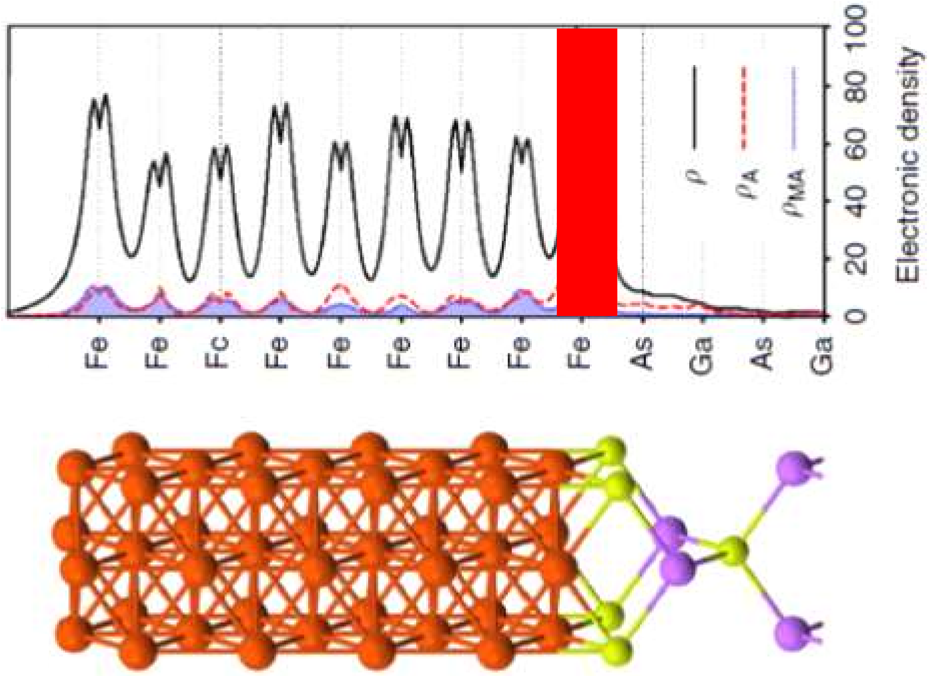
- Higher order contributions for higher energies

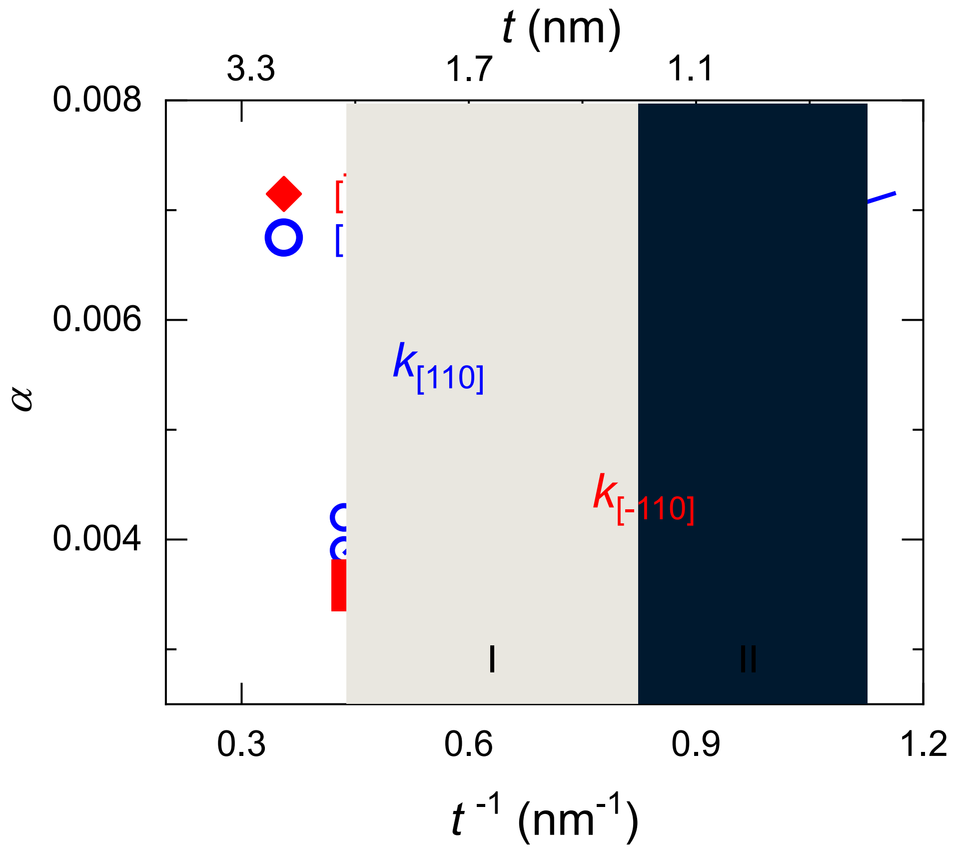


Magnetization along: [1$\underline{1}$0] [110]

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

In essence: anisotropic (C_{2V}) density of states at E_F





Tunneling AMR (TAMR)

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

Crystalline AMR (CAMR)

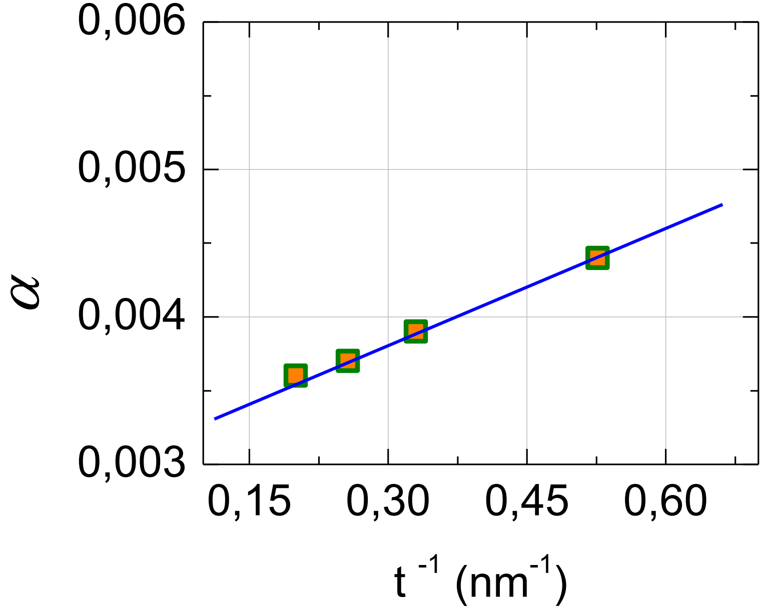
T. Hupfauer *et al.*, Nat. Commun. **6**, 7374 (2015)

Anisotropic damping

L. Chen *et al*. Nature Phys. **14**, 490 (2018)

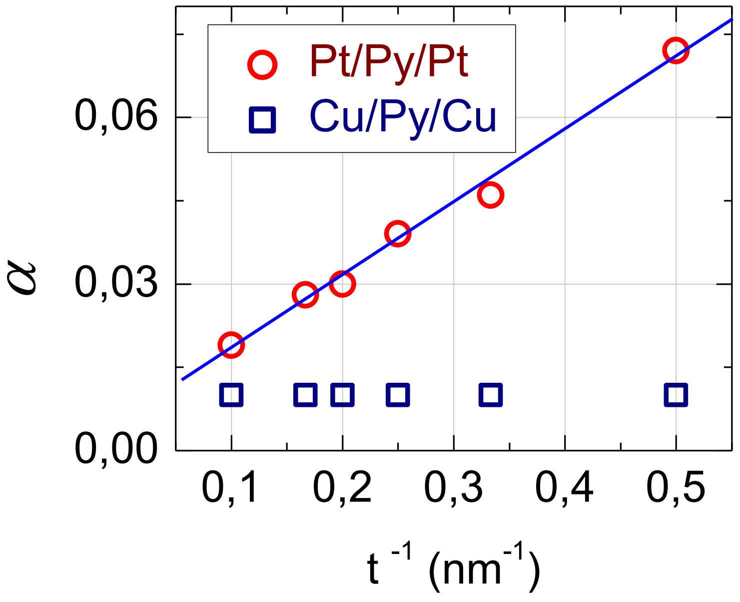
Side note: Spin pumping in Fe/GaAs

Fe(*t*)/GaAs



$g_{eff}^{\uparrow\downarrow} = 2.8 \times 10^{18}\ m^{-2}$

$g_{eff}^{\uparrow\downarrow} = 7.0 \times 10^{19}\ m^{-2}$

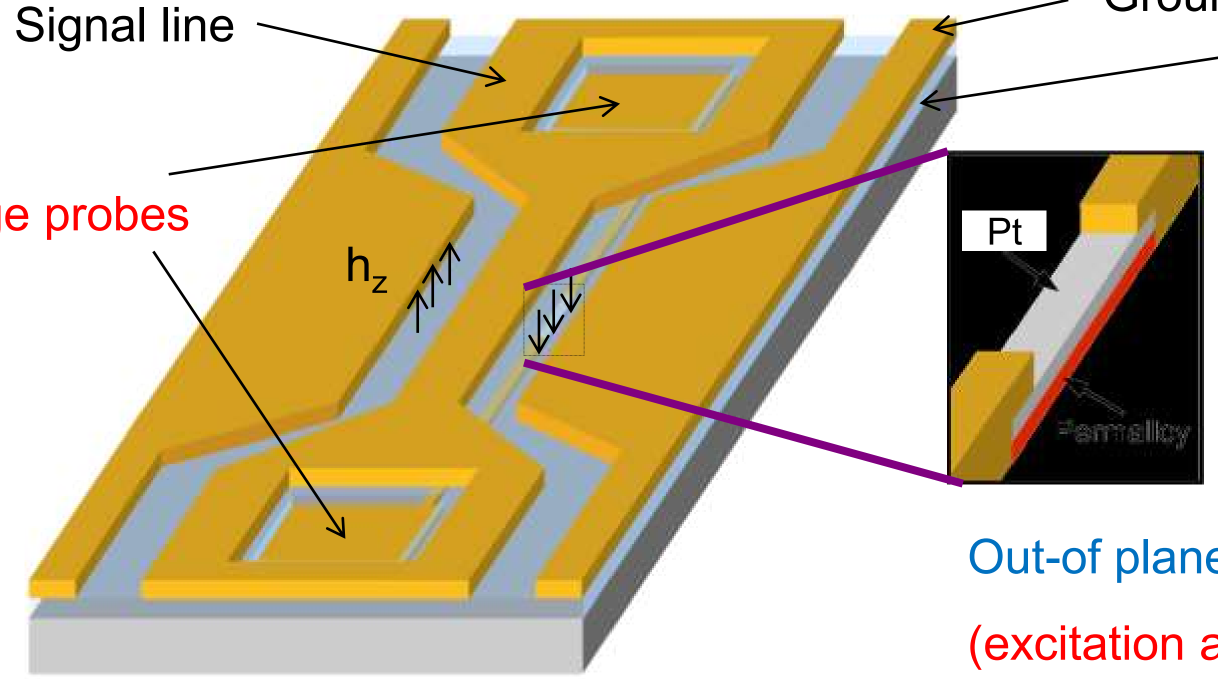


from spin pumping theory:

