How electrons move?

Hall effect

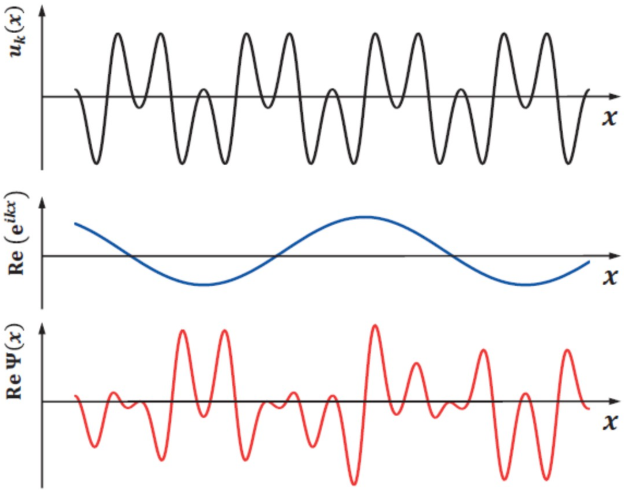
strontium titanate ($SrTiO_3$)

Marvin Cohen

by Alexander Tsirlin, Leipzig University

Lecture 22: January 17, 2024

Before we start,
please take 5 minutes
to fill in the evaluation form
for this module



