Egzotikus elektromágneses jelenségek alacsony hőmérsékleten

Mihály György
BME Fizikai Intézet

Hall effektus

- Edwin Hall és az „összenyomhatatlan elektromosság”
- Kvantum Hall effektus

Mágneses áram

- anomális Hall effektus
- spin forgatónyomaték

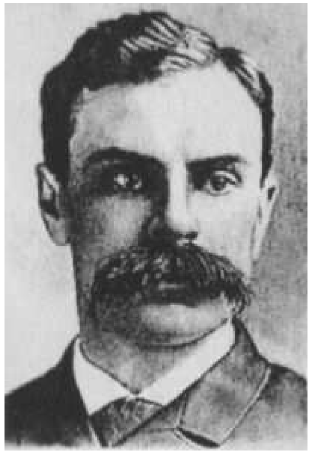
Spin-polarizáció mérése

- Andrejev reflexió
- Mágneses mikroszkópia nanométeres tartományban

http://dept.phy.bme.hu/egzotikus.pdf

Hall effektus

Hall jelenség



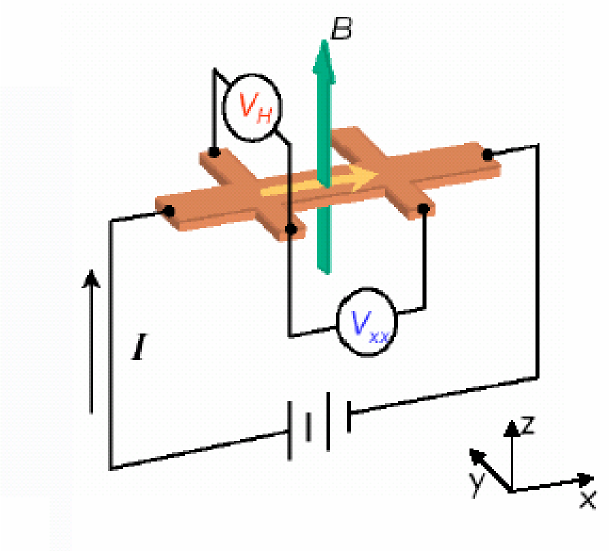
Edwin Hall (1855-1938)

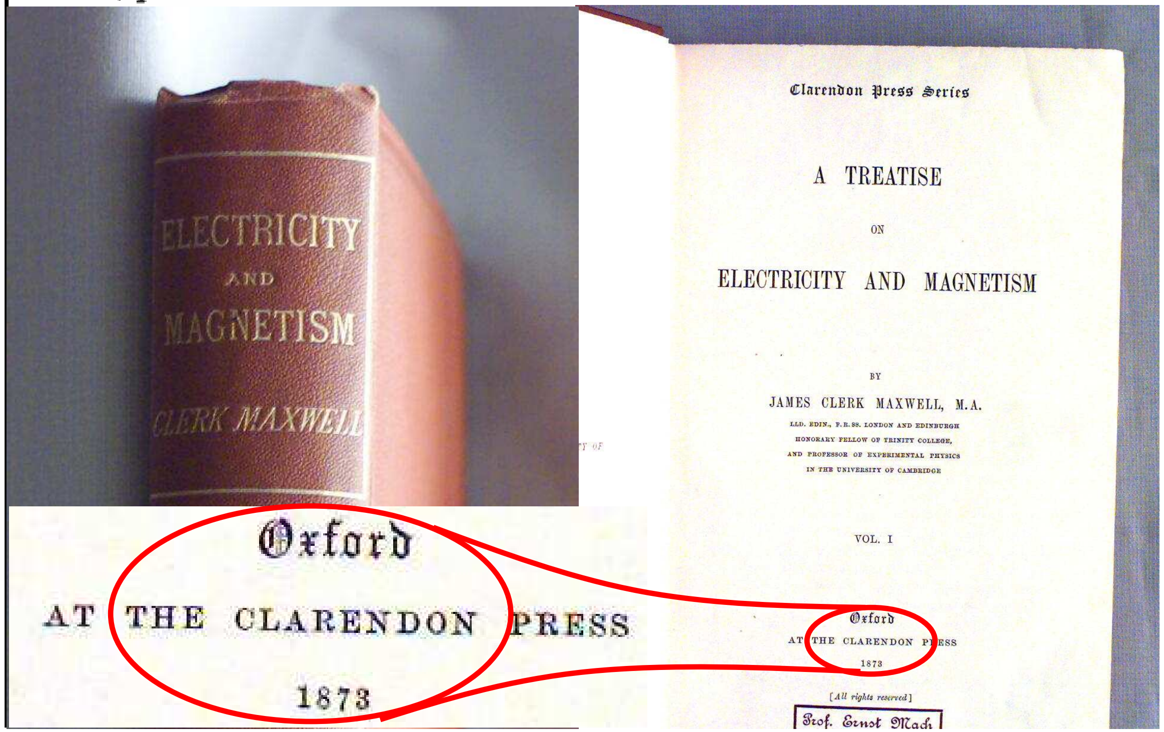
American Journal of Mathematics, vol **2** (1879)

On a New Action of the Magnet on Electric Currents.