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

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

Spin Pumping and SGE



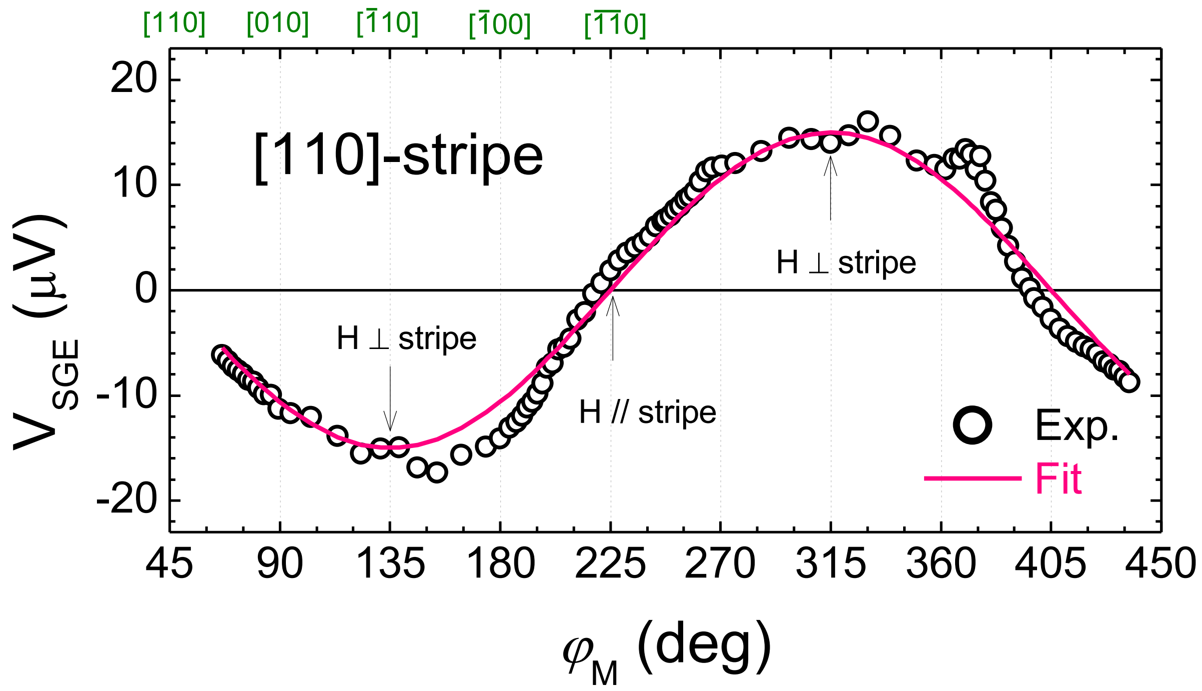
Here: Fe/GaAs

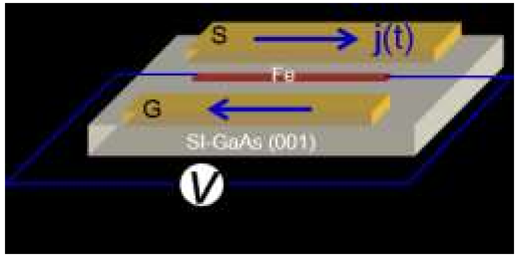
Out-of plane excitation

(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: $\mathbf{J}_e \sim \mathbf{n} \times \boldsymbol{\sigma}$

Spin galvanic effect (SGE): no NM conducting layer

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

Fe/GaAs system

Spin Orbit FMR

Voltage control of spin orbit fields

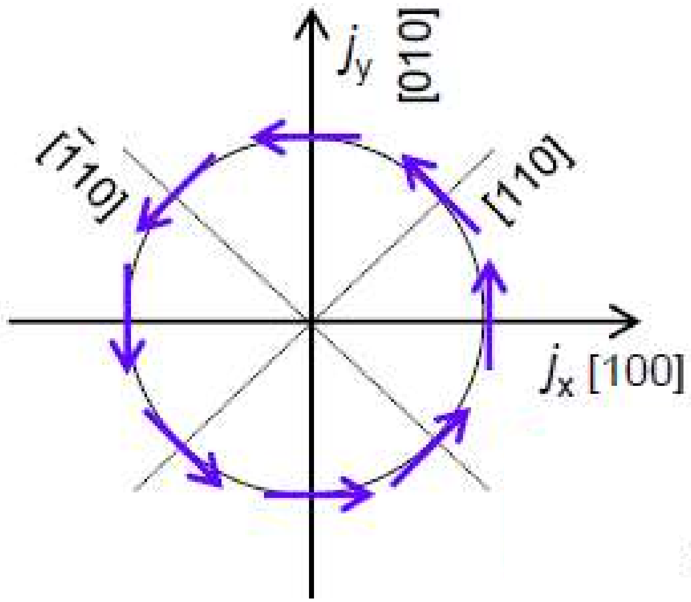
Optical detection of spin orbit fields

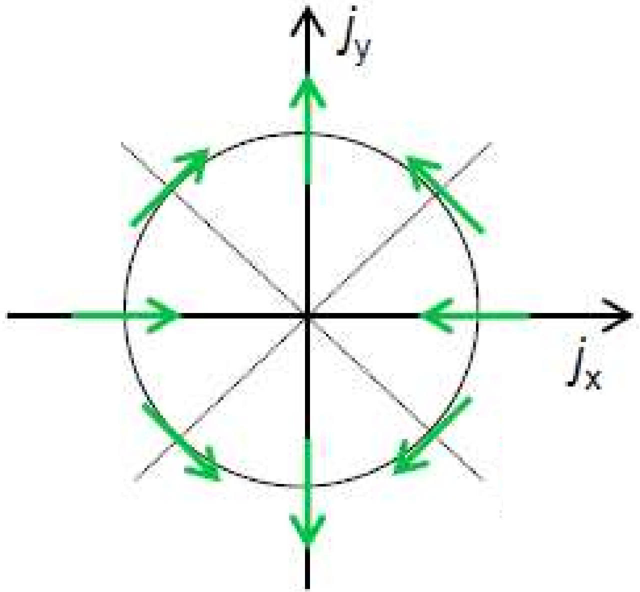
SOFs at the Fe/GaAs interface

Bychkov-Rashba (like) and Dresselhaus (like)

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

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





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

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

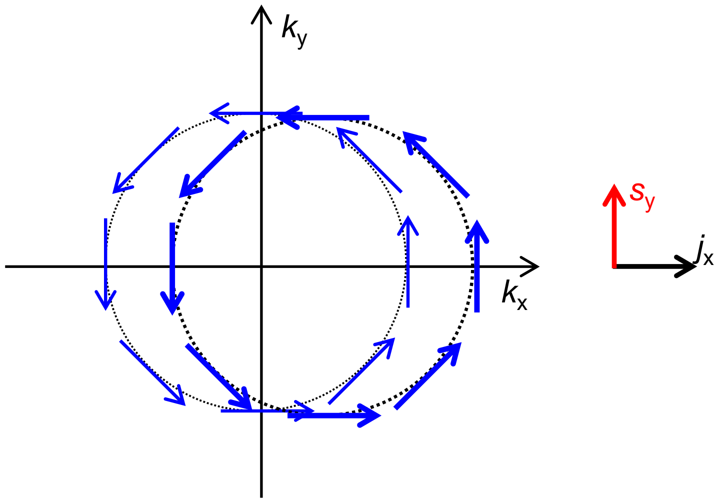
No net spin accumulation

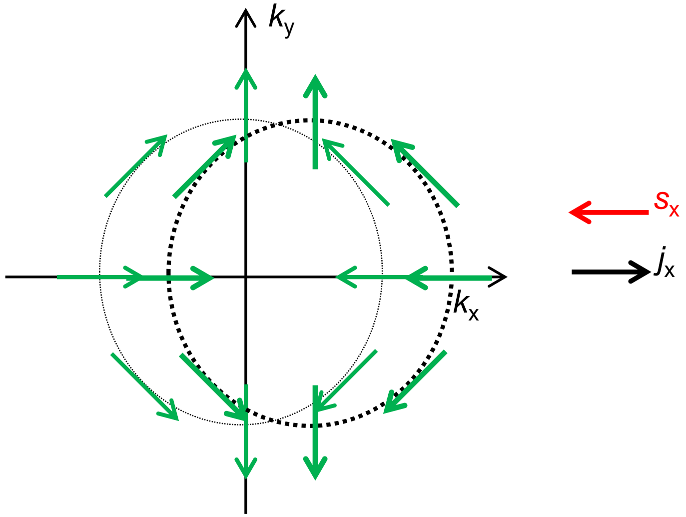
SOFs at the Fe/GaAs interface

Bychkov-Rashba (like) and Dresselhaus (like)

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

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





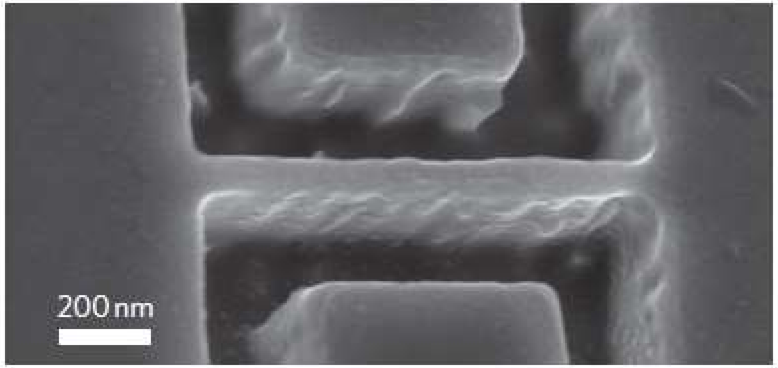
$$H_R = \alpha_{BR}(\sigma_x k_y - \sigma_y k_x)$$

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

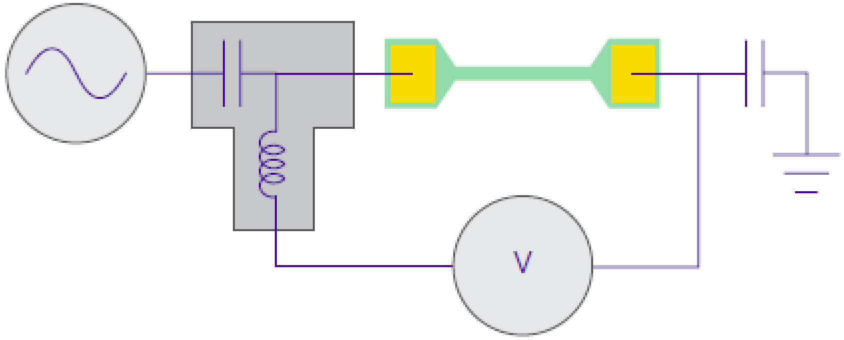
$$H_D = \beta_D(\sigma_x k_x - \sigma_y k_y)$$

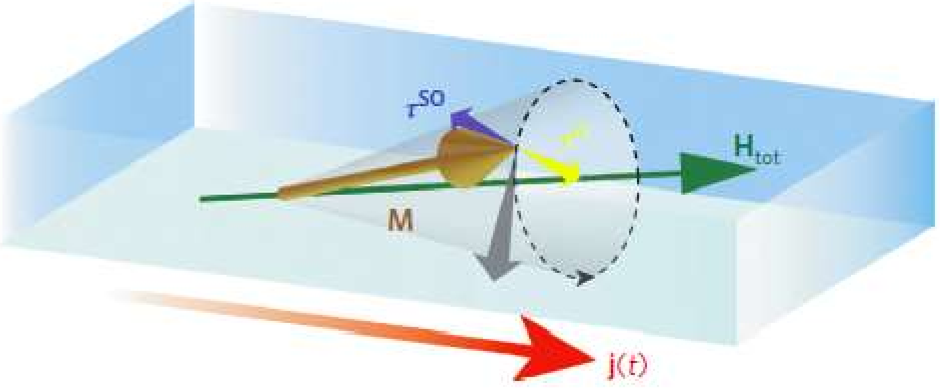
$$\langle s_x \rangle \sim -\beta_D j_x$$

Spin Orbit FMR



GaMnAs bar

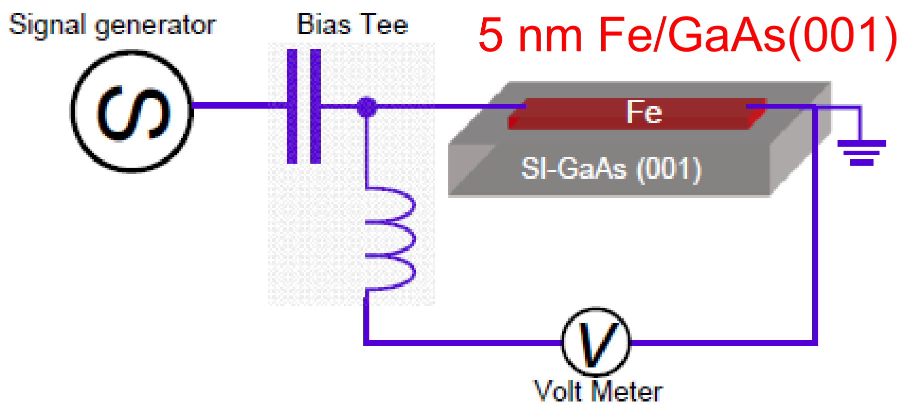


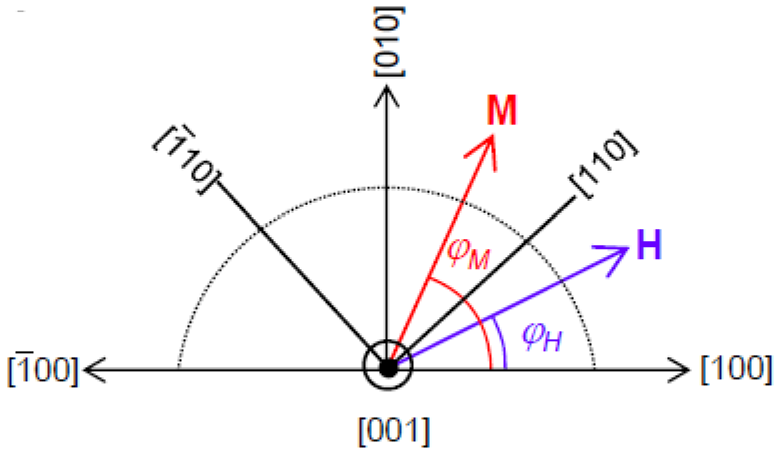


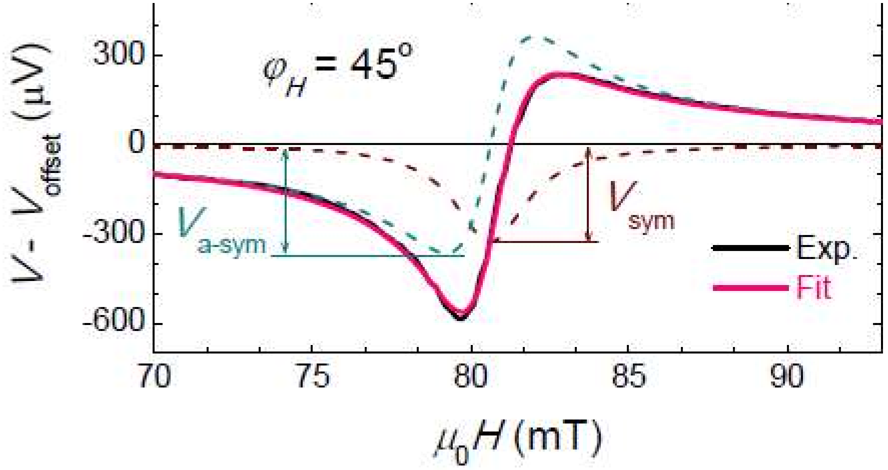
- $\mathbf{j}(t) \Rightarrow \mathbf{h}(t)$
- $\mathbf{h}(t) \Rightarrow \mathbf{M}(t) \Rightarrow \mathrm{R}(t)$
- $V \sim \overline{\mathbf{j}(t)\,\mathrm{R}(t)}$