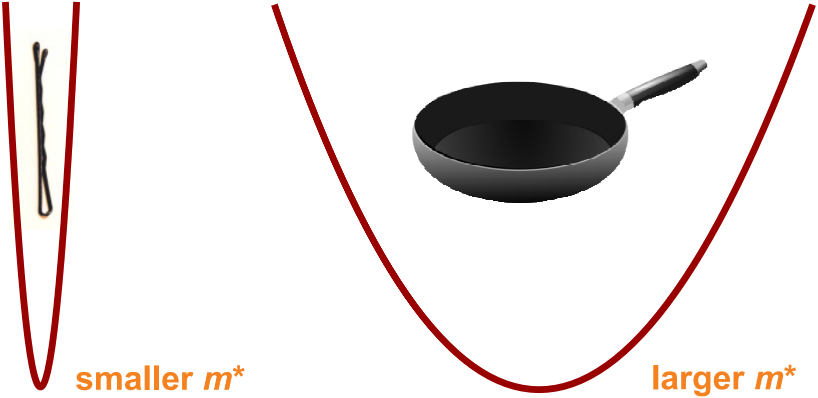
periodic part $u_{n\mathbf{k}}$

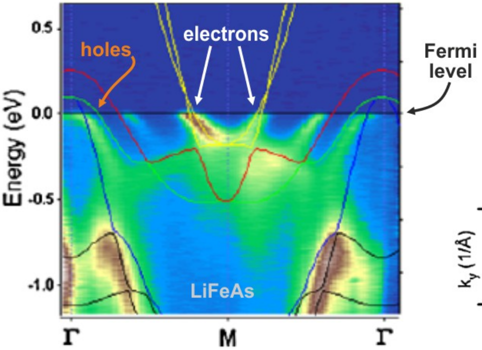
plane wave

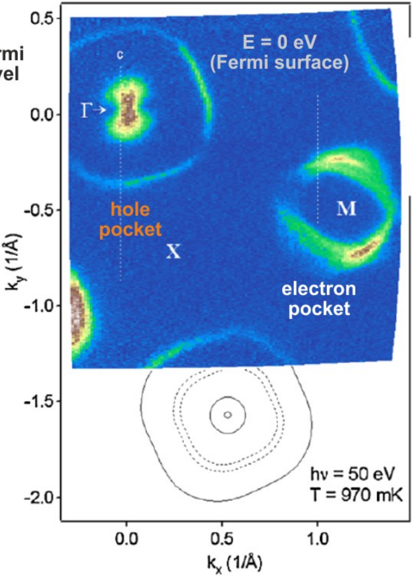
Bloch wave

Gross and Marx, Festkörperphysik

a hairpin is lighter than a frying pan

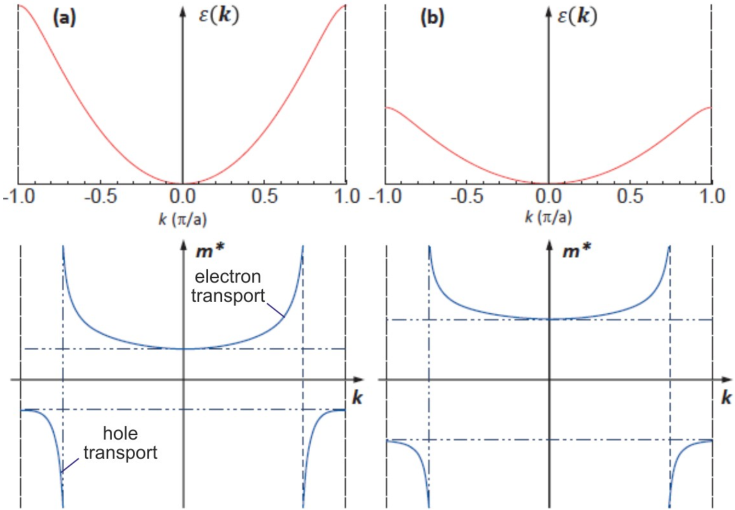






Bands of different type
may occur near the Fermi level

Phys. Rev. Lett. 105, 067002 (2010)

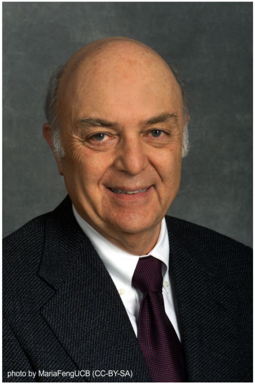


Even single band may have hole and electron regions

Gross and Marx, Festkörperphysik

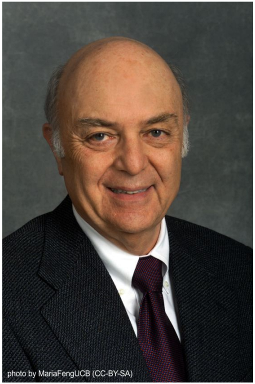
Person

Marvin Cohen



Marvin Cohen
(born 1935)

- 1953-1957: bachelor in Berkley,
  not accepted for master program
- 1958-1963: master and PhD in Chicago
  theory work based on electronic structure calculations for real materials
- 1963-1964: very short postdoc at Bell Labs
- since 1964: professor at Berkley
- 1960-70's: optical properties of semiconductors
- since 1970's: high-pressure transformations of solids
- 1980's: superconductors
- since 1990's: carbon allotropes, nanotubes



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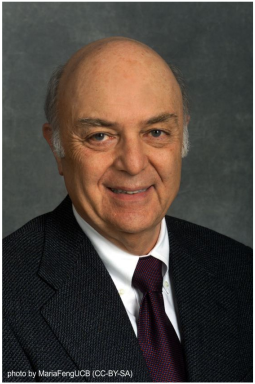

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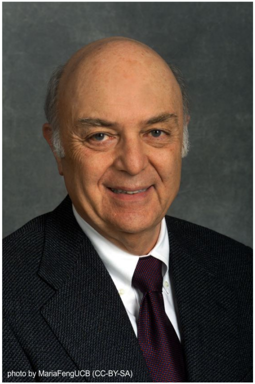

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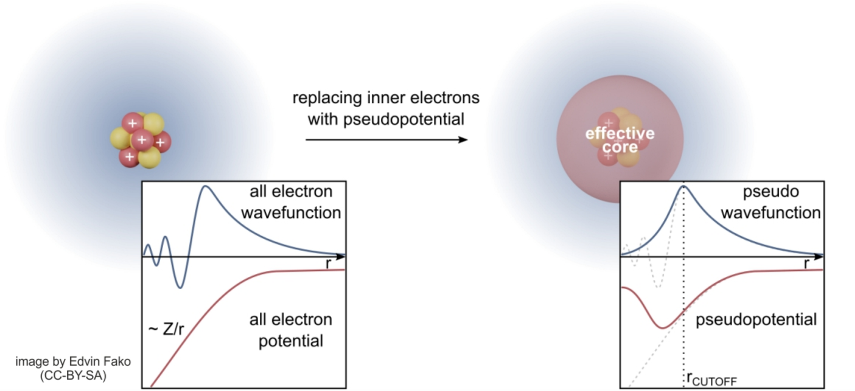
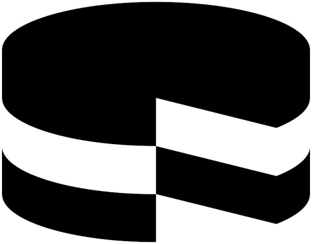


image by Edvin Fako (CC-BY-SA)

