Announcement

En raison du festival Balélec, nous avons dû procéder au(x) changement(s) de salle suivant pour votre cours :

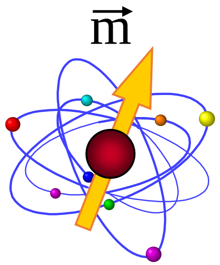
Matière	**Enseignant**	**Classe**	**Date**	**Heure**	**Salles concernées**	**Nouvelle salles**
PHYS-510	Pivetta/Rusponi	PH-MA2	08.05.2025	8h-12h	CM 1 221	**PH H3 31**

Lecture 7

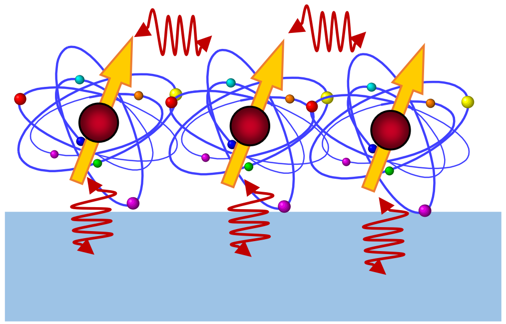
Spin Orbit Torque (SOT)

The spintronics “goose game”

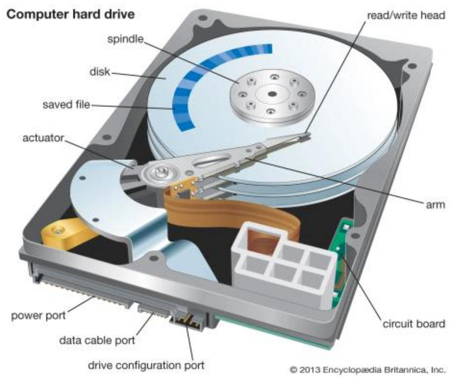
Atom magnetism

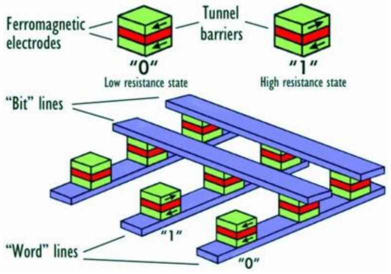


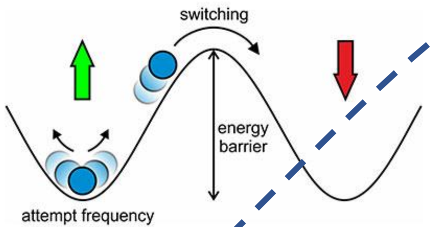
interactions between spins and with the supporting substrate



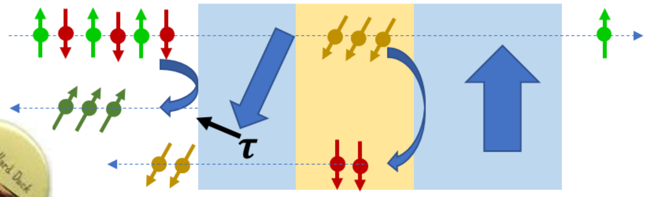
applications

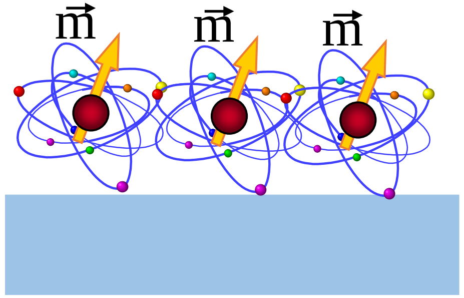




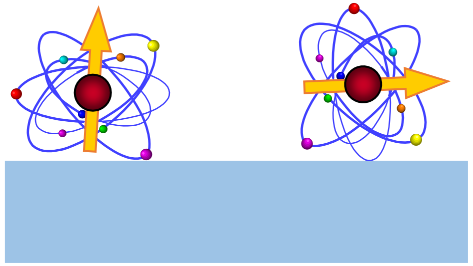


STT - SOT

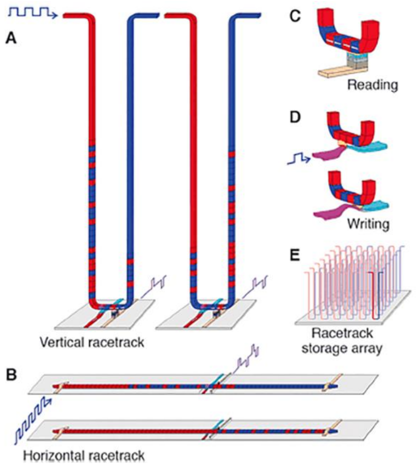




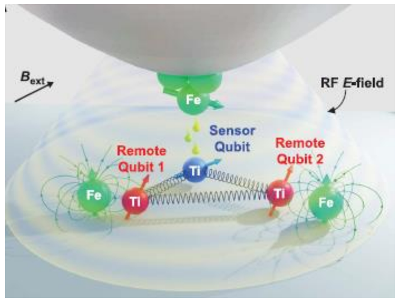
magnetic moment in a cluster and/or on a support

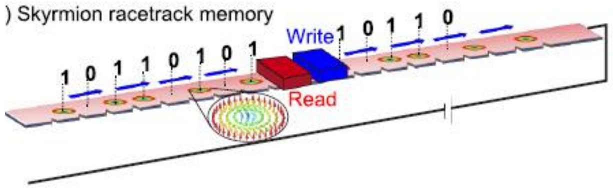


Magnetization easy axis

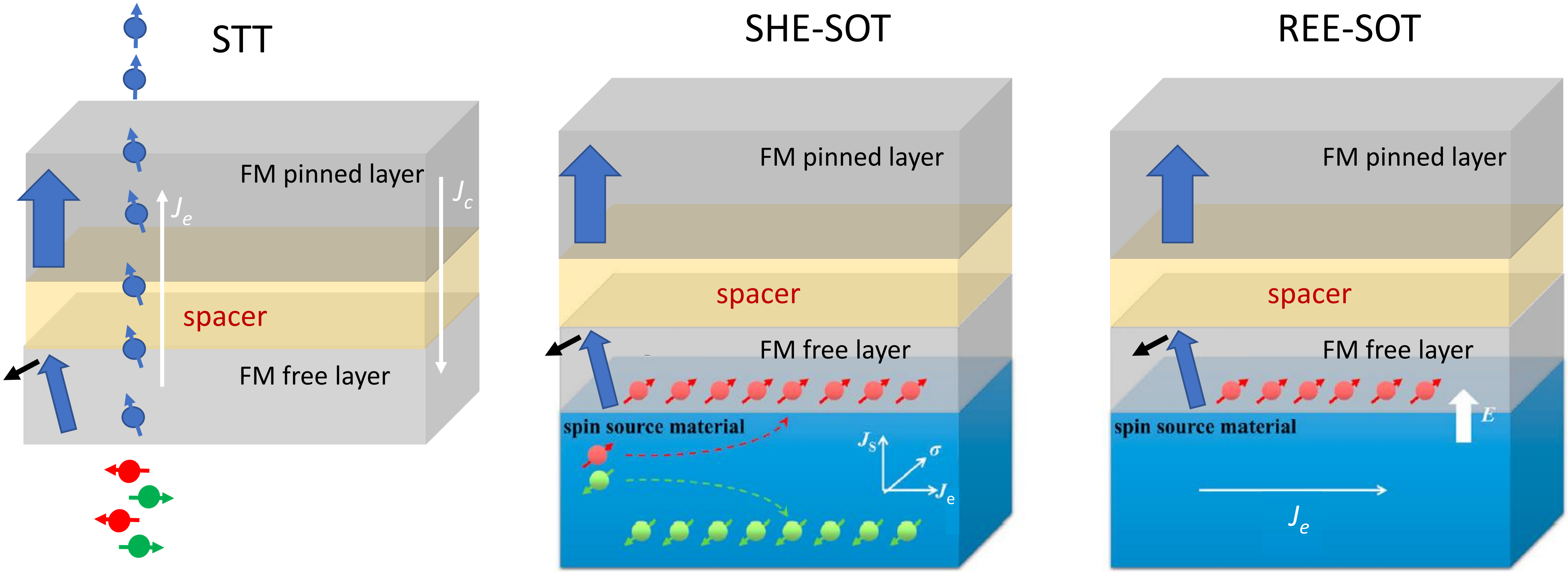


Future





MRAM: STT vs SOT



SOT employs in-plane current injection to write:

1) separates the reading and writing paths
2) Less power required since current does need to pass through the insulating spacer

Adapted from doi: 10.3389/fnano.2021.732916

SOC in non magnetic (NM) bulk

EPFL

A free electron with spin $\boldsymbol{\sigma}$ and moment $\boldsymbol{p}$ moving in an external magnetic field $\boldsymbol{B}$ feels:

$$F_{Lorentz} = \frac{-e}{m}\boldsymbol{p} \times \boldsymbol{B}$$

$$H_{Zeeman} = -\mu_B \, \boldsymbol{B} \cdot \boldsymbol{\sigma}$$

In crystals, electrons move with relativistic speed in the gradient of the crystal field potential. In the electron rest frame, this correspond to a magnetic field:

$$\boldsymbol{B}_{eff} = \frac{1}{mc^2} \boldsymbol{\nabla} V \times \boldsymbol{p}$$

Spin-orbit coupling: $H_{SO} = -\mu_B \boldsymbol{B}_{eff} \cdot \boldsymbol{\sigma} = -\mu_B / mc^2 \ (\boldsymbol{\nabla} V \times \boldsymbol{p}) \cdot \boldsymbol{\sigma} \propto \boldsymbol{l} \cdot \boldsymbol{\sigma}$

A twofold degenerate spin level might be split by SOC into two levels with spin parallel ($H_{SO} \propto l \, \sigma$) and antiparallel ($H_{SO} \propto - \, l \, \sigma$) to the orbit.

However, such splitting is symmetry forbidden for central symmetric systems (impossible to define the direction for spin up and down).

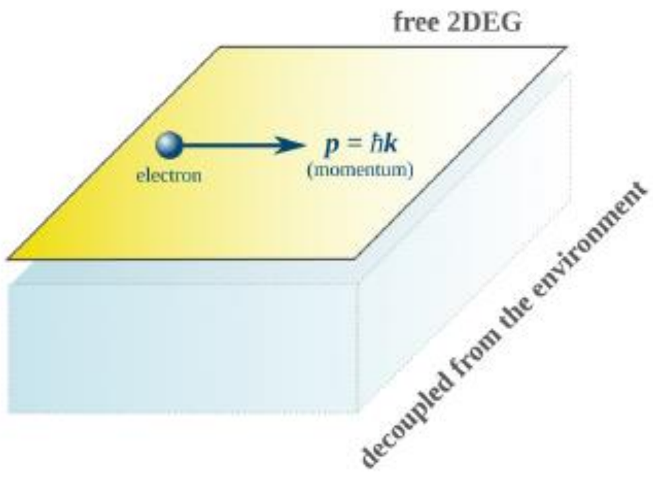
Rashba-Edelstein effect (REE): 2D interfaces

The absence of an inversion symmetry center at the crystal surface or at 2D interfaces breaks this symmetry

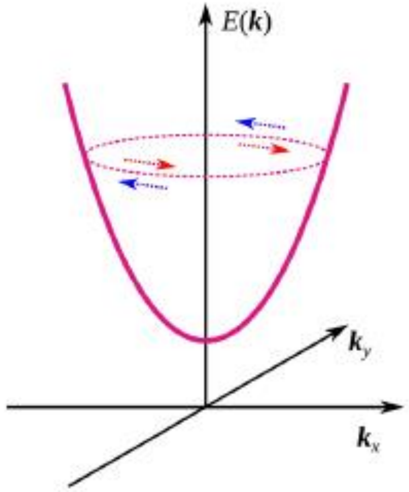
Free-standing 2D electron gas: $V = V_{at}$

Symmetric case

$$H = \frac{\boldsymbol{p}^2}{2m_e} + eV_{at} - \frac{e\hbar}{2m_e^2c^2}(\nabla V_{at} \wedge \boldsymbol{p}_{//}) \cdot \boldsymbol{\sigma}$$