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

Spin Orbit FMR at the Fe/GaAs interface







We obtain:

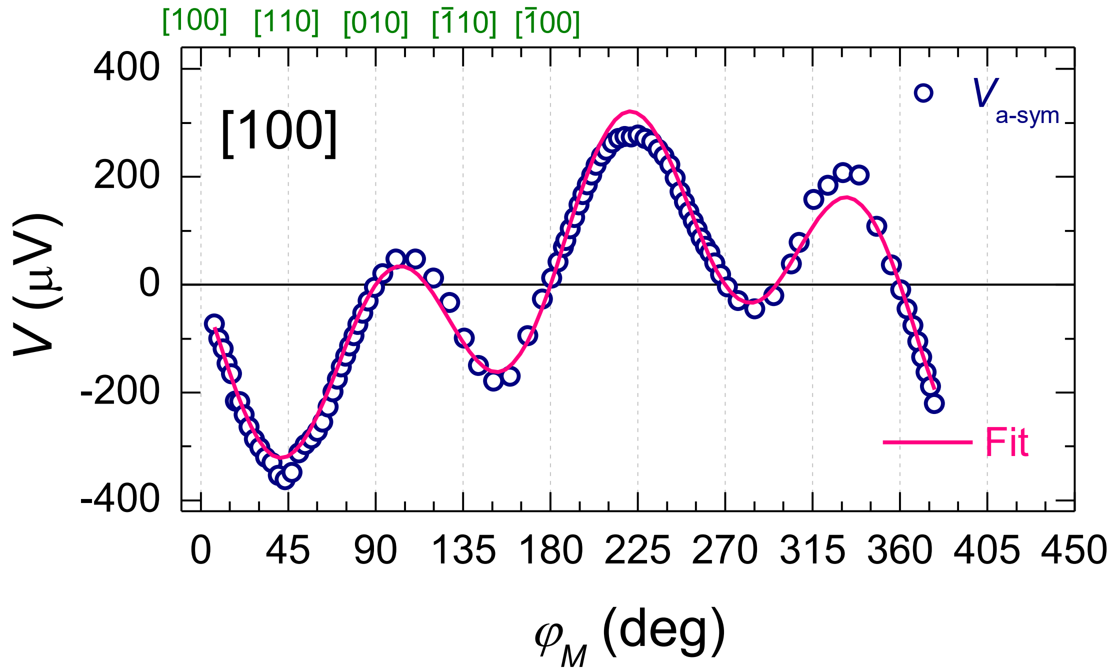
- H_R, $\Delta H \Rightarrow$ FMR
- $V_{a\text{-}sym} \Rightarrow$ in-plane SO fields
- $V_{sym} \Rightarrow$ out-of-plane SO fields

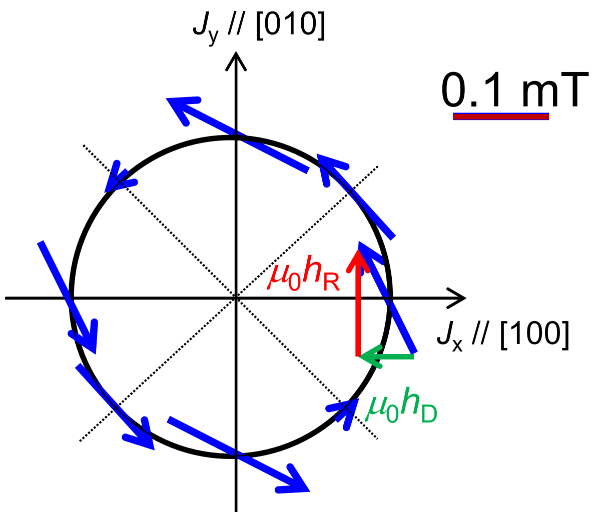
$$V(H) - V_{offset} = V_{sym}\frac{\Delta H^2}{4(H-H_R)^2 + \Delta H^2} + V_{a-sym}\frac{-4\Delta H(H-H_R)}{4(H-H_R)^2 + \Delta H^2}$$

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

Spin Orbit FMR: results

One device! Repeat for devices structured along different directions





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

Dresselhaus and Bychkov-Rashba contributions

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

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

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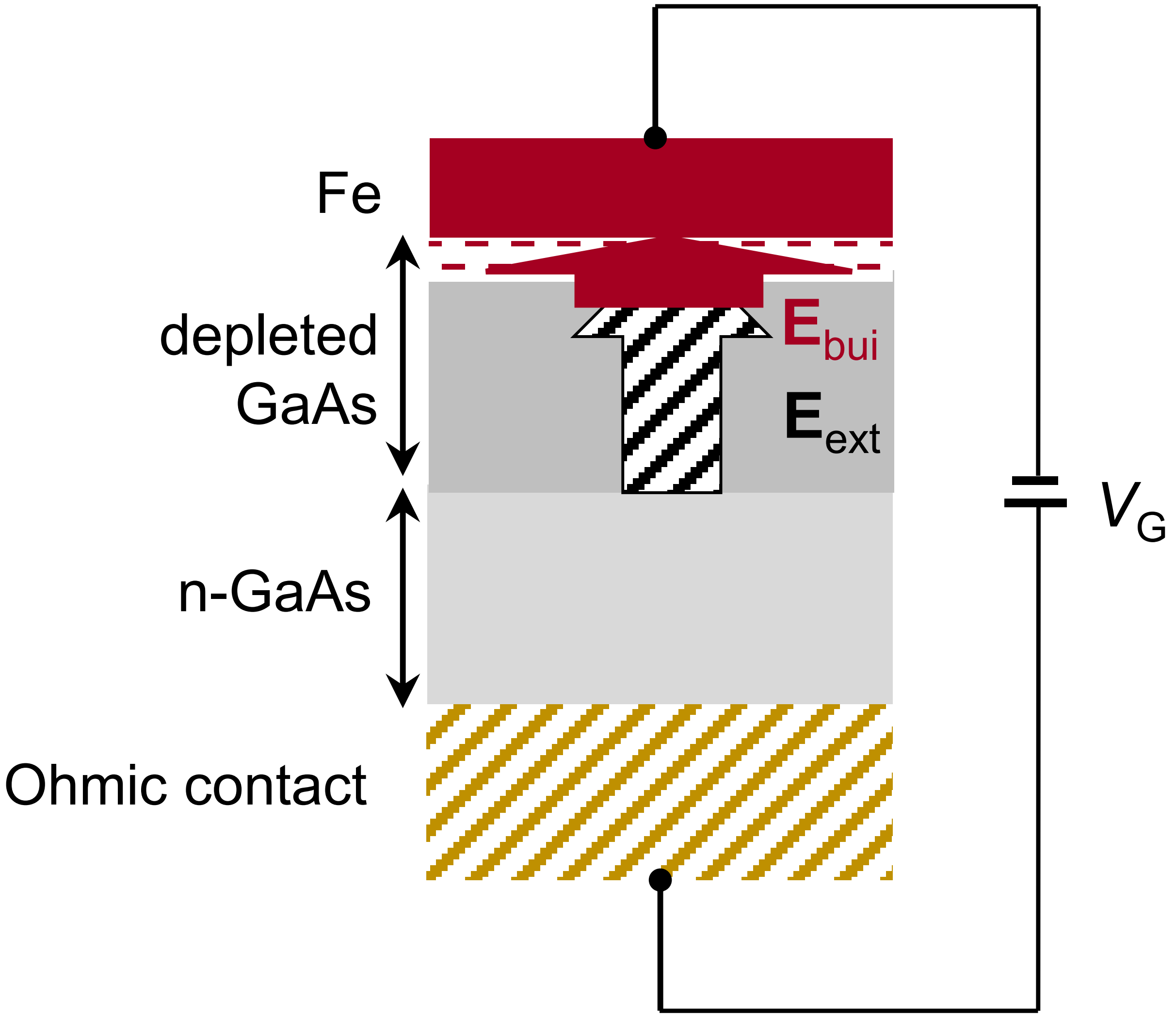
Optical detection of spin orbit fields

Electric field control of SOFs: Fe/n-GaAs Schottky junction



$|V_G|$ ~ **1 V** for $E = 10^7$ V/m

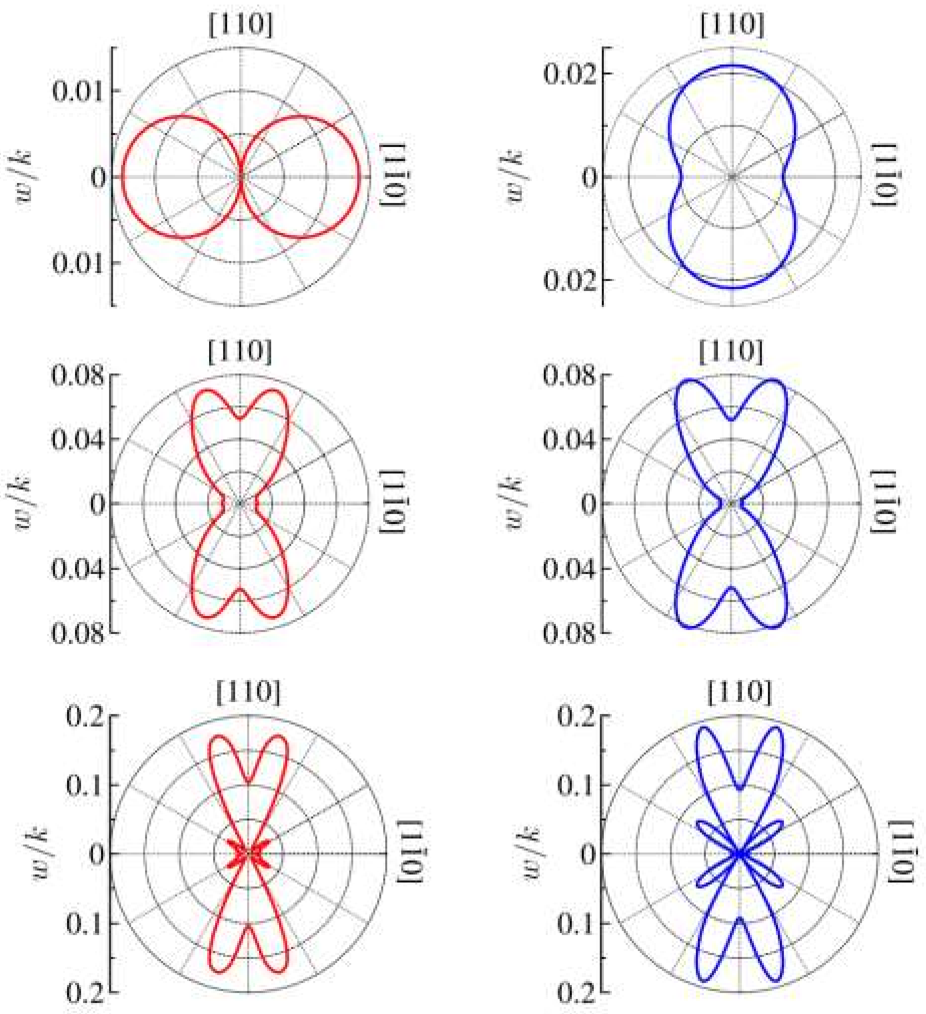
Lin Chen *et al.*, Nature Electronics **1**, 350 (2018)

