Spin-orbit torques

in ferromagnets and antiferromagnets

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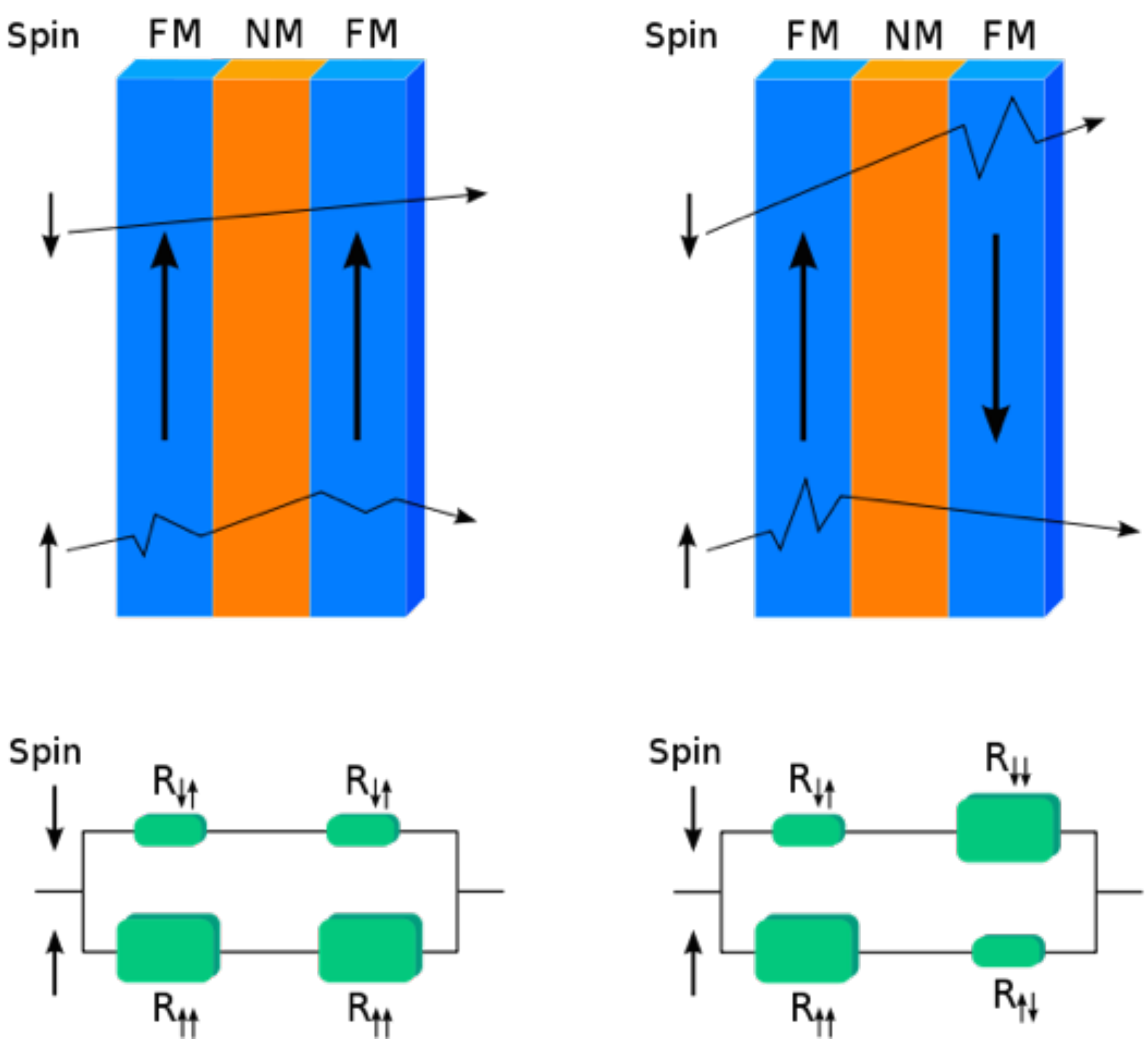
Memory device (one possible concept)

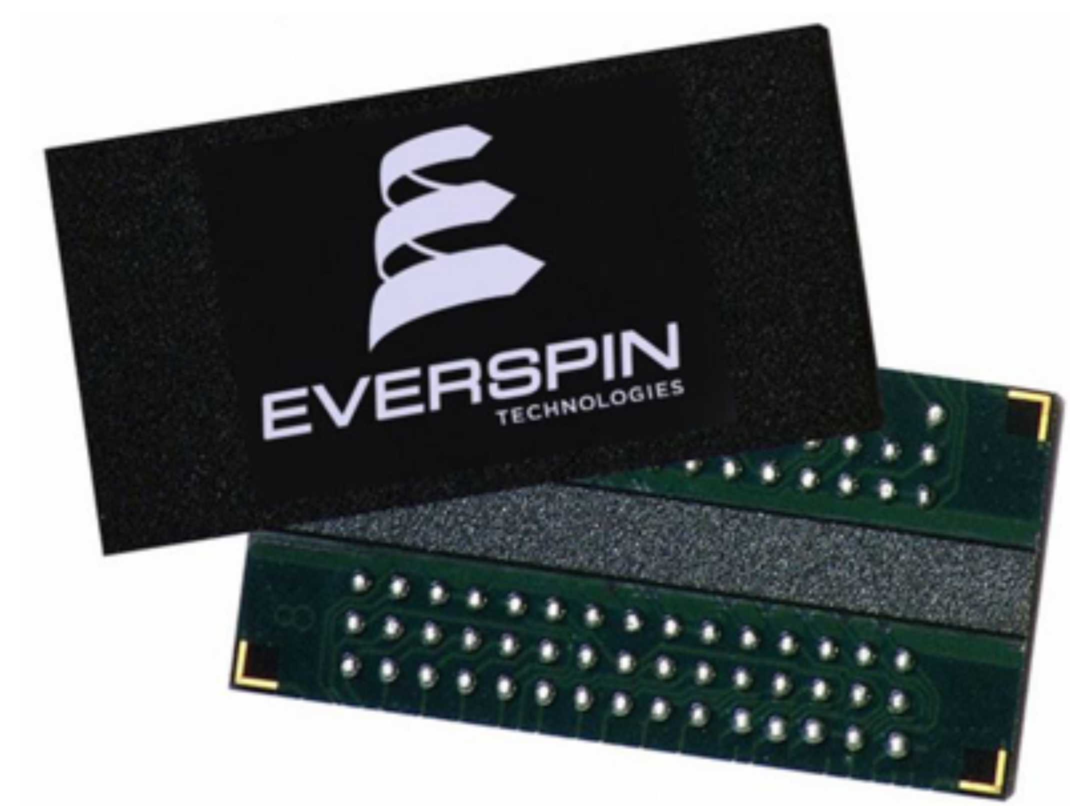
Giant Magnetoresistance (GMR)



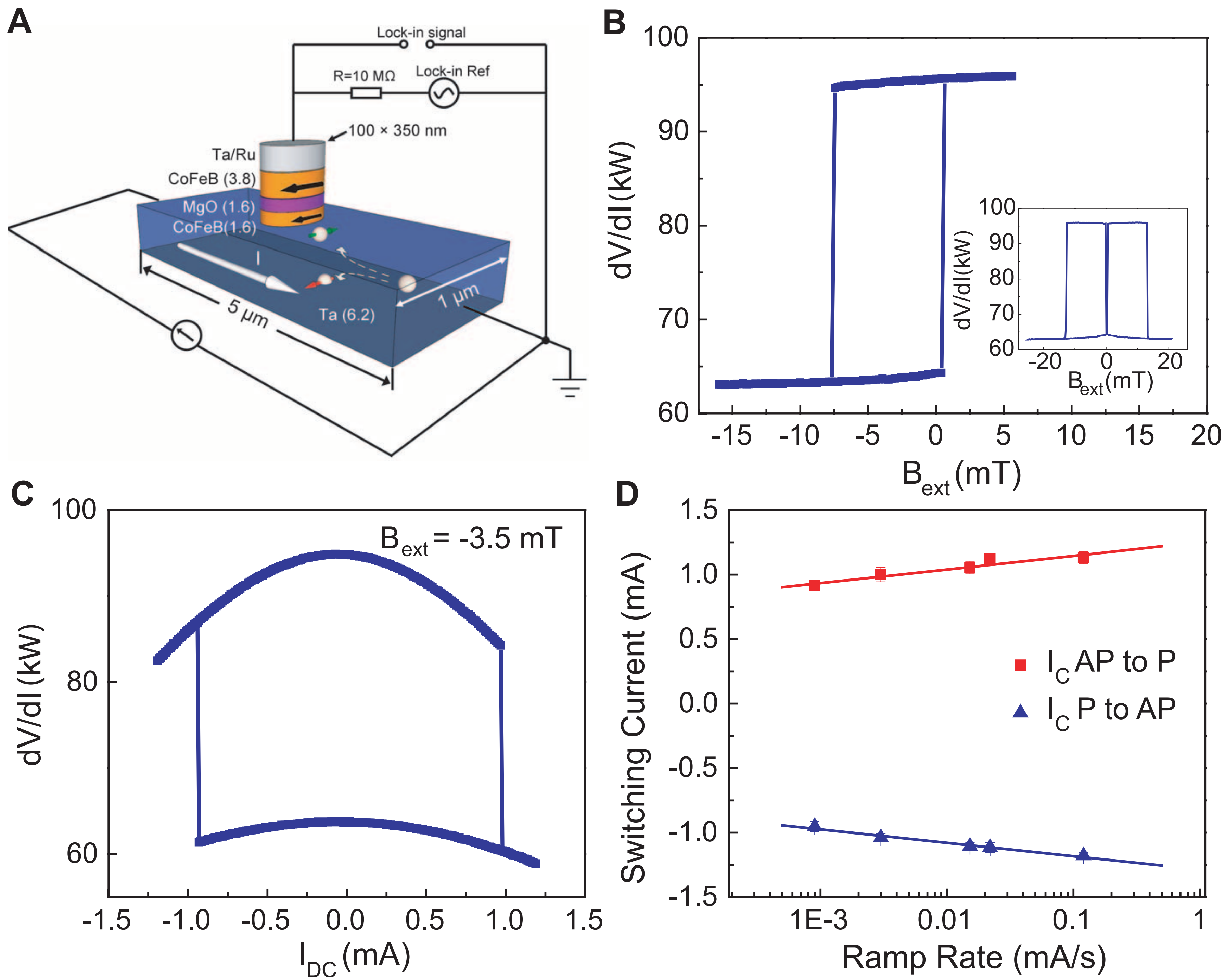
[wikipedia]

alternative:

- magnetic tunnel junctions
- how to write?
- spin transfer torque



New developments - switching by SHE-spin torque



Ralph&Buhrman, Science 336, 555 (2012)

Magnetic tunnel junctions as memory elements

writing information:

- spin-transfer torque
- using spin Hall effect (SHE-torque)
- spin-orbit torque

reading information:

- tunnelling magnetoresistance (similar to GMR)
- anisotropic magnetoresistance (AMR)
- … and more (tunnelling AMR)

Magnetic tunnel junctions as memory elements

writing information:

- spin-transfer torque
- using spin Hall effect (SHE-torque)
- spin-orbit torque

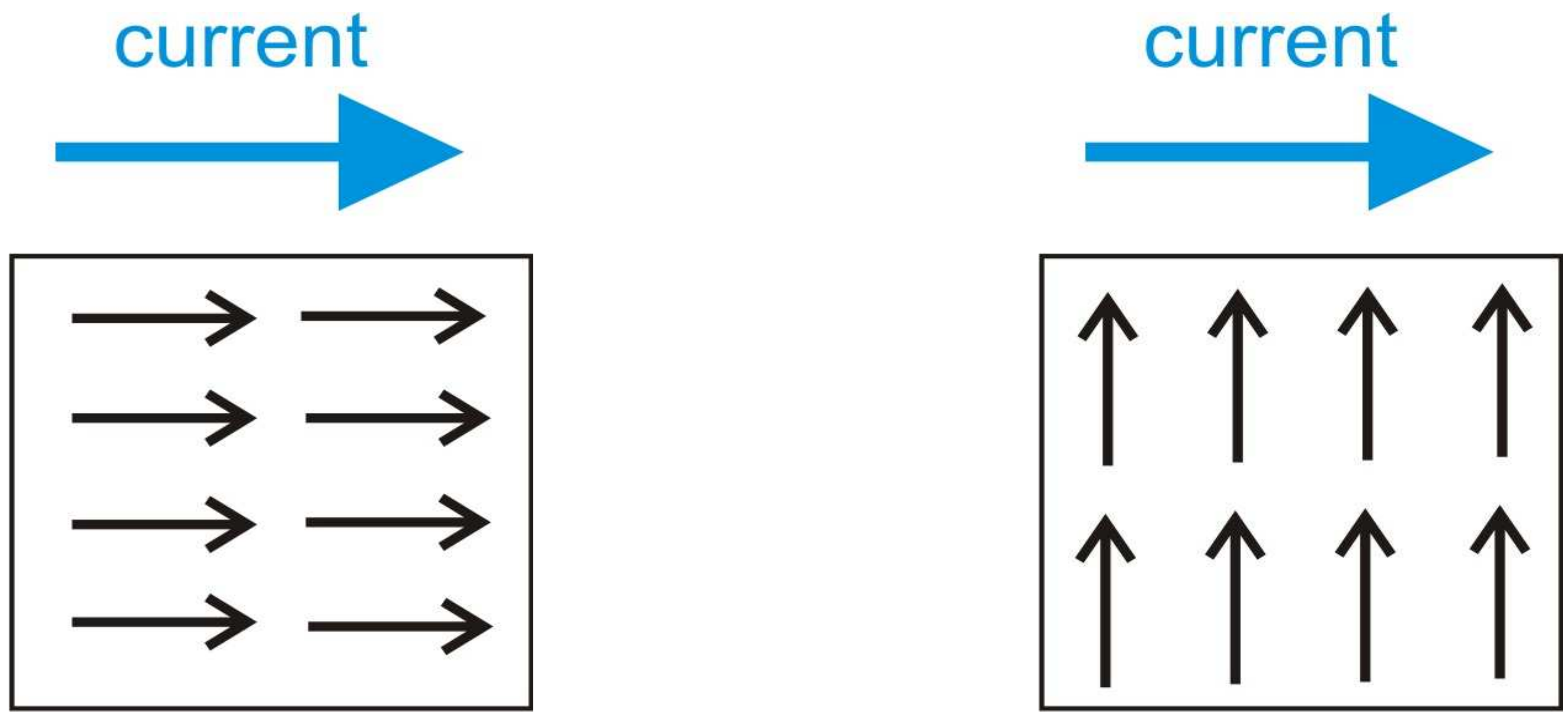
current-induced ‘effective mag. field’

reading information:

- tunnelling magnetoresistance (similar to GMR)
- anisotropic magnetoresistance (AMR)
- … and more (tunnelling AMR)

Anisotropic magnetoresistance (AMR)

the resistance depends on magnetization direction



$\rho_{||}$ $\quad >, <, = ??? \quad$ $\rho_{\perp}$

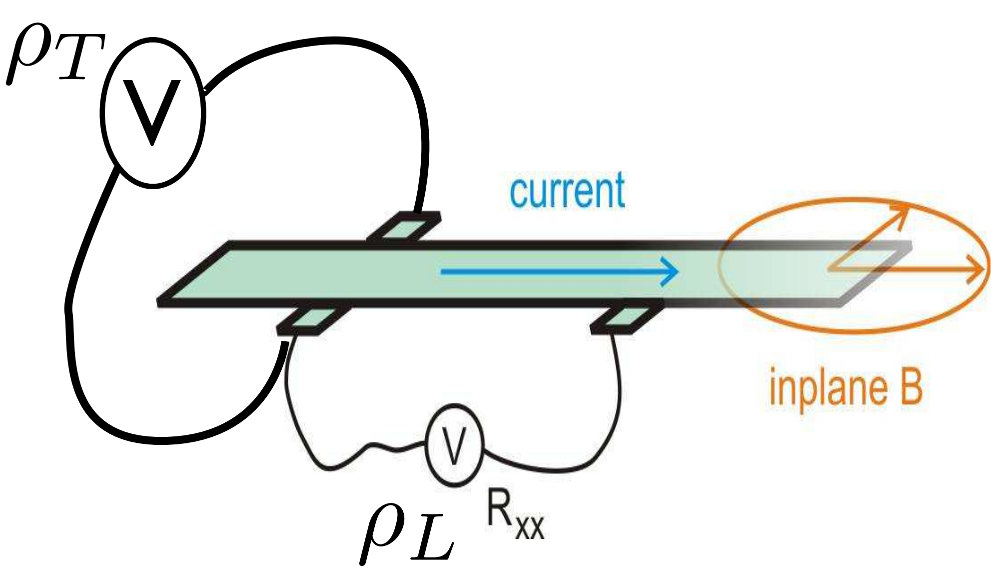
W. Thomson, Proc. Roy. Soc. London (1857)	Fe, Ni	~1%
P. Wiśniewski, Appl. Phys. Lett. (2007)	U_3As_4	~50%
A. Rushforth, Phys. Rev. Lett. (2007)	GaMnAs	few %

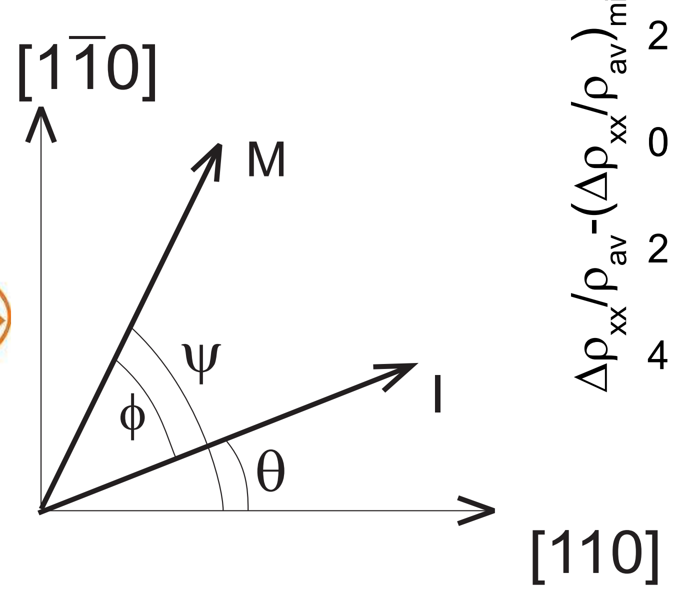
AMR: crystalline and non-crystalline components

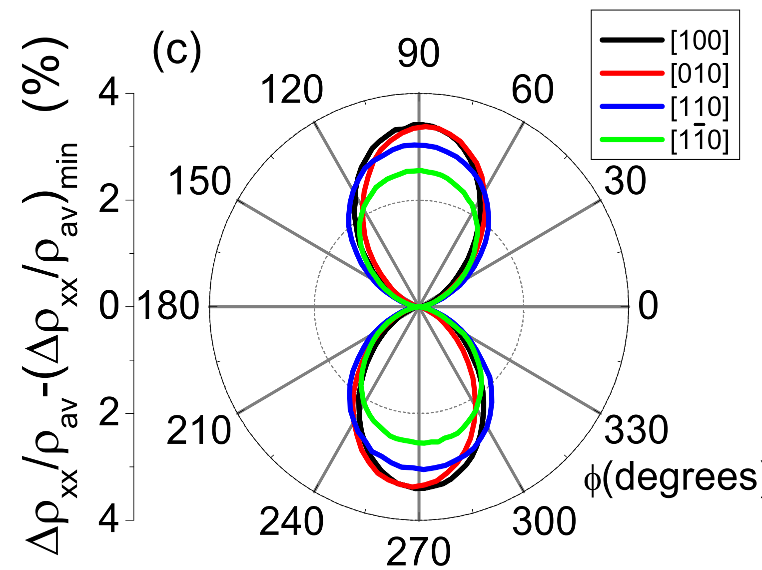
$$\Delta\rho_L/\rho_{av} = C_I \cos 2\phi + C_{I,C}\cos(2\phi+4\theta) + C_C\cos(4\phi+4\theta) + C_U\cos(2\phi+2\theta)$$

$$\Delta\rho_T/\rho_{av} = C_I \sin 2\phi - C_{I,C}\sin(2\phi+4\theta)$$

de Ranieri et al., NJP '08

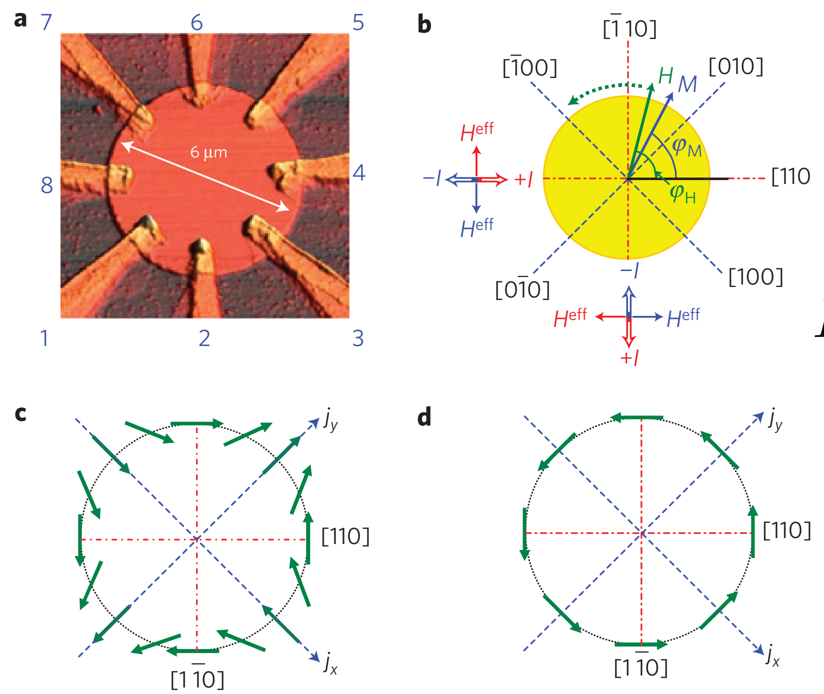






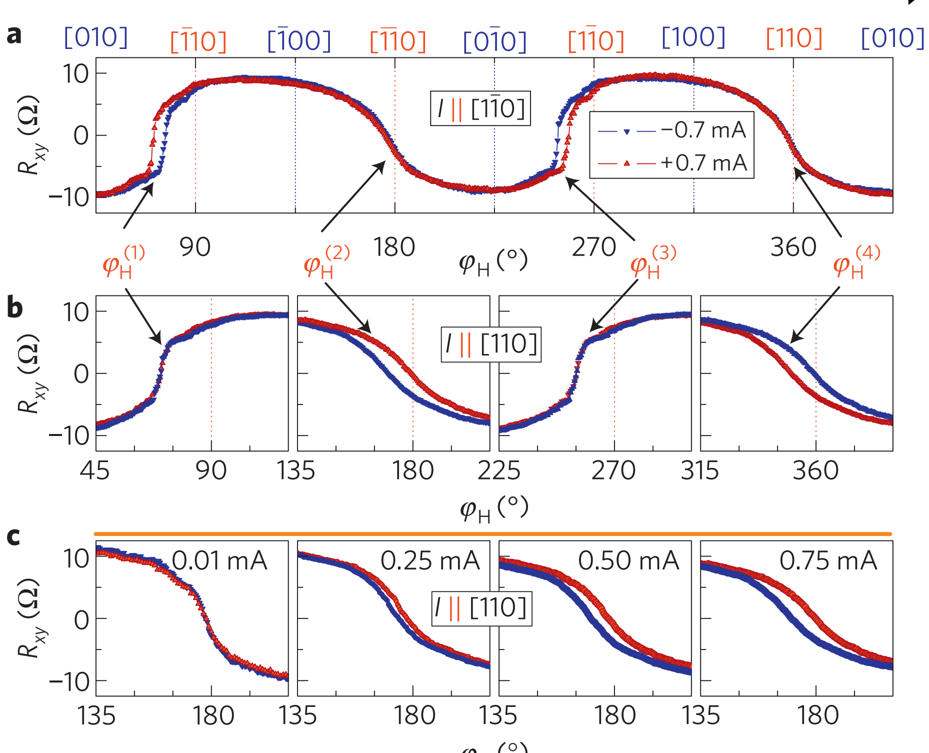
Current-induced field - experiment in (Ga,Mn)As

static case



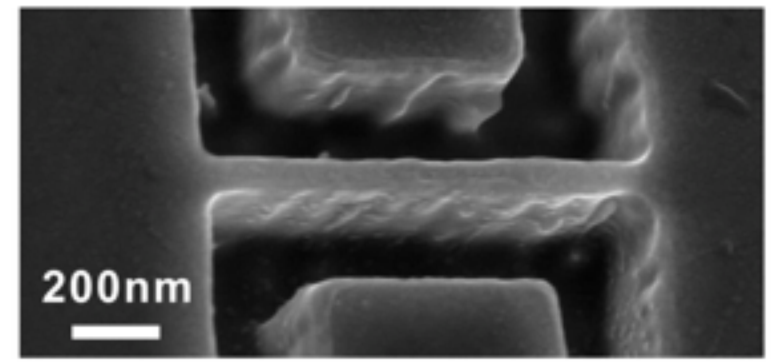
transversal AMR
(planar Hall effect)

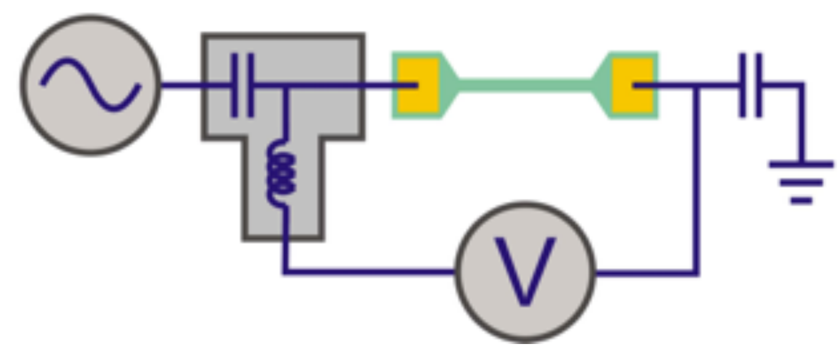
$$R_{xy} = (R_{||} - R_{\perp}) \sin 2\varphi_M$$

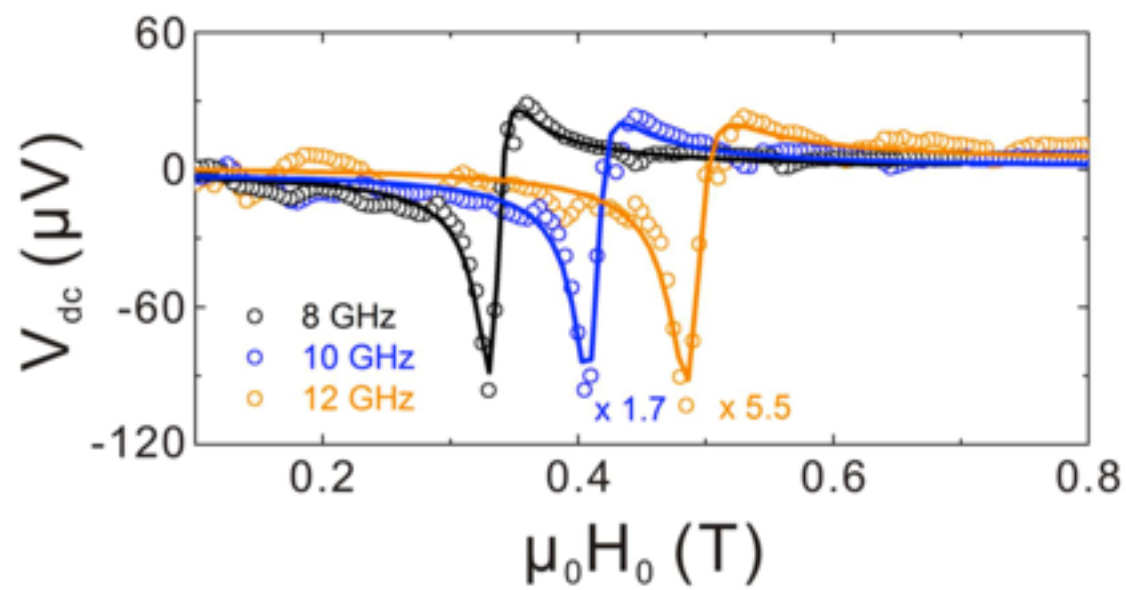


Chernyshev et al., Nat Phys (2009)

dynamic case







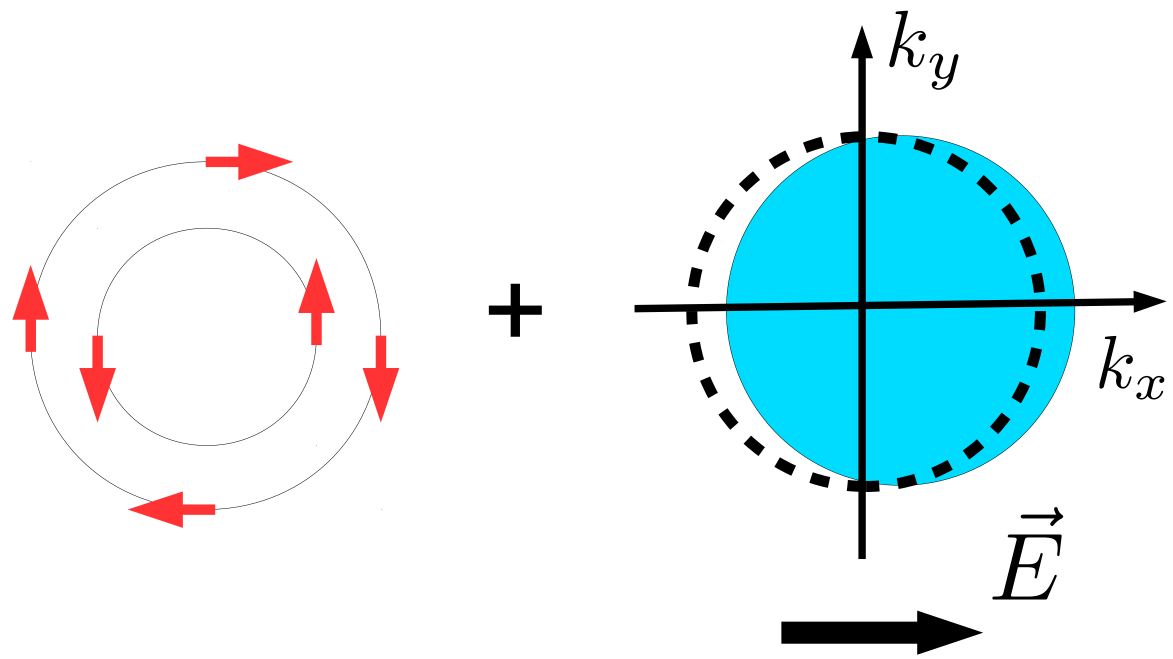
Fang et al., Nat Nano (2011)

Current-induced spin-orbit torque

Edelstein effect…

$$\delta \mathbf{S} = \chi \, \mathbf{E}$$

simplest example: Rashba-Bychkov spin-orbit int. (Sol. st. comm. 73, 233)



$$\delta \mathbf{S} = \int S \delta f \; dk + \int f \delta S \; dk$$

… action on magnetic moments

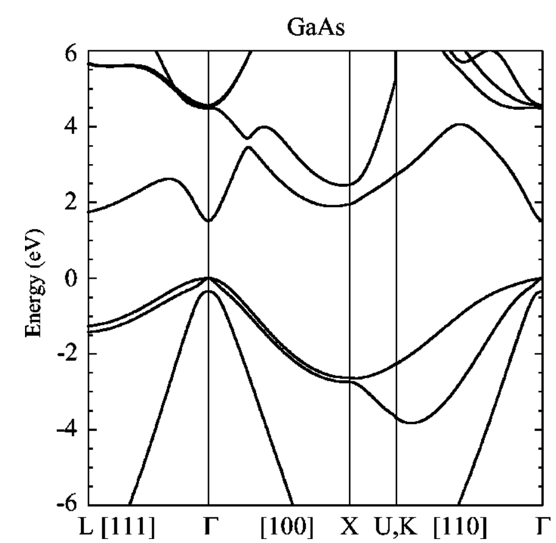
Phys. Rev. B 79, 094422 (2009)

$$\vec{T} = \frac{J_{ex}}{\hbar} \vec{m} \times \vec{M}$$

in the context of s-d type Hamiltonian

$$H = H_{KL} + h \hat{e}_M \cdot \mathbf{s}$$

… applicable to (Ga,Mn)As



- ferromagnetism ind. by carriers
- Mn d-states coupled to hole p-states (carrier)

$$H = H_{KL} + J_{pd} \sum_{i,I} \vec{S}_I \cdot \vec{s}_i \delta(\vec{r}_i - \vec{R}_I)$$

Current-induced spin-orbit torque in (Ga,Mn)As

… a long history

PHYSICAL REVIEW B **80**, 134403 (2009)

Influence of a transport current on magnetic anisotropy in gyrotropic ferromagnets

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PHYSICAL REVIEW B **91**, 134402 (2015)

Intraband and interband spin-orbit torques in noncentrosymmetric ferromagnets

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Current-induced spin-orbit torque

$$\delta\mathbf{S} = \chi\,\mathbf{E}$$

$$S_i = \chi_{ij} E_j$$

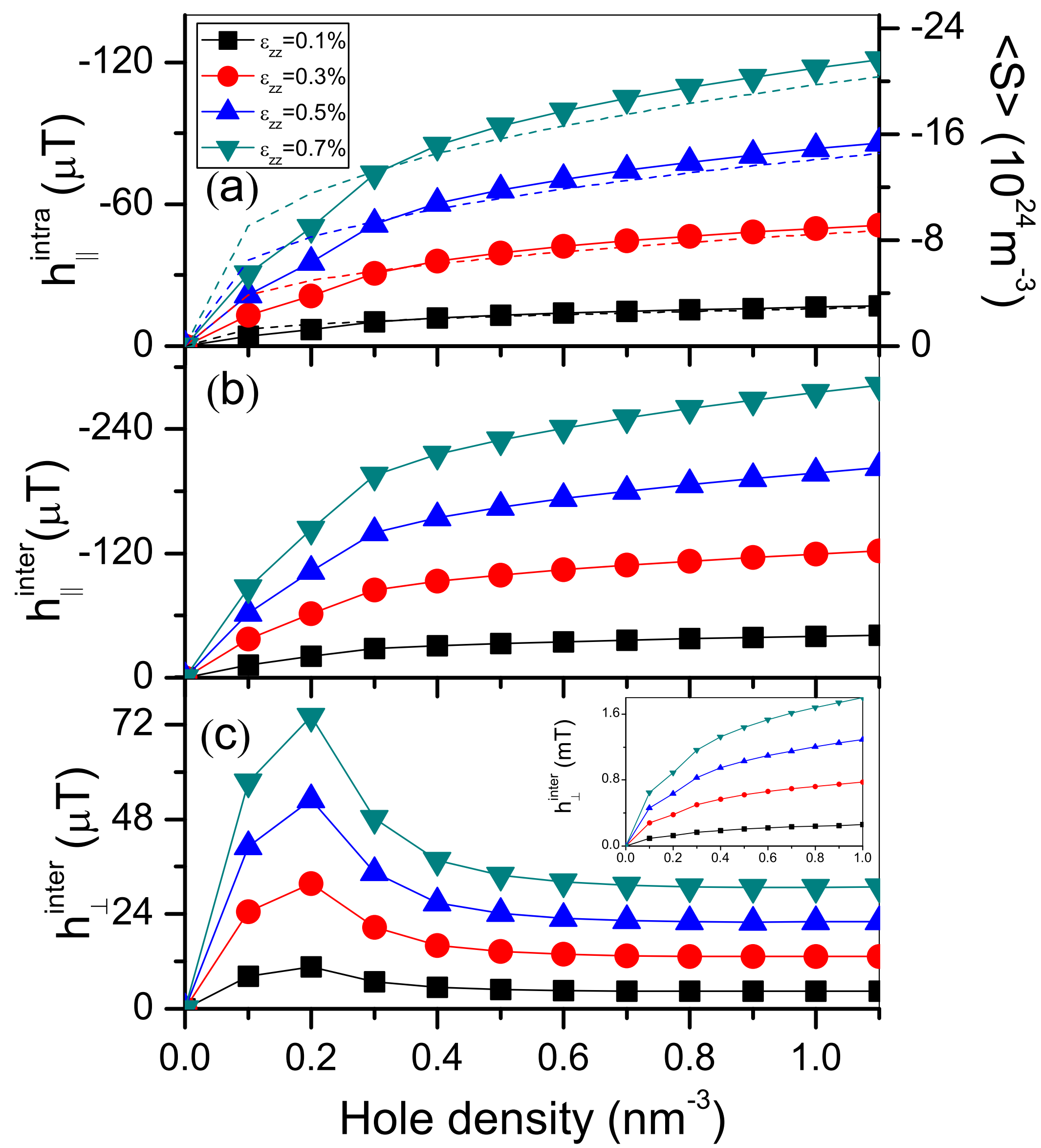
Current-induced (non-equilibrium) spin polarisation - in linear response

$$\delta\mathbf{S} = \delta\mathbf{S}^{\text{intra}} + \delta\mathbf{S}_1^{\text{inter}} + \delta\mathbf{S}_2^{\text{inter}}$$

$$\delta\mathbf{S}^{\text{intra}} = \frac{1}{V}\frac{e\hbar}{2\Gamma}\sum_{\mathbf{k},a}\langle\psi_{\mathbf{k}a}|\hat{\mathbf{s}}|\psi_{\mathbf{k}a}\rangle\langle\psi_{\mathbf{k}a}|\mathbf{E}\cdot\hat{\mathbf{v}}|\psi_{\mathbf{k}a}\rangle \times \delta(E_{\mathbf{k}a}-E_F), \tag{3}$$

$$\delta\mathbf{S}_1^{\text{inter}} = -\frac{e\hbar}{V}\sum_{\mathbf{k},a\neq b} 2\mathrm{Re}[\langle\psi_{a\mathbf{k}}|\hat{\mathbf{s}}|\psi_{b\mathbf{k}}\rangle\langle\psi_{b\mathbf{k}}|\mathbf{E}\cdot\hat{\mathbf{v}}|\psi_{a\mathbf{k}}\rangle] \times \frac{\Gamma(E_{\mathbf{k}a}-E_{\mathbf{k}b})}{[(E_{\mathbf{k}a}-E_{\mathbf{k}b})^2+\Gamma^2]^2}(f_{\mathbf{k}a}-f_{\mathbf{k}b}), \tag{4}$$

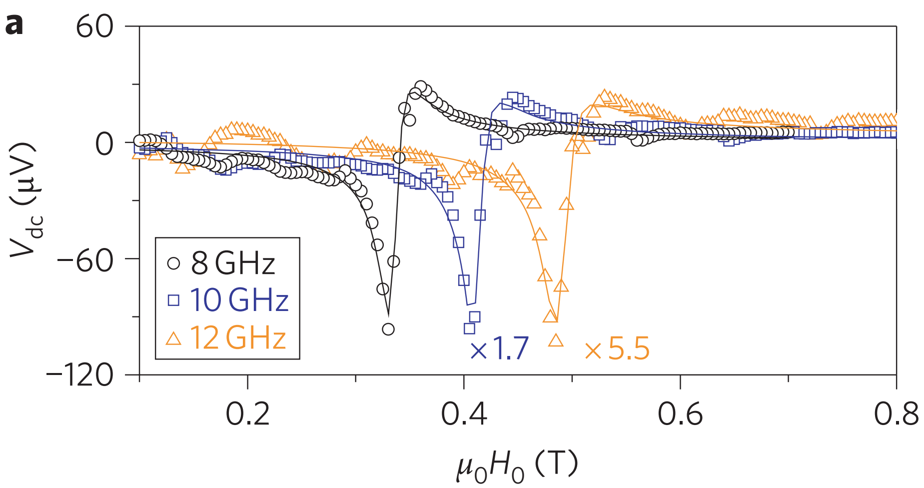
$$\delta\mathbf{S}_2^{\text{inter}} = -\frac{e\hbar}{V}\sum_{\mathbf{k},a\neq b} \mathrm{Im}[\langle\psi_{\mathbf{k}a}|\hat{\mathbf{s}}|\psi_{\mathbf{k}b}\rangle\langle\psi_{\mathbf{k}b}|\mathbf{E}\cdot\hat{\mathbf{v}}|\psi_{\mathbf{k}a}\rangle] \times \frac{\Gamma^2-(E_{\mathbf{k}a}-E_{\mathbf{k}b})^2}{[(E_{\mathbf{k}a}-E_{\mathbf{k}b})^2+\Gamma^2]^2}(f_{\mathbf{k}a}-f_{\mathbf{k}b}). \tag{5}$$



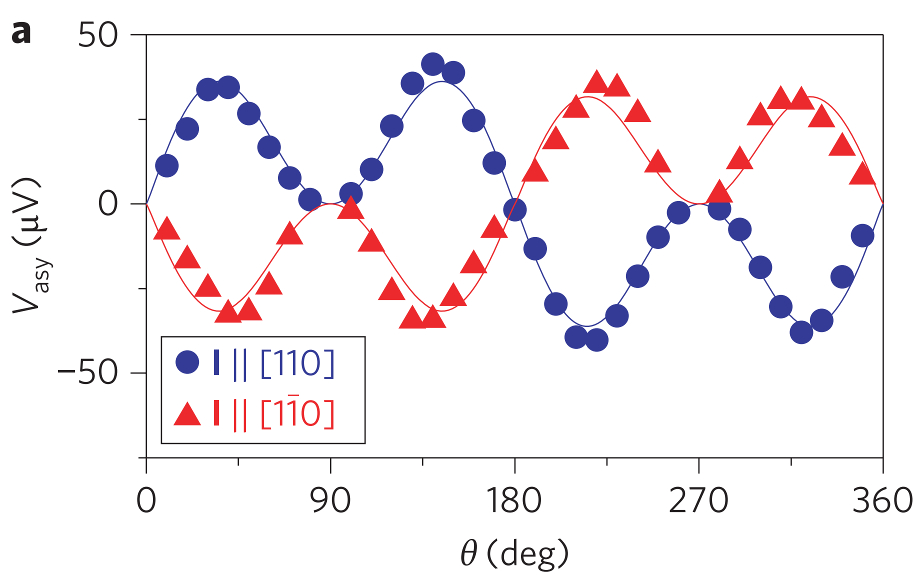
Current-induced spin-orbit torque

intraband

Nat. Nanotech. 6, 413 (2011)

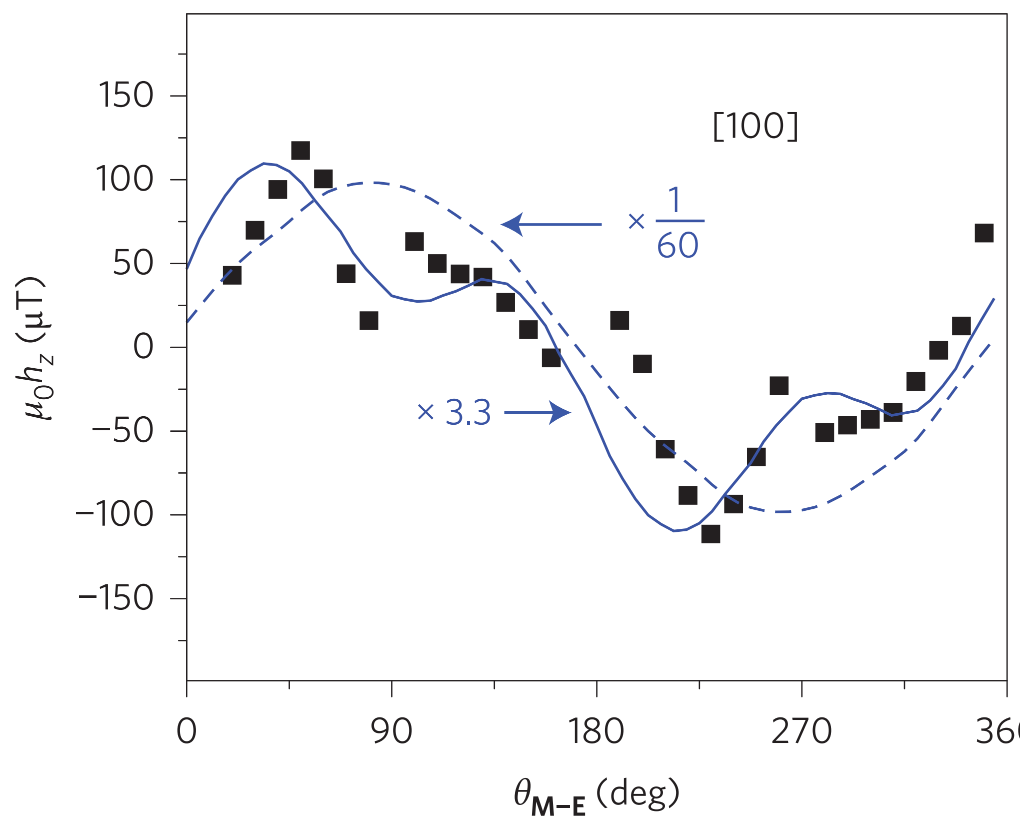


$$\mathrm{Re}\{V_{\mathrm{dc}}\} = V_{\mathrm{sym}} \frac{\Delta H^2}{(H_0 - H_{\mathrm{res}})^2 + \Delta H^2} + V_{\mathrm{asy}} \frac{\Delta H (H_0 - \Delta H)}{(H_0 - H_{\mathrm{res}})^2 + \Delta H^2}$$



interband

Nat. Nanotech. 9, 211 (2014)



Berry-curvature type expressions…

$$S_z = \frac{\hbar}{V} \sum_{\mathbf{k}, a \neq b} (f_{\mathbf{k},a} - f_{\mathbf{k},b}) \frac{\mathrm{Im}[\langle \mathbf{k}, a | s_z | \mathbf{k}, b \rangle \langle \mathbf{k}, b | e\boldsymbol{E} \cdot \mathbf{v} | \mathbf{k}, a \rangle]}{(E_{\mathbf{k},a} - E_{\mathbf{k},b})^2}$$

$$S_z = ieE \sum_{\text{occ. states}} \left[\left\langle \frac{\partial \psi}{\partial h_z} \middle| \frac{\partial \psi}{\partial k_x} \right\rangle - \left\langle \frac{\partial \psi}{\partial k_x} \middle| \frac{\partial \psi}{\partial h_z} \right\rangle \right]$$

(Partial) summary

magnetisation switching by current-induced spin-orbit torque

(Ga,Mn)As

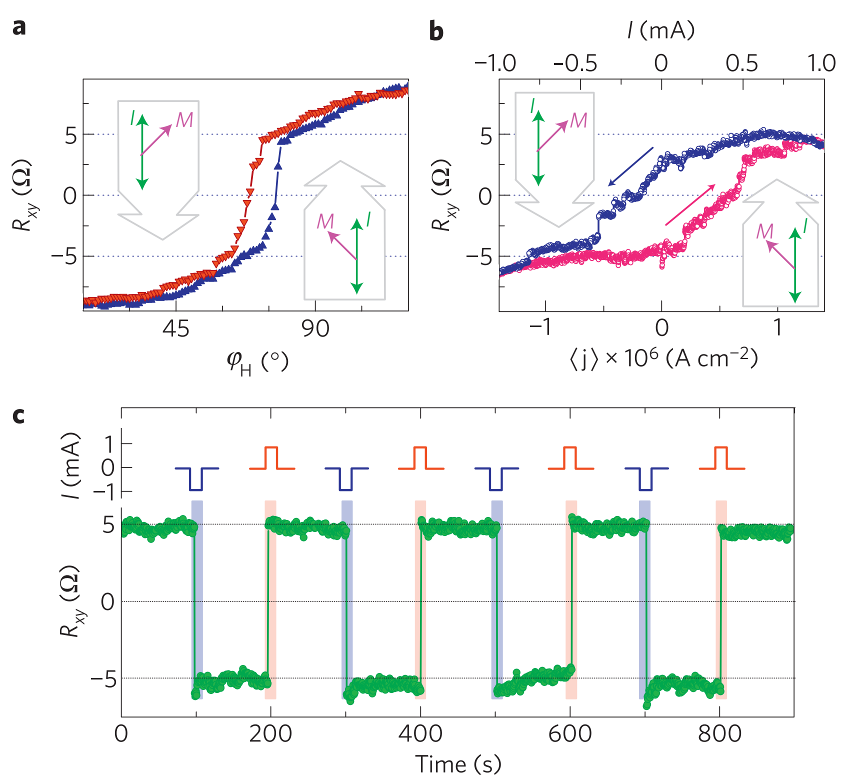


Figure 4 | Current-induced reversible magnetization switching. a, φ_H dependence of R_{xy} near the [010] → [$\bar{1}$00] magnetization switching for $I = \pm 0.7$ mA in sample A for $I \| [1\bar{1}0]$. **b**, R_{xy} shows hysteresis as a function of current for a fixed field $H = 6$ mT applied at $\varphi_H = 72°$. **c**, Magnetization switches between the [010] and [$\bar{1}$00] directions when alternating ±1.0 mA current pulses are applied. The pulses have 100 ms duration and are shown schematically above the data curve. R_{xy} is measured with $I = 10$ μA.

Nat. Phys. 5, 656 (2009)

multilayers - CoPt

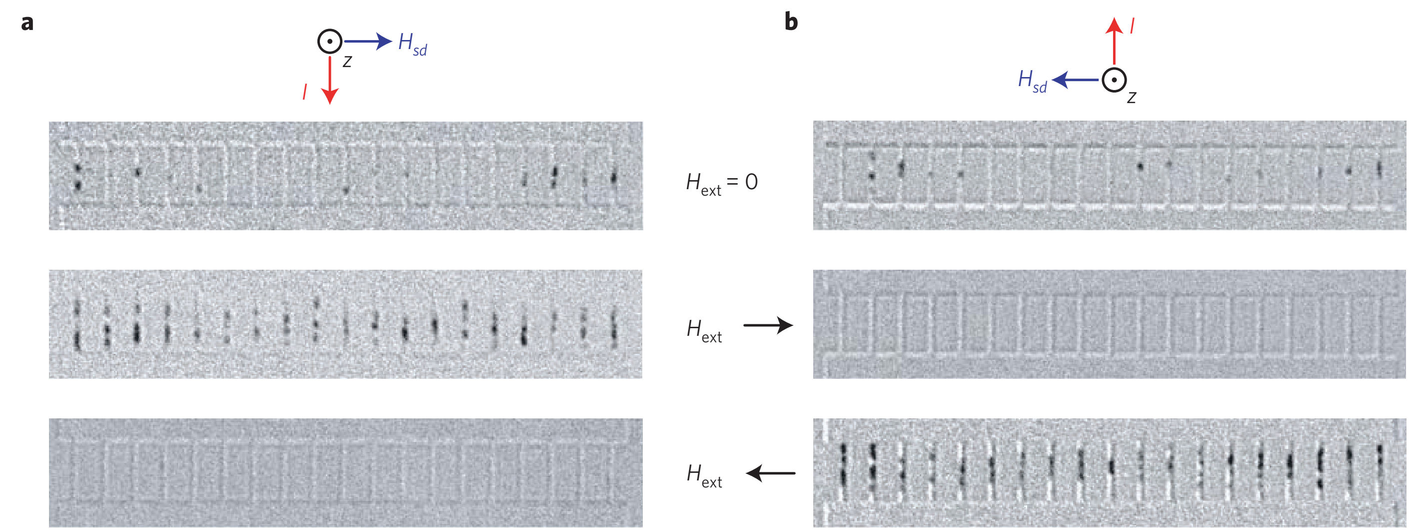


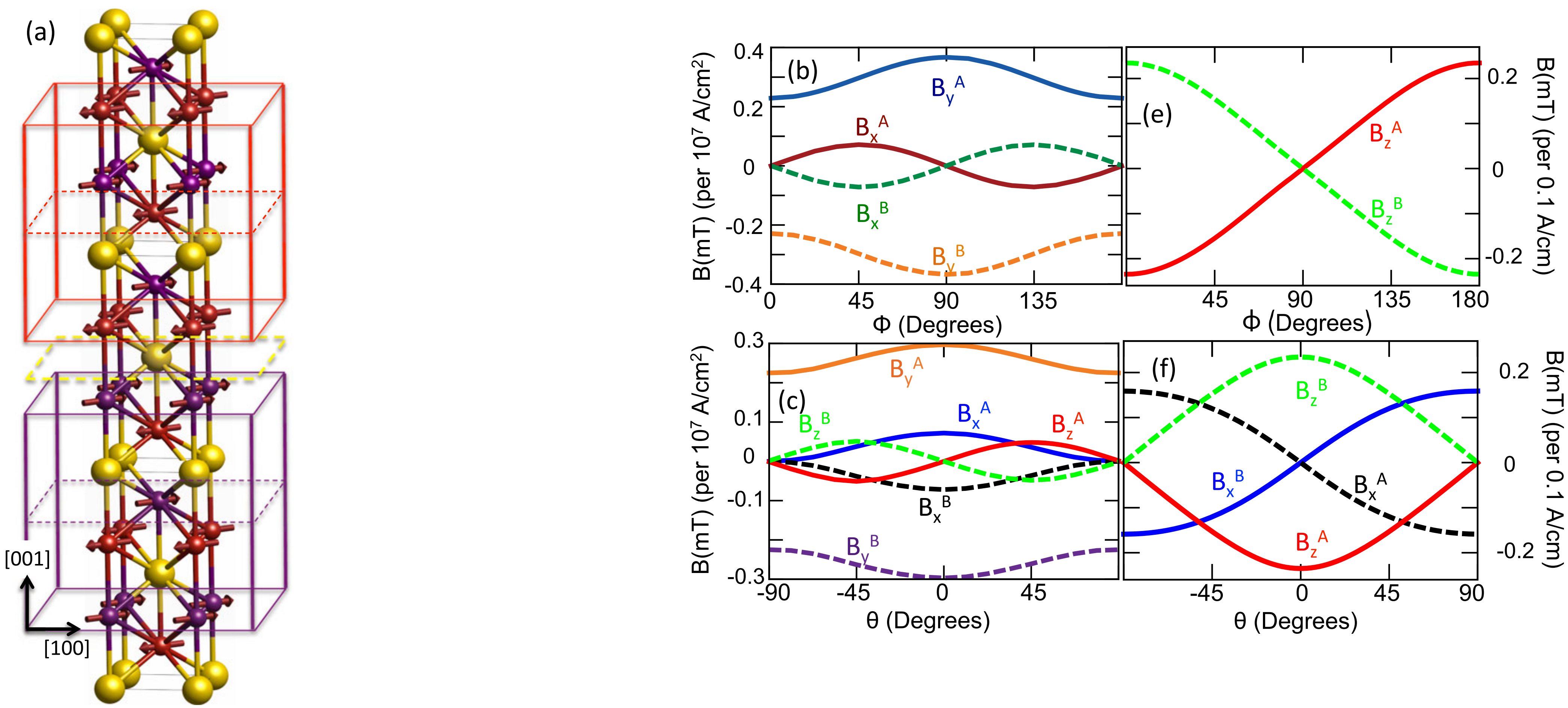
Figure 2 | Differential Kerr microscopy images recorded after current pulse injection. a,**b**, Positive (**a**) and negative (**b**) current values with external field $\mu_0 H_{ext} = 0, \pm 47.5$ mT applied parallel to $\hat{\mathbf{y}}$. The pulse amplitude is set to 7.8×10^7 A cm^{-2} in all cases. Note that the topographic contrast in each image varies depending on the drift between pre-pulse and post-pulse images.

Nat. Mater. 9, 230 (2010)

So far: ferromagnets

Now: antiferromagnets

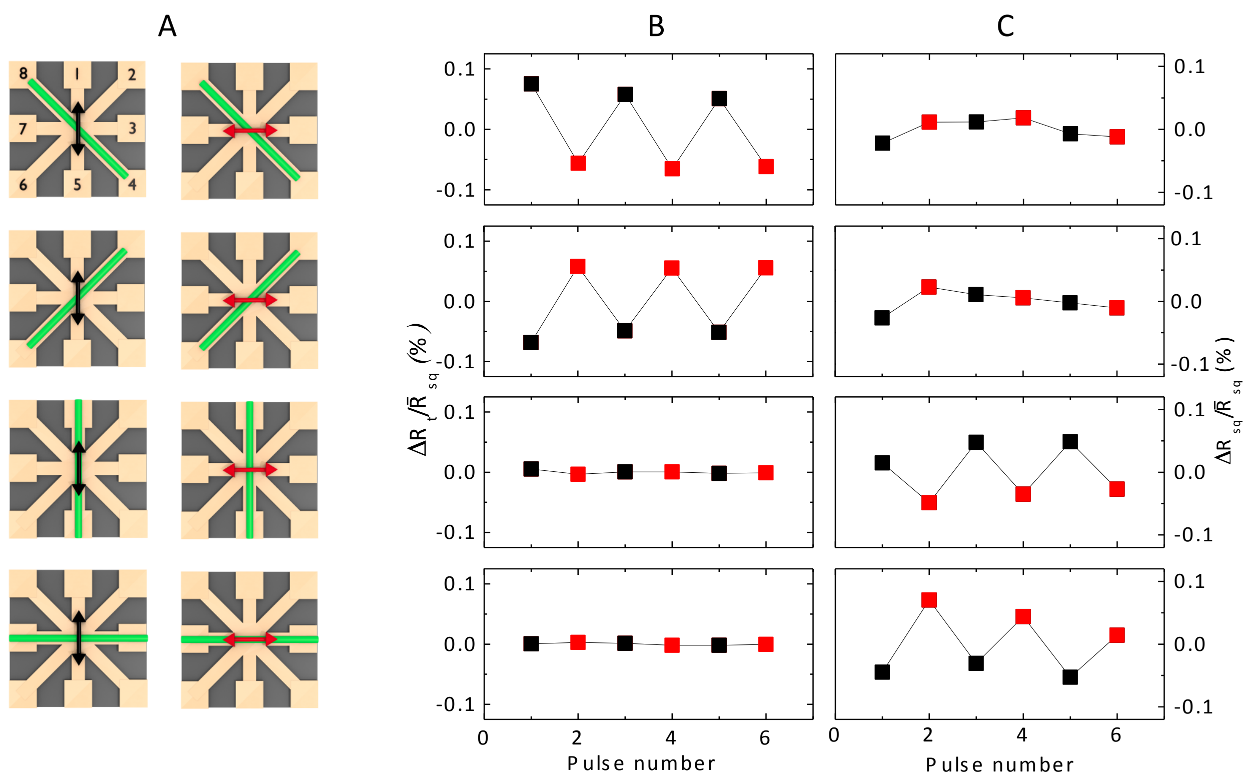
example: Mn_2Au (Phys. Rev. Lett. 113, 157201)



- two sublattices, opposite mag. moments
- current-induced fields resolved by sublattice

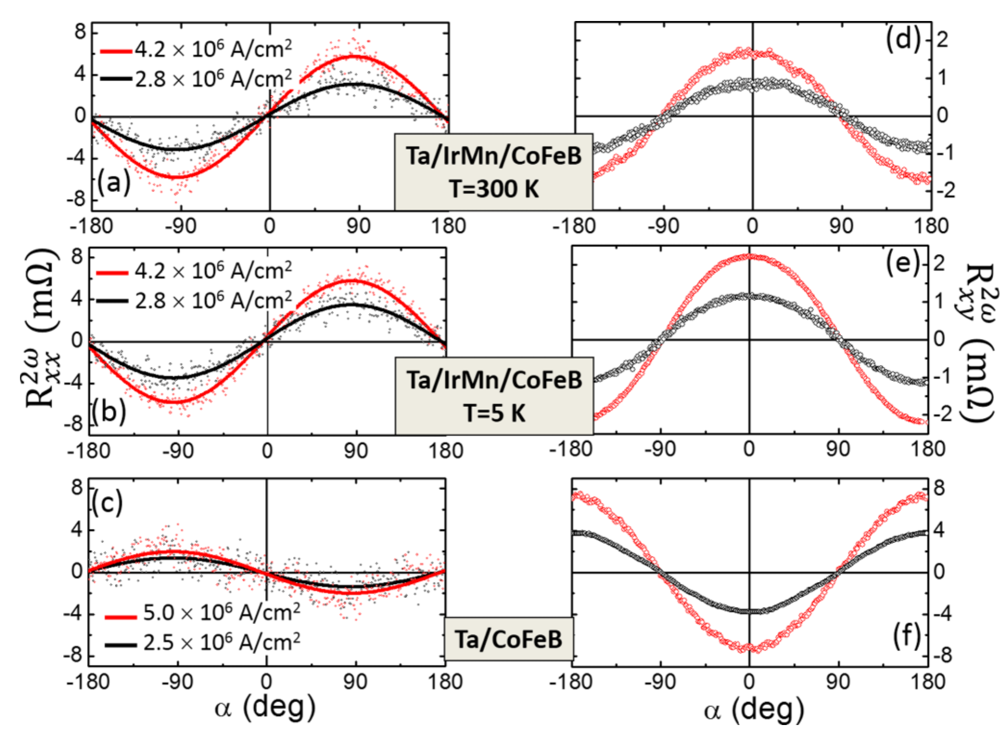
Current-induced spin-orbit torque in antiferromagnets

switching observed in CuMnAs



arXiv1503.03765
(to appear in Science)

difficult to discriminate from other effects (IrMn)



Phys. Rev. B 92, 165424 (2015)

Summary

- current-induced spin-orbit torques observed in various metals
- microscopic theory available
- can be (potentially) used to write information in memory devices
- works both in ferromagnets and antiferromagnets