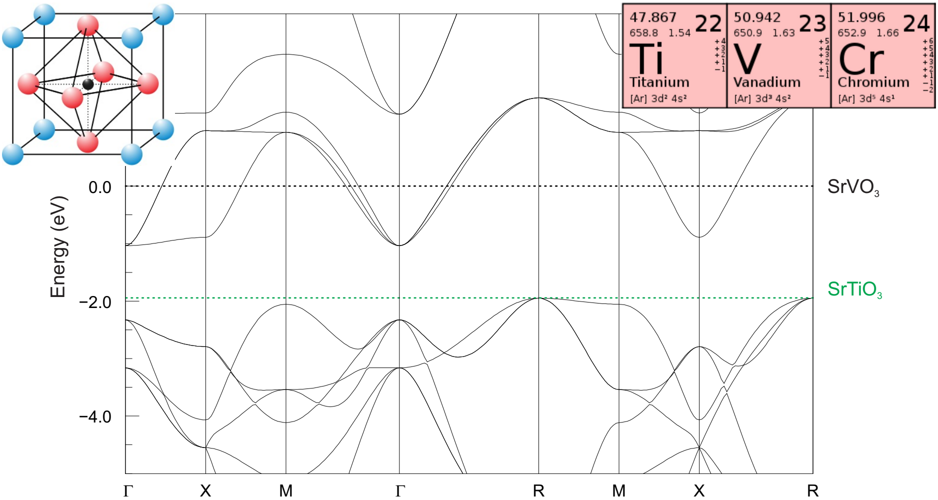
	lattice constant (Å)	cohesive energy (eV)	bulk modulus (Mbar)
Si			
Calc.	5.45	4.67	0.98
Expt.	5.43	4.63	0.99
% Diff.	0.4%	1%	− 1%
Ge			
Calc.	5.66	4.02	0.73
Expt.	5.65	3.85	0.77
% Diff.	0.1%	4%	− 5%

M.L. Cohen
Phys. Scr. T1, 5 (1982)

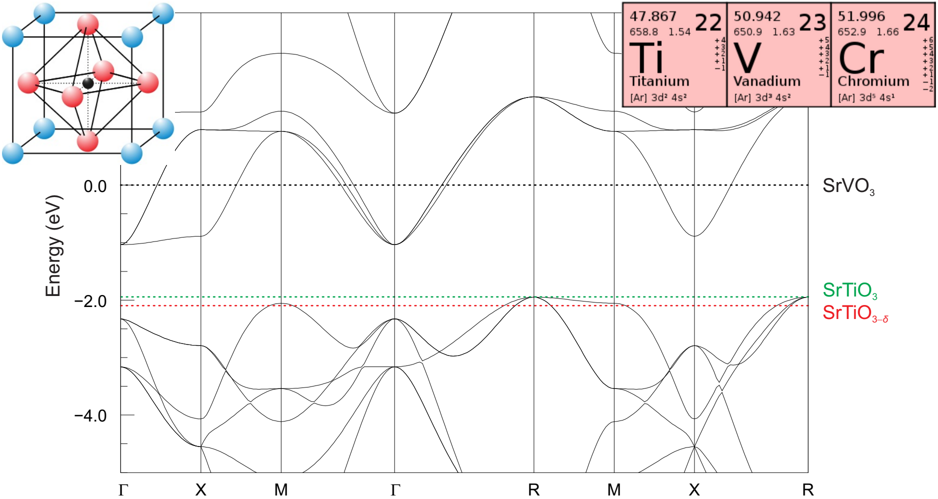


Material

strontium titanate ($SrTiO_3$)