SOFs at the Fe/GaAs interface

- Calculated SO coupling strengths for different energies and magnetization directions

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

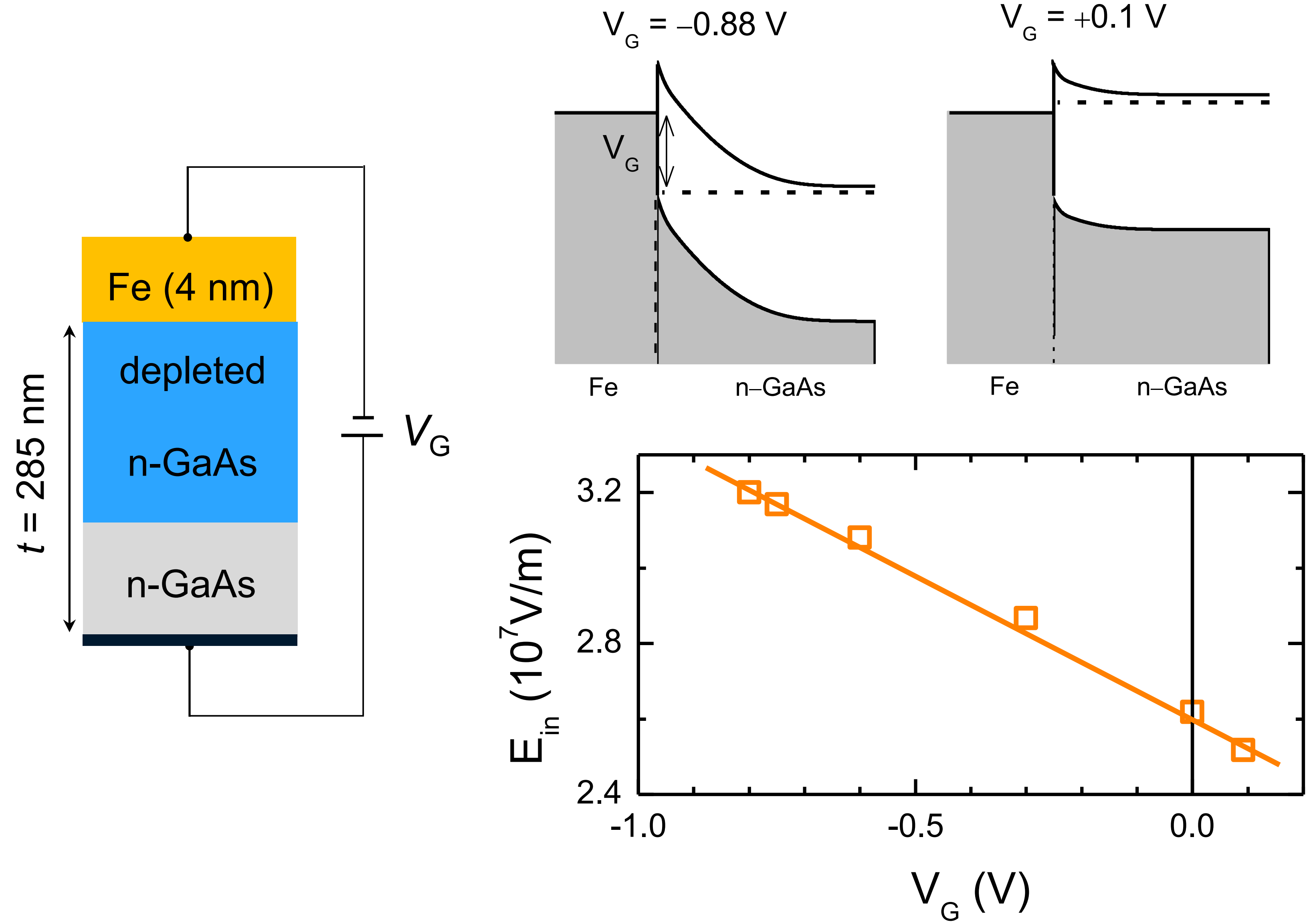
- Higher order contributions for higher energies



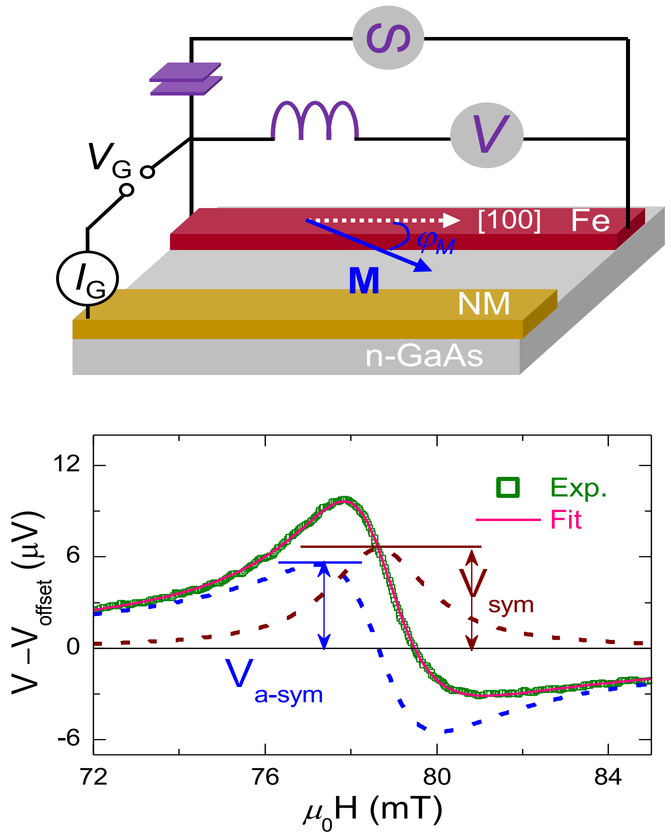
Magnetization along: [1$\underline{1}$0] [110]

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

Electric field control of SOFs: Schottky barrier



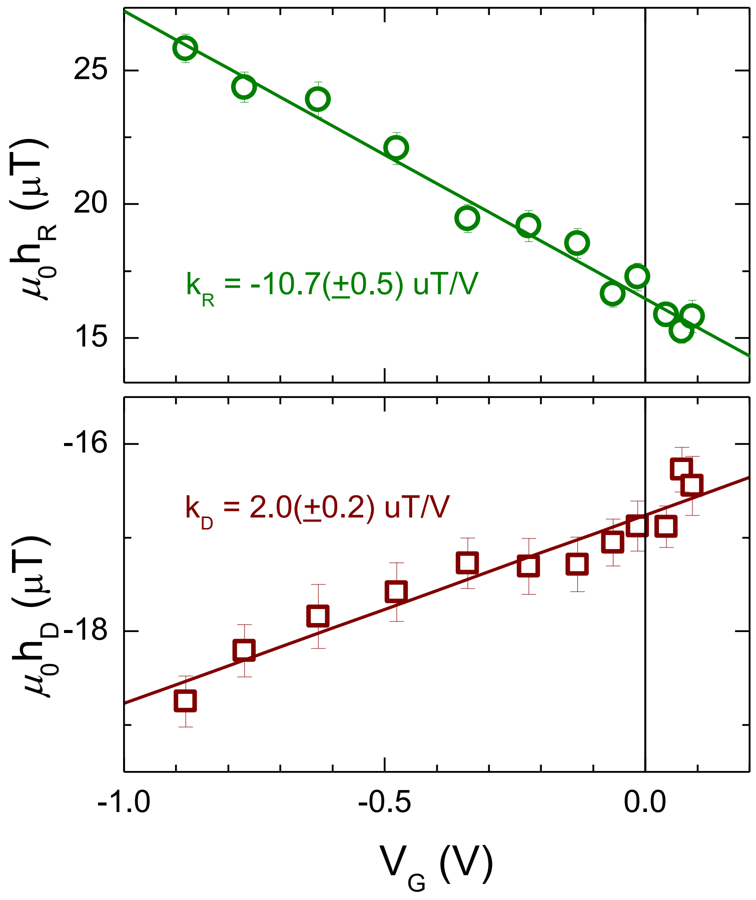
Electric field control of SOFs (12.5 GHz)

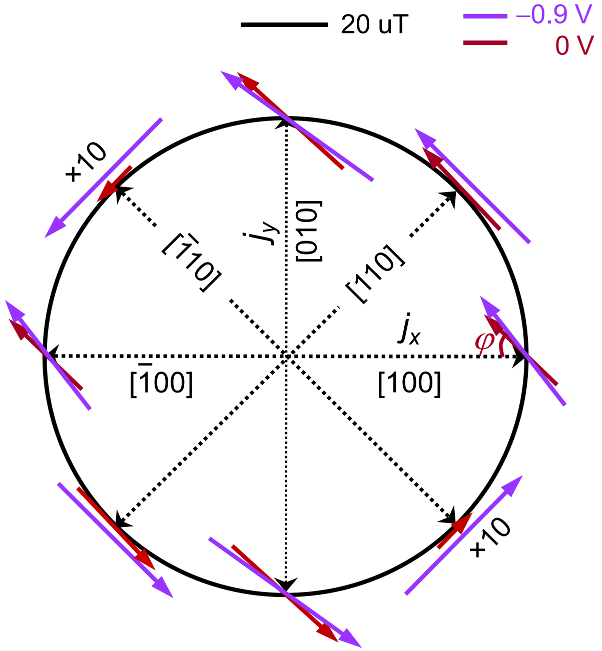


Electric field control of SOFs

Rashba vs. Dresselhaus in-plane SOFs show linear dependence on V_G

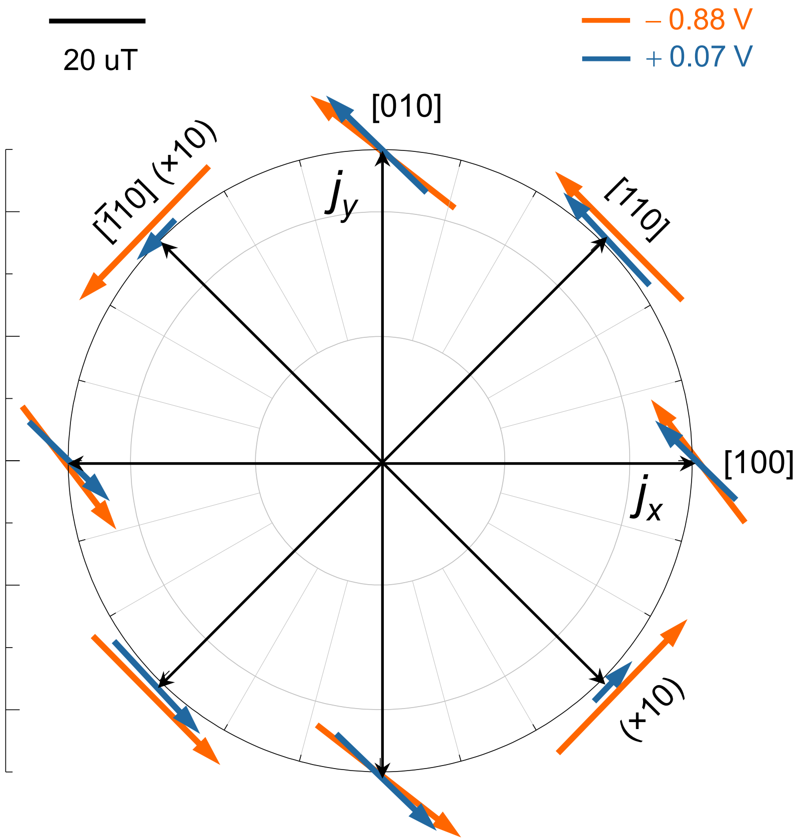
[100]-oriented device





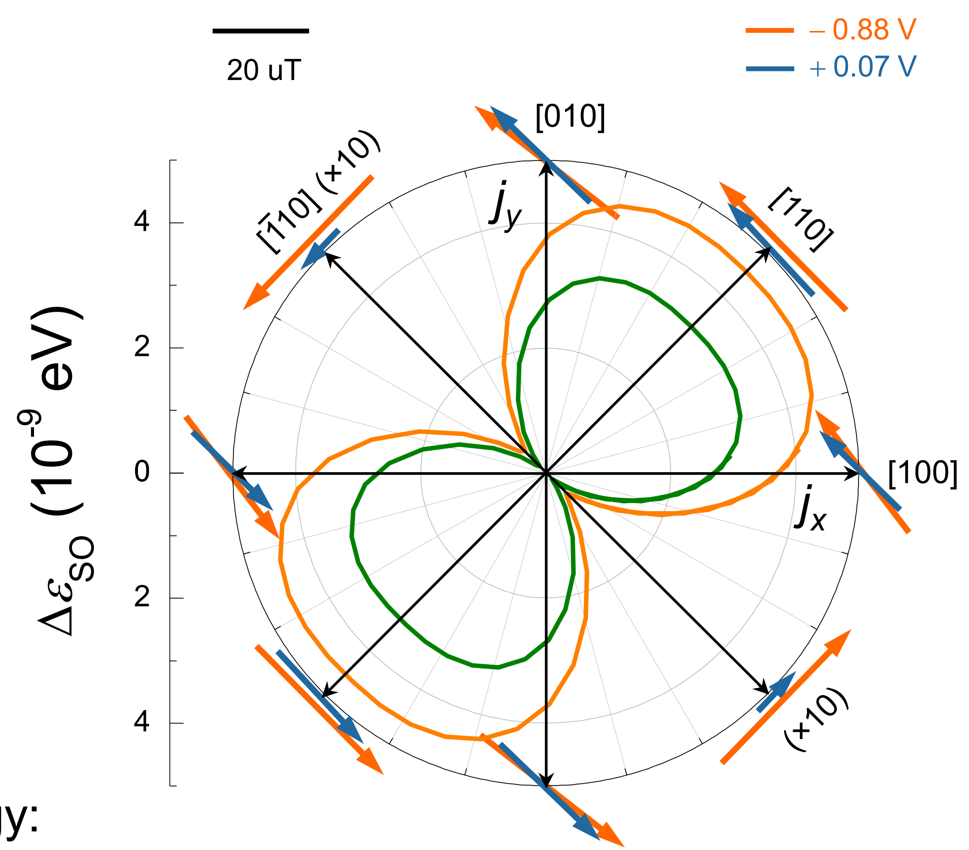
Lin Chen *et al.*, Nature Electronics **1**, 350 (2018)

