Radboud Universiteit Nijmegen

Lecture I

Spin-Orbitronics

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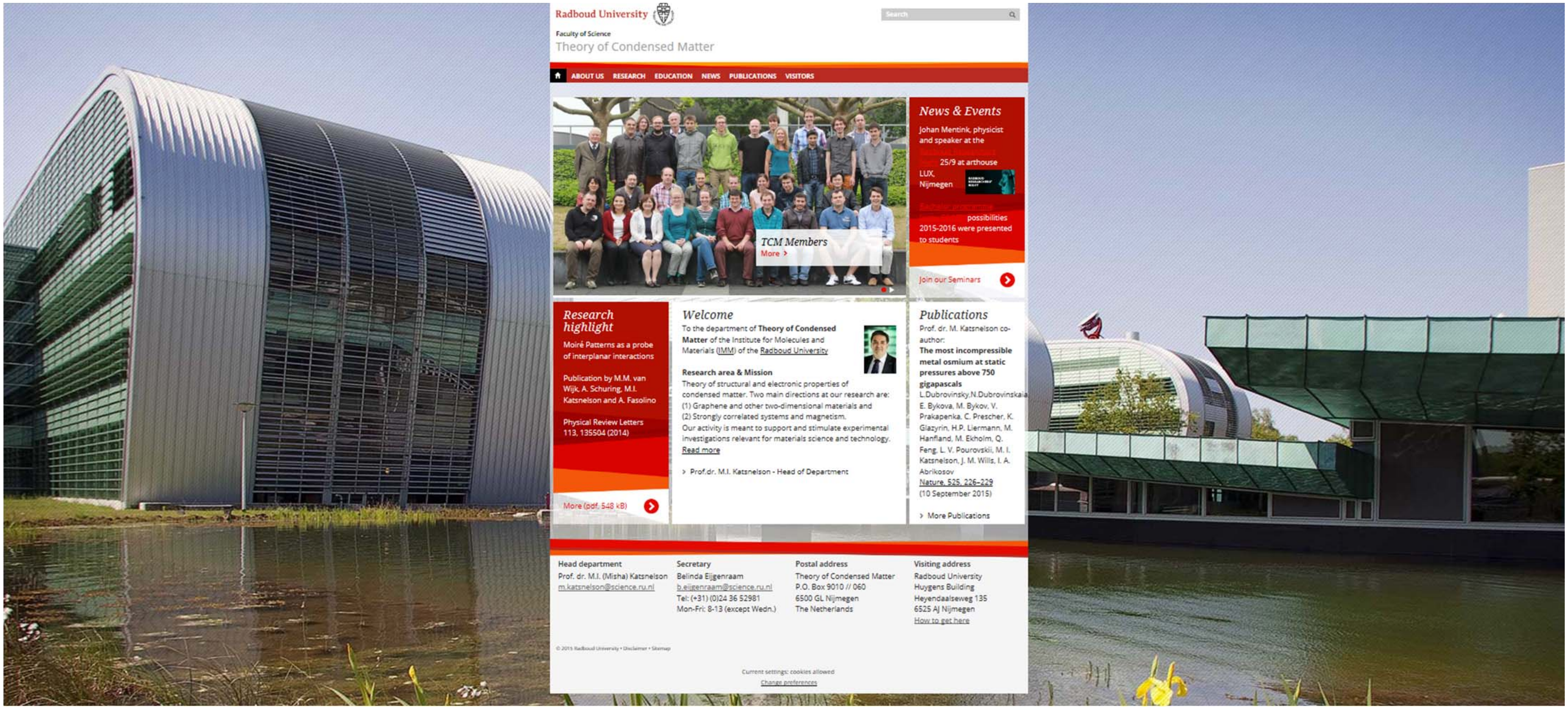

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Johan Mentink, physicist and speaker at the
25/9 at arthouse LUX, Nijmegen
possibilities 2015-2016 were presented to students
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Research highlight
Moiré Patterns as a probe of interplanar interactions
Publication by M.M. van Wijk, A. Schuring, M.I. Katsnelson and A. Fasolino
Physical Review Letters 113, 135504 (2014)
More (pdf, 548 kB)
Welcome
To the department of Theory of Condensed Matter of the Institute for Molecules and Materials (IMM) of the Radboud University
Research area & Mission
Theory of structural and electronic properties of condensed matter. Two main directions at our research are:
(1) Graphene and other two-dimensional materials and
(2) Strongly correlated systems and magnetism.
Our activity is meant to support and stimulate experimental investigations relevant for materials science and technology.
Read more
Prof.dr. M.I. Katsnelson - Head of Department
Publications
Prof. dr. M. Katsnelson co-author:
The most incompressible metal osmium at static pressures above 750 gigapascals
L.Dubrovinsky,N.Dubrovinskaia, E. Bykova, M. Bykov, V. Prakapenka, C. Prescher, K. Glazyrin, H.P. Liermann, M. Hanfland, M. Ekholm, Q. Feng, L. V. Pourovskii, M. I. Katsnelson, J. M. Wills, I. A. Abrikosov
Nature, 525, 226–229
(10 September 2015)
More Publications
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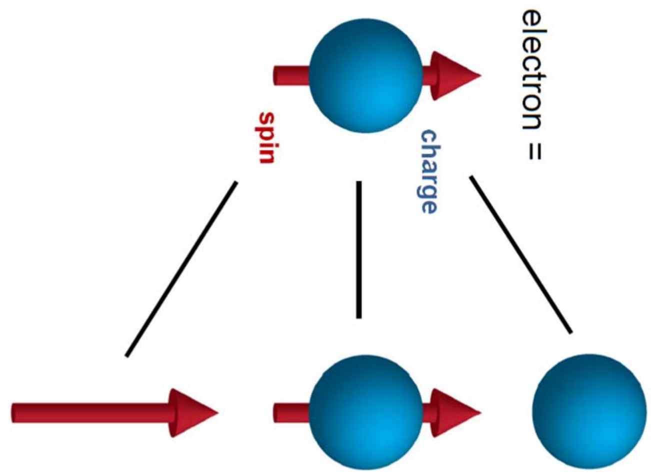
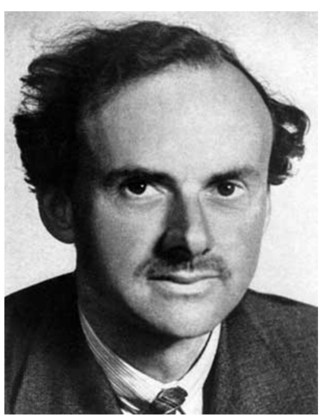
What We Talk About When We Talk About Spin-Orbitronics



"Mott" non-relativistic two-spin-channel model of ferromagnets



"Dirac" relativistic spin-orbit coupling

$$(\boldsymbol{\sigma} \times \nabla V) \cdot \mathbf{p}$$

What We Talk About When We Talk About Spin-Orbitronics

Anomalous Hall effect

Spin Hall effect and inverse effect

Spin galvanic effect and inverse effect

Spin-orbit torques and inverse effect

Magnon Hall effect

Topoligical insulators

⋮

Outlook:

1. Rashba spin-orbit interaction

2. Extraordinary Hall Effect

3. Spin transfer torques

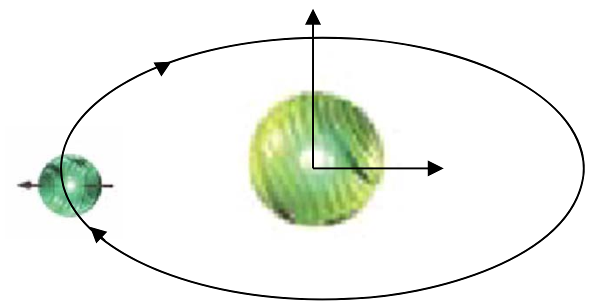
4. Spin-orbit torques

1. Rashba spin-orbit interaction

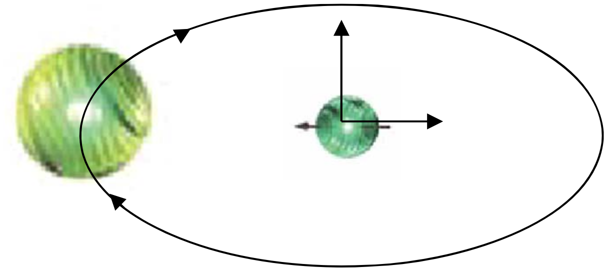
D. Bercioux and P. Lucignano, Rep. Prog. Phys. **78**, 106001 (2015).
A. Manchon, H. C. Koo, J. Nitta, S. M. Frolov, and R. A. Duine, Nat. Mater. **14**, 871 (2015).