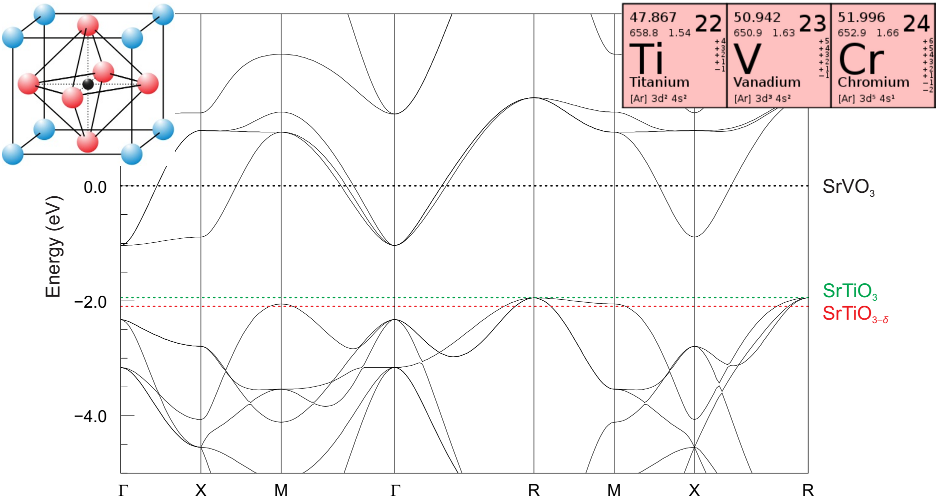


$SrTiO_3$ is mundane wide-gap semiconductor ($\rho = 10^9\ \Omega\cdot$cm)



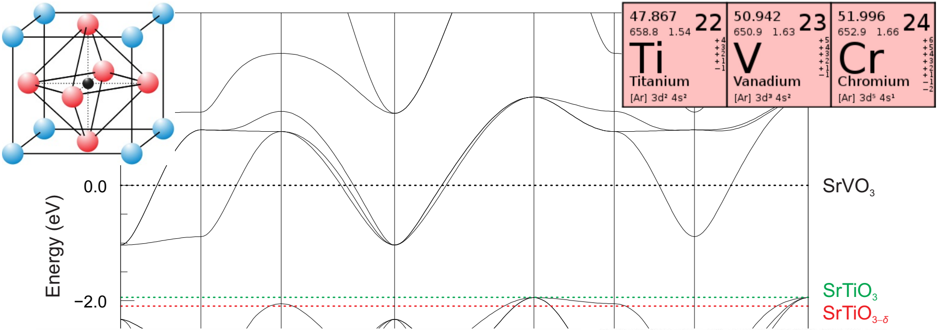
$SrTiO_3$ is mundane wide-gap semiconductor ($\rho = 10^9\ \Omega{\cdot}\mathrm{cm}$), while $SrTiO_{3-\delta}$ is **metallic** ($\rho \sim 10\,\mathrm{m}\Omega{\cdot}\mathrm{cm}$)

Superconducting semiconductor



$SrTiO_3$ is mundane wide-gap semiconductor ($\rho = 10^9\ \Omega{\cdot}\text{cm}$),

while $SrTiO_{3-\delta}$ is **metallic** ($\rho \sim 10\,\text{m}\Omega{\cdot}\text{cm}$), possibly superconducting



PHYSICAL REVIEW LETTERS

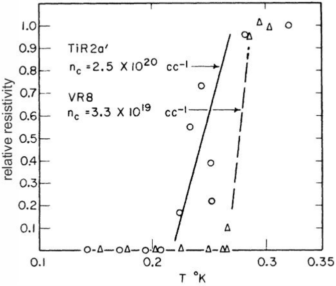
SUPERCONDUCTIVITY IN SEMICONDUCTING $SrTiO_3$