Electric field control of SOFs



Lin Chen *et al.*, Nature Electronics **1**, 350 (2018)

Electric field control of SOFs



Spin-orbit energy:

$\Delta\varepsilon_{SO} = 2\mu_B|\mathbf{B}_{eff}|$

$\mathbf{B}_{eff} = \mu_B^{-1}\,(\beta k_x - \alpha k_y,\ \alpha k_x - \beta k_y)$

Lin Chen *et al.*, Nature Electronics **1**, 350 (2018)

Fe/GaAs system

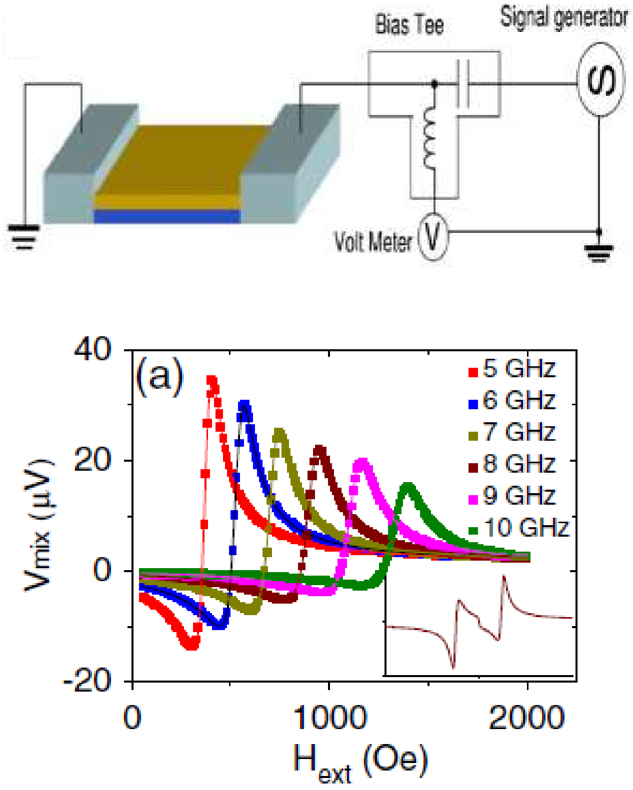
Spin Orbit FMR

Voltage control of spin orbit fields

Optical detection of spin orbit fields

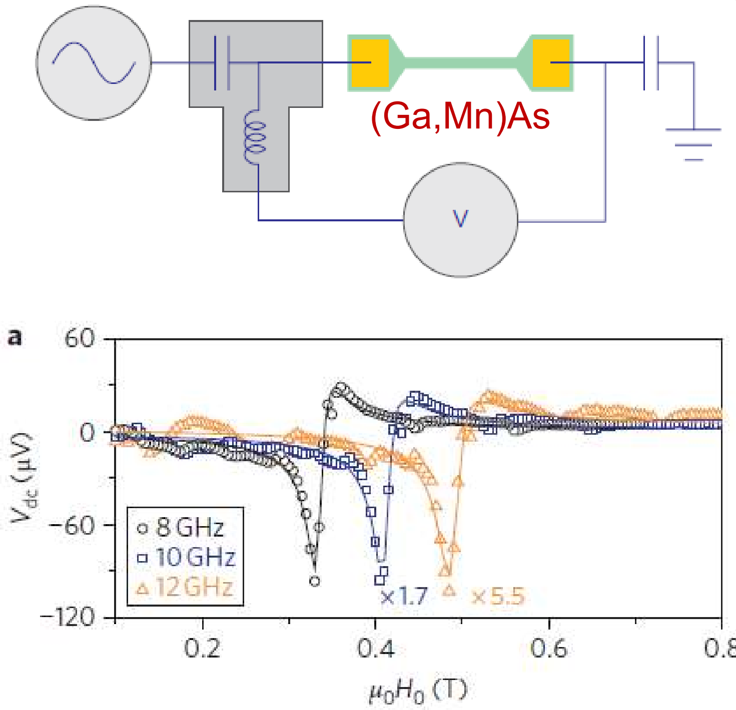
Typical ferromagnetic resonance based techniques

STT-FMR (FM/NM bi-layer)



L. Liu *et al*. Phys. Rev. Lett. **106**, 036601 (2011)

SOT-FMR (single crystalline FM)



D. Fang *et al*. Nat. Nanotech. **6**, 413-417 (2011)

Typical ferromagnetic resonance based techniques

STT-FMR (FM/NM bi-layer)

$$V_{\text{a-sym}} \propto h^{\text{Oe}} \approx \frac{J_e^{rf} d_{NM}}{2}$$

$$V_{\text{sym}} \propto h^{\text{DL}} \propto \theta_{\text{SHE}} J_e^{rf}$$

$$\Rightarrow \theta_{\text{SHE}} \propto \frac{V_{\text{sym}}}{V_{\text{a-sym}}}$$

L. Liu *et al*. Phys. Rev. Lett. **106**, 036601 (2011)

SOT-FMR (single crystalline FM)

$$V_{\text{a-sym}} \propto h^{FL}$$

$$V_{\text{sym}} \propto h^{DL}$$

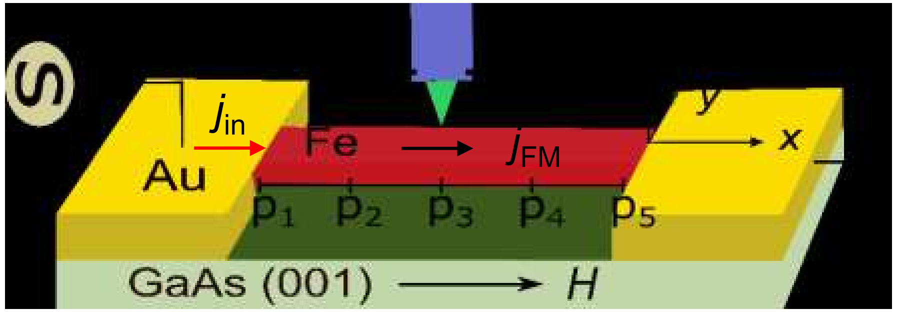
D. Fang *et al*. Nat. Nanotech. **6**, 413-417 (2011)

- Lineshape method
- Heavy metals, single crystalline ferromagnets, antiferromagnets, topological materials, and transition metal dichalcogenides, etc…

Recent detailed discussion: Resolving Discrepancies in Spin-Torque Ferromagnetic Resonance Measurements: Lineshape vs. Linewidth Analyses, arXiv:2103.04172v1

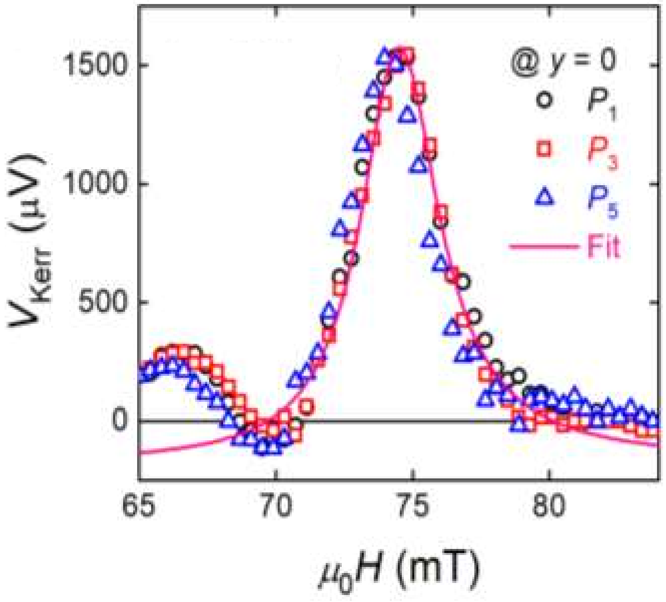
Problem for electrical detection

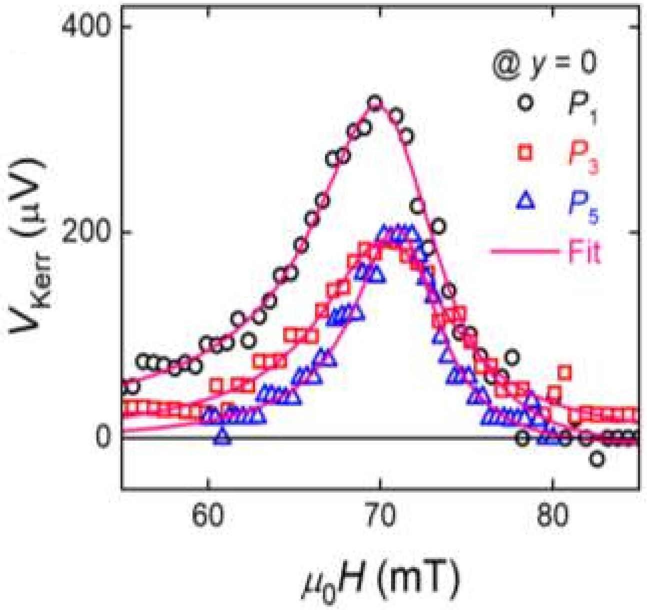
Time and spatially resolved magneto-optic Kerr microscopy