Spin-orbit coupling (classic description)

nucleus rest frame



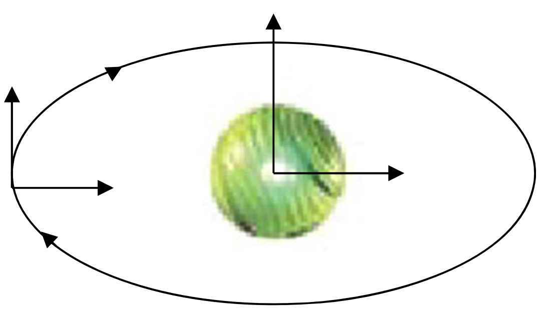
electron rest frame



$$\mathbf{I} = Q\mathbf{v} \qquad \mathbf{E} = \frac{Q}{4\pi\varepsilon_0 r^3}\mathbf{r} \qquad \mathbf{B} = \frac{\mu_0}{4\pi}\frac{\mathbf{I}\times\mathbf{r}}{r^3}$$

$$\mathbf{B} = \mu_0\varepsilon_0\mathbf{v}\times\mathbf{E} = \frac{1}{c^2}\mathbf{v}\times\mathbf{E} \qquad H_{SO} = \frac{g\mu_B}{2\hbar}\mathbf{S}\cdot\mathrm{B} = \frac{e}{2mc^2}\mathbf{S}\cdot\mathbf{v}\times\mathbf{E}$$

Lorentz transformation $\rightarrow$ Thomas precession



Relativistic SOI

$$H_{\text{Dirac}} = c\boldsymbol{\alpha}\cdot(\mathbf{p}-e\mathbf{A}) + \beta mc^2 + eV,$$

$$\beta = \begin{pmatrix} I & 0 \\ 0 & -I \end{pmatrix}$$

$$\boldsymbol{\alpha} = \begin{pmatrix} 0 & \boldsymbol{\sigma} \\ \boldsymbol{\sigma} & 0 \end{pmatrix}$$

Pauli equation

$$H \sim \underbrace{\frac{1}{2m}(\mathbf{p}-e\mathbf{A})^2 + mc^2 + eV - \mu_B\boldsymbol{\sigma}\cdot\mathbf{B}} - \frac{e\hbar}{4m^2c^2}\boldsymbol{\sigma}\cdot[\mathbf{E}\times(\mathbf{p}-e\mathbf{A})]$$
$$- \frac{1}{8m^3c^2}(\mathbf{p}-e\mathbf{A})^4 + \frac{e\hbar^2}{8m^2c^2}(\nabla\cdot\mathbf{E})$$

$$H_{SO} = -\lambda_{vac}\boldsymbol{\sigma}\cdot(\mathbf{k}\times\nabla V)$$

$$\lambda_{vac} = \frac{e\hbar^2}{4m^2c^2} = 3.7\times10^{-6}A^2$$

$$\begin{aligned} H_{SO} = -\frac{e\hbar}{4m^2c^2}\boldsymbol{\sigma}\cdot(\mathbf{E}\times\mathbf{p}) &= -\frac{e\hbar(-\frac{1}{r}\frac{dV}{dr})\boldsymbol{\sigma}\cdot(\mathbf{r}\times\mathbf{p})}{4m^2c^2} \\ &= \frac{e}{2m^2c^2}\frac{1}{r}\frac{dV}{dr}\mathbf{S}\cdot\mathbf{L}. \end{aligned}$$

$$\mathbf{B} = \nabla\times\mathbf{A}$$

$$\mathbf{E} = -\nabla V - \frac{\partial\mathbf{A}}{\partial t}$$

Intrinsic vs. Extrinsic SOI

$$V = V_{cr} + \tilde{V}$$

$$\begin{aligned} H_{\text{int}} &= -\frac{1}{2}\mathbf{b}(\mathbf{k}).\boldsymbol{\sigma}, \\ H_{\text{ext}} &= -\lambda\boldsymbol{\sigma}.(\mathbf{k}\times\nabla V_{imp}), \end{aligned}$$

Time reversal symmetry:

$$H_{\text{int}}(\mathbf{k},\mathbf{r},\boldsymbol{\sigma}) = H_{\text{int}}(-\mathbf{k},\mathbf{r},-\boldsymbol{\sigma}) \Longrightarrow \mathbf{b}(\mathbf{k}) = -\mathbf{b}(-\mathbf{k})$$

Inversion symmetry:

$$H_{\text{int}}(\mathbf{k},\mathbf{r},\boldsymbol{\sigma}) = H_{\text{int}}(-\mathbf{k},-\mathbf{r},\boldsymbol{\sigma}) \Longrightarrow \mathbf{b}(\mathbf{k}) = \mathbf{b}(-\mathbf{k})$$

$$\mathbf{b}(\mathbf{k}) = 0$$

Intrinsic Spin-Orbit Interaction

k-cubic Dresselhaus SOI:

n-doped 3D semiconductors with the bulk inversion asymmetry (BIA), III-V and II-VI zinc blende structures

$$H_{\rm int}^{D-3d} = B[k_x(k_y^2 - k_z^2)\sigma_x + k_y(k_z^2 - k_x^2)\sigma_y + k_z(k_x^2 - k_y^2)\sigma_z]$$

k-linear Dresselhaus SOI:

the electrons are conned to 2D, in semiconductors with BIA

$$H_{\rm int}^{\beta} = \beta(k_x\sigma_x - k_y\sigma_y)$$

$$H_{\rm int}^{D-2d} = Bk_xk_y(k_y\sigma_x - k_x\sigma_y)$$

$$\beta = -B(\pi/d)^2$$

K-linear Rashba SOI:

n-doped 3D semiconductors with the structure inversion asymmetry (SIA)

$$H_{\rm int}^{R} = \alpha_R(k_y\sigma_x - k_x\sigma_y)$$

K-cubic Rashba SOI:

$$H_{\rm R-hole-2d} = i\lambda_{\rm R-h}(k_-^3\sigma_+ - k_+^3\sigma_-)$$

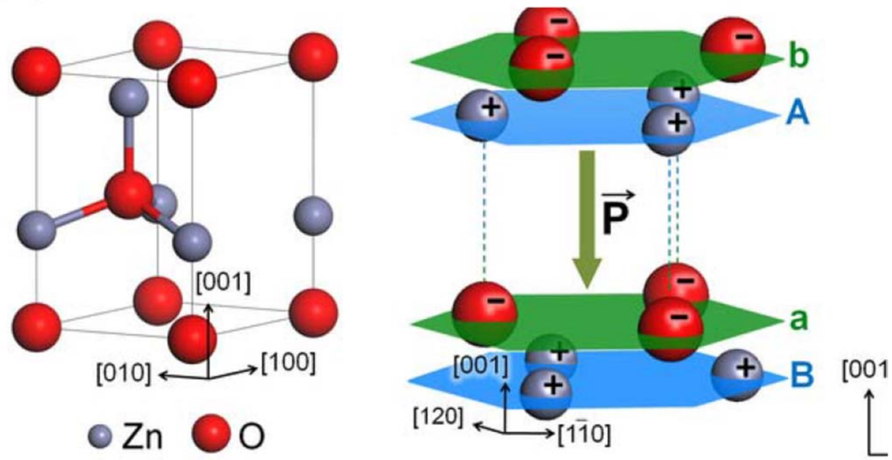
Luttinger SOI:

p-doped GaAs

$$H_{\rm KL} = \frac{\hbar^2}{2m}\left[(2\gamma_1 + 5\gamma_2)k^2 - 2\gamma_3(\mathbf{k}\cdot\mathbf{J})^2 + 2(\gamma_3 - \gamma_2)\sum_i k_i^2 J_i^2\right]$$

Rashba term – wurtzite structure

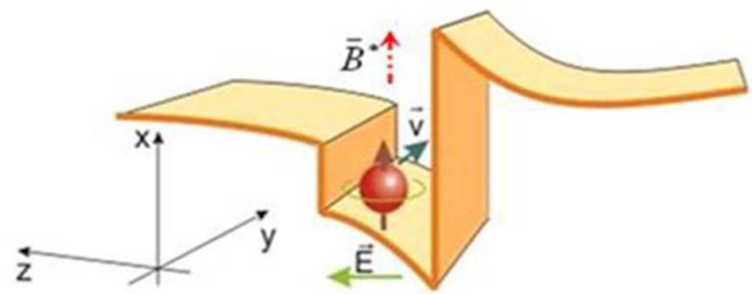
ZnO, GaN, CdSe, …

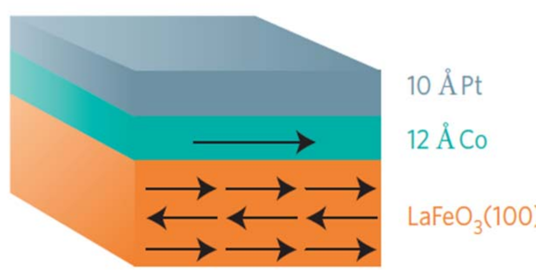


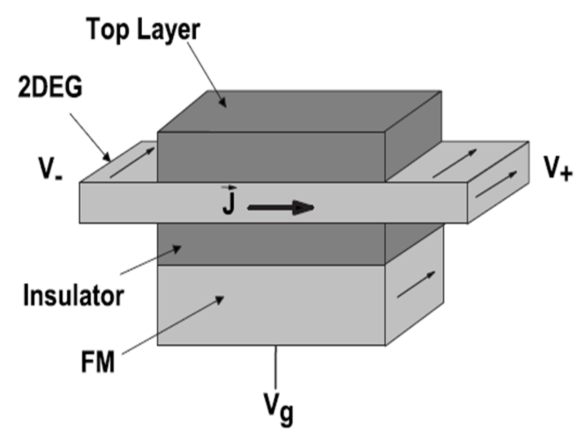
inversion symmetry broken and
time reversal symmetry conserved ➔
$\mathcal{H}_R = \lambda_{so}(\boldsymbol{s} \times \boldsymbol{k})\,\hat{\boldsymbol{c}}$