(c)



(d)

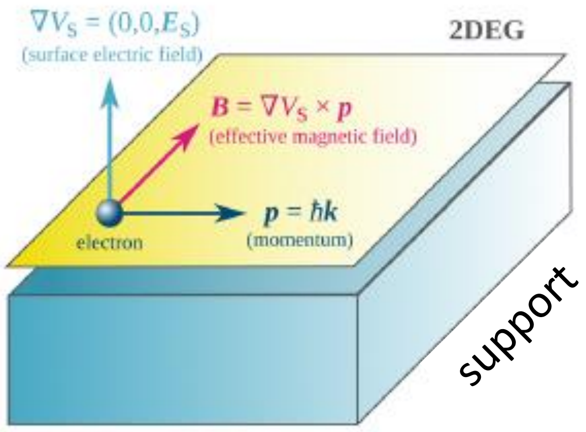
N.B.:

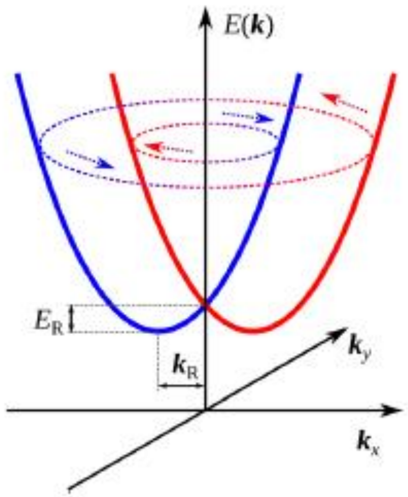
1) in these Hamiltonians V_{ee} is not included for simplicity
2) at surface electrons move parallel to the surface -> $\boldsymbol{p} = \boldsymbol{p}_{//}$

2D electron gas + support: $V = V_{at} + E_s z$

Broken symmetry

$$H = \frac{\boldsymbol{p}^2}{2m_e} + eV_{at} - \frac{e\hbar}{2m_e^2c^2}(\nabla V_{at} \wedge \boldsymbol{p}_{//}) \cdot \boldsymbol{\sigma} + $$
$$- \frac{e\hbar E_s}{2m_e^2c^2}(\hat{\boldsymbol{z}} \wedge \boldsymbol{p}_{//}) \cdot \boldsymbol{\sigma}_{//} + eE_s z$$





E_s originates from the atomic potential perturbed by the breaking symmetry at interface

https://doi.org/10.1039/D3CP04242A

REE splitting

$$H = \frac{\boldsymbol{p}^2}{2m_e} + eV_{at} - \frac{e\hbar}{2m_e^2c^2}(\nabla V_{at} \wedge \boldsymbol{p}_{//}) \cdot \boldsymbol{\sigma} + - \frac{e\hbar E_s}{2m_e^2c^2}(\hat{\boldsymbol{z}} \wedge \boldsymbol{p}_{//}) \cdot \boldsymbol{\sigma}_{//} + eE_s z$$

$$H = \frac{\boldsymbol{p}^2}{2m_e} + eV + V_{SO}\, \boldsymbol{l} \cdot \boldsymbol{\sigma} + H_{RE} + eE_s z$$

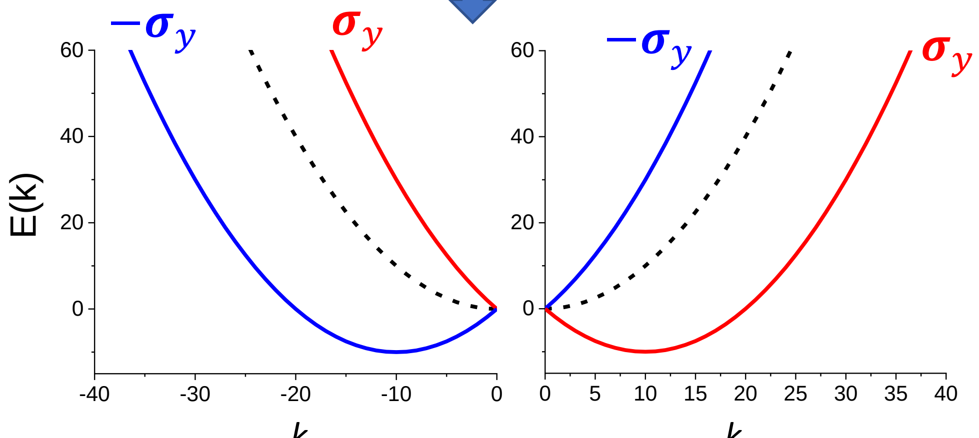
Because of SOC:

1) spins align perpendicularly to the momenta
2) splitting of spin bands

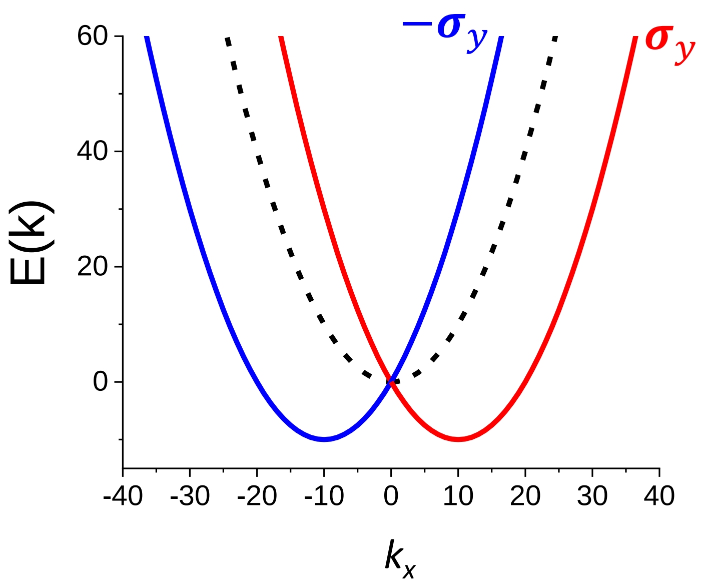
RE (Rashba-Edelstein) Hamiltonian:

$$H_{RE} = \frac{-e\hbar E_s}{2m_e^2c^2}(\hat{\boldsymbol{z}} \wedge \boldsymbol{p}_{//}) \cdot \boldsymbol{\sigma}_{//} = \frac{-e\hbar^2 E_s}{2m_e^2c^2}(\hat{\boldsymbol{z}} \wedge \boldsymbol{k}_{//}) \cdot \boldsymbol{\sigma}_{//} = \alpha_{RE}(\hat{\boldsymbol{z}} \wedge \boldsymbol{k}_{//}) \cdot \boldsymbol{\sigma}_{//}$$

Inverted splitting between spin polarized bands at inverted wave vector $\boldsymbol{k}$ (black corresponds to $H_{RE} = 0$)



1D case

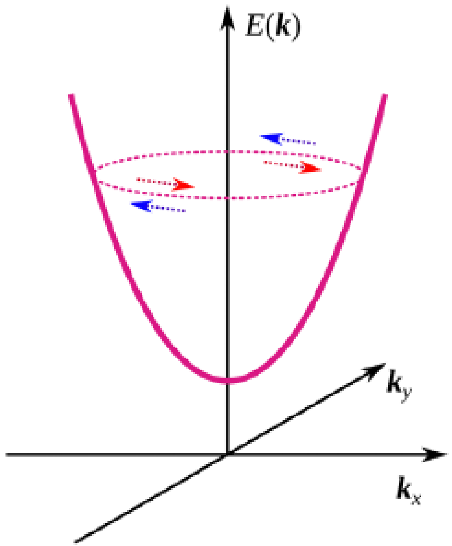


REE splitting

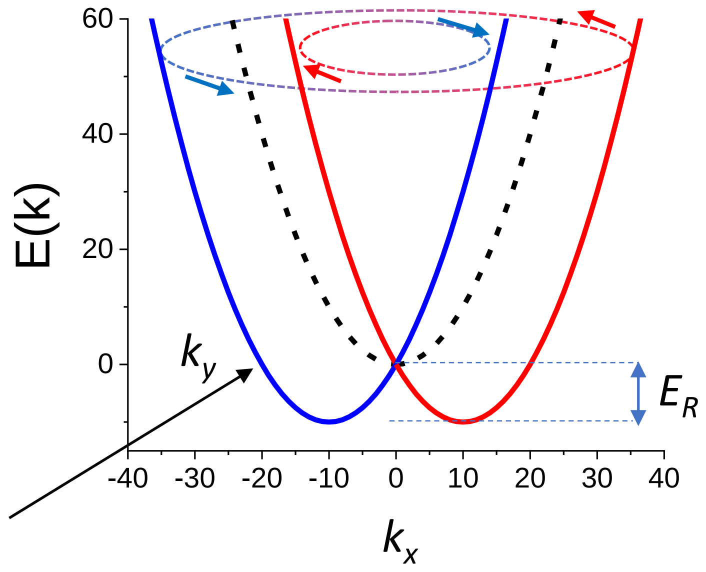
Because of SOC:

1) spins align perpendicularly to the momenta
2) splitting of spin bands

$H_{RE} = 0$

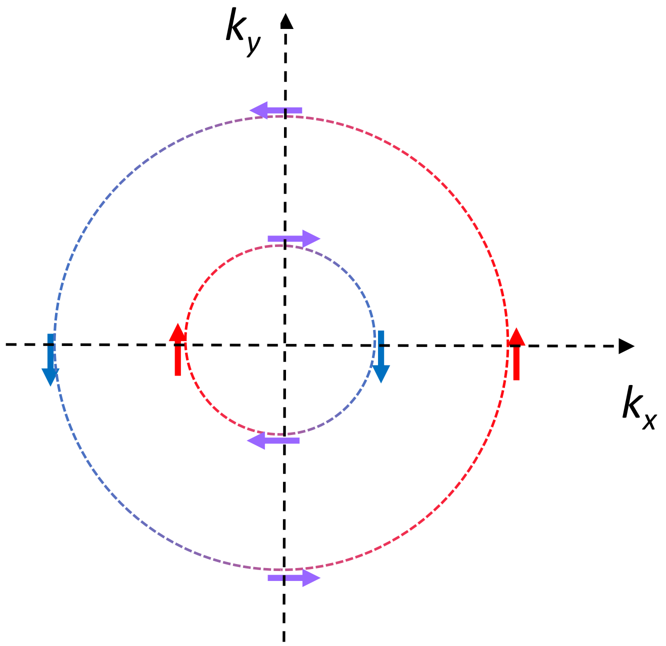


Chiral spin texture characterized by $\boldsymbol{k}_x\boldsymbol{\sigma}_y$ $(\boldsymbol{k}_y\boldsymbol{\sigma}_x)$ spin-momentum locking