J. F. Schooley and W. R. Hosler
National Bureau of Standards, Washington, D. C.

and

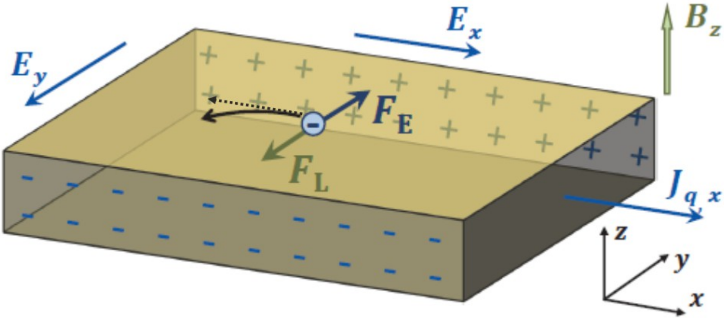
Marvin L. Cohen
Bell Telephone Laboratories, Murray Hill, New Jersey

(Received 6 March 1964)
Vol. 12, Page 474



Experimental technique

Hall effect

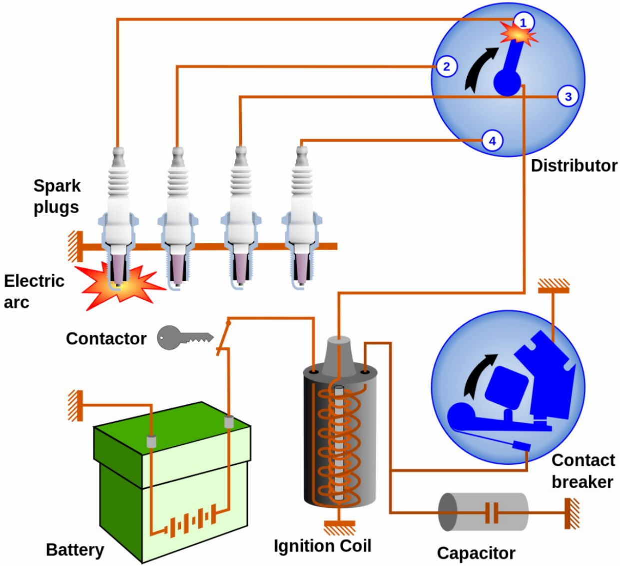


$$E_y = -\frac{B_z}{n_e e} j_x \quad \Rightarrow \quad R_H = \frac{E_y}{B_z j_x} = -\frac{1}{n_e e}$$

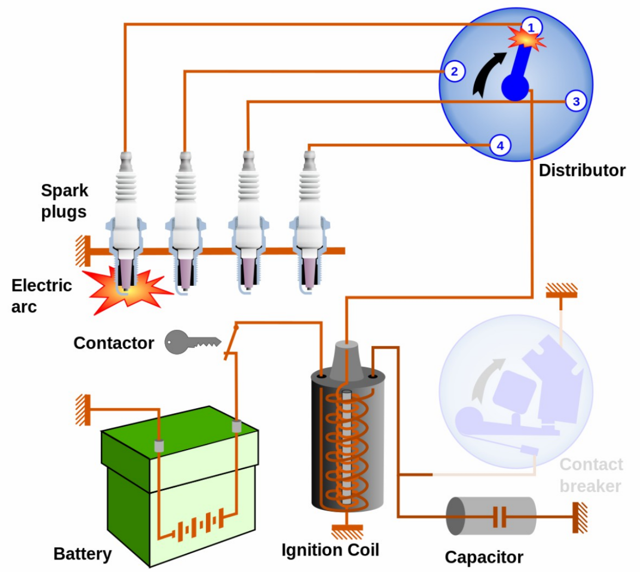
(direct measure of charge-carrier concentration)

Gross and Marx, Festkörperphysik

Image credit: Mitchell Instrument (fair use)


1
2
3
4
Distributor
Spark plugs
Electric arc
Contactor
Battery
Ignition Coil
Capacitor
Contact breaker

Hall sensor in cars



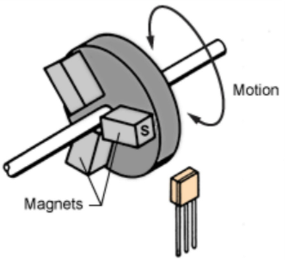


Image credit: Frédéric MICHEL and Vauxford (CC-BY-SA), Allegro Microsystems (fair use)