E. I. Rashba, V. I. Sheka (FTT, 1959); B. C. Casella (IBM – PRL, 1960)

Rashba term – 2D Confinement







(Quasi) 2D systems with structure inversion asymmetry

$$\mathcal{H} = \frac{\boldsymbol{p}^2}{2m_e} + \alpha_R(\boldsymbol{\sigma} \times \hat{z}) \cdot \boldsymbol{p}$$

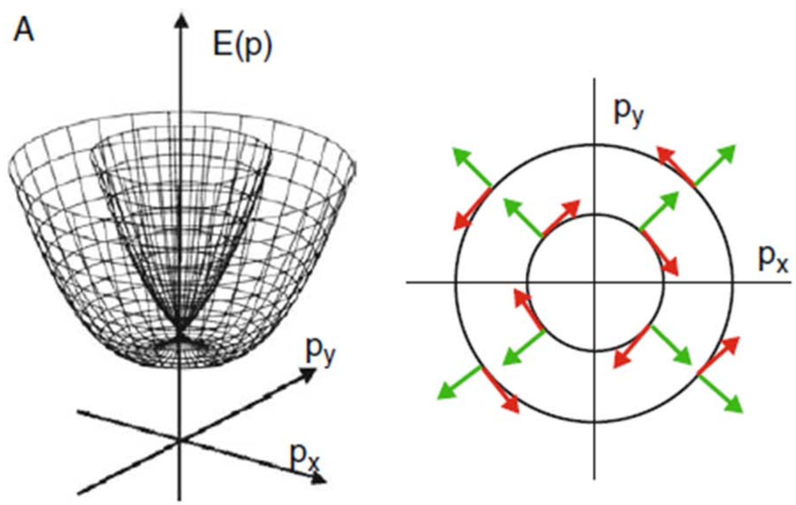
1. E. Rashba, Properties of semiconductors with an extremum loop. 1. Cyclotron and combinational resonance in a magnetic field perpendicular to the plane of the loop. *Sov. Phys. Solid State* **2,** 1109–1122 (1960).
2. F. T. Vas'ko, Spin splitting in the spectrum of two-dimensional electrons due to the surface potential. *P. Zh. Eksp. Teor. Fiz.* **30,** 574–577 (1979).
3. Y. A. Bychkov & E. I. Rasbha, Properties of a 2D electron gas with lifted spectral degeneracy. *P. Zh. Eksp. Teor. Fiz.* **39,** 66–69 (1984).

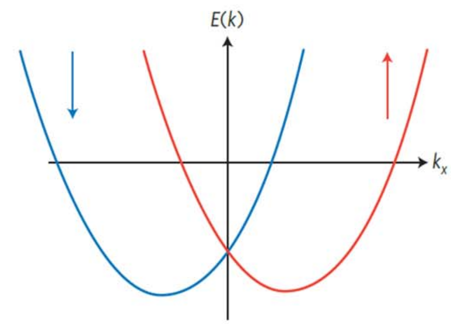
$$E(k) = \frac{k^2}{2m} + s\alpha_R k$$

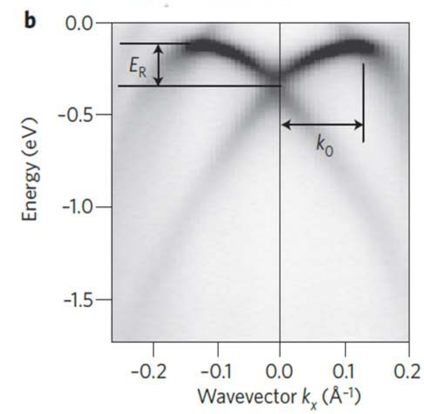
$$\psi_\pm(\mathbf{r}) \;=\; e^{i\mathbf{k}.\mathbf{r}} \begin{pmatrix} \pm e^{i\phi} \\ 1 \end{pmatrix}.$$

Bi/Ag(111)

$\alpha_R = 3.05$ (eV Å)

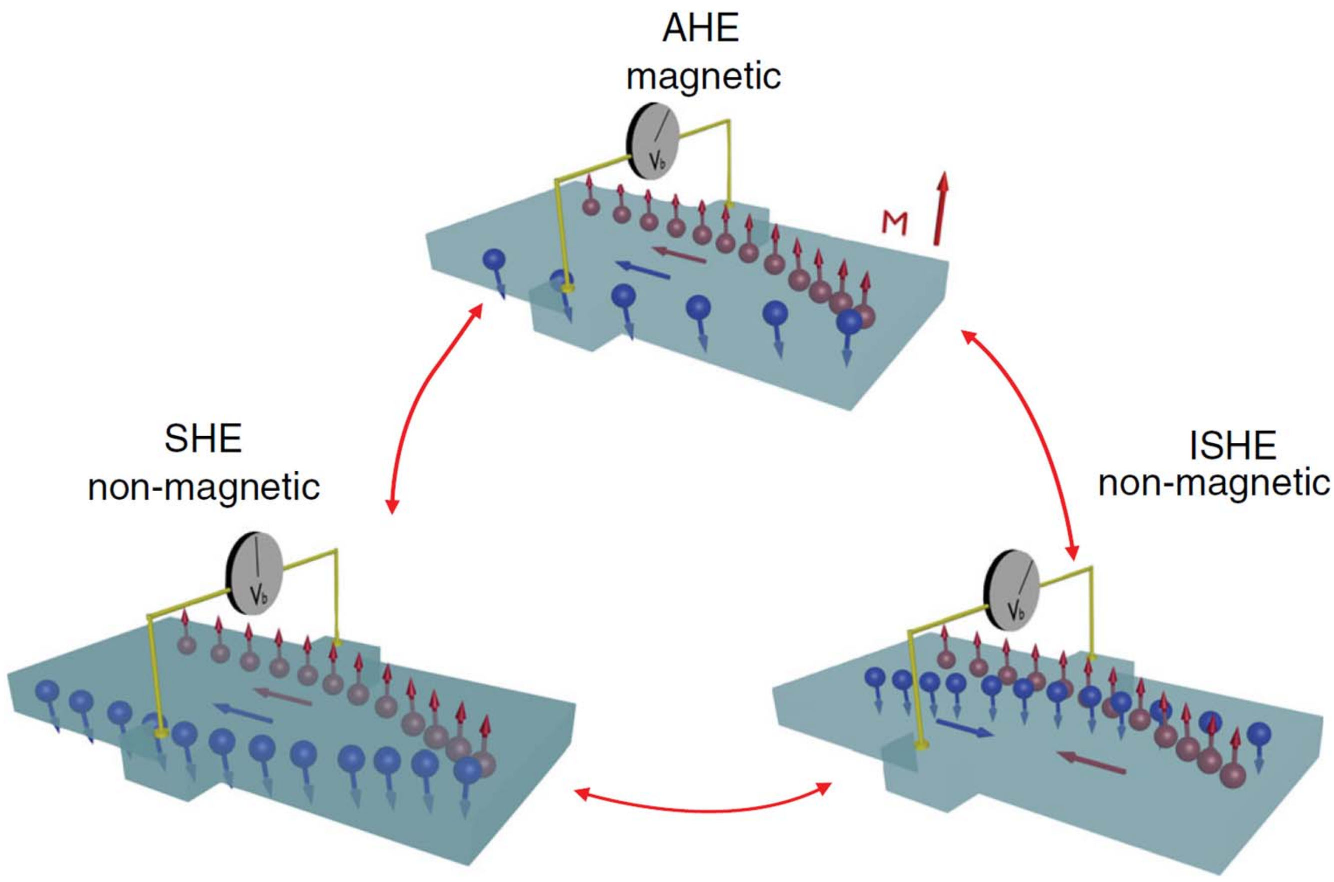






1. C. Ast, *et al.* Giant spin splitting through surface alloying. *Phys. Rev. Lett.* **98,** 186807 (2007).
2. A. Manchon, *et al.* New perspectives for Rashba spin-orbit coupling. Nat. Mater. **14**, 871 (2015).

2. Extraordinary Hall Effect



N. Nagaosa *et al.,* Rev. Mod. Phys. **82**, 1539 (2010).
D. Xiao *et al.,* Rev. Mod. Phys. **82**, 1959 (2010).
J. Sinova *et al.,* Rev. Mod. Phys. **87**, 1213 (2015).