E_R is used to quantify the REE

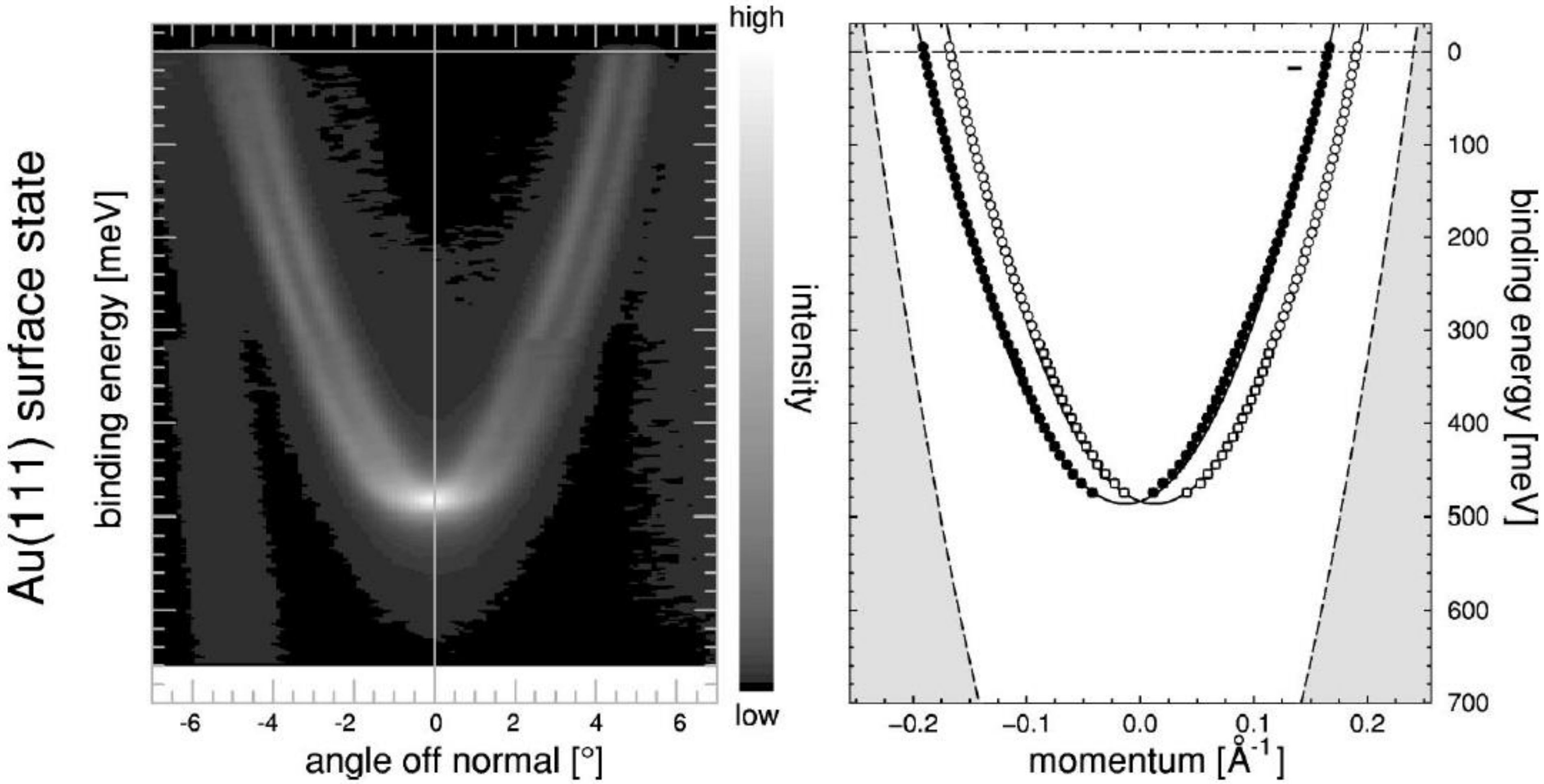
Top view



N.B.: arrow color code reflects the $\boldsymbol{\sigma}_y$ character

Rashba splitting of Au(111) surface state

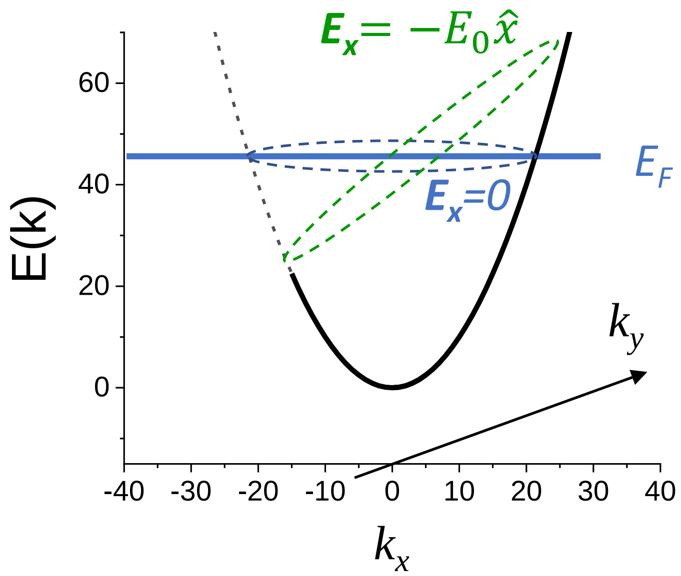
See exercises: 7.1-7.2



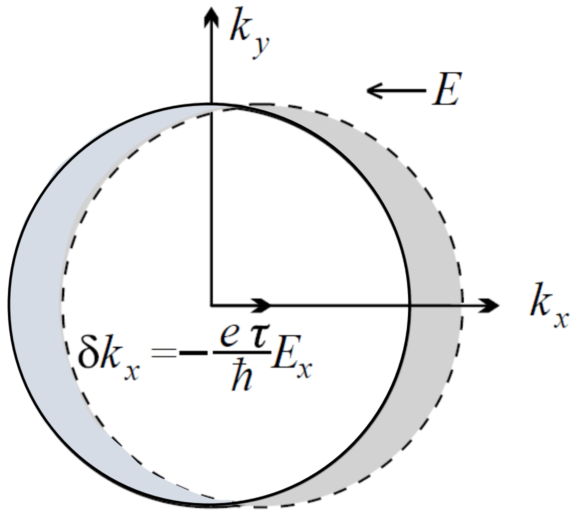
Phys. Rev. Lett. **77**, 3419 (1996); Phys. Rev. B **63**, 115415 (2001)

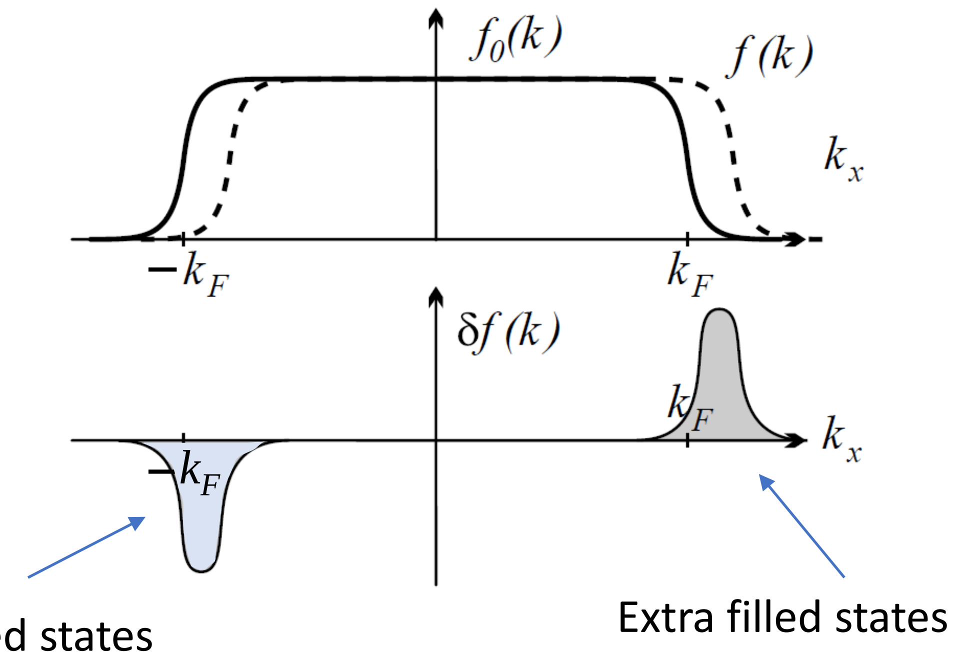
Free standing 2D electron gas in an applied electric field

Band dispersion



Momentum space





Displacement of the Fermi surface under the effect of an electric field generating an unbalanced distribution of states in the *k*-space:
increased (decreased) number of states with positive (negative) k_x moment

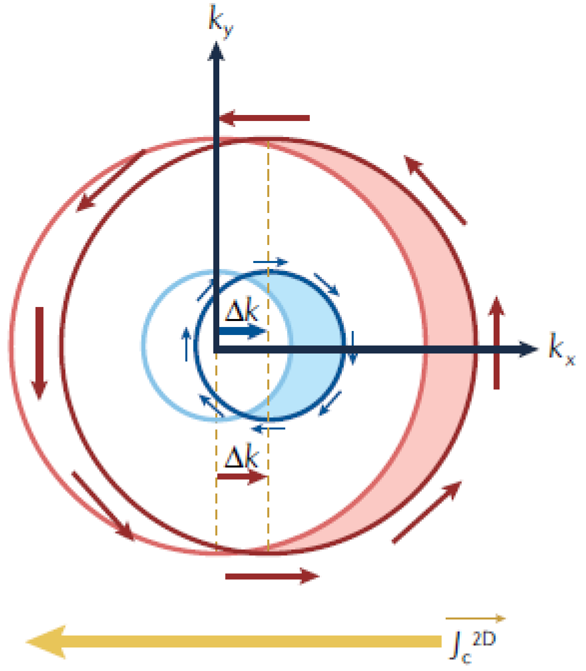
N.B.: in the sketch the blue-gray (gray) part shows the states emptied (filled) as a consequence of the applied electric field

2D Rashba spin texture in an applied electric field: origin of SOT

Rashba spin texture for the majority chiral states

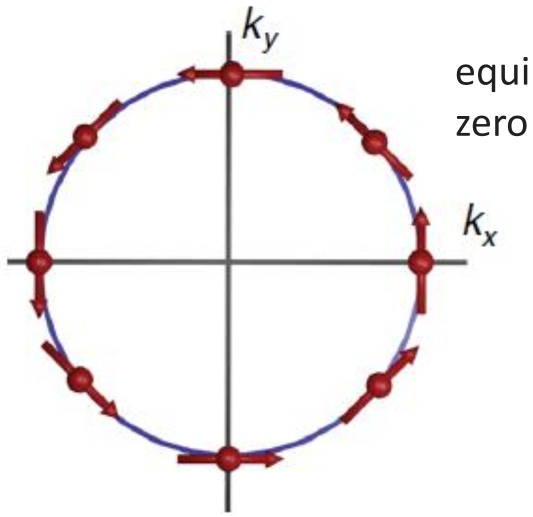
The reversed chirality will give an opposite but lower contribution

Displacement of the Fermi surface under the effect of an electric field

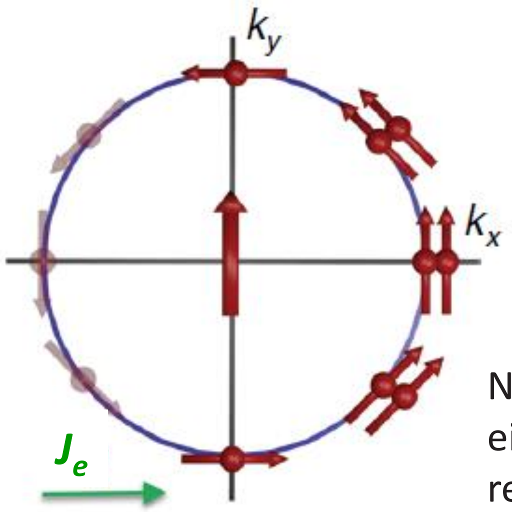


Current flows opposite to electrons

$\boldsymbol{J_c = -J_e}$

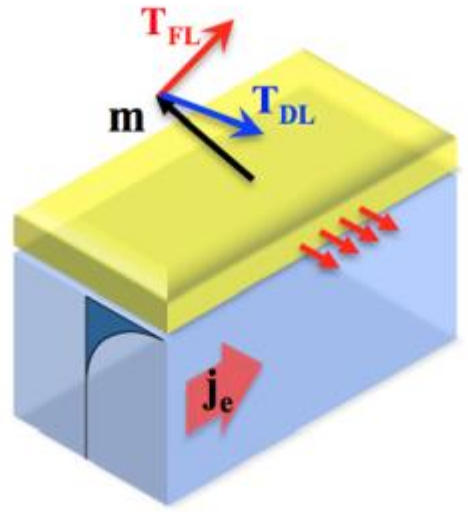


equilibrium ($J_e = 0$) with zero net spin density



Nonequilibrium redistribution of eigenstates in an applied electric field resulting in a nonzero spin density