t_{Fe}= 3.5 nm

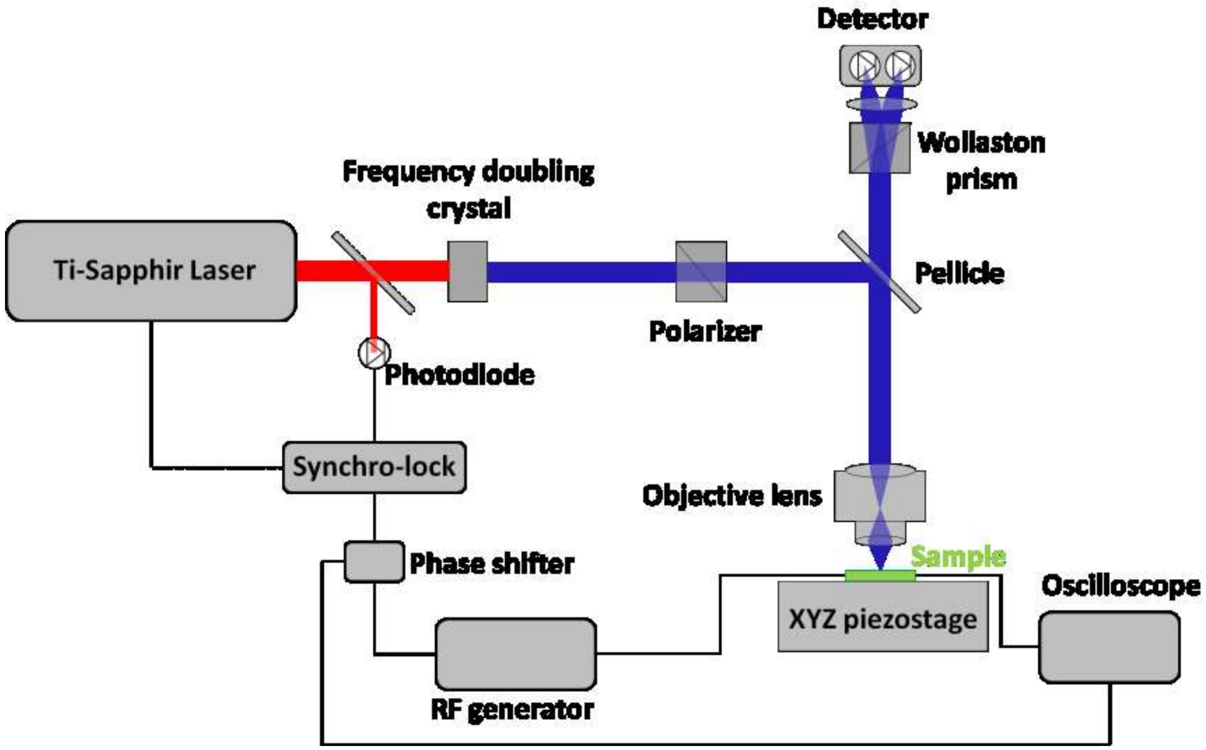
f= 12 GHz



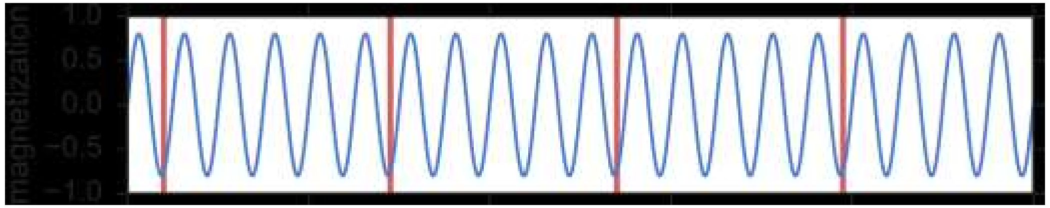


t_{Fe}= 0.8 nm

Alternative detection method: time resolved Kerr microscopy

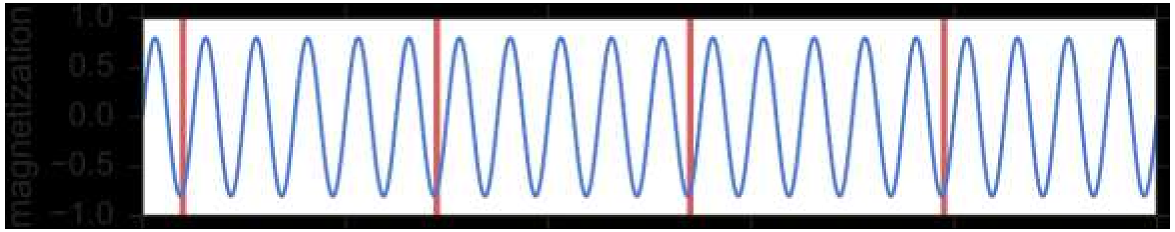


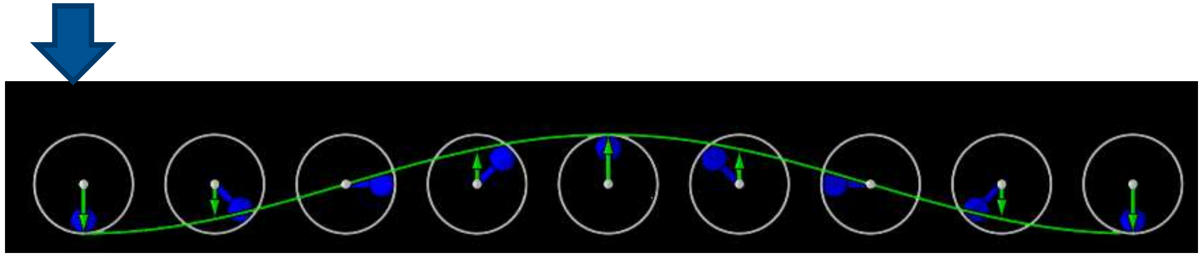
- MOKE: Magnetization modulates light polarization
- Polar MOKE configuration
- Sensitive to out-of-plane component of dynamic magnetization

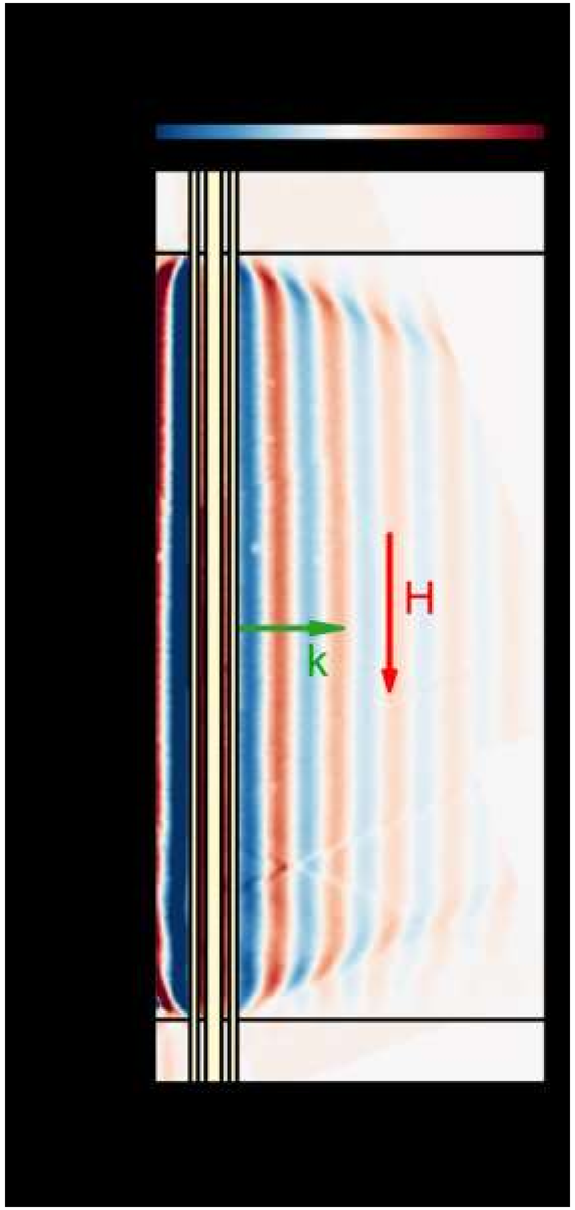


- 120 fs/80 MHz pulses as probe to phase locked microwave pump
- Optically detected FMR

Recording of Snapshots in time/phase





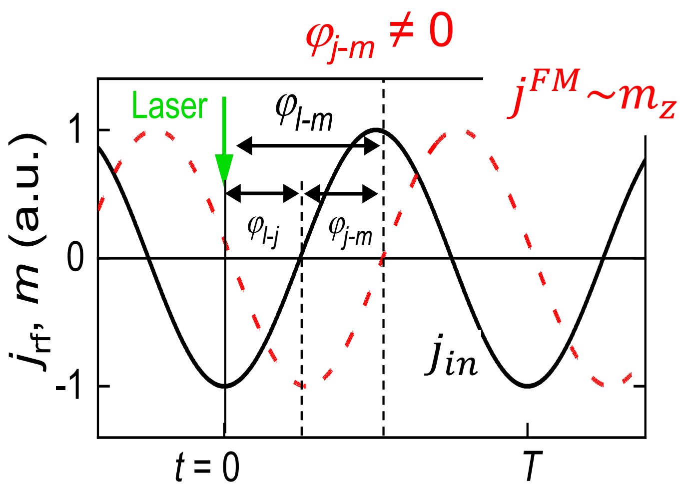


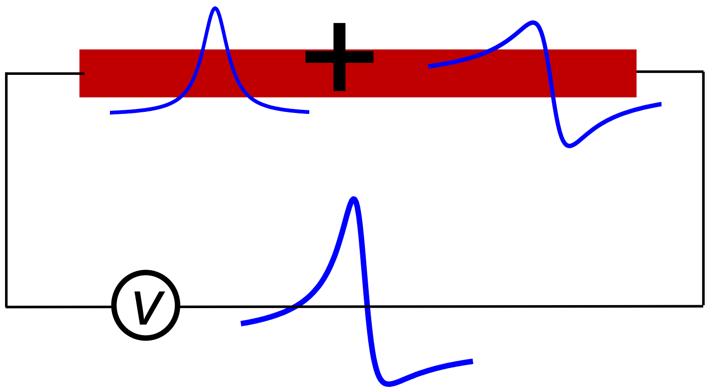
2D scans:
→ Images of the dynamic out-of-plane magnetization m_z

J. Stigloher *et al*., Phys. Rev. Lett. **117**, 037204 (2016)

Problem for electrical detection

Phase lag between the input current j_{in} and the driving current in SO material j^{FM}

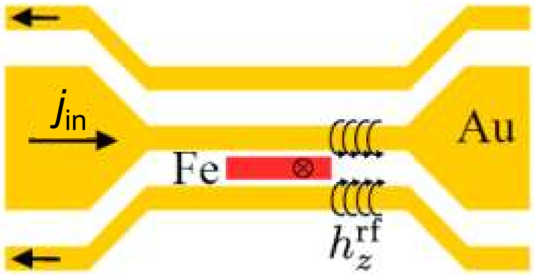


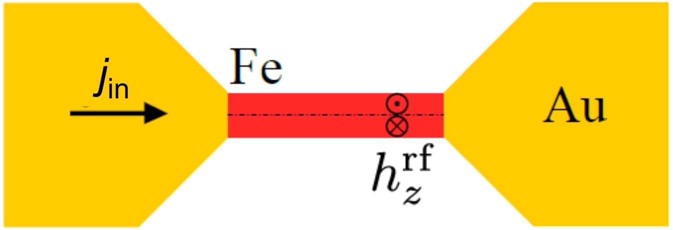


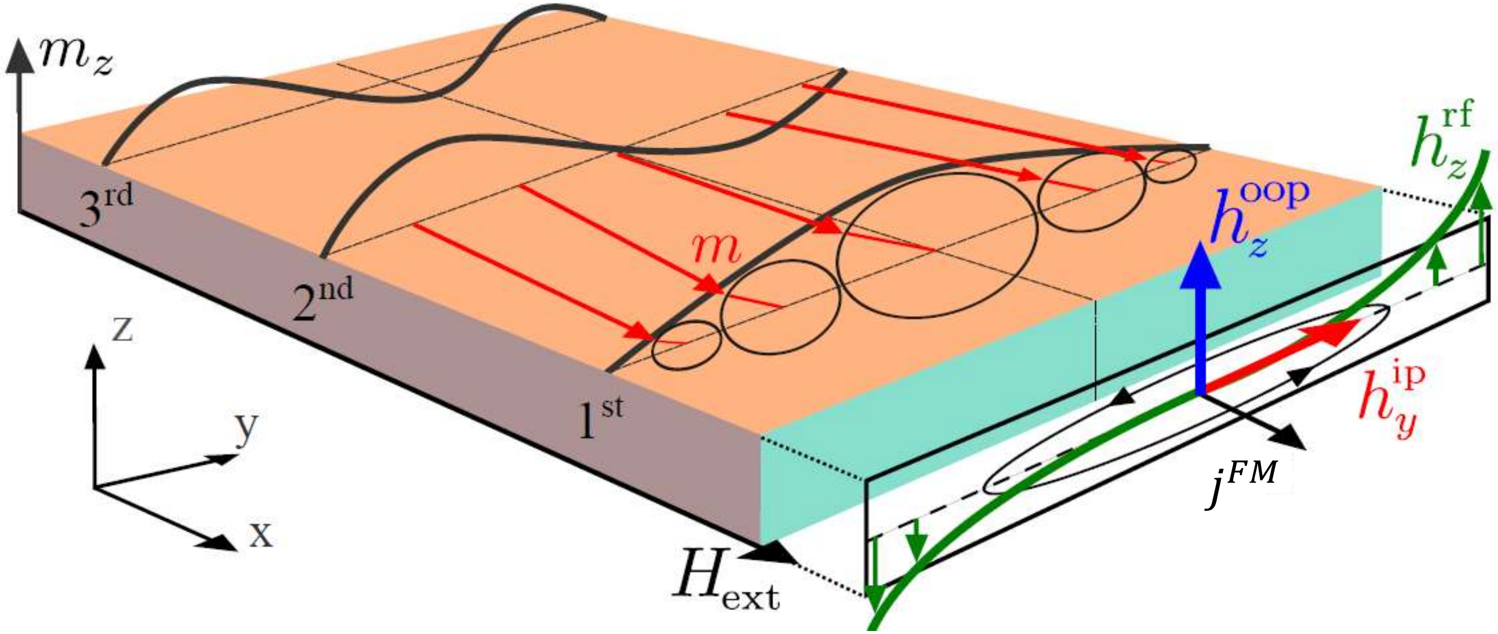
- Problem: averages different lineshapes
- Problematic for highly resistive materials (e.g. BiSe/NiFe)
- Wrong estimation of SOFs

Open question: can we still determine SOFs by magnetization dynamics?