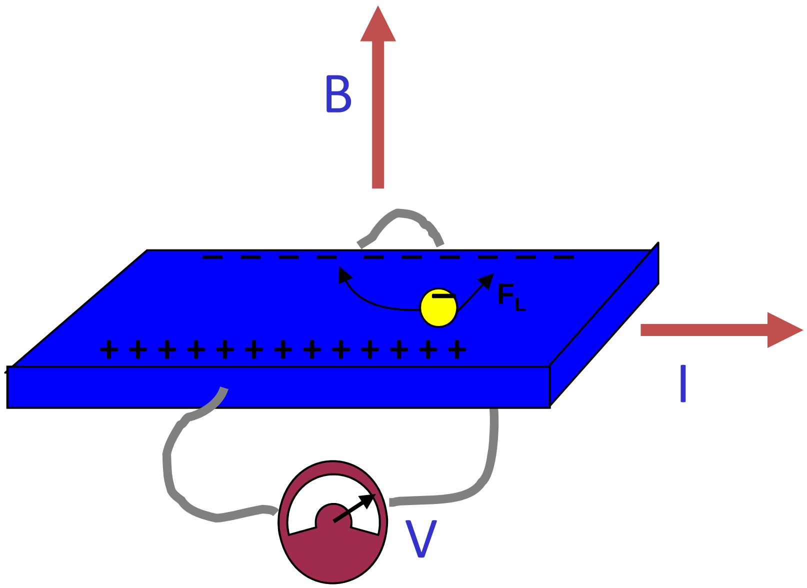
Sinova and Jungwirth presentations

Extraordinary magnetoresistance

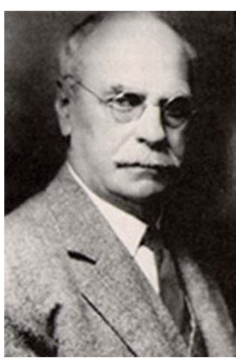
Queen of solid-state transport experiments

***Ordinary magnetoresistance**:*
response to external magnetic field
Acting via classical Lorentz force

ordinary Hall effect (1879)

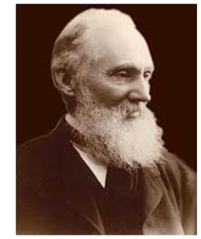


E. H. Hall, Amer. J. Math. **2**, 287 (1879)



(*Edwin Hall* 1855-1938)

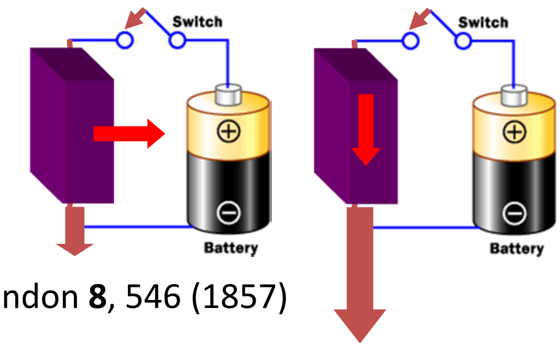
***Extraordinary magnetoresistance**:*
response to internal quantum-relativistic spin-orbit field



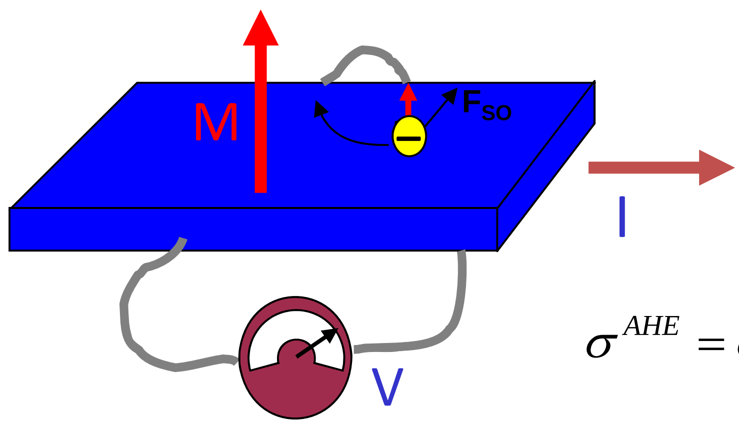
(Lord Kelvin (1824-1907*)*

anisotropic magnetoresistance (AMR) (1857)

$$\sigma^{AMR} = \sigma^{s} \equiv \frac{1}{2}(\sigma_{ij} + \sigma_{ji})$$



W. Thomson, Proc. Royal Soc. London **8**, 546 (1857)



$$\sigma^{AHE} = \sigma^{A} \equiv \frac{1}{2}(\sigma_{ij} - \sigma_{ji})$$

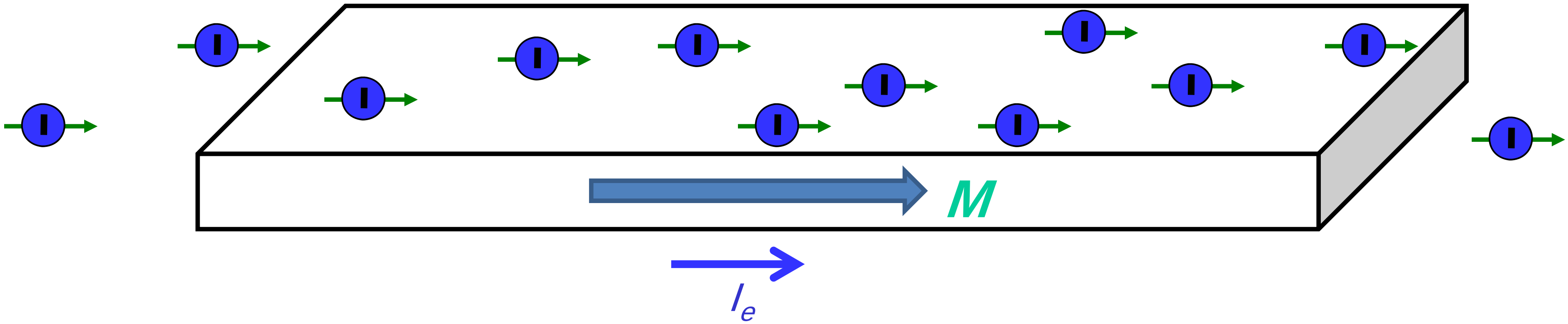
anomalous Hall effect (AHE) (1881)

$$\rho_{xy} = R_0 H_z + R_s M_z$$

E. Hall, Phil. Mag. **12**, 157 (1881)

Relativistic anisotropic magnetoresistance (AMR)

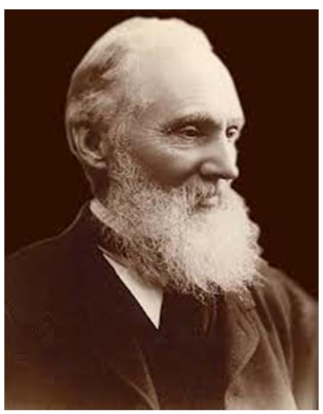
Spintronic effect 150 years ahead of time



XIX. "On the Electro-dynamic Qualities of Metals:—Effects of Magnetization on the Electric Conductivity of Nickel and of Iron." By Professor W. THOMSON, F.R.S. Received June 18, 1857.

I have already communicated to the Royal Society a description of experiments by which I found that iron, when subjected to magnetic force, acquires an increase of resistance to the conduction of electricity along, and a diminution of resistance to the conduction of electricity across, the lines of magnetization*. By experiments more recently made, I have ascertained that the electric conductivity of nickel is similarly influenced by magnetism, but to a greater degree, and with a curious difference from iron in the relative magnitudes of the transverse and longitudinal effects.

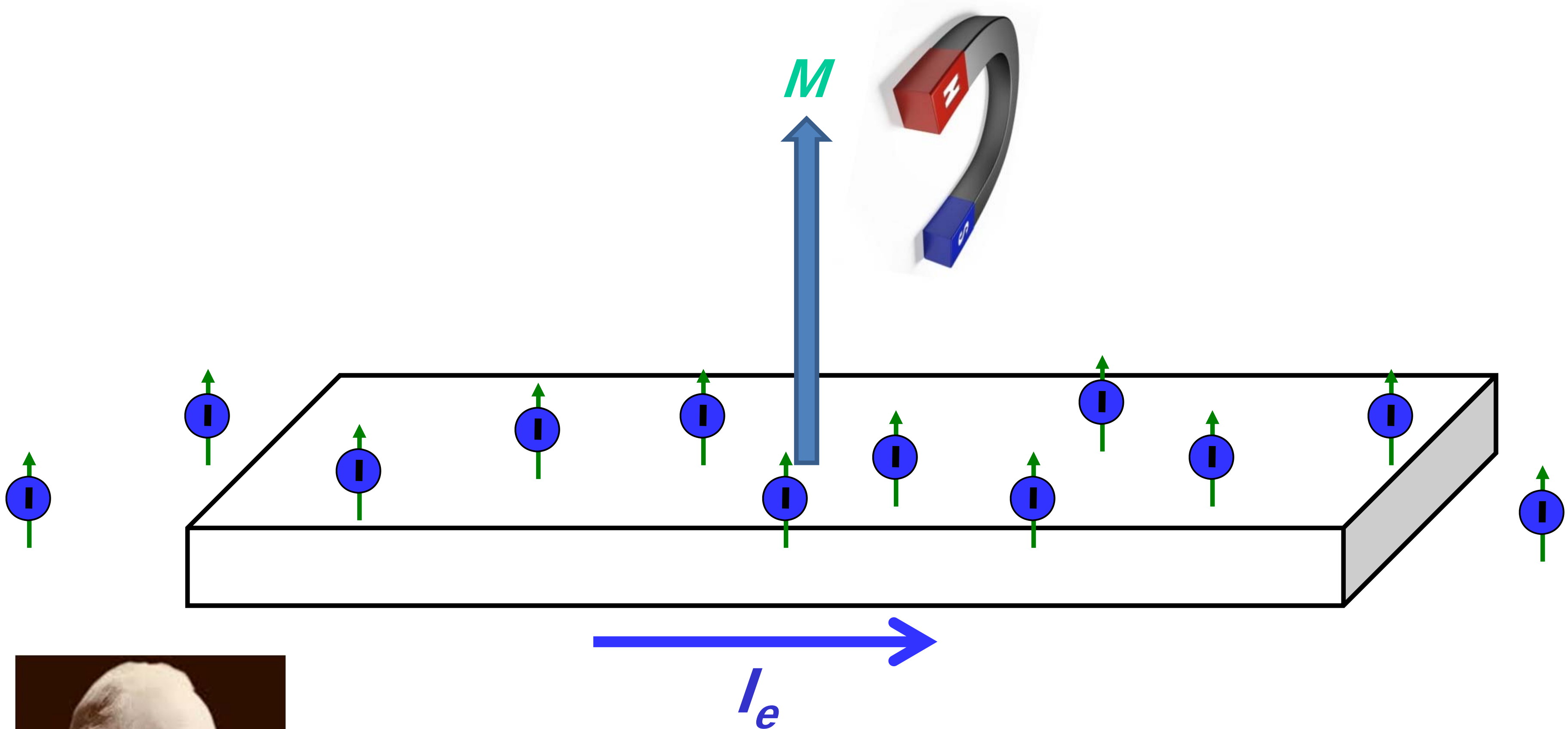
W. Thomson, Proc. Royal Soc. London **8**, 546 (1857)