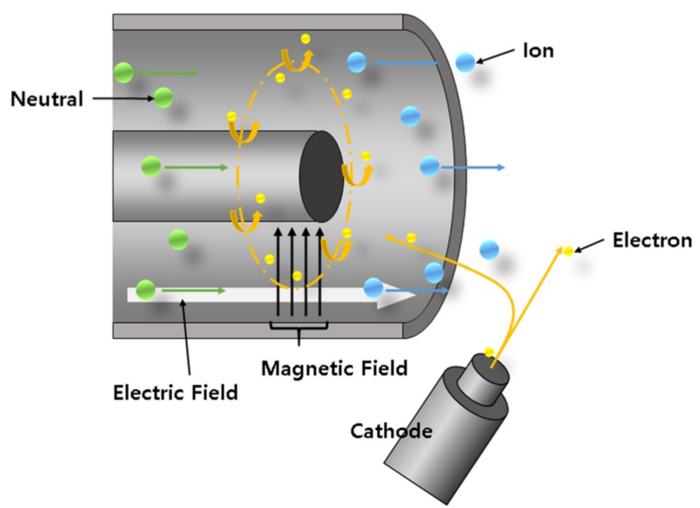
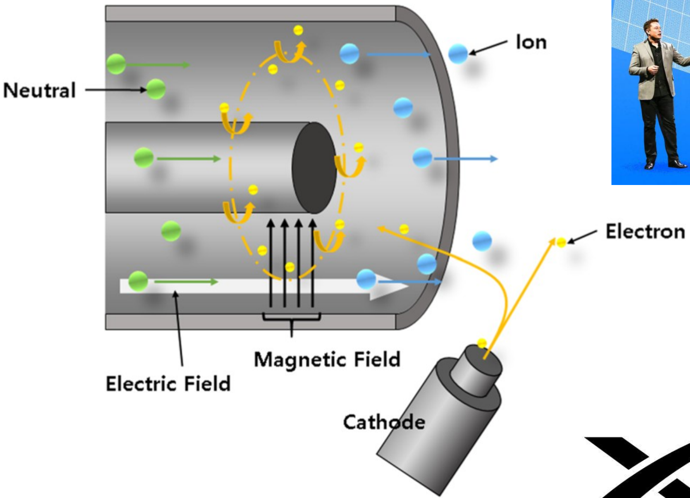


Image credit: Int. J. Aeronaut. Space Sci. 21, 1028 (2020)

Hall-effect thruster



STARLINK

Image credit: Int. J. Aeronaut. Space Sci. 21, 1028 (2020) and Starlink

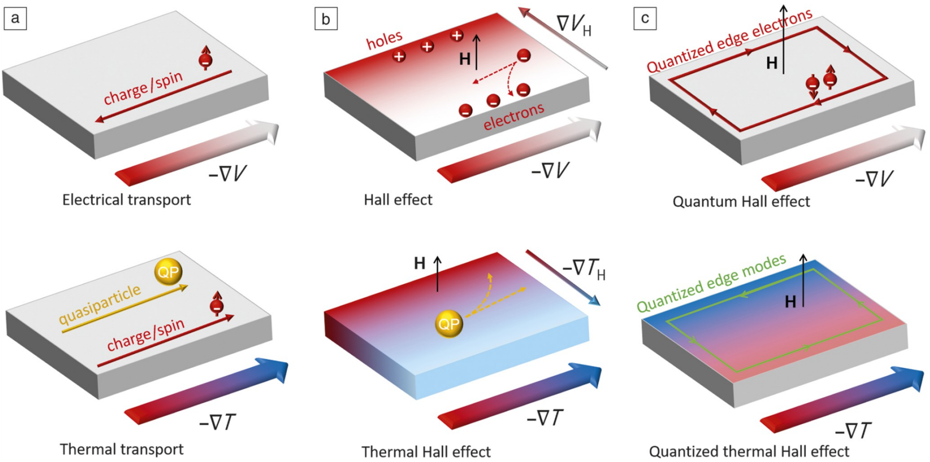
METAL	VALENCE	$-1/R_H nec$
Li	1	0.8
Na	1	1.2
K	1	1.1
Rb	1	1.0
Cs	1	0.9
Cu	1	1.5
Ag	1	1.3
Au	1	1.5
Be	2	−0.2
Mg	2	−0.4
In	3	−0.3
Al	3	−0.3