By E. H. Hall, *Fellow of the Johns Hopkins University.*

Sometime during the last University year, while I was reading Maxwell's Electricity and Magnetism in connection with Professor Rowland's lectures, my attention was particularly attracted by the following passage in Vol. II, p. 144:



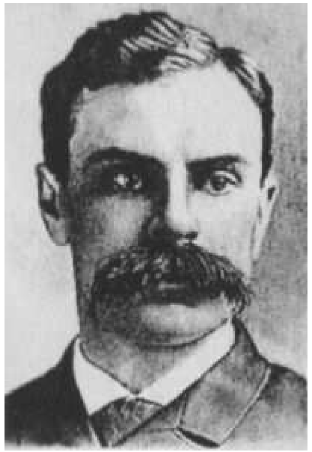


Hall-állandó

$$\boxed{R_H = \frac{E_y}{j_x B_z} = \frac{1}{ne}}$$

Hall effektus

Hall jelenség: Lorentz erő



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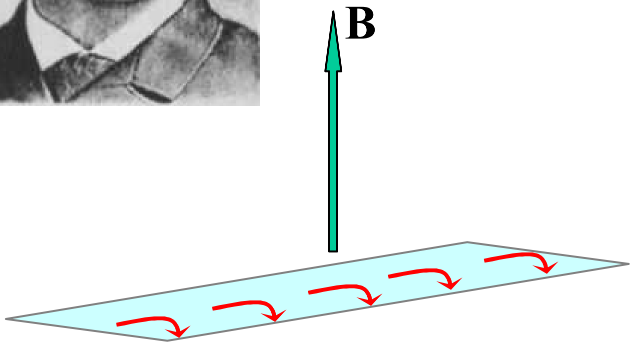
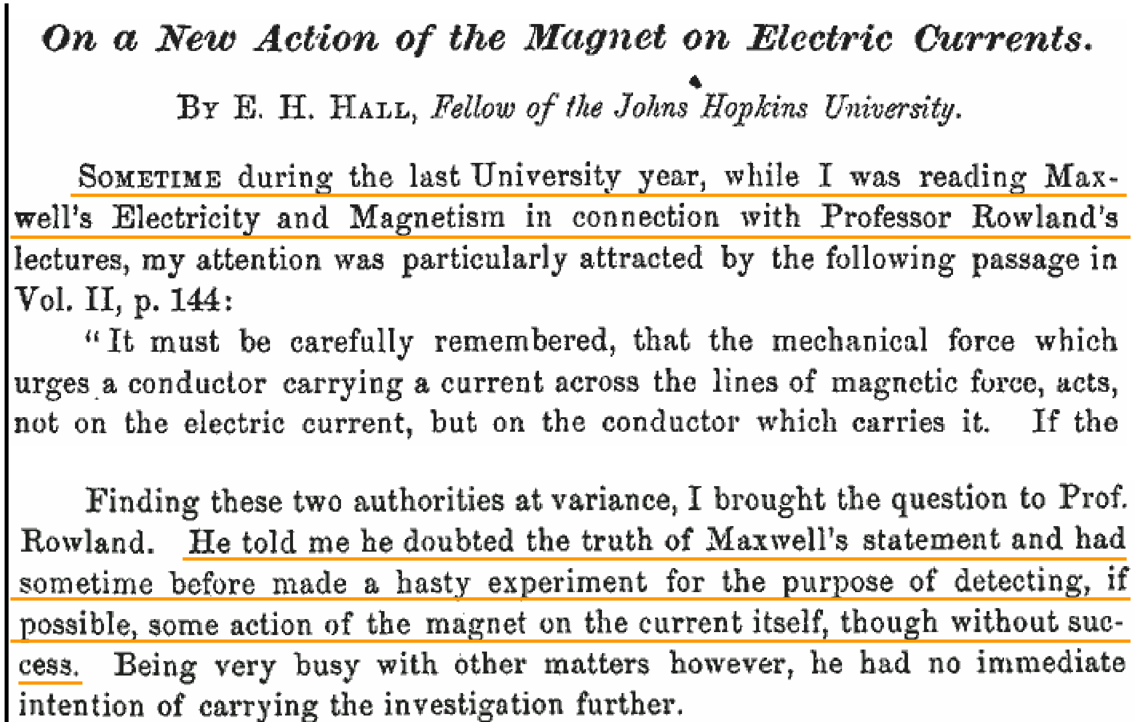


Lorentz erő:

$$\vec{\mathbf{F}} = -e\left[\vec{\mathbf{E}} + \vec{\mathbf{v}} \times \vec{\mathbf{B}}\right]$$



On a New Action of the Magnet on Electric Currents.

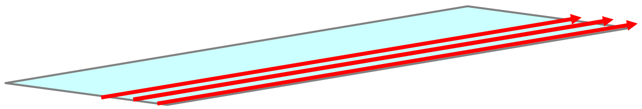
BY E. H. HALL, *Fellow of the Johns Hopkins University.*

SOMETIME during the last University year, while I was reading Maxwell's Electricity and Magnetism in connection with Professor Rowland's lectures, my attention was particularly attracted by the following passage in Vol. II, p. 144:

"It must be carefully remembered, that the mechanical force which urges a conductor carrying a current across the lines of magnetic force, acts, not on the electric current, but on the conductor which carries it. If the

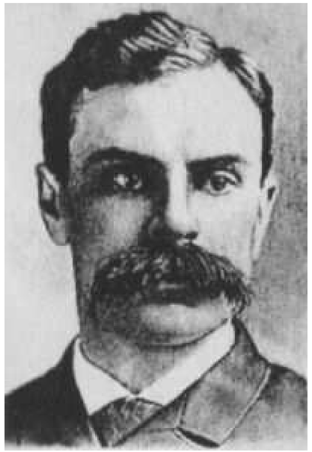
Finding these two authorities at variance, I brought the question to Prof. Rowland. He told me he doubted the truth of Maxwell's statement and had sometime before made a hasty experiment for the purpose of detecting, if possible, some action of the magnet on the current itself, though without success. Being very busy with other matters however, he had no immediate intention of carrying the investigation further.