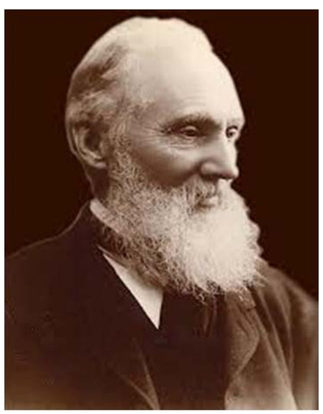


Kelvin, 1857

Read-out: relativistic anisotropic magnetoresistance (AMR)

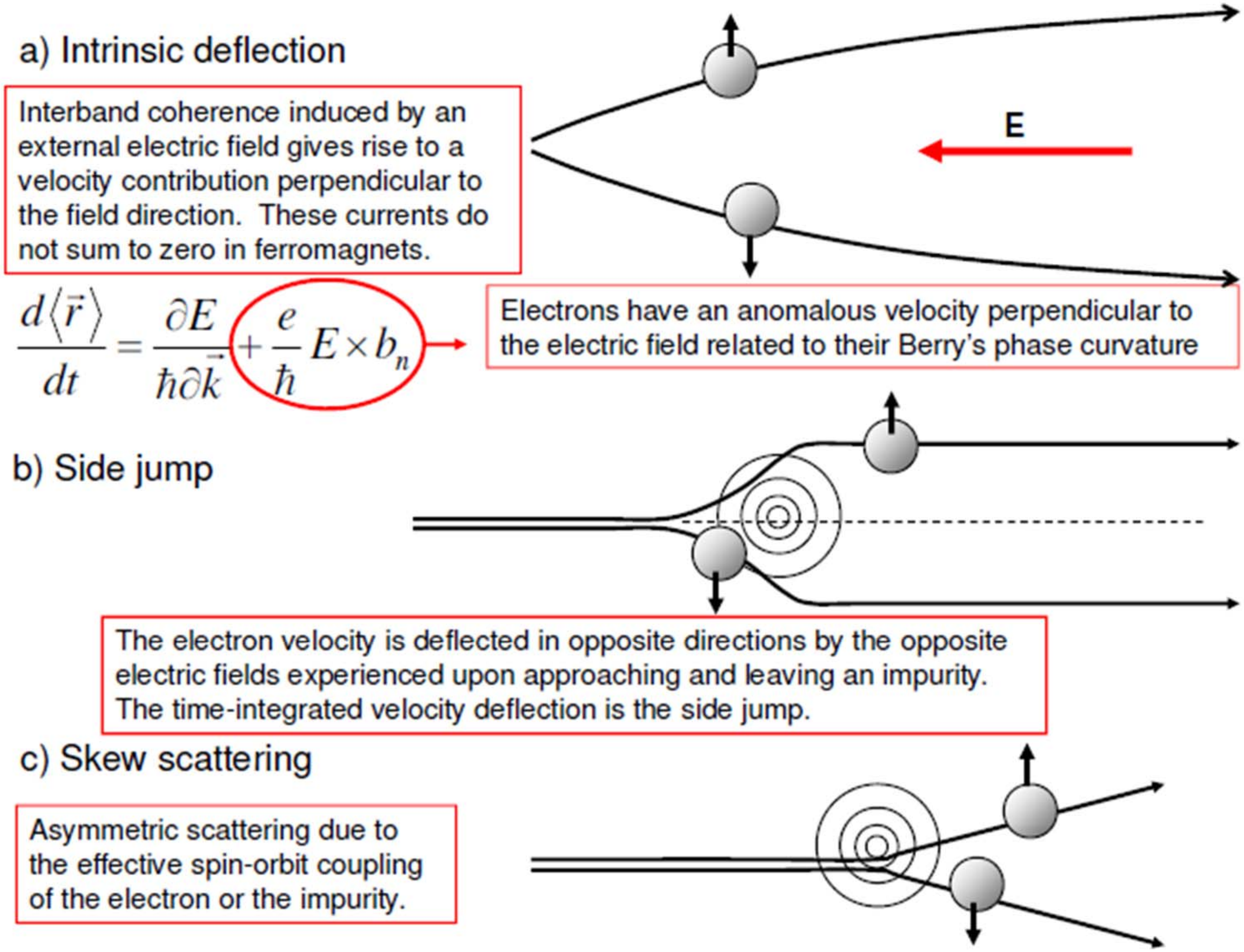
Spintronic effect 150 years ahead of time





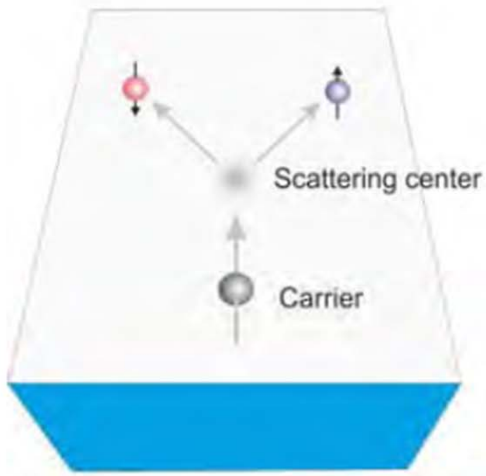
Kelvin, 1857

Mechanisms which are responsible for spin-orbitrnics



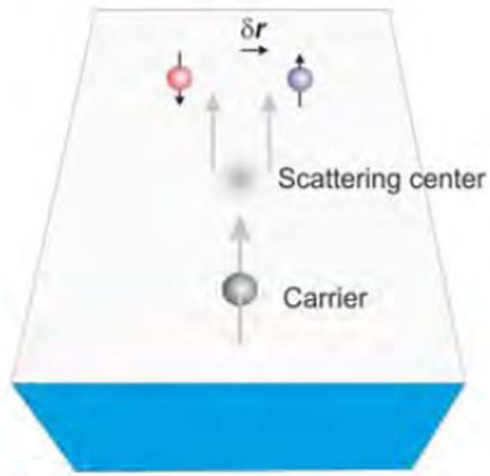
Extrinsic

Intrinsic



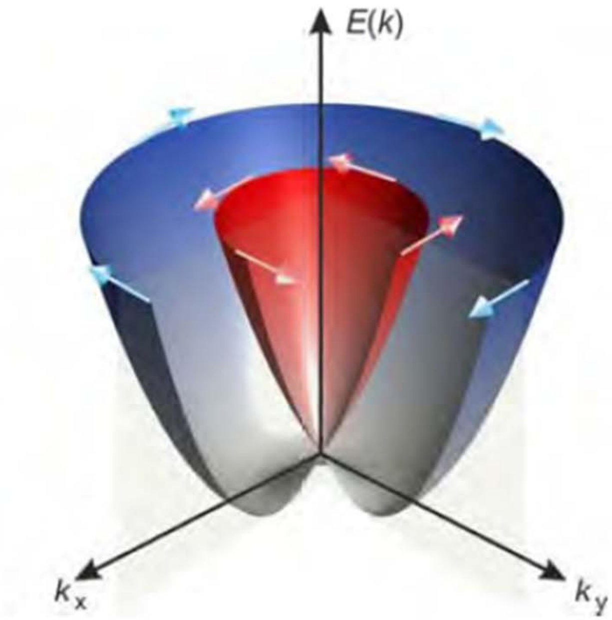
Skew Scattering

Smit, Physica 24, 39 (1958)