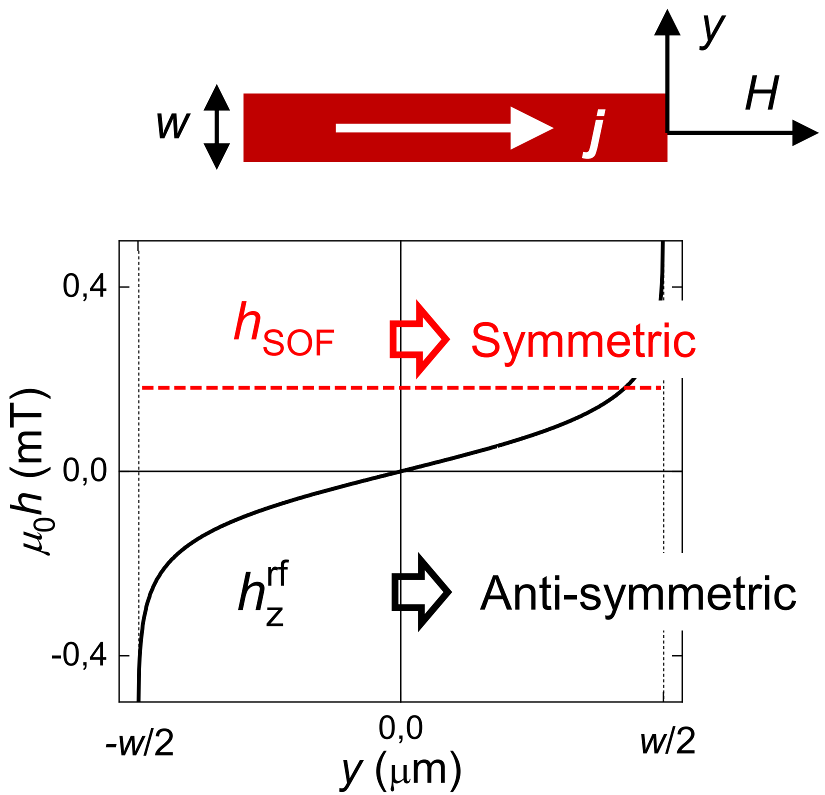
Idea: use spatially resolved method
Recording of linescans as a function of magnetic field: Mode structure





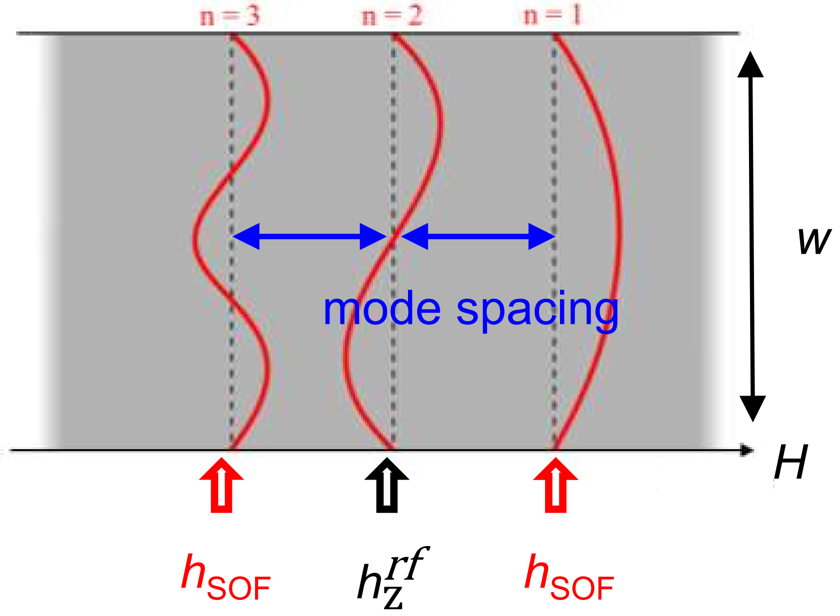


Formation of SSW due to lateral confinement



h_Z^{rf} does not contribute to all−electrical measurements

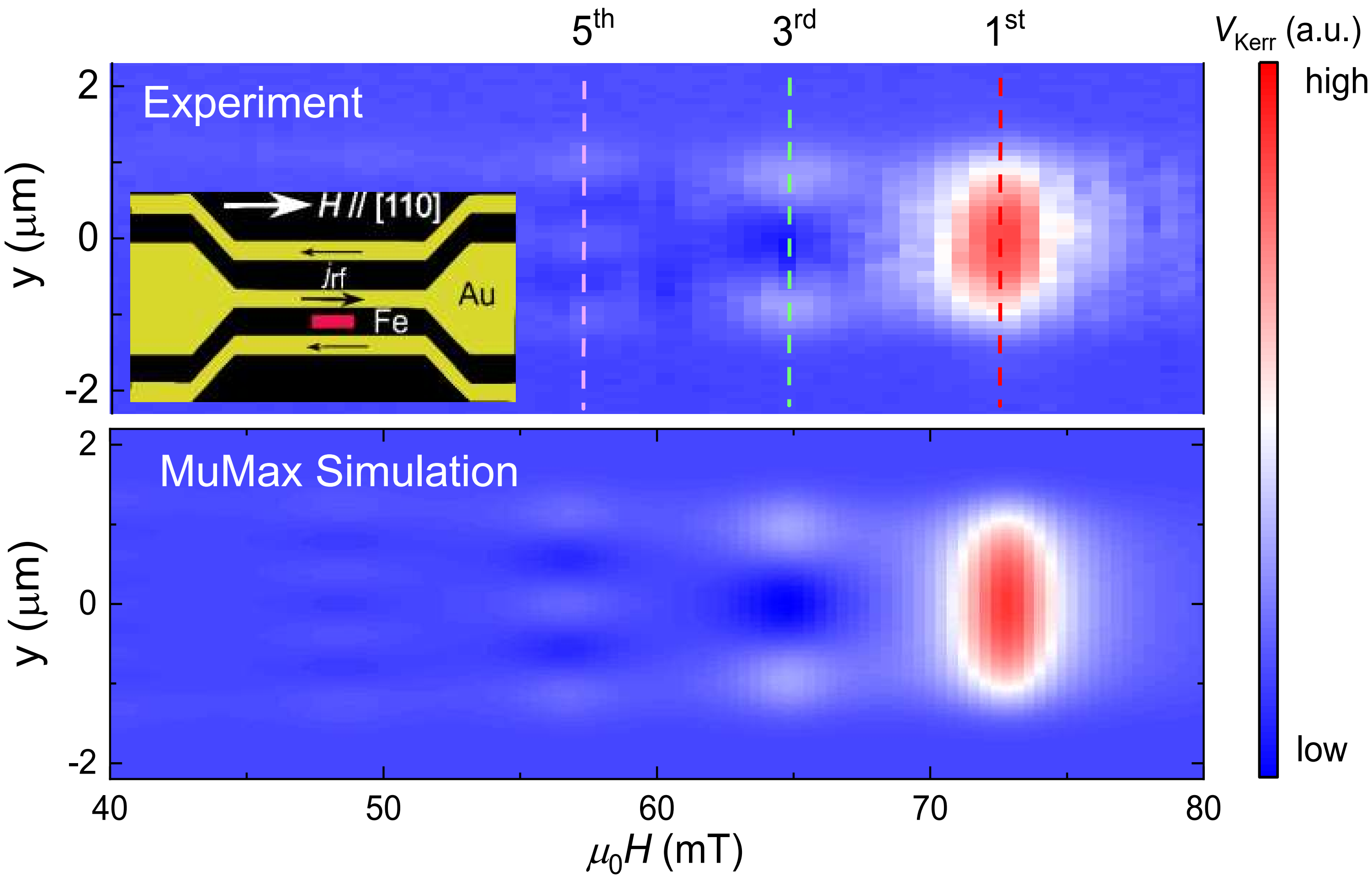
Confinement → standing spin wave (SSW)



Mode spacing ~ FMR linewidth

- Interference of nearest modes
- A chance to determine SOFs

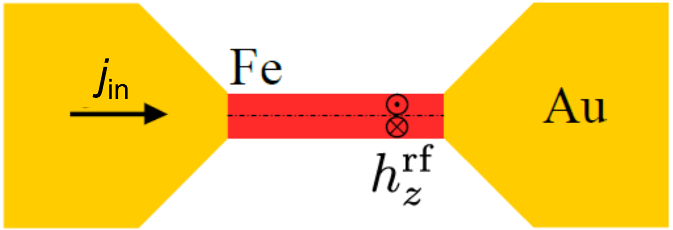
Formation of standing spin wave: CPW driven

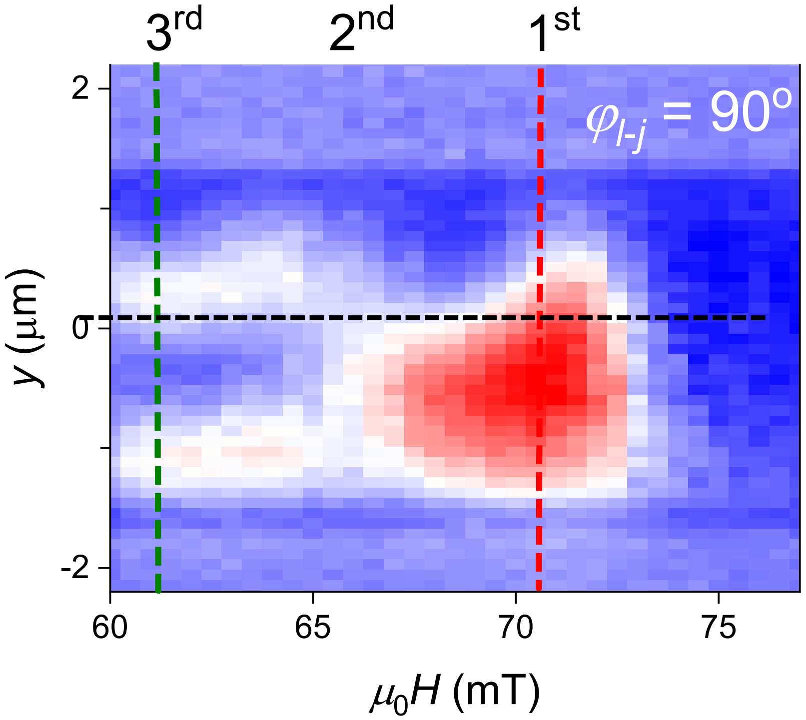


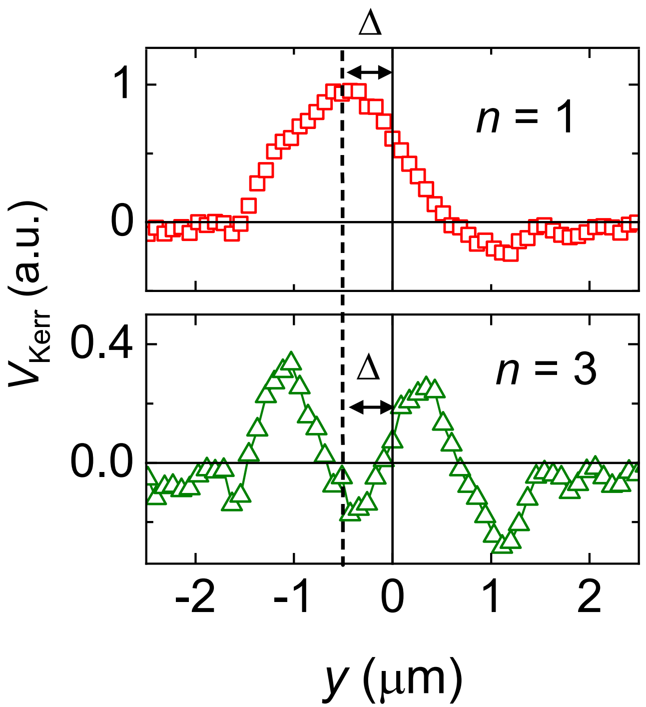
f= 12 GHz

- w = 2.8 µm, t = 3.5 nm, in the gap of CPW
- Symmetric h_{Oe} → symmetric modes

Formation of standing spin waves: electric current driven







f= 12 GHz

φ_{lj} is the phase difference between the input current J_{in} and the laser pulses (controlled phase)

- SSW pattern shifts from center point
- Emergence of 2nd mode excited by $h_{rf}^{FM,z}$
- Impossible to determine SOFs since φ_{j-m} is unkown