Prof. Rowland hipotézise



Hall effektus

Hall jelenség: Lorentz erő



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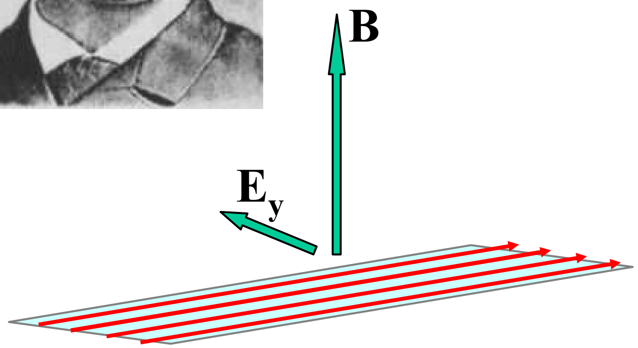


Lorentz erő:

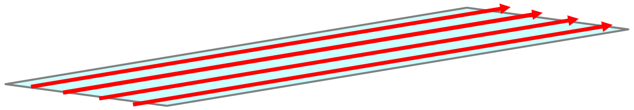
$$\vec{\mathbf{F}} = -e\left[\vec{\mathbf{E}} + \vec{\mathbf{v}} \times \vec{\mathbf{B}}\right] \qquad \vec{\mathbf{j}} = -ne\vec{\mathbf{v}}$$

Hall-állandó

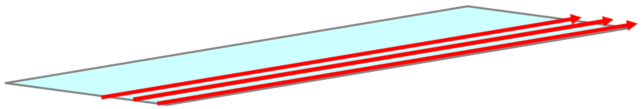
$$\boxed{R_H = \frac{E_y}{j_x B_z} = \frac{1}{ne}}$$

But though conclusive, apparently, in respect to any change of resistance, the above experiments are not sufficient to prove that a magnet cannot affect an electric current. If electricity is assumed to be an incompressible fluid, as some suspect it to be, we may conceive that the current of electricity flowing in a wire cannot be forced into one side of the wire or made to flow in any but a symmetrical manner. The magnet may *tend* to deflect the current without being able to do so. It is evident, however, that in this case there would exist a state of stress in the conductor, the electricity pressing, as it were, toward one side of the wire. Reasoning thus, I thought it necessary, in order to make a thorough investigation of the matter, to test for a difference of potential between points on opposite sides of the conductor.

Edwin Hall elképzelése



Prof. Rowland hipotézise



Összenyomhatatlan „elektromosság" - kvantummechanika

<u>Shcrödinger egyenlet</u>

$$-\frac{\hbar^2}{2m}\nabla^2\psi = \varepsilon\psi$$

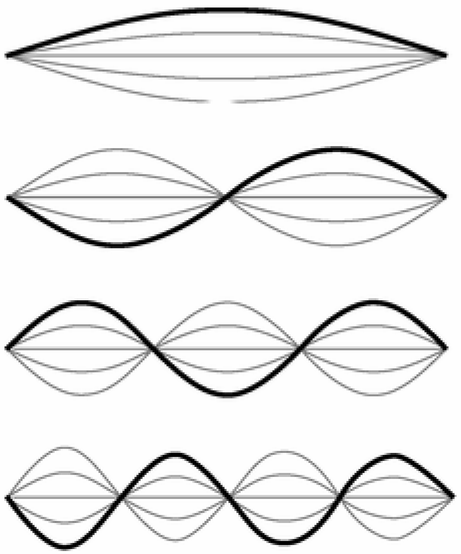
síkhullám

$$\psi(\mathbf{r}) = \frac{1}{\sqrt{V}}e^{i\mathbf{kr}}$$

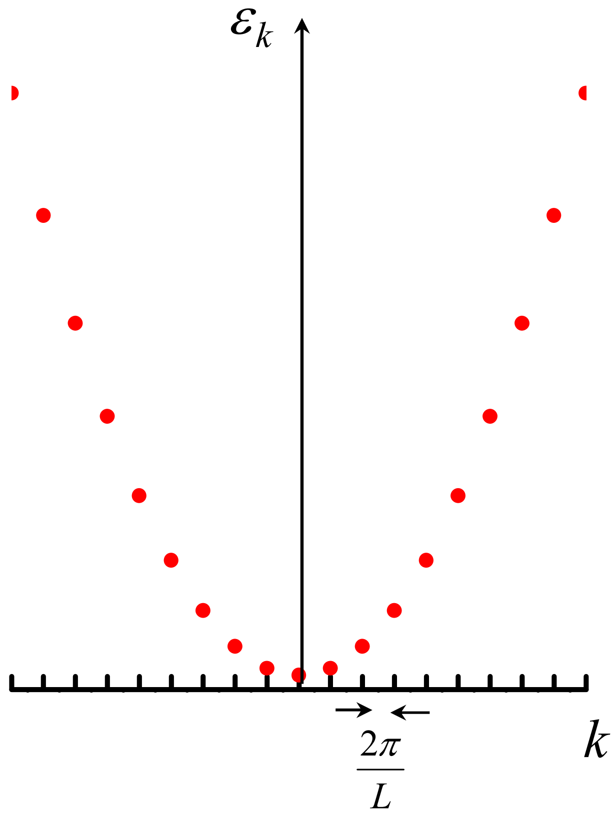
energia $\varepsilon(\mathbf{k}) = \frac{\hbar^2\mathbf{k}^2}{2m}$

impulzus $\mathbf{p} = \hbar\mathbf{k}$

A hullámszám lehetséges értékei



$$k = \frac{2\pi}{L}n$$



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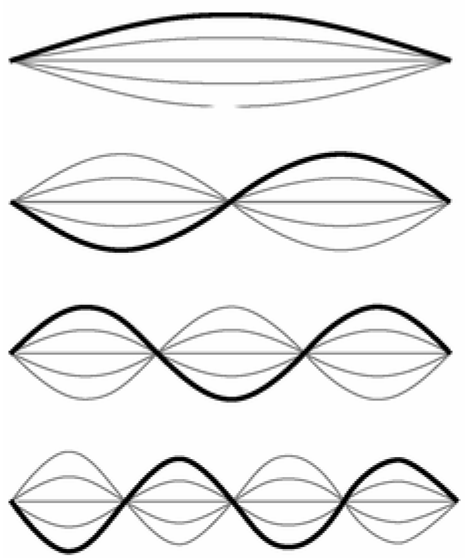
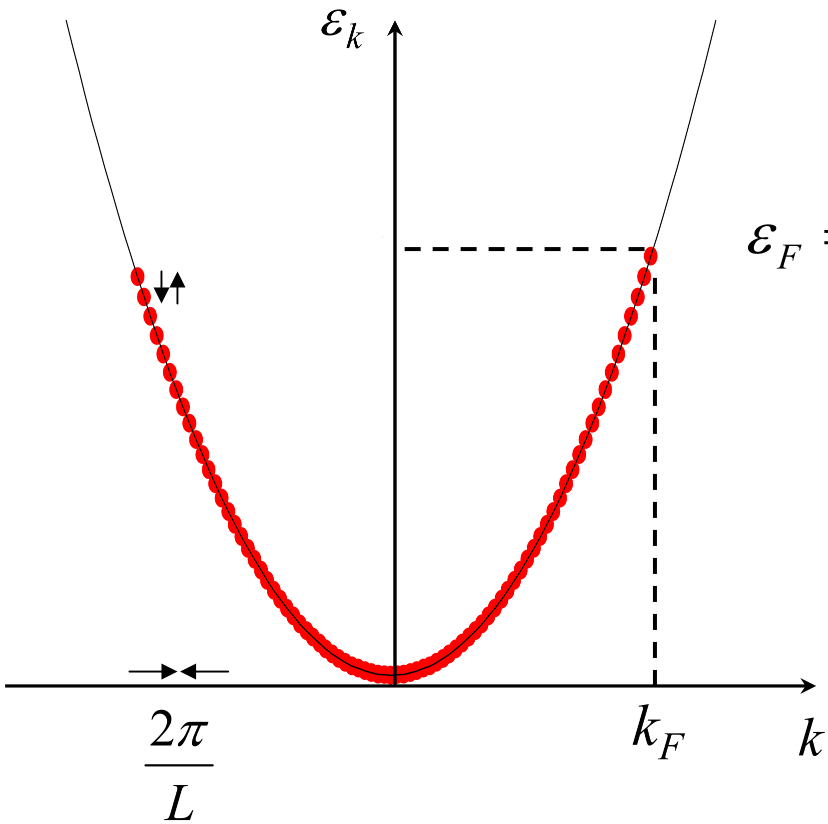
Sok elektron – **Pauli elv**

Alapállapot





$\varepsilon_F = 5-8\,eV$

Összenyomhatatlan „elektromosság" - kvantummechanika

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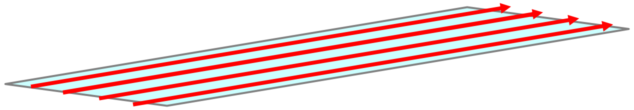
Alapállapot

Ugyanannyi elektron kisebb helyen:
sokkal nagyobb kinetikus energia

Edwin Hall elképzelése



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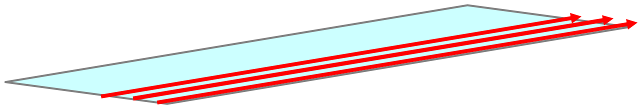
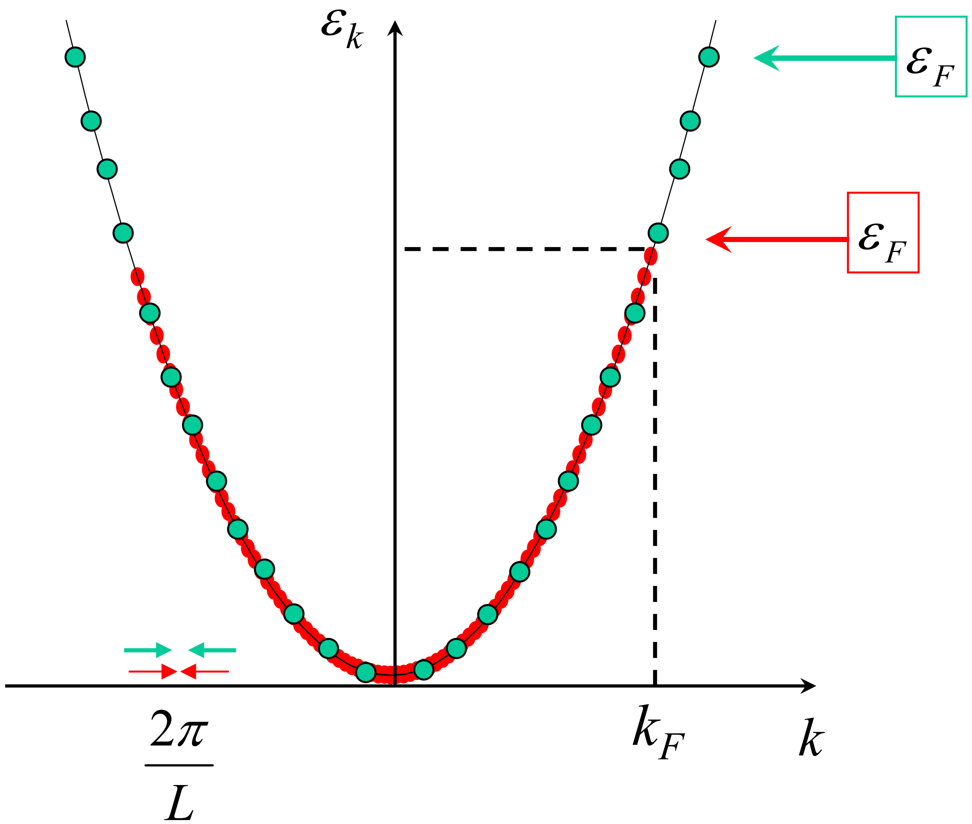




Kvantum Hall effektus

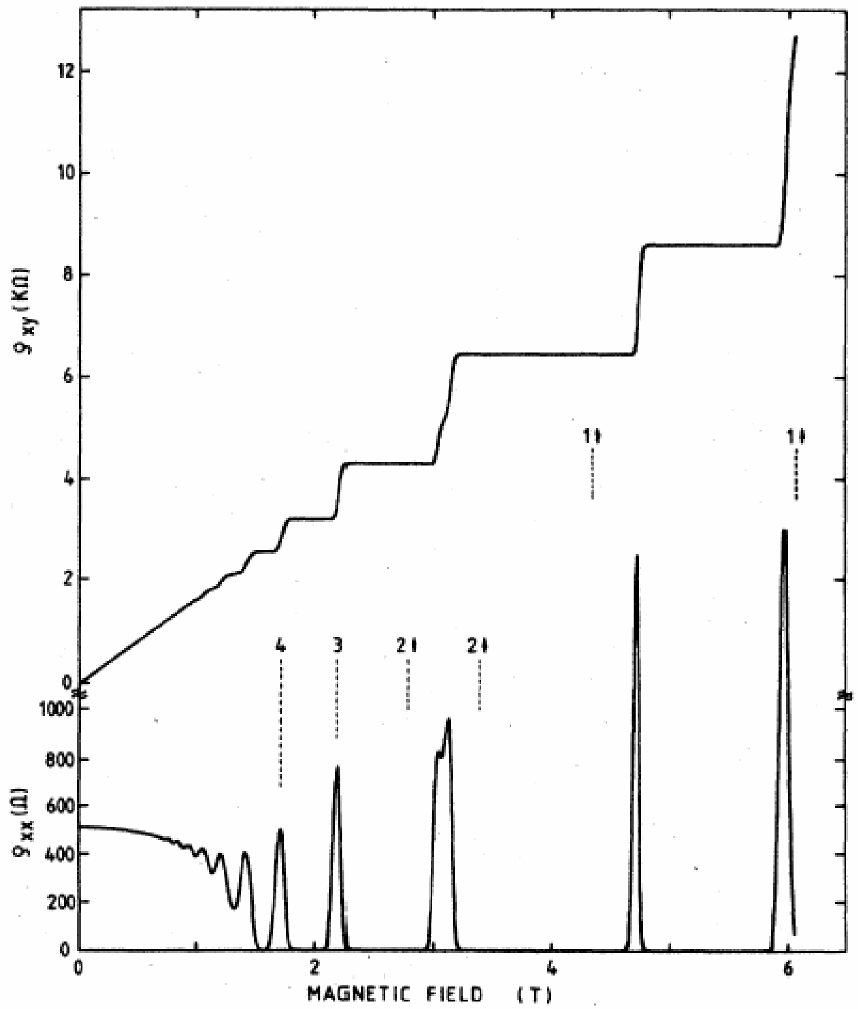


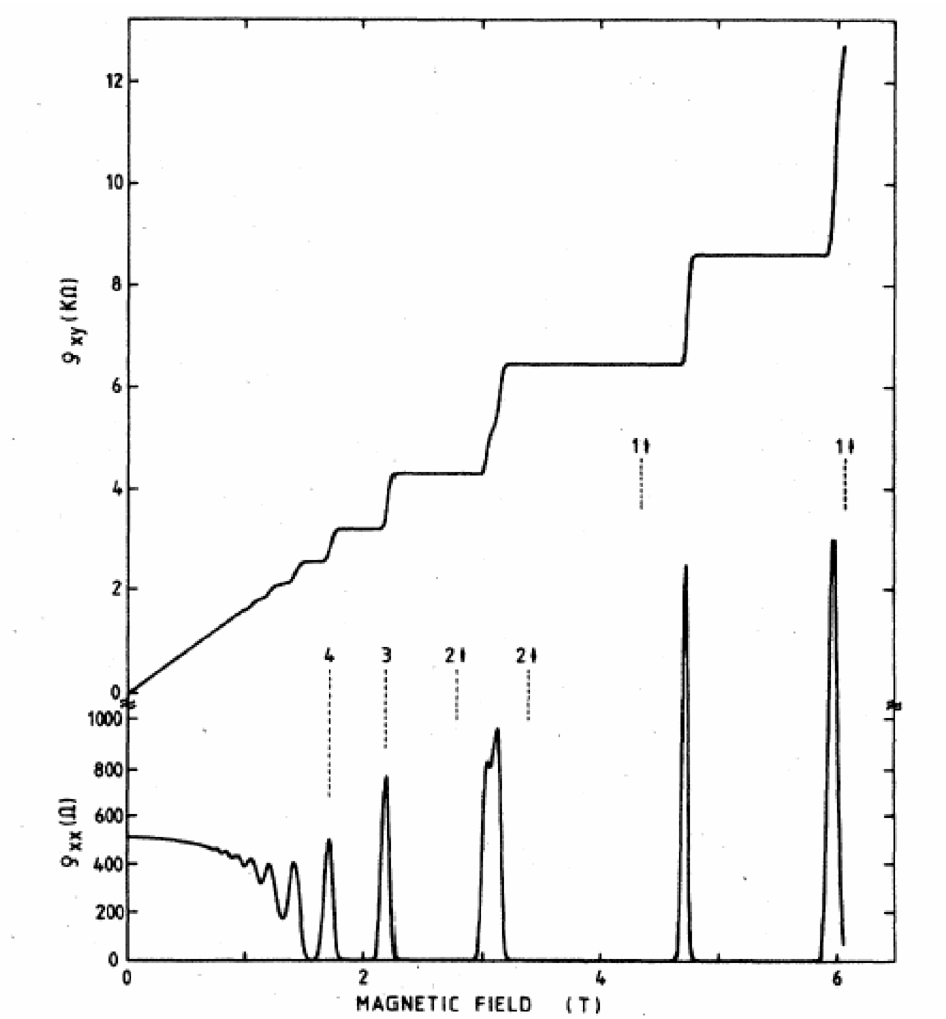
FIG. 14. Experimental curves for the Hall resistance $R_H = \rho_{xy}$ and the resistivity $\rho_{xx} \sim R_x$ of a heterostructure as a function of the magnetic field at a fixed carrier density corresponding to a gate voltage $V_g = 0$ V. The temperature is about 8 mK.

Klaus von Klitzing
Nobel-díj, 1985

T=8 mK

K. von Klitzing, Rev. Mod. Phys **58**, 519 (1986)

Kvantum Hall effektus



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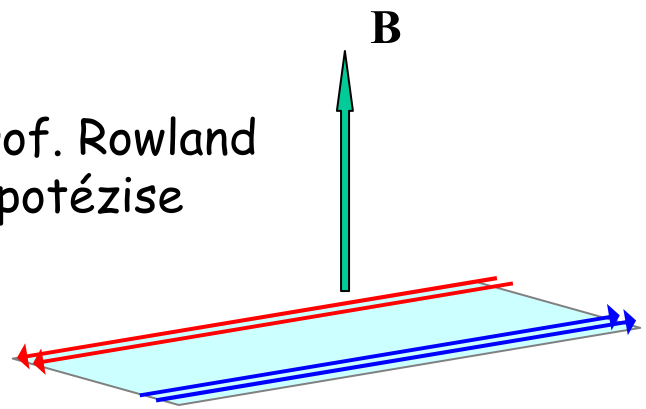
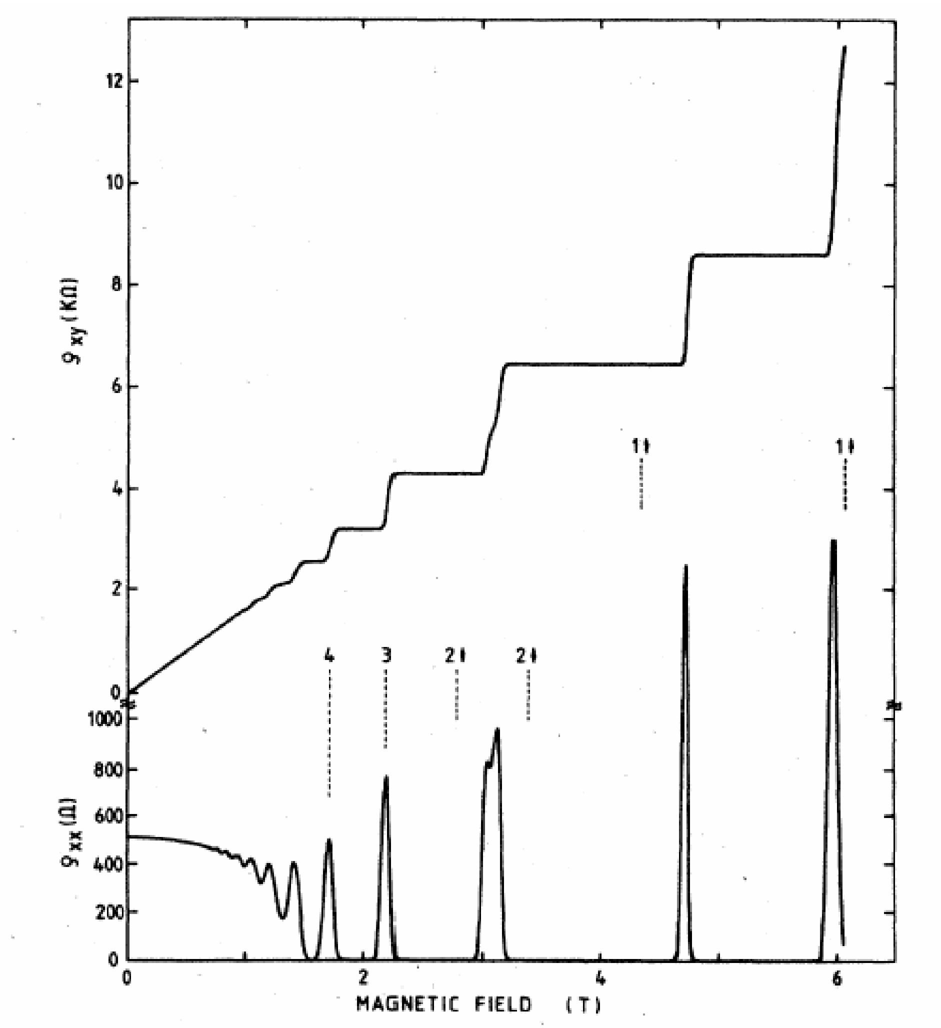
K. von Klitzing, Rev. Mod. Phys **58**, 519 (1986)

Henry Augustus Rowland
(1848-1901)



Prof. Rowland
hipotézise

Kvantum Hall effektus



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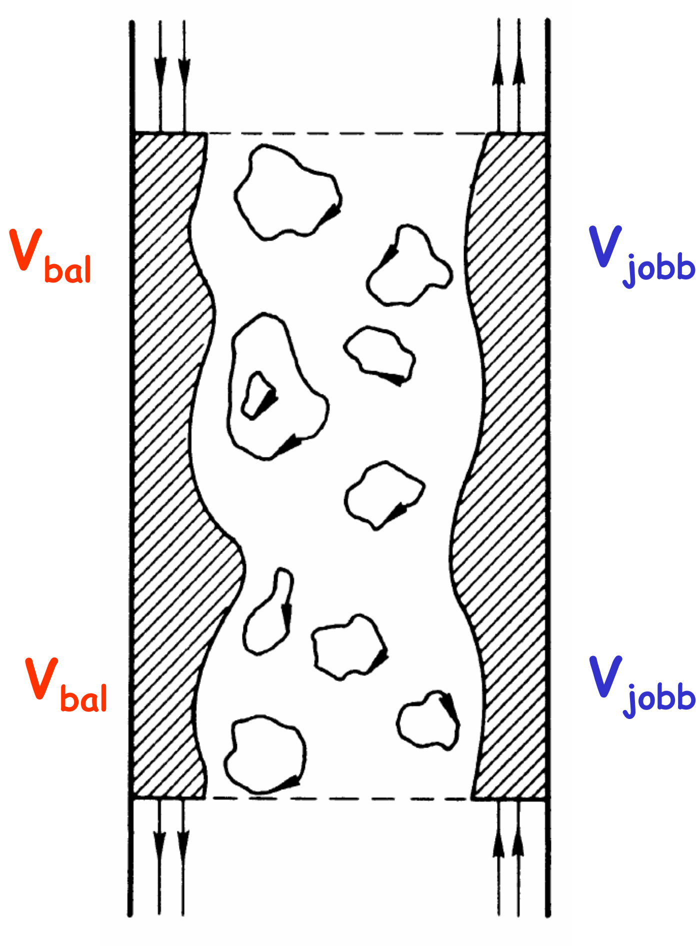
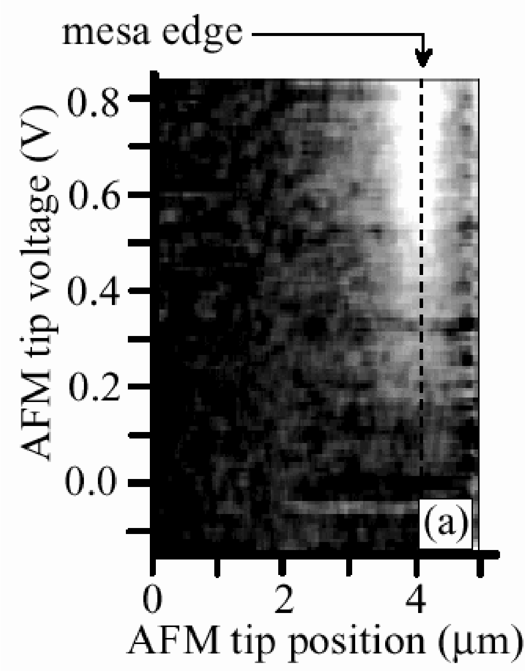
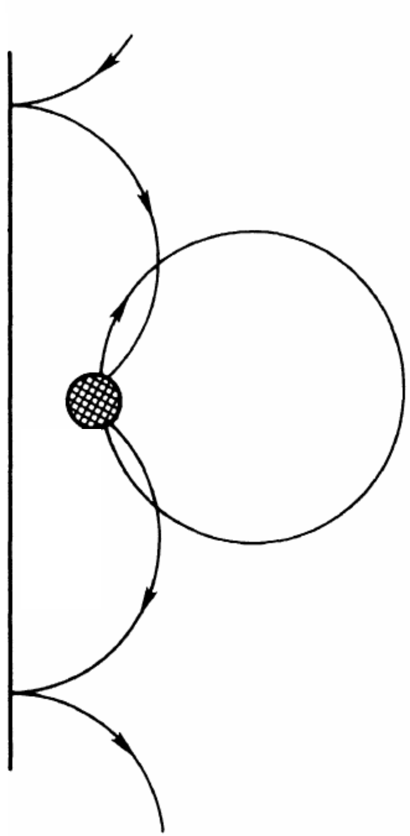


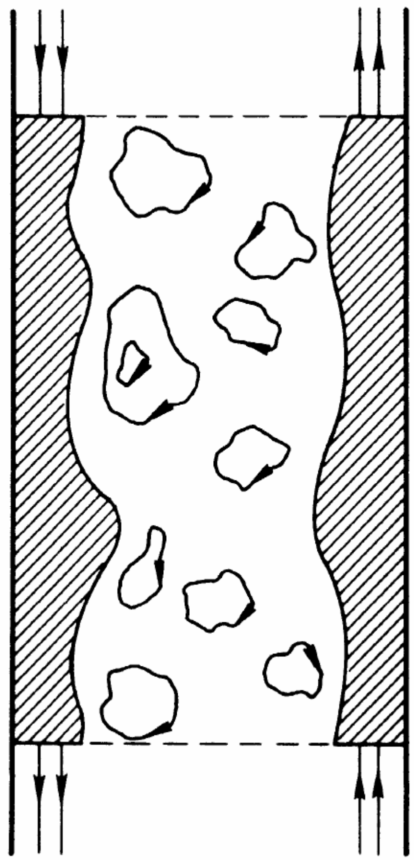
Az áramot ellentétes irányban
szállító elektronok
nem találkoznak

Kvantum Hall effektus

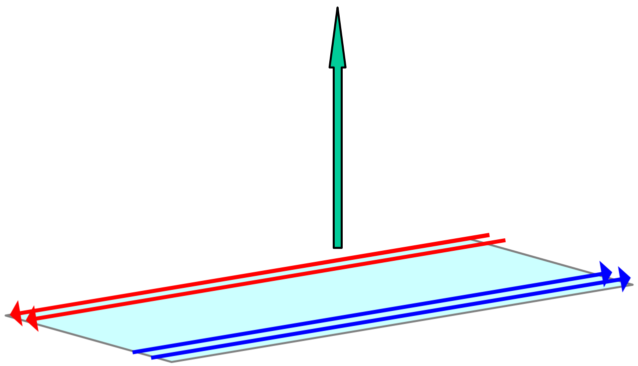
M. Büttiker, PRB **38**, 9375 (1988)

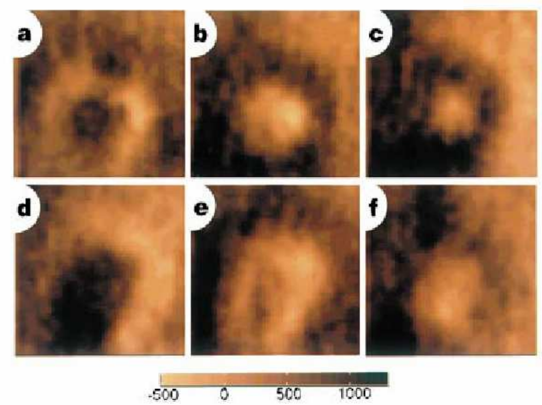




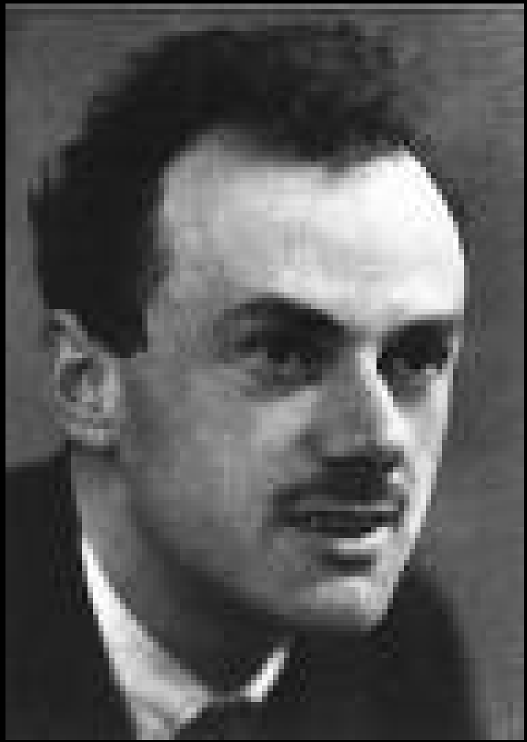


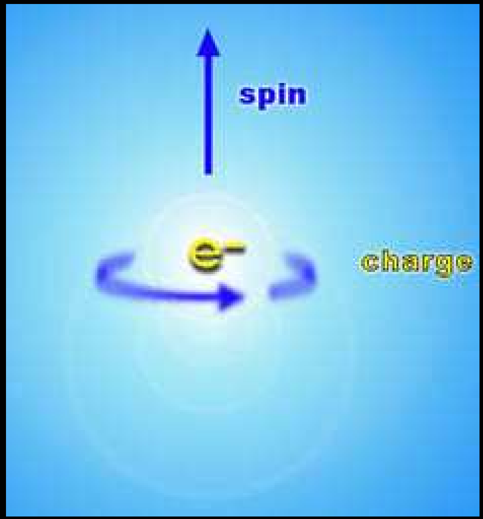
N. B. Zhitenev et al. Nature **404**, 473 (2000)





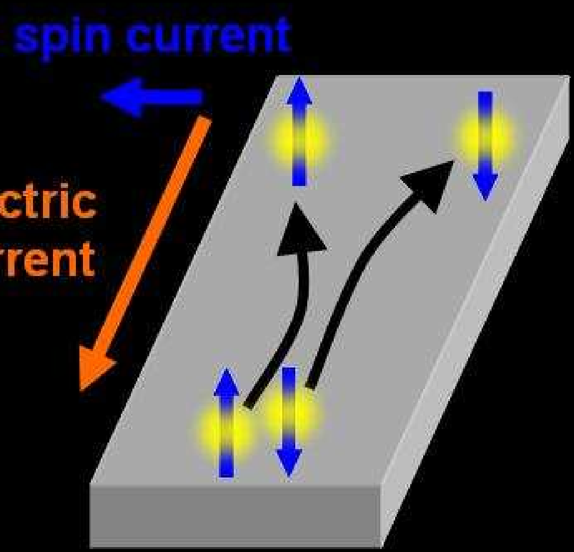
Paul Dirac
1928
relativisztikus kvantummechanika