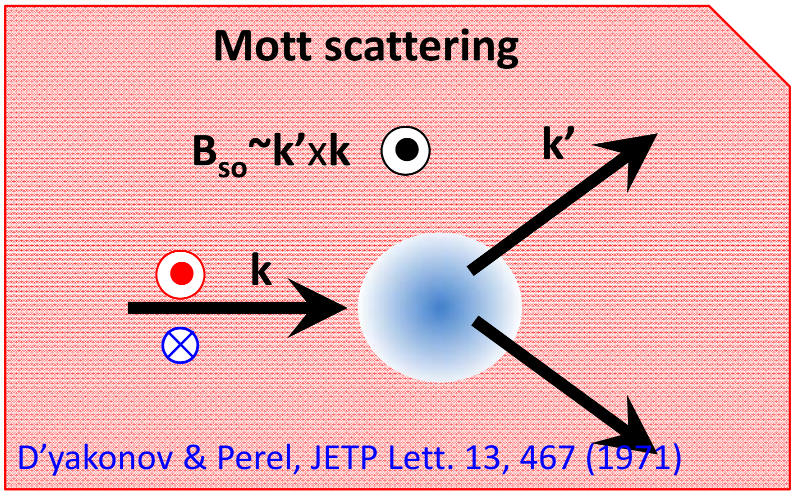
Side-Jump Scattering

Berger, PRB 2, 4559 (1970)



Band Structure
E.g. Rashba

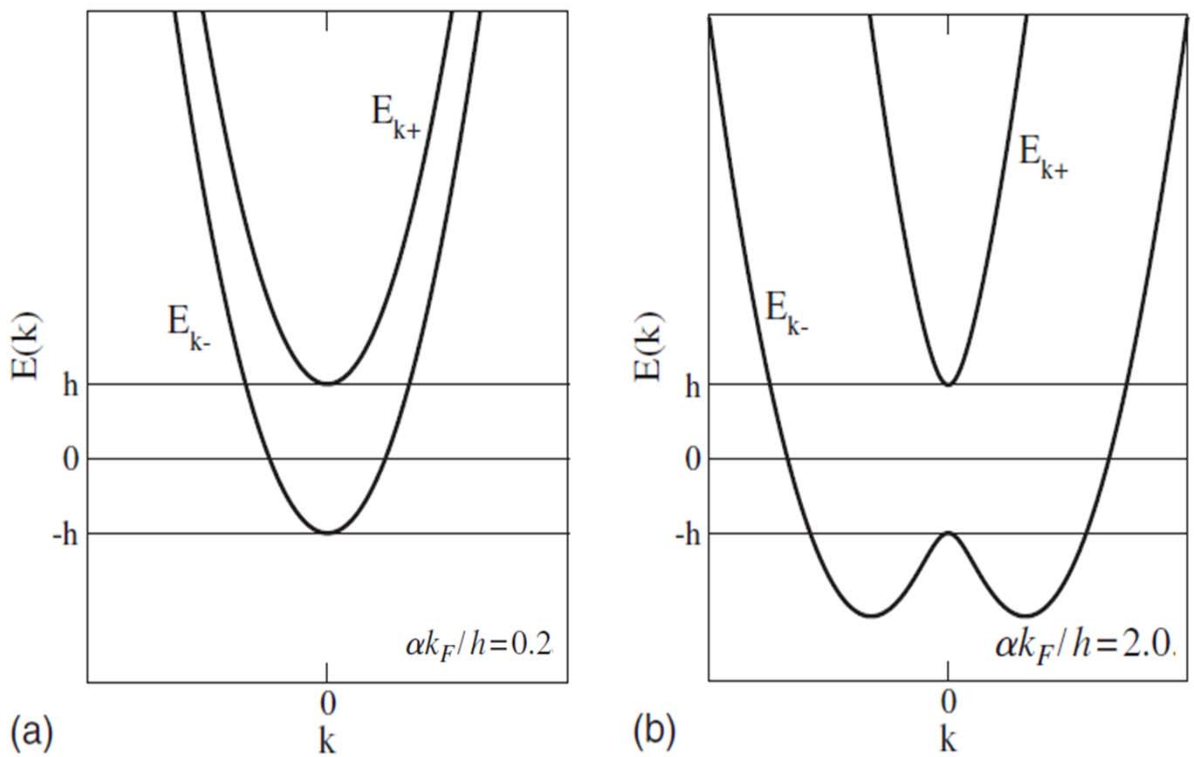
S. Zhang, PRL **85**, 393 (2000); S. Murakami, N. Nagaosa, S.C. & Zhang. Science **301**, 1348 (2003); J. Sinova, *et al.*, PRL **92**, 126603 (2004).


Mott scattering
B_{so}~k'xk
k'
k
D'yakonov & Perel, JETP Lett. 13, 467 (1971)

Intrinsic Anomalous Hall effect

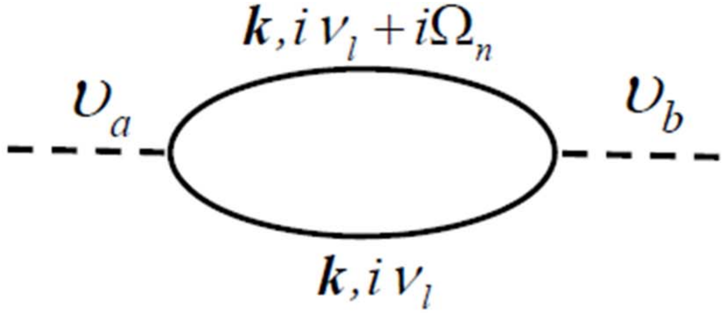
In systems with broken time-reversal symmetry and SOI

$$H = \frac{k^2}{2m}\sigma_0 + \alpha(\sigma_x k_y - \sigma_y k_x) - h\sigma_z + V(\mathbf{r})\sigma_0$$



Nunner *et al.* Phys. Rev. B **76**, 235312 (2007)
Sinitsyn *et al.* Phys. Rev. B **75**, 045315 (2007)

Intrinsic Anomalous Hall effect



$$\sigma_{ab}(\Omega) = \frac{ie^2}{\Omega}\int\frac{d\boldsymbol{k}}{(2\pi)^2}\frac{1}{\beta}\sum_l \mathrm{Tr}\{\langle v_a G_0(\boldsymbol{k}, i\nu_l) v_b G_0(\boldsymbol{k}, i\nu_l + i\Omega_n)\rangle\}_{i\Omega_n \to \Omega + i0},$$

$$v_a = \frac{\partial \mathcal{H}_0}{\partial k_a} \Longrightarrow v_x = \frac{k_x}{m}\sigma_0 - \alpha\sigma_y, \quad v_y = \frac{k_y}{m}\sigma_0 + \alpha\sigma_x,$$

$$\sigma_{yx} = \sigma_{yx}^{\mathrm{I}(a)} + \sigma_{yx}^{\mathrm{I}(b)} + \sigma_{yx}^{\mathrm{II}},$$

$$\sigma_{yx}^{\mathrm{I}(a)} = \frac{e^2}{2\pi V}\mathrm{Tr}\langle v_y G^R(\epsilon_F) v_x G^A(\epsilon_F)\rangle,$$

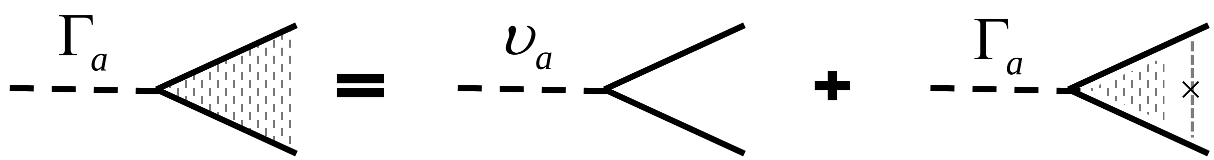
$$\sigma_{yx}^{\mathrm{I}(b)} = -\frac{e^2}{4\pi V}\mathrm{Tr}\langle v_y G^R(\epsilon_F) v_x G^R(\epsilon_F) + v_y G^A(\epsilon_F) v_x G^A(\epsilon_F)\rangle,$$

$$\sigma_{yx}^{\mathrm{II}} = \frac{e^2}{4\pi V}\int_{-\infty}^{\infty} d\epsilon f(\epsilon)\mathrm{Tr}\left\langle v_y G^R(\epsilon) v_x \frac{\partial G^R(\epsilon)}{\partial\epsilon} - v_y \frac{\partial G^R(\epsilon)}{\partial\epsilon} v_x G^R(\epsilon) - v_y G^A(\epsilon) v_x \frac{\partial G^A(\epsilon)}{\partial\epsilon} + v_y \frac{\partial G^A(\epsilon)}{\partial\epsilon} v_x G^A(\epsilon)\right\rangle.$$

$$\sigma_{yx}^{\mathrm{II}} = -\frac{e^2}{4\pi}\left(1 - \frac{h}{\sqrt{h^2 + 2\alpha^2 m\epsilon_F + (\alpha^2 m)^2}}\right)\Theta(h - \epsilon_F)$$

$$\sigma_{yx}^{\mathrm{I}(a),b} = -\frac{e^2}{2\pi}\frac{\alpha^2 mh}{\lambda_F^2}$$

$$\lambda_F = \sqrt{h^2 + 2\alpha^2 m\epsilon_F}$$

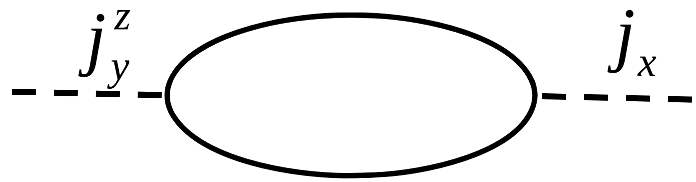


$$n_i V_0^2 \int\int \frac{dkkd\phi}{(2\pi)^2} G^R(\epsilon_F)\upsilon_x G^A(\epsilon_F) = \gamma_x\sigma_x + \gamma_y\sigma_y$$

$$\sigma_{yx}^{\mathrm{I}(a),b} + \sigma_{yx}^{\mathrm{I}(a),l} = 0$$

Intrinsic Spin Hall Effect

In systems with time-reversal symmetry and SOI:

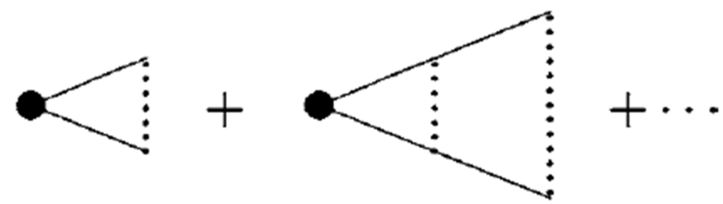


$$\boldsymbol{J}^z = (\hbar/4)\{\sigma^z, \boldsymbol{v}\}$$

$$\sigma^0_{sH} = \frac{e}{8\pi}\left(1 - \frac{1}{1 + (\Delta\tau)^2}\right) \quad \xrightarrow{\text{Disorder free limit}} \quad \sigma_{sH} = \frac{e}{8\pi}$$

$$\Delta = 2p_F\alpha$$

$\tilde{J}_y^z =$

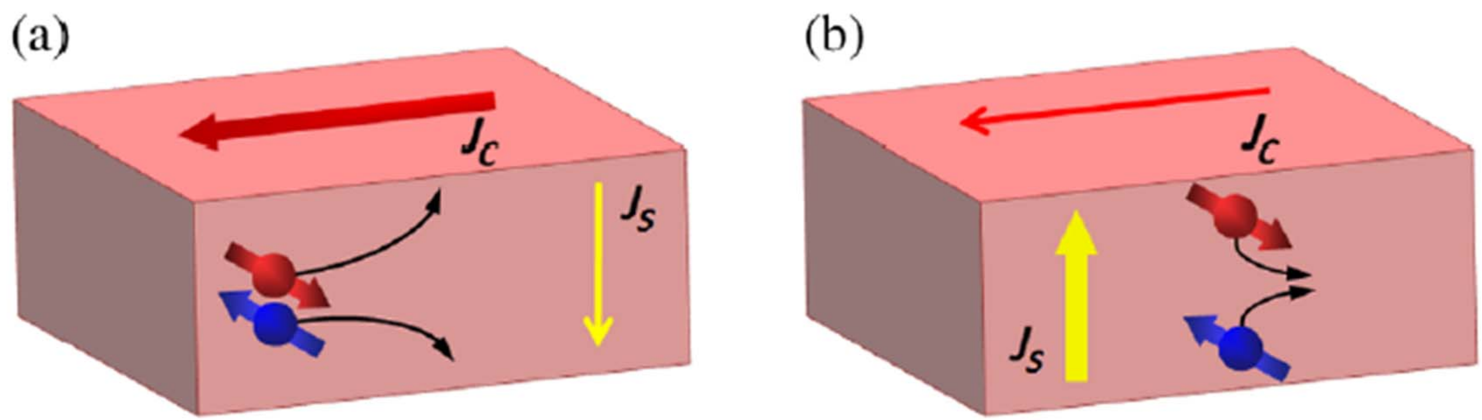


P. Wang, Y-Q. Li, and X. Zhao, PRB, **75**, 075326 2007

M.I. Dyakonov, Spin Hall Effect, Future Trends in Microelectronics, S. Luryi, J. Xu, and A. Zaslavsky (eds), Wiley 2010, p. 251

(Inverse) Spin Hall Effect

$$\vec{J}_S = \theta_{SH}(\hbar/2e)\vec{J}_C \times \vec{\sigma} \qquad \vec{J}_C = \theta_{SH}(2e/\hbar)\vec{J}_S \times \vec{\sigma}$$

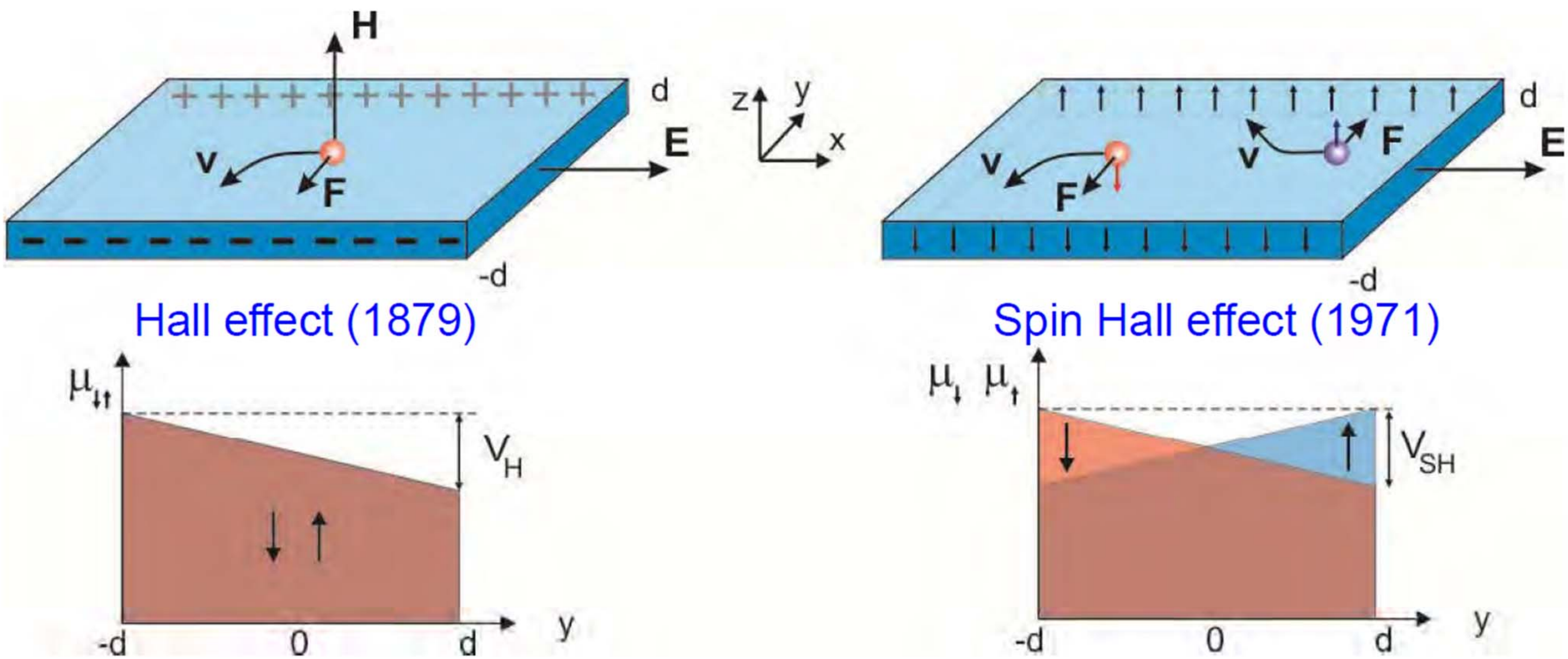


$$\sigma_{SH} = [\hbar/(2e)]\theta_{SH}\sigma$$

Magnus effect: https://www.youtube.com/watch?v=2OSrvzNW9FE

B. F. Miao, S.Y. Huang, D. Qu, and C. L. Chien, PRL **111**, 066602 (2013)

The spin Hall effect has the symmetry of the conventional Hall effect



M.I. Dyakonov & V.I. Perel, JETP Lett. **13**, 467 (1971); J.E. Hirsch, PRL **83**, 1834 (1999);

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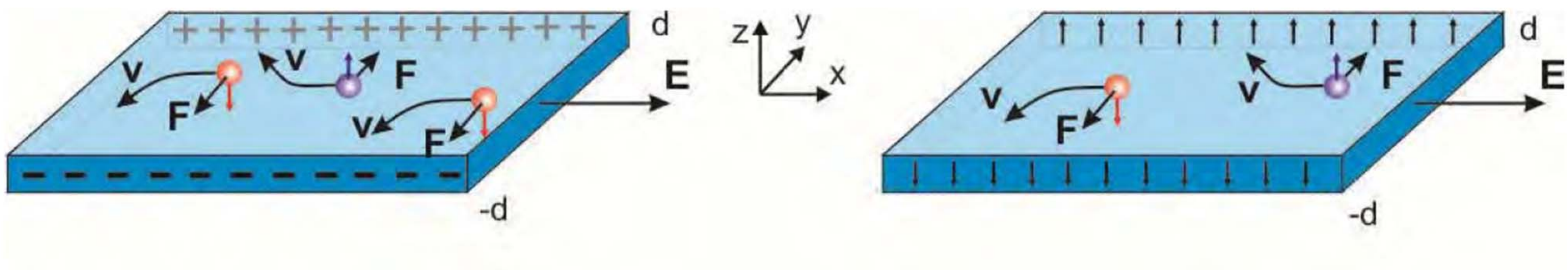
J. Sinova, *et al.*, PRL **92**, 126603 (2004).