REE - SOT



Torque on the top magnetic layer via exchange

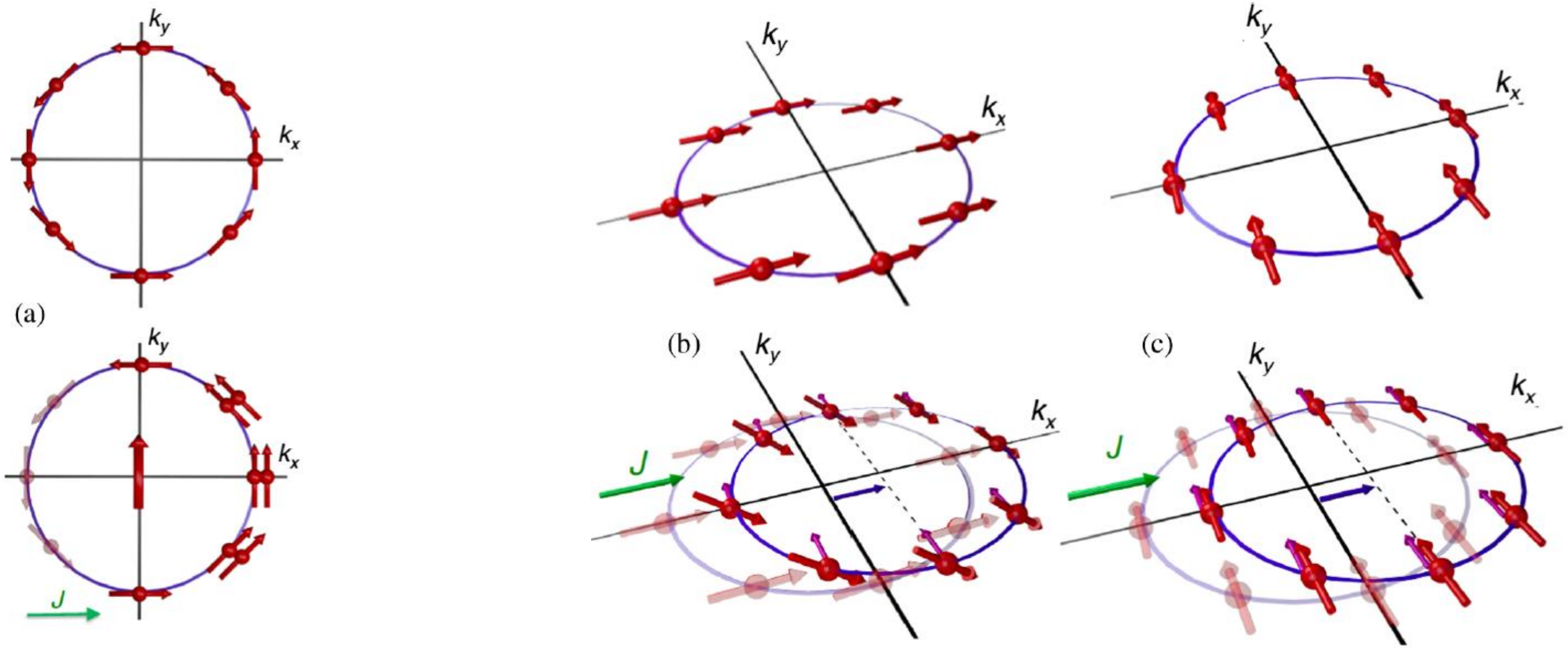
https://doi.org/10.1038/s42254-022-00490-y

10.1103/RevModPhys.87.1213

REE-SOT torques

Non magnetic material

Ferromagnetic material



(a) Top: Rashba spin texture for one of the chiral states in equilibrium with zero net spin density. **Bottom**: Nonequilibrium redistribution of eigenstates in an applied electric field resulting in a nonzero spin density due to broken inversion symmetry of the spin texture. The exchange coupling of the carrier spin density to magnetization overlayer is responsible for the REE-SOT torque

(b) Top: A model equilibrium spin texture in a 2D Rashba spin-orbit coupled system with an additional time-reversal symmetry breaking exchange field (magnetization) of a strength much larger than the spin-orbit field. In equilibrium, all spins in this case align approximately with the *x* direction of the exchange field (magnetization). **Bottom**: In the presence of an electrical current along the *x* direction the Fermi surface (circle) is displaced along the same direction. When moving in momentum space, electrons experience an additional spin-orbit field proportional to $\hat{\boldsymbol{z}} \wedge \boldsymbol{p}_x$ (purple arrows). In reaction to this nonequilibrium current-induced field ($\frac{d\boldsymbol{m}}{dt} = -\gamma(\boldsymbol{m} \wedge \boldsymbol{H}_{eff})$), spins tilt and generate a uniform, nonequilibrium out-of-plane spin density (REE-SOT torque).

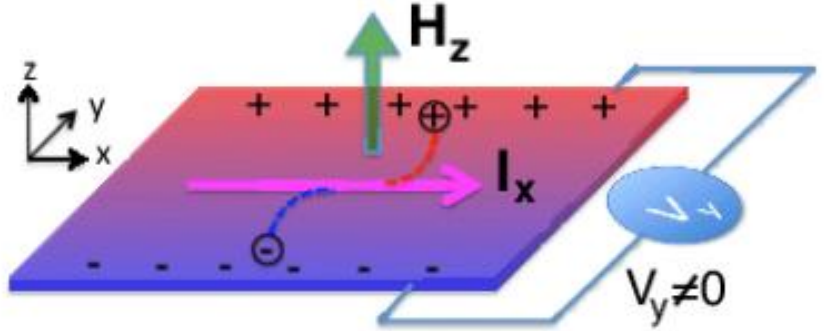
(c) Top: Same as in (b) for the y direction of the exchange field. **Bottom**: Same as in (b) but now with the current-induced spin-orbit field align with the exchange field, resulting in zero tilt of the carrier spins

https://doi.org/10.1103/RevModPhys.91.035004

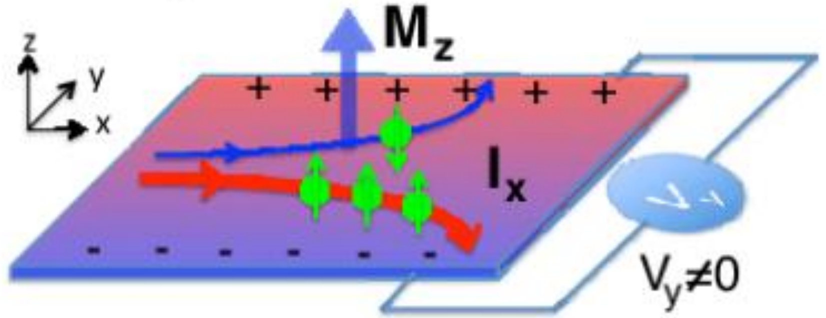
Hall effect (HE): The longitudinal current I_x under vertical external magnetic field H_z contributes to the transversal voltage V_y due to the Lorentz force experienced by carriers.

Anomalous Hall effect (AHE): The electrons with majority and minority spin (due to spontaneous magnetization M_z) have opposite "anomalous velocity" due to spin-orbit coupling. The spin polarization of the current causes unbalanced electron concentration at two transversal sides and leads to finite voltage V_y.

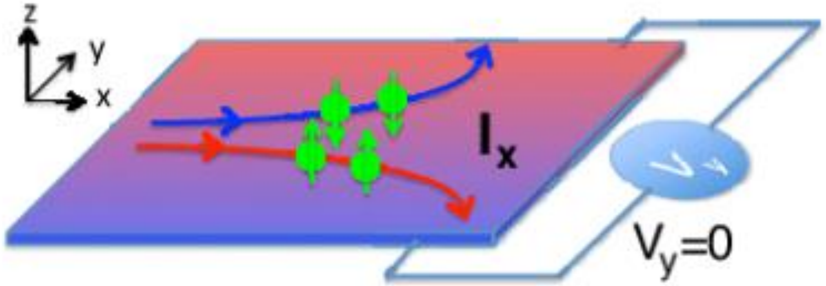
Spin Hall effect (SHE): In nonmagnetic conductor, equivalent currents in both spin channels with opposite velocity leads to a net spin current in transversal direction (but with balanced electron concentration at both sides $\Rightarrow V_y = 0$)



(a) Hall effect



(c) Anomalous Hall effect

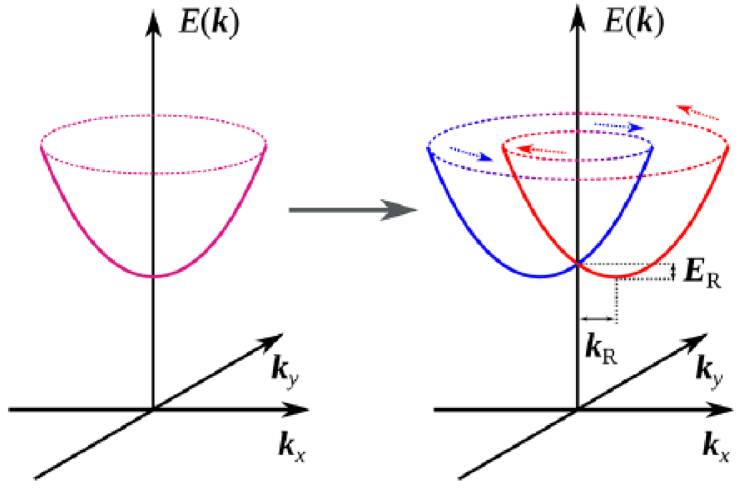


(e) Spin Hall effect

Rashba vs. atomic SOC splitting

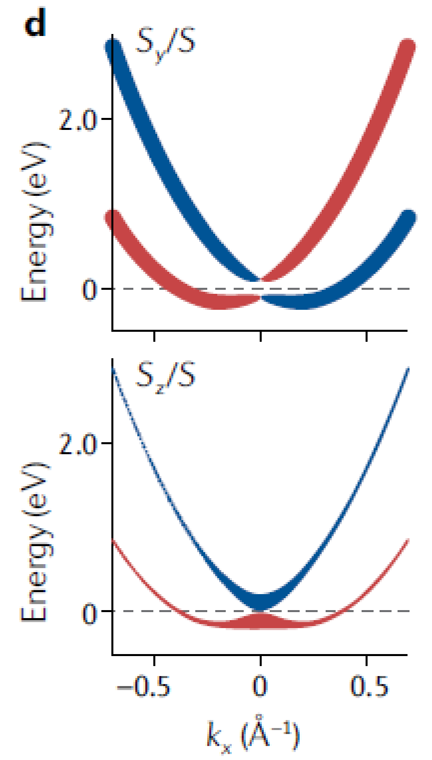
REE SOC: acts only on in-plane spins

$$E_R = \alpha_R(\hat{\boldsymbol{z}} \wedge \boldsymbol{p}_{//}) \cdot \boldsymbol{\sigma}_{//}$$



REE + atomic SOC

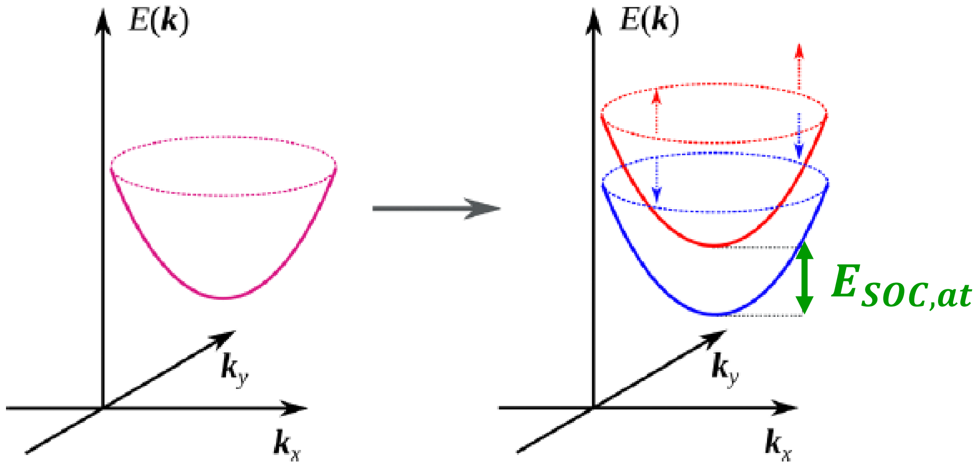
Magnetization along ***z***



Atomic SOC: acts on both in-plane and out-of-plane spins

$$\boldsymbol{E}_{SOC,at} = \frac{e\hbar}{2m_e^2c^2}(\nabla V_{at} \wedge \boldsymbol{p}) \cdot \boldsymbol{\sigma} =$$

$$= \boldsymbol{B}_{SOC,at} \cdot \boldsymbol{\sigma} \propto V_{SO}\, \boldsymbol{l} \cdot \boldsymbol{\sigma}$$



normalized S_x (S_y) components as line thickness (different orientations are in red and blue). Reduced momentum locking for $k \approx 0 \Rightarrow$ stronger S_z character

https://doi.org/10.1039/D3CP04242A

https://doi.org/10.1038/s42254-022-00490-y

Intrinsic AHE in a 2D REE system

Spin split bands due to REE + Atomic SOC

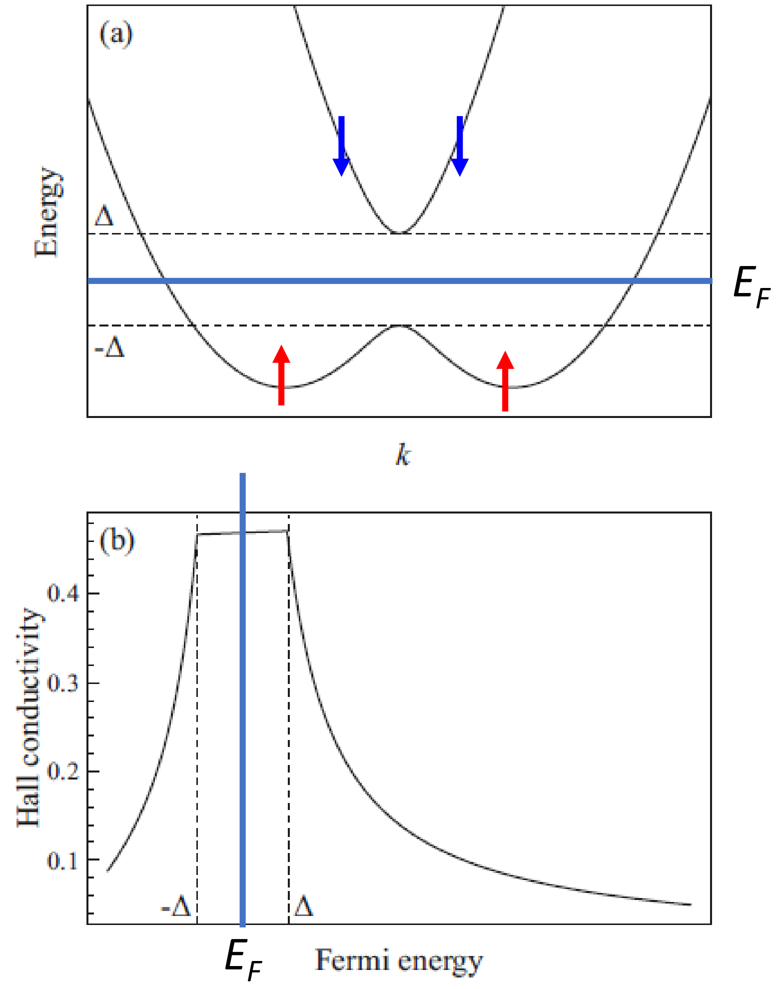


FIG. 6. Anomalous Hall effect in a simple two-band model. (a) Energy dispersion of spin-split bands. (b) The Hall conductivity $-\sigma_{xy}$ in the units of e^2/h as a function of Fermi energy.

If $E_F < -\Delta$, the states with energies just below $-\Delta$, which contribute most to the AHE, are empty.
If $E_F > \Delta$, contributions from upper and lower bands cancel each other, and the AHE decreases quickly as E_F moves away from the band gap.
If E_F is in the gap region $-\Delta < E_F < \Delta$, the AHE is resonantly enhanced and reaches its maximum value about $-e^2/2h$.

Similar arguments hold for the spin-split polarized bands of a bulk material

10.1103/RevModPhys.82.1959 ; 10.1103/PhysRevLett.97.126602

Extrinsic AHE and SHE

Skew (Mott) scattering: inhomogeneous atomic potential results in a inhomogeneous effective magnetic field

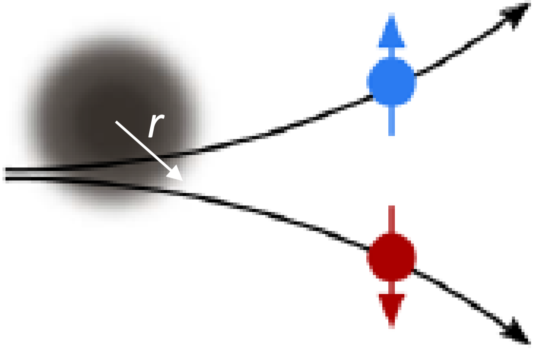
Atomic potential: $V(r) = \dfrac{Ze}{4\pi\varepsilon_0 r}$

$$\boldsymbol{\nabla} V = \frac{1}{r}\frac{dV(r)}{dr}\boldsymbol{r}$$

$$\boldsymbol{B}_{eff} = \frac{1}{mc^2}\boldsymbol{\nabla} V \times \boldsymbol{p}$$

$\boldsymbol{B}_{eff}$ is a function of r $\Rightarrow$ gradient of $\boldsymbol{B}$

Similar to Stern-Gerlach experiment:
opposite spins are deflected in opposite directions



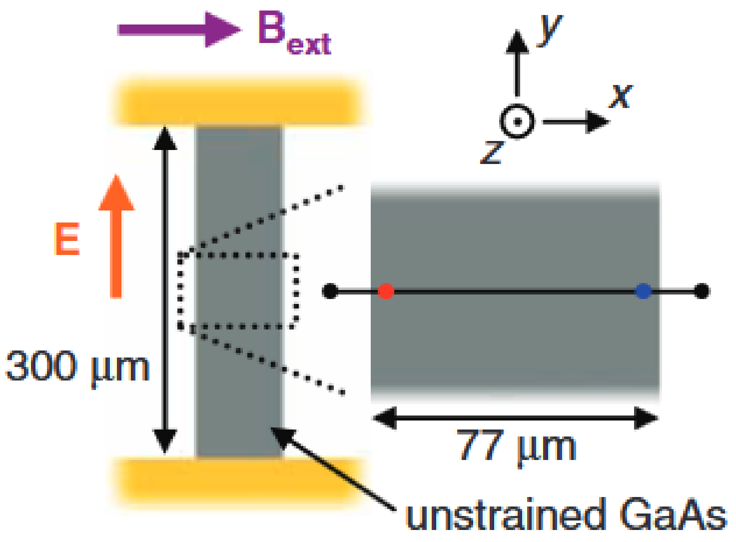
Screw defects or impurities are the source of these extrinsic scattering events

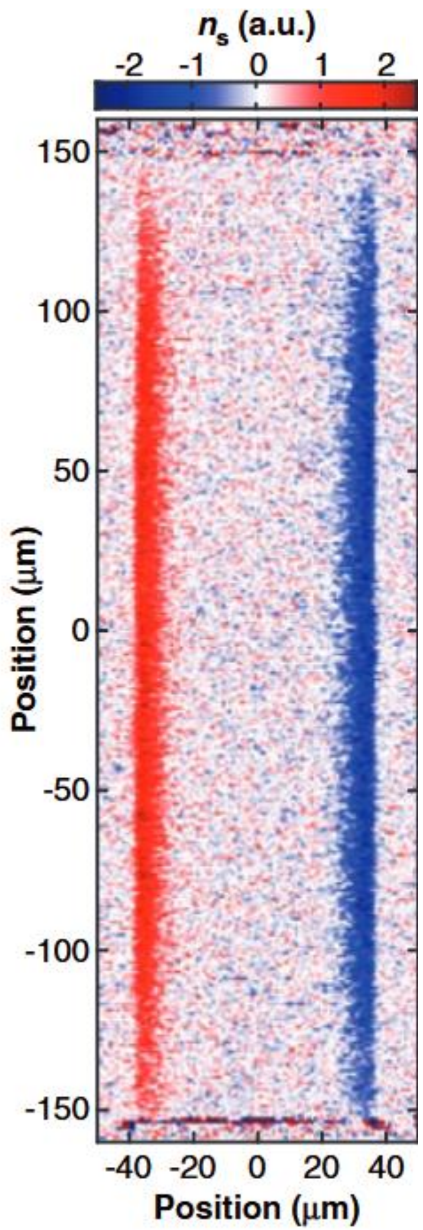
AHE: unbalanced number of spin up and down $\Rightarrow$ $J_s \neq 0 \quad V_y \neq 0$

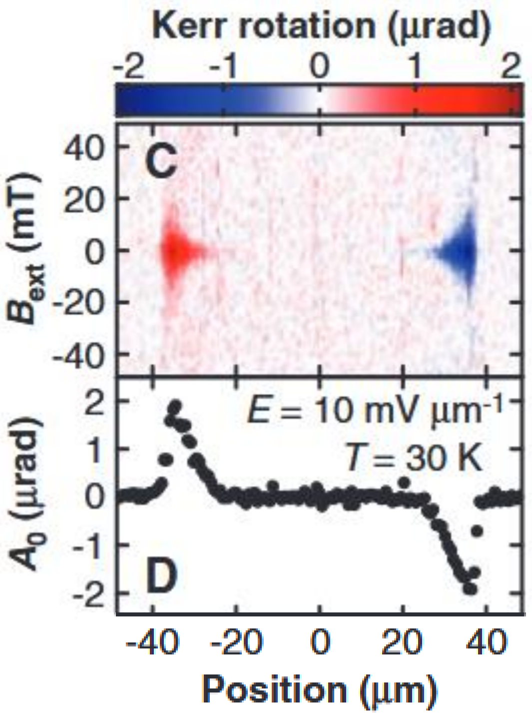
SHE: balanced number of spin up and down $\Rightarrow$ $J_s \neq 0 \quad V_y = 0$

https://doi.org/10.1007/s10909-024-03219-6

Observation of SHE by magneto-optical Kerr effect







Out-of-plane spin polarization

2 μm thick GaAs
n_s is the spin density
T = 30 K and E = 10 mV/μm

$$P_x = P_y = 0 \qquad P_z(y) = P_z(0)e^{-y/L_s}$$

$$P_z(0) = -\frac{\gamma\,\mu\,n_s E\,L_s}{D}$$

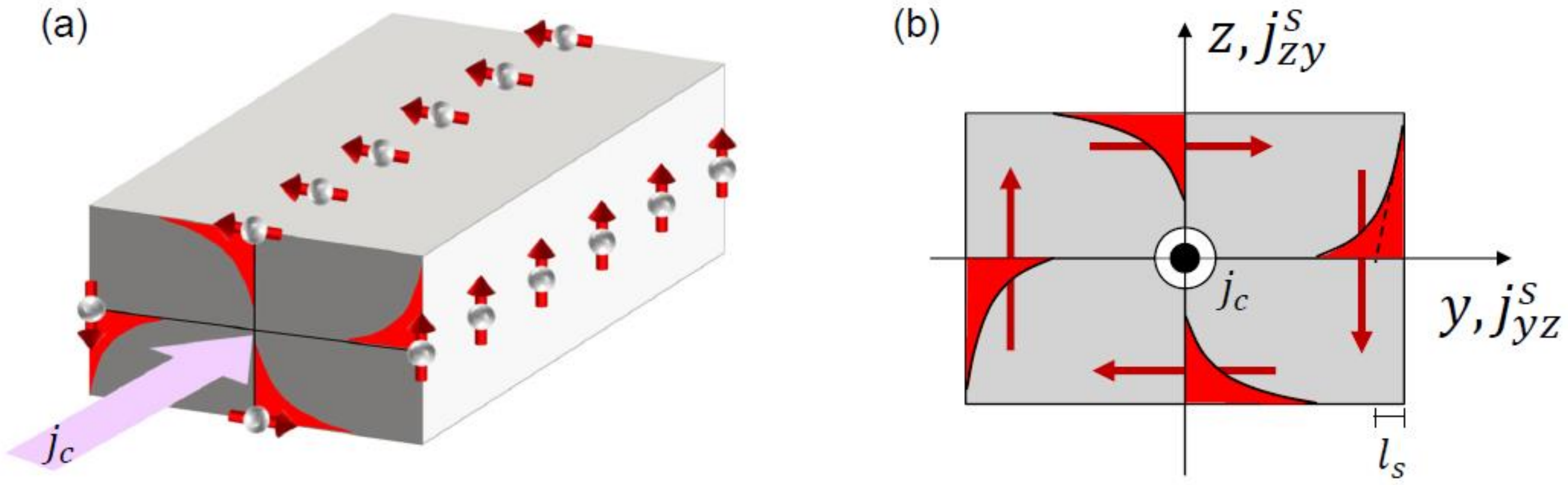
$J_s \cong 10$ nA/μm^2

$J_c \cong 50$ μA/μm^2

γ coefficient accounting for the SOC
μ and D are the mobility and the diffusion coefficient
$L_s = \sqrt{D\tau_s}$ is the spin diffusion length ≅ 10 μm
τ_s is the spin lifetime

DOI: 10.1126/science.1105514 (2004)

SHE: spin current perpendicular to charge current



Charge current: $J_c = J^+ + J^-$

Spin current: $J_s = \frac{\hbar}{2e}(J^+ - J^-)$

$$J_S = \theta_{SH} \frac{\hbar}{2e} J_c \wedge \boldsymbol{\sigma}$$

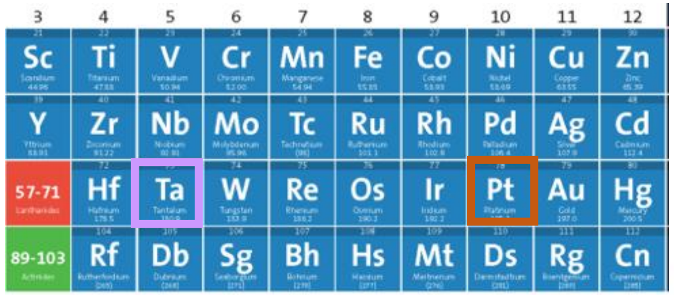
$\theta_{SH}(Pt, Ta) \approx 0.05 - 0.2$
spin to charge conversion factor

Spin Hall effect: reversed spin polarized currents for Pt *vs* Ta

SOC has opposite effect in Pt *vs* Ta

Pt: more than half filled

Ta: less than half filled



AHE detection

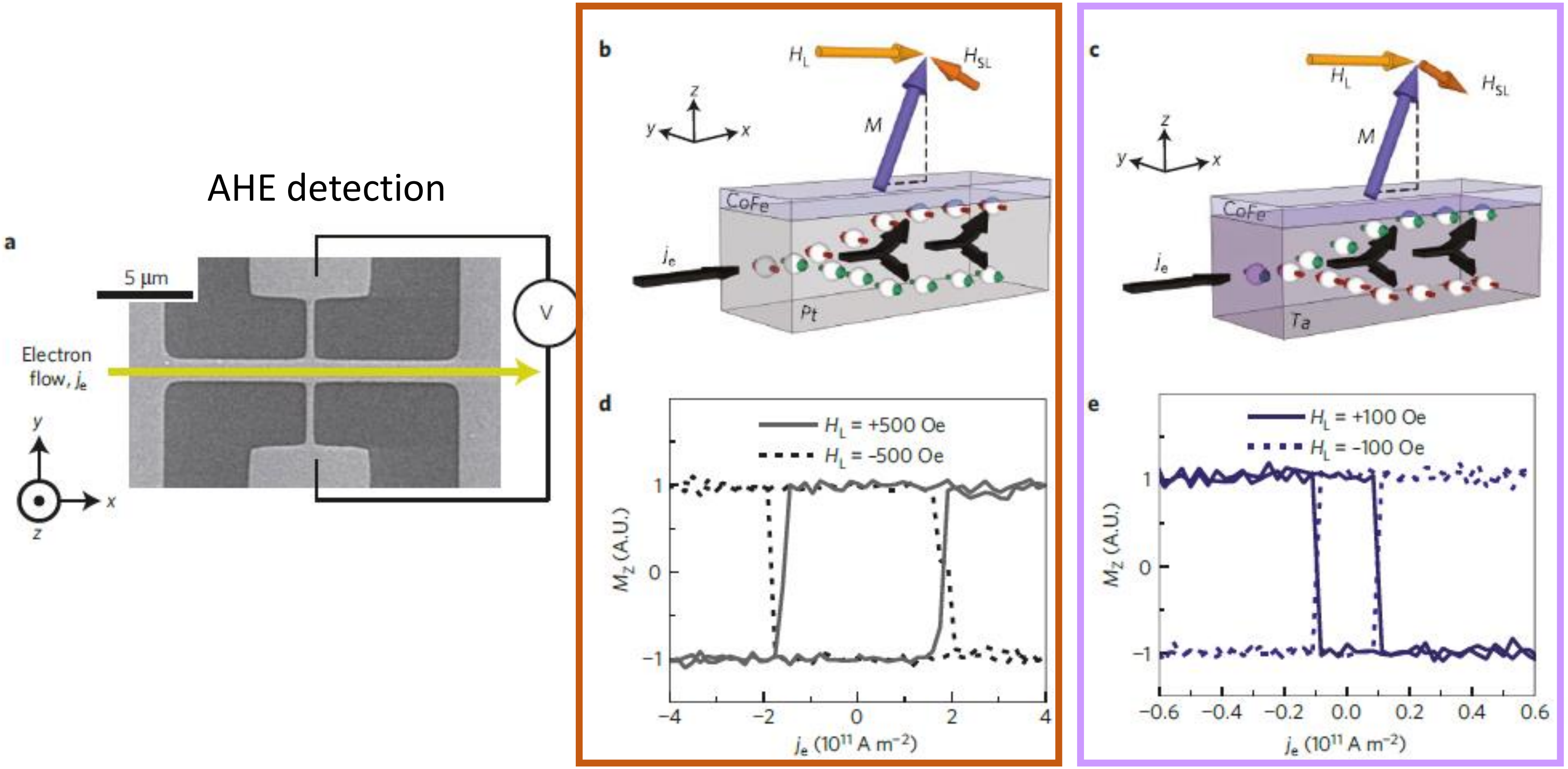


Figure 2 | Current-induced switching under a constant in-plane longitudinal field. a, Scanning electron micrograph of a Hall cross. **b**,**c**, Illustrations of Pt/CoFe/MgO (**b**) and Ta/CoFe/MgO (**c**) in the up magnetization state with the injected electron current and applied longitudinal field H_L in the +*x* direction. Owing to the combination of the current-induced Slonczewski-like torque (producing an effective field H_{SL}) and the applied longitudinal field, up magnetization is stable in Pt/CoFe/MgO whereas it is unstable in Ta/CoFe/MgO. **d**,**e**, Out-of-plane magnetization M_z (normalized anomalous Hall signal) as a function of electron current density j_e under a constant H_L in Pt/CoFe/MgO (**d**) and Ta/CoFe/MgO (**e**). The magnitude of H_L is 500 Oe for Pt/CoFe/MgO (**d**) and 100 Oe for Ta/CoFe/MgO (**e**). When H_L is reversed from +*x* (solid line) to −*x* (dotted line), the stable magnetization direction under a given current polarity reverses.

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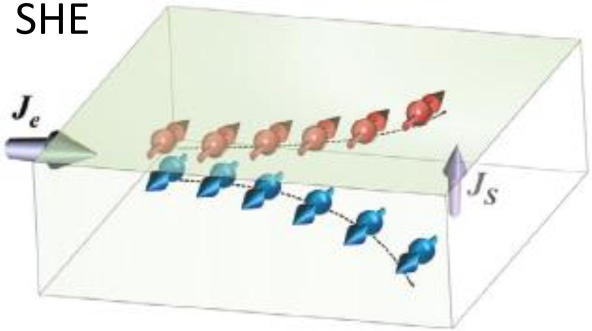
SHE vs Rashba-Edelstein effect (REE)

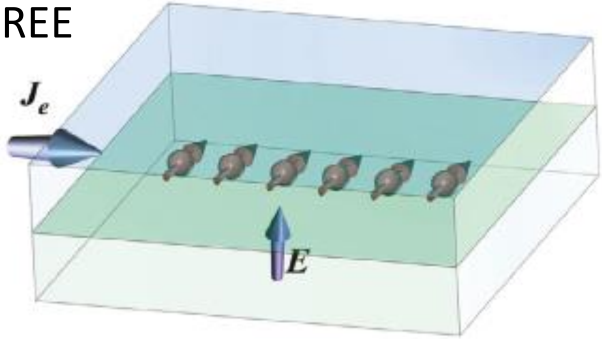
SHE: a charge current flowing in an NM layer generates a spin current owing to asymmetric spin deflection induced by SOC.
The polarization direction is perpendicular to both the directions of the charge and spin currents.

REE: an internal electrical field ***E*** = E_z***z*** is generated at the interface/surface because of the spatial inversion symmetry breaking. When an in-plane charge current flows through the FM/NM heterostructure, the conduction electrons near the interface move in the electrical field ***E***, and they experience an effective magnetic field perpendicular to the current direction (SOC-induced Rashba field $\boldsymbol{H}_{\mathrm{RE}}$): accumulation of spins perpendicular to both the charge current $\boldsymbol{J}_{\mathbf{e}}$ and ***E*** = E_z***z***.

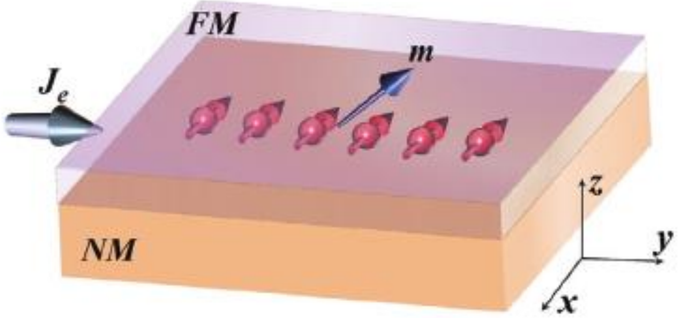
SHE



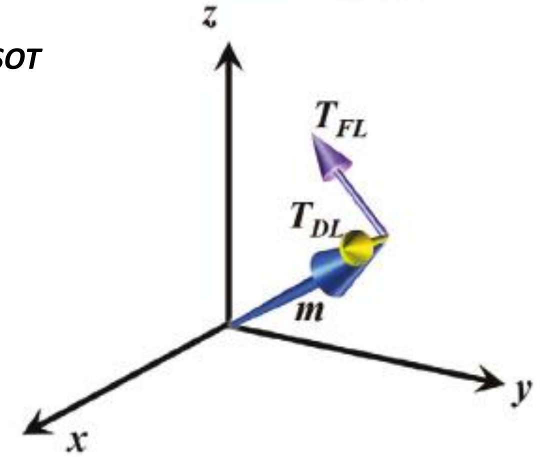
REE



$\boldsymbol{T}_{SOT}$



$\boldsymbol{T}_{SOT}$



As the spin current diffuses into the adjacent FM layer, a SOT torque $\boldsymbol{T}_{SOT}$ (via exchange) is exerted on the magnetization ***m***.
This torque has two components $\boldsymbol{T}_{SOT} = \boldsymbol{T}_{DL} + \boldsymbol{T}_{FL}$

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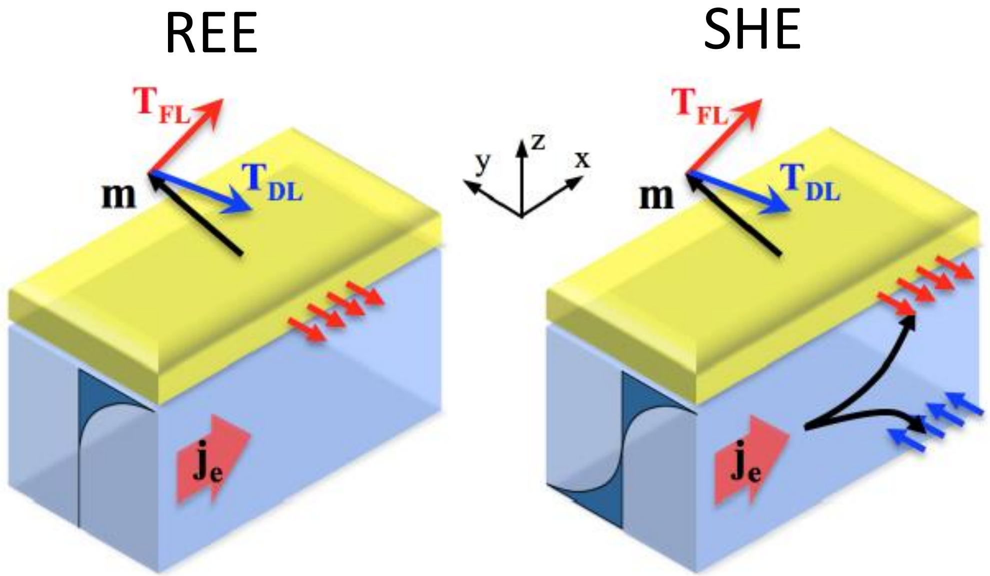
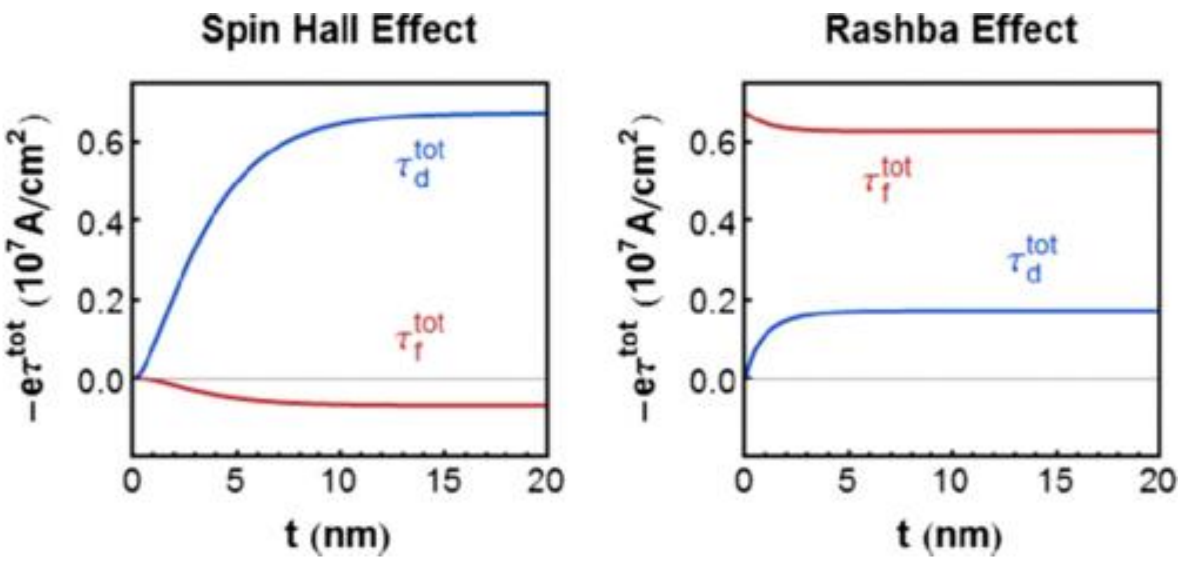
SHE vs Rashba-Edelstein effect (REE)



$T_{FL} \sim m \times (z \times j_e)$
$T_{DL} \sim m \times [(z \times j_e) \times m]$

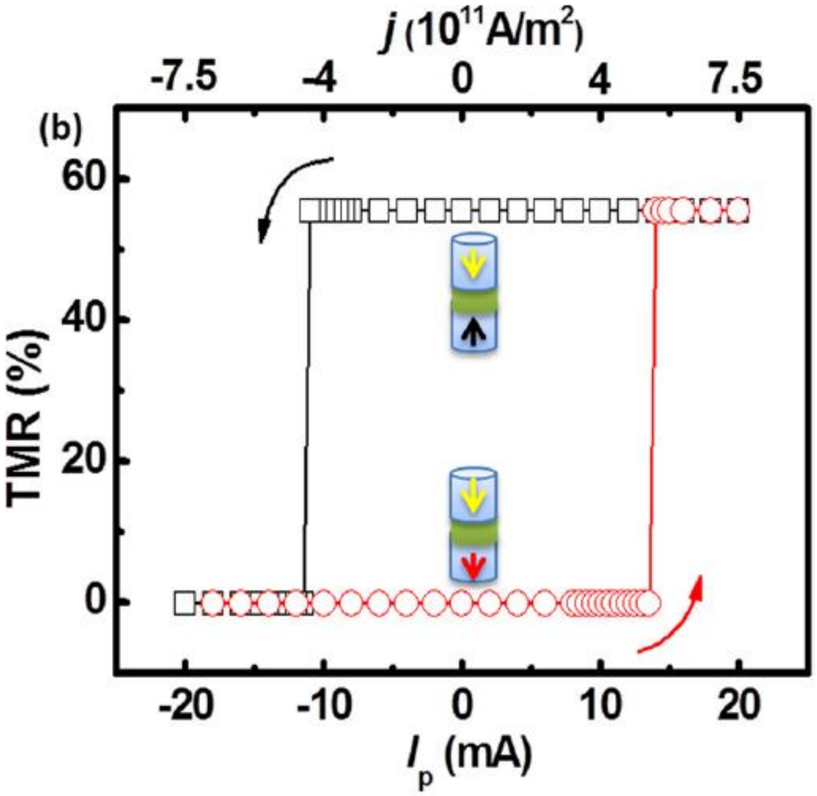
Both mechanisms produce damping-like and field-like torques. The small red and blue arrows denote the nonequilibrium spin density accumulating at the interfaces, and their corresponding spatial distribution is sketched as a shaded area on the structure's side. The large red and blue arrows represent the field-like and damping-like torques, respectively.

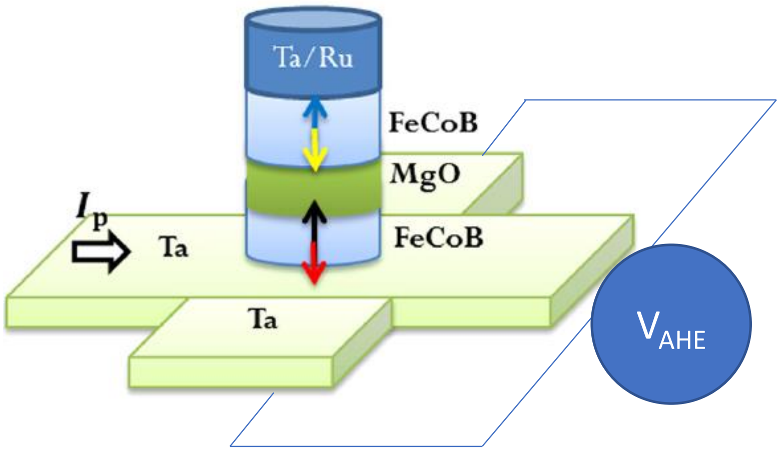


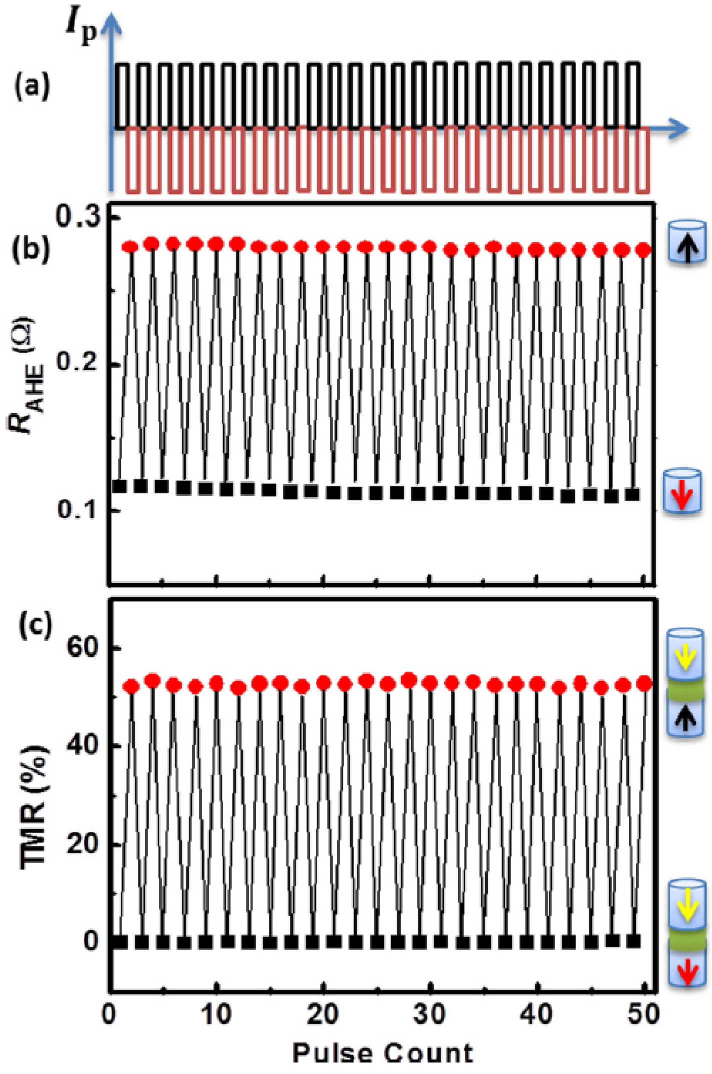
Torque components as a function of the nonmagnetic metal thickness

https://doi.org/10.1103/RevModPhys.91.035004

SOT writing and TMR read-out in p-MTJ







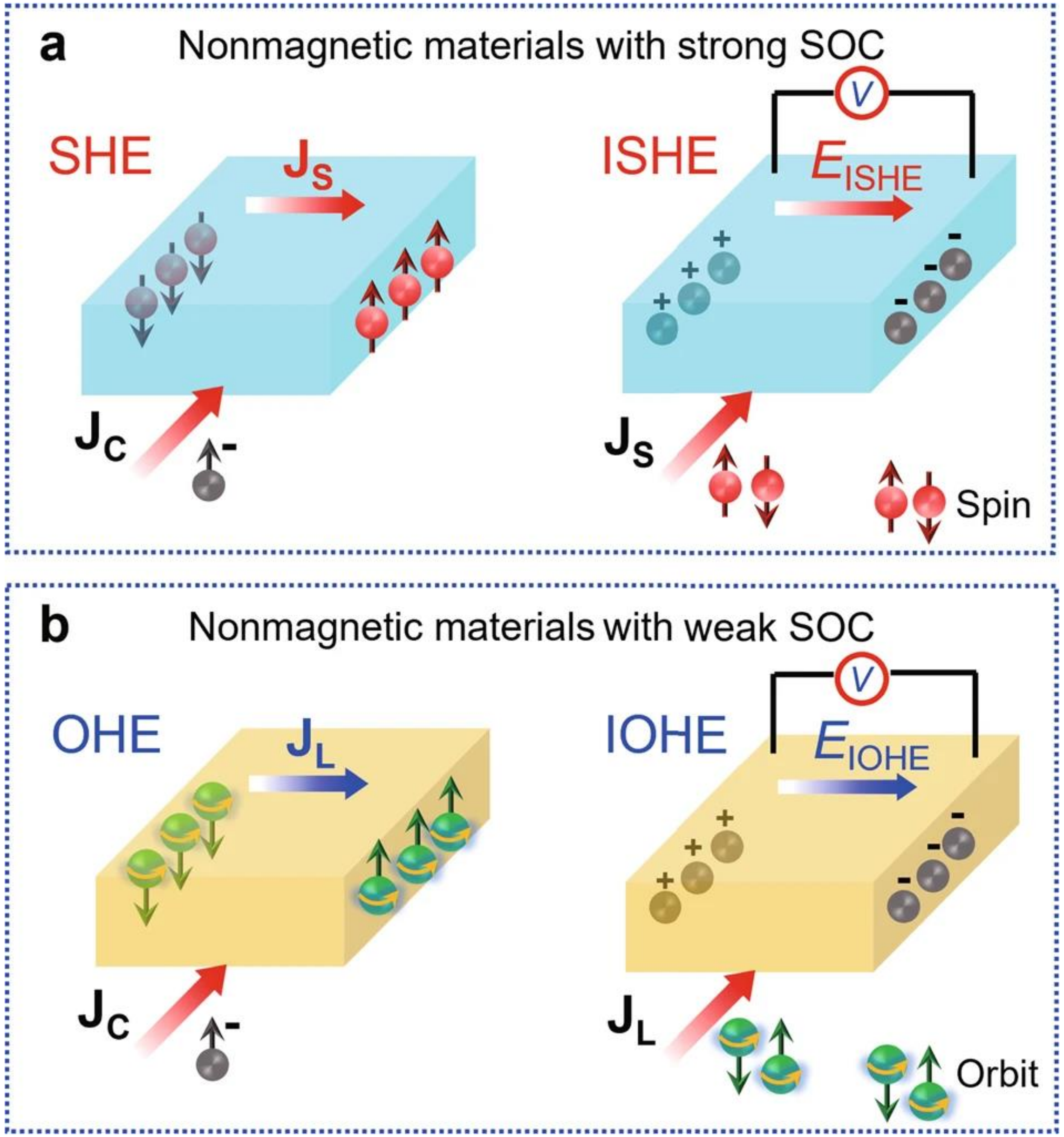
TMR as a function of current pulse amplitude I_p injected in the Ta electrode using 50 ns long pulses under an in-plane magnetic field H=-0.4 kOe along the current. The arrows show the sweep direction of I_p.

FIG. 3. (a) Schematic of the pulse sequence. (b) The AHE resistance (proportional to the M_z component of the bottom FeCoB layer) and (c) TMR measured after the injection of positive (black squares) and negative (red circles) current pulses of amplitude $I_p = 20$ mA and 50 ns long under $H_l = -0.4$ kOe.

https://doi.org/10.1063/1.4863407

Orbitronics

SHE and ISHE (invers SHE) refer to the conversions of $J_C \rightarrow J_S$ and $J_S \rightarrow J_C$ in the heavy metals with strong SOC, where a transverse flow of spin angular momentum and voltage are generated, respectively.



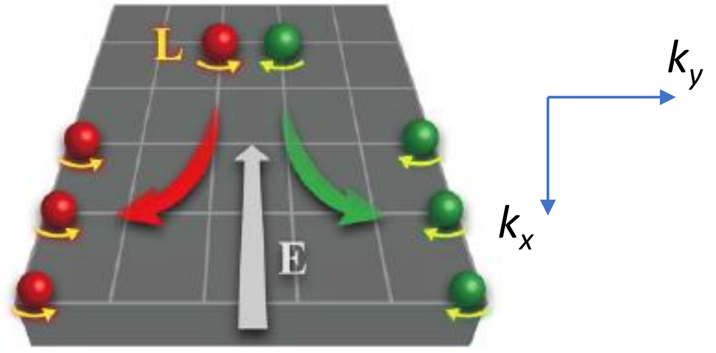
OHE and IOHE are the conversion of $J_C \rightarrow J_L$ and $J_L \rightarrow J_C$ in the materials with weak SOC, where a transverse flow of orbital angular momentum and voltage are induced, respectively. Thanks to SOC in an adjacent FM layer, the orbital current exerts a torque on the FM layer

https://doi.org/10.1038/s41535-023-00559-6

OHE without SOC

Schematic illustration of the OHE without SOC

The angular momentum **L** is defined from localized orbitals around the atom at each lattice. In the presence of an external electric field **E**, electrons with opposite **L** deflect in the clockwise (red arrow) or anticlockwise (green arrow) direction.



Formal approach (ex. for *p*-waves)

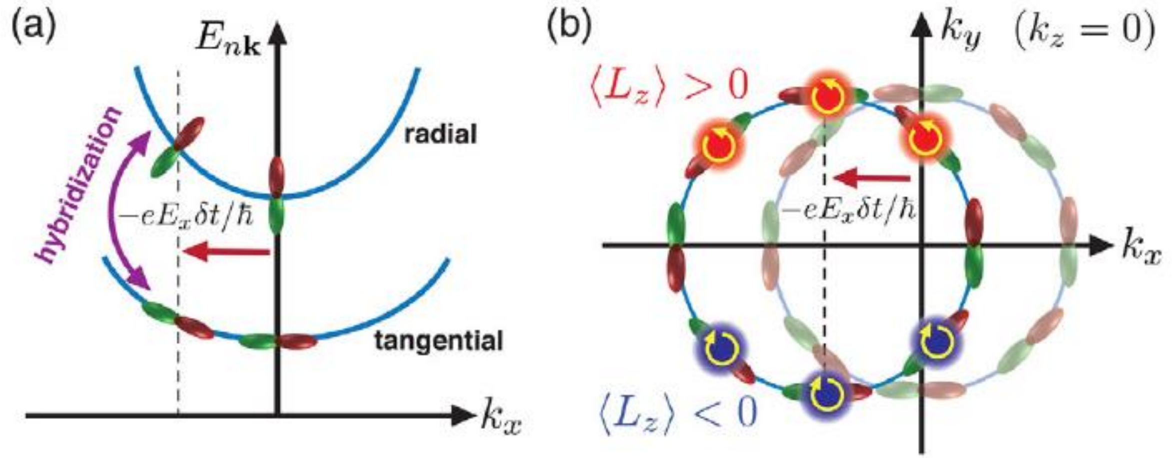
$$p_{radi} = \cos\phi \, p_x + \sin\phi \, p_y$$

$$p_{tang} = \sin\phi \, p_x - \cos\phi \, p_y$$

Under the effect of the external field, p_{radi} and p_{tang} get hybridized resulting in new states that can have finite L_z

Table 2. Matrix elements $\langle p_i|\hat{e}\cdot L|p_j\rangle$.

	$\langle x|$	$\langle y|$	$\langle z|$
$|x\rangle$	0	$i\hat{e}_z$	$-i\hat{e}_y$
$|y\rangle$	$-i\hat{e}_z$	0	$i\hat{e}_x$
$|z\rangle$	$i\hat{e}_y$	$-i\hat{e}_x$	0

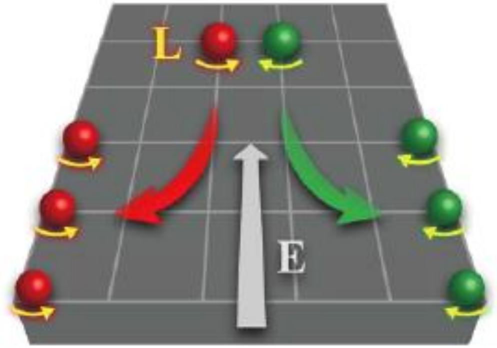


(a) Schematic band structure with plots of wave function character at each band. Here, $k_y = k_z = 0$.
(b) When an electron in the lower band is pushed from ***k*** to ***k*** + *δ**k*** by an external electric field ***E*** = E_x ***x***, positive (negative) L_z is induced for the nonequilibrium state with $k_y > 0$ ($k_y < 0$).

doi.org/10.1103/PhysRevLett.121.086602 ; 10.1103/PhysRevB.98.214405

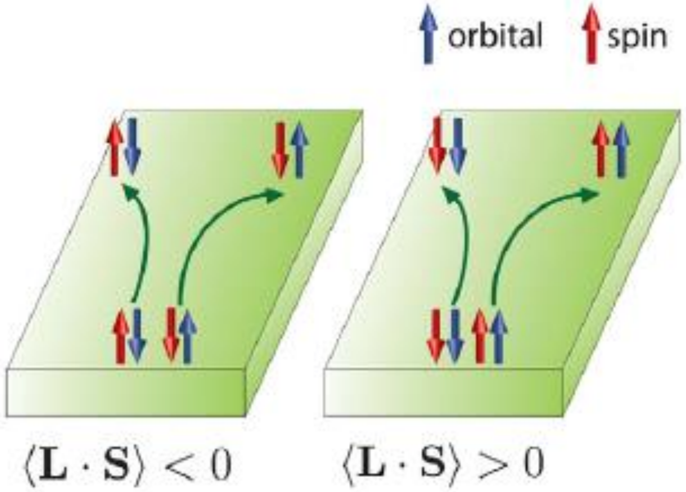
Schematic illustration of the OHE without SOC

The angular momentum **L** is defined from localized orbitals around the atom at each lattice. In the presence of an external electric field **E**, electrons with opposite **L** deflect in the clockwise (red arrow) or anticlockwise (green arrow) direction.



Schematic illustration when SOC is taken into account.

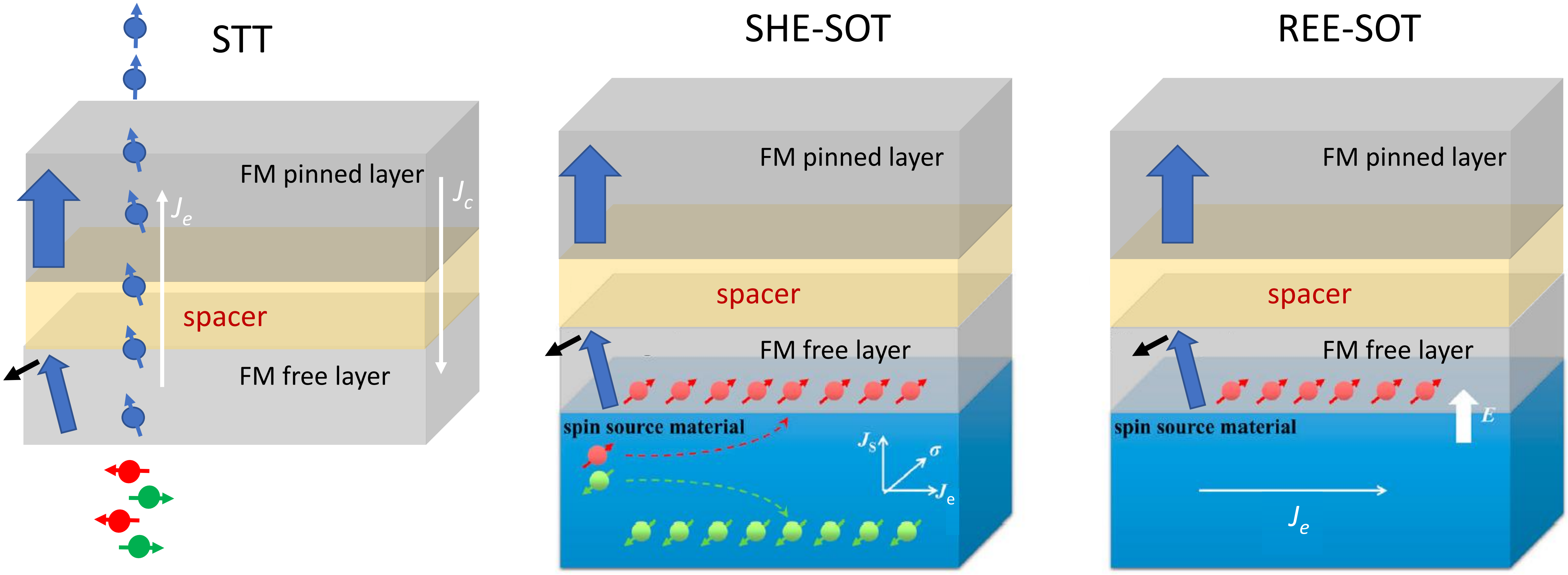
Spin and orbital momenta are locked by SOC.
SHE occurs in the same or opposite direction of OHE depending on whether $\boldsymbol{L} \cdot \boldsymbol{S}$ is positive or negative.



The intrinsic SHE then emerges as a by-product of the OHE resulting from the orbital-to-spin conversion in materials with nonzero SOC

doi.org/10.1103/PhysRevLett.121.086602 ; 10.1103/PhysRevB.98.214405

MRAM: STT vs SOT



SOT employs in-plane current injection:

1) separates the reading and writing paths
2) Less power since current does need to pass through the insulating spacer