electron carriers

hole carriers

N.W. Ashcroft, N.D. Mermin, Solid State Physics

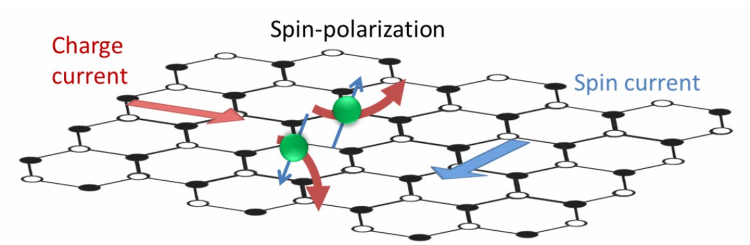
N.B. R_H values in the high-field limit; experimentally, R_H depends on the magnetic field!

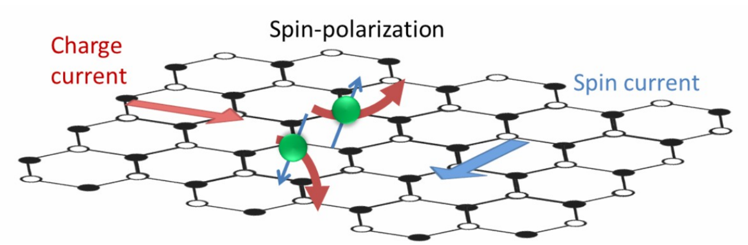


Signature of non-trivial features in electronic/magnetic structure

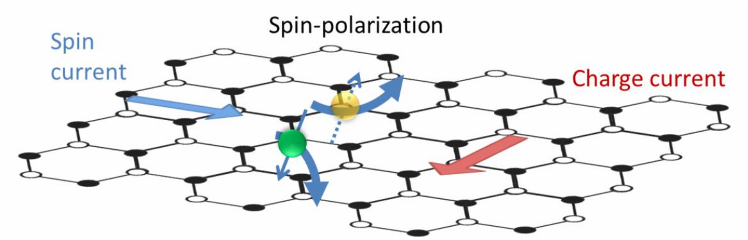
occurs in metals, magnetic insulators...

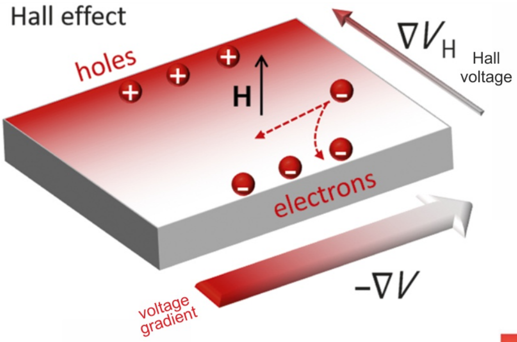
MRS Bulletin 45, 348 (2020)


Charge current
Spin-polarization
Spin current



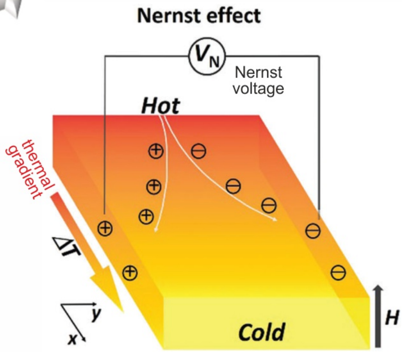
caused by spin-orbit coupling
common in “heavy” metals (Os, Pt)





same $SrTiO_3$

$$\nu = 40 \, \frac{\mu V}{T \cdot K}$$



doped $SrTiO_3$ at 4.2 K

$(n_e = 5.5 \cdot 10^{17}\,\mathrm{cm}^{-3})$

$$R_H \simeq 1000 \, \frac{\mu V \cdot m}{T \cdot A}$$

MRS Bulletin 45, 348 (2020) and Energy Environ. Sci. 11, 2813 (2018)