Scattering of unpolarized electrons by an unpolarized target results in spatial separation of electrons with different spins due to spin-orbit interaction

N. F. Mott and H. S. W. Massey, The theory of atomic collisions (Clarendon Press, Oxford, 1965)

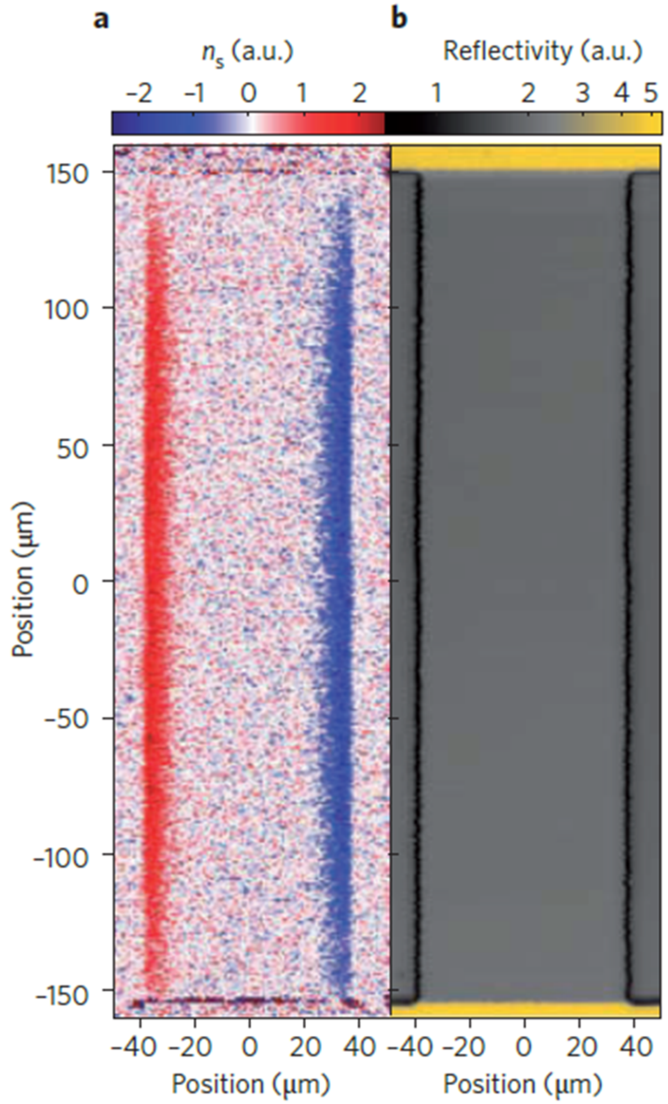


Anomalous Hall effect (1881)

Spin Hall effect

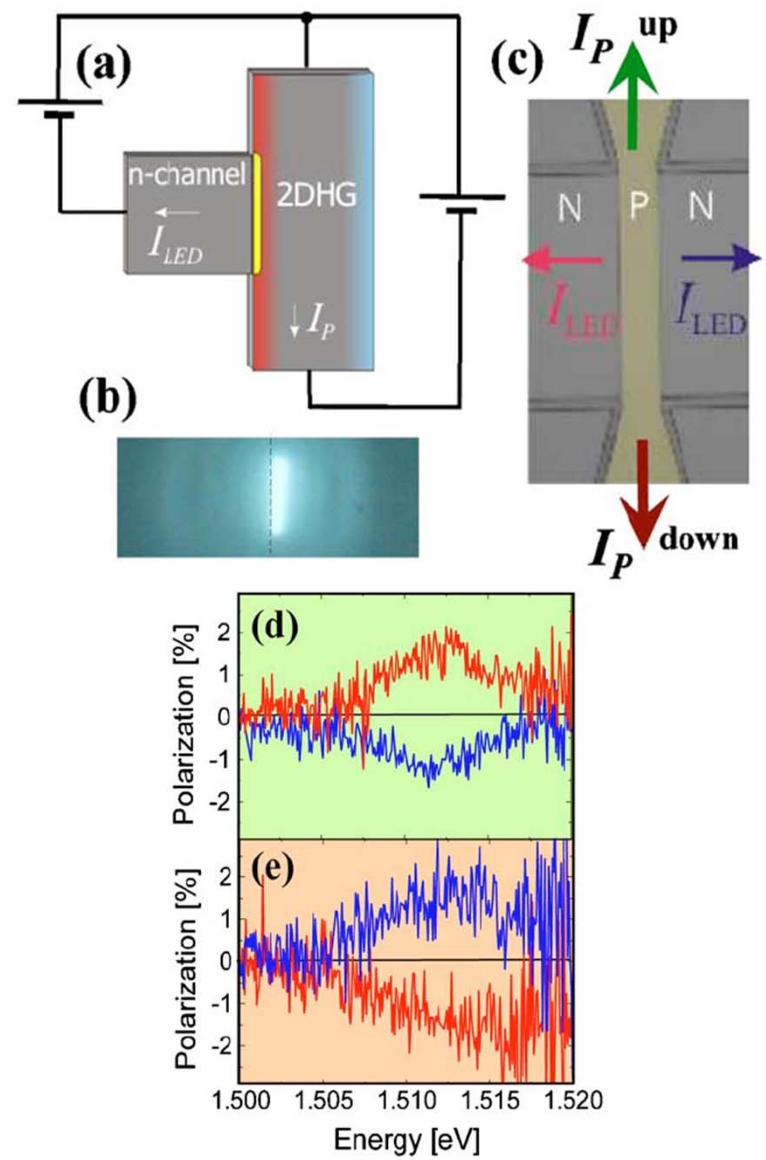
E.H. Hall, Phil . Mag. 12, 157 (1881)

Magneto-optical Kerr microscopy



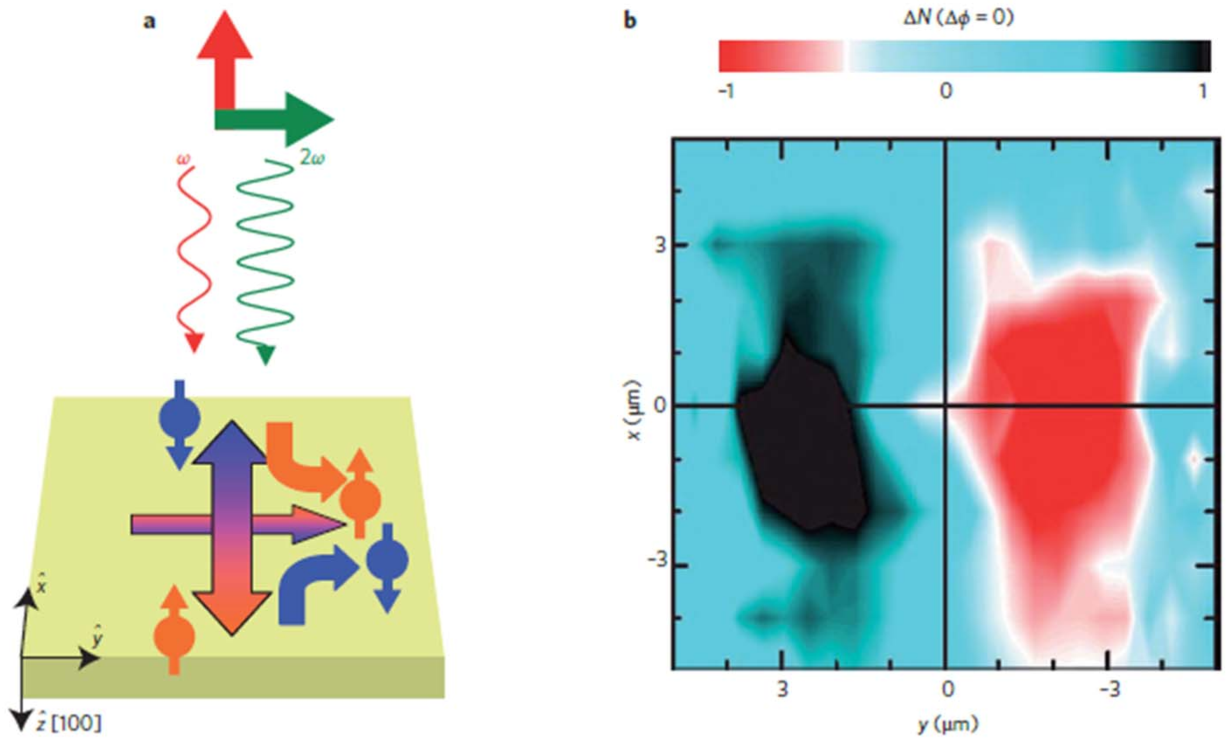
Extrinsic SHE *Kato, Awschalom, et al., Science'04*

Edge polarized electro-luminescence



Intrinsic SHE *Wunderlich, Kaestner, Sinova, TJ, PRL'05*

Inverse Spin Hall Effect



Zhao, H. *et al. Phys. Rev. Lett.* **96,** 246601 (2006).