Determine SOF: phase independent approach

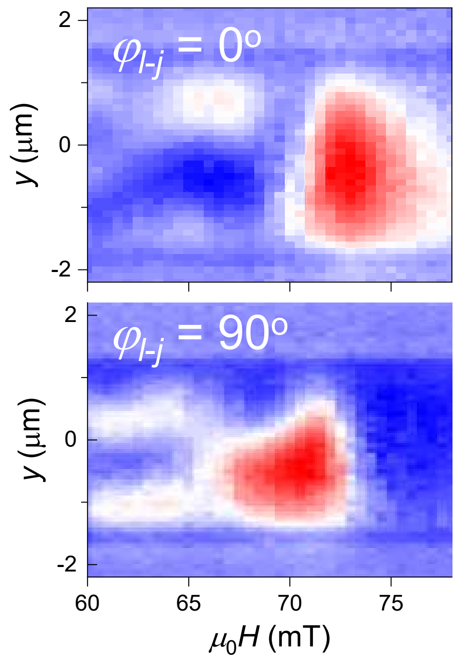
$$V_{\mathrm{Kerr}}(\varphi_{l\text{-}j}) \sim [\mathrm{Re}(\chi^{o})h^{o} - \mathrm{Im}(\chi_a^{i})h^{i}]\cos(\varphi_{l\text{-}j}+\varphi_{j\text{-}m}) - [\mathrm{Im}(\chi^{o})h^{o} + \mathrm{Re}(\chi_a^{i})h^{i}]\sin(\varphi_{l\text{-}j}+\varphi_{j\text{-}m})$$

⇩

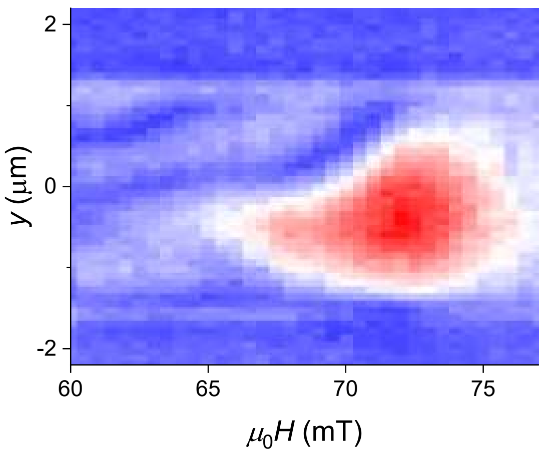
$$\sqrt{[V_{\mathrm{Kerr}}(0^{o})]^2+[V_{\mathrm{Kerr}}(90^{o})]^2}$$

⇩

$$V_{Kerr}^{\varphi-free} = \sqrt{\left[\mathrm{Re}\left(\chi^{o}\right)h^{o} - \mathrm{Im}\left(\chi_a^{i}\right)h^{i}\right]^2 + \left[\mathrm{Im}\left(\chi^{o}\right)h^{o} + \mathrm{Re}\left(\chi_a^{i}\right)h^{i}\right]^2}$$

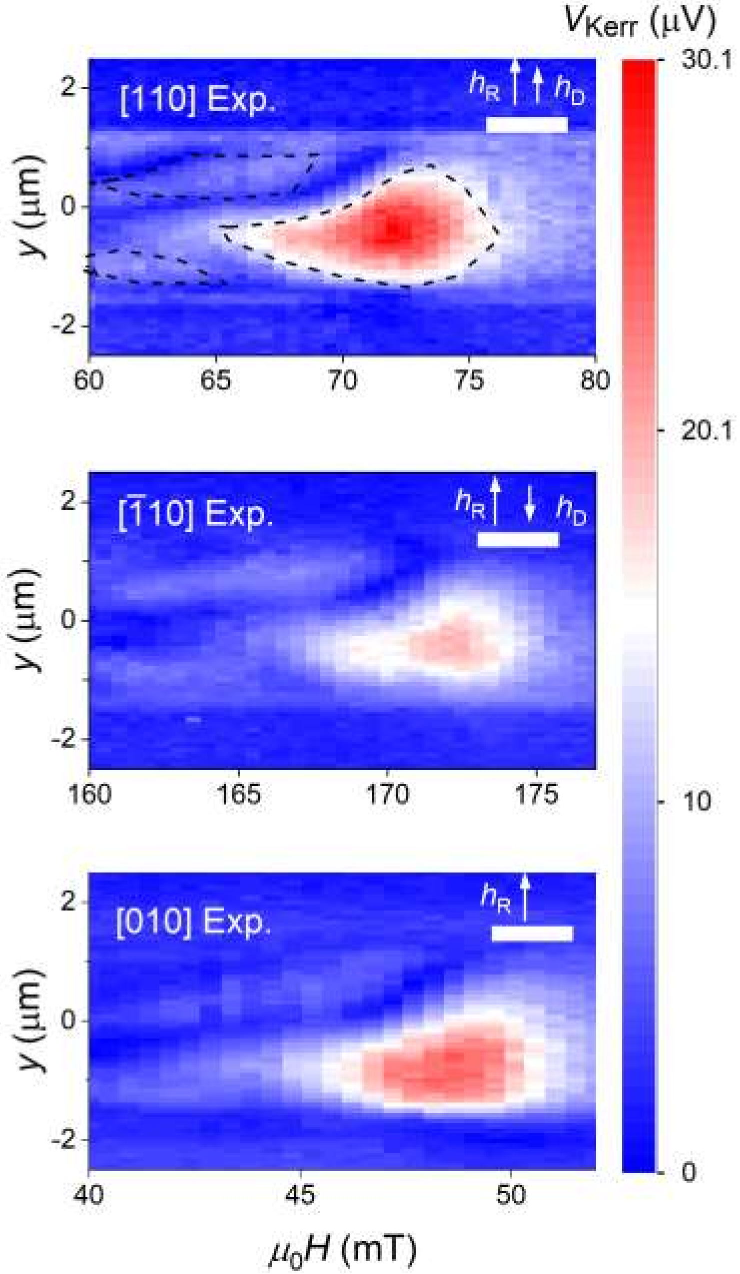


⇨



$\varphi_{j\text{-}m}$-free

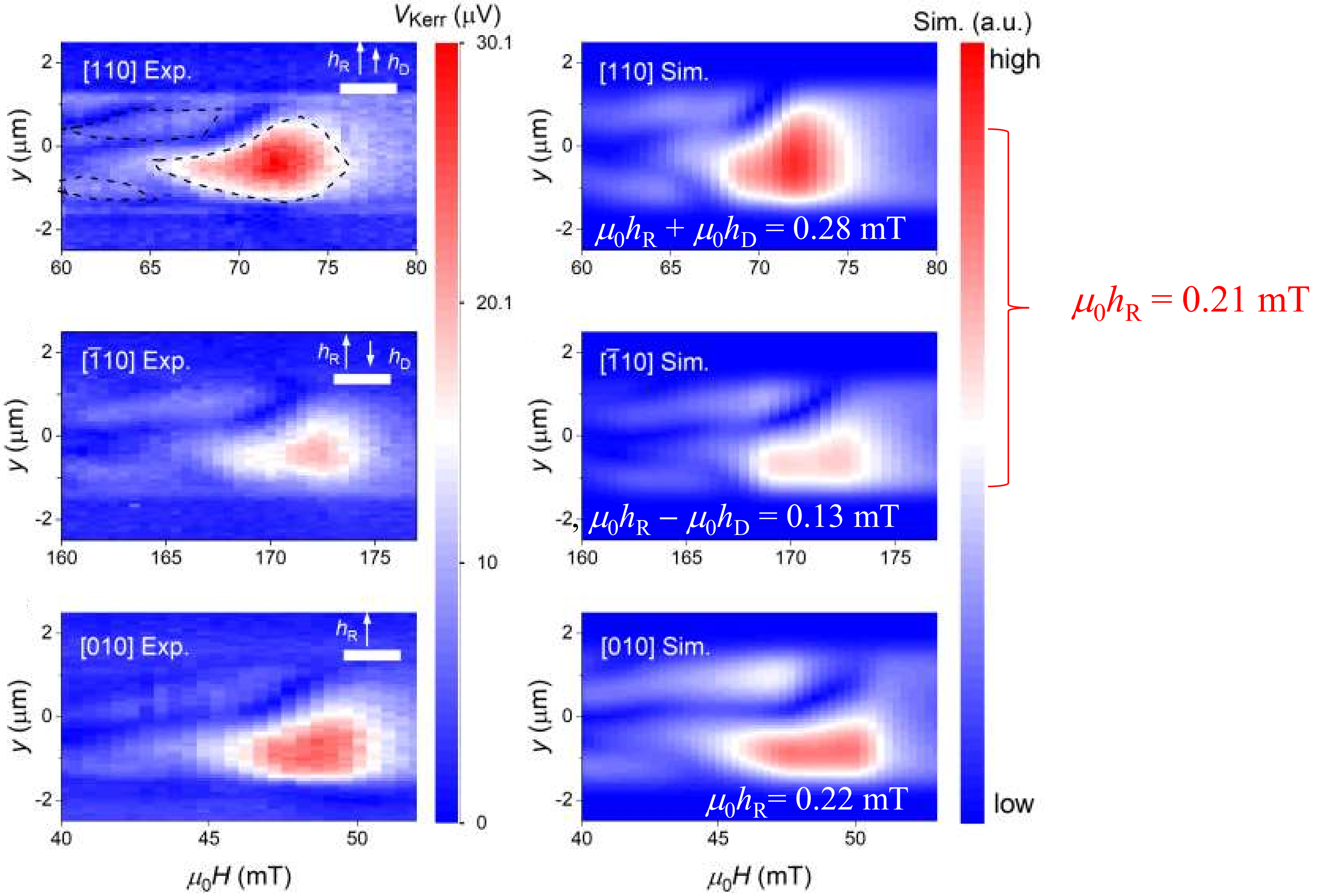
Determine SOF by SSW pattern



$j = 1 \times 10^{11}$ Am^{-2}

$$V_{max}^{[110]} = 1.2 V_{max}^{[010]} = 1.7 V_{max}^{[-110]}$$

Determine SOF by SSW pattern

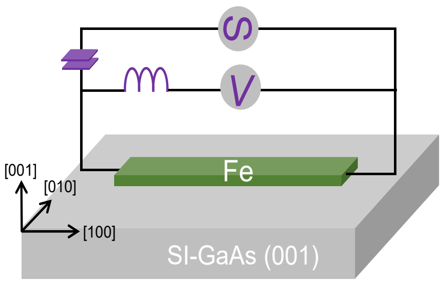


L. Chen *et al*. arXiv:2010.06960

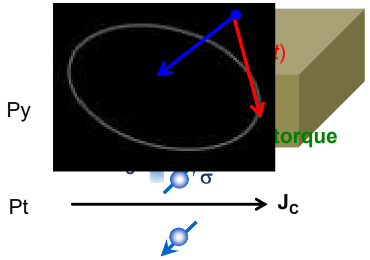
- Electronic properties of Fe/GaAs(001) interface are dominated by C_{2v} symmetry
- Mutual conversion of spin and charge currents at Fe/GaAs(001) interface
- Voltage control of SOFs demonstrated
- The ferromagnetic layer can be very thick! (> 1 nm)
- Sizeable effects at a simple interface!
- Electrically detected ST-FMR: be careful about the phase
- A new approach to determine the SOF by SSW pattern
- Phase independent and self-calibrated
- Can be applied to FM/HM bi-layers

Methods to determine interfacial/bulk SOI

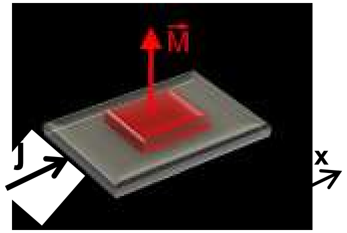
1. SOT-FMR



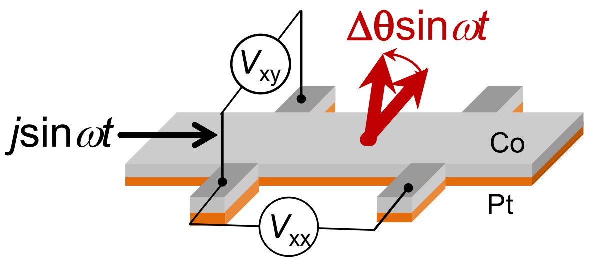
2. Modulation of damping



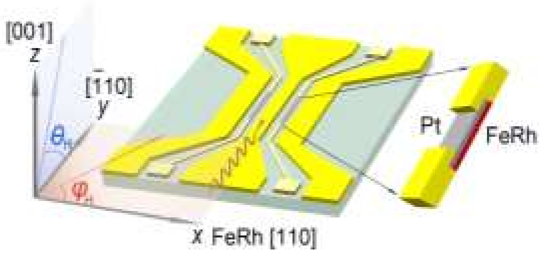
3. SOT-switching



4. 2[nd] harmonic method



5. iSHE (or SGE) via Spin pumping



Charge-to-spin conversion

Spin-to-charge conversion

Thank you for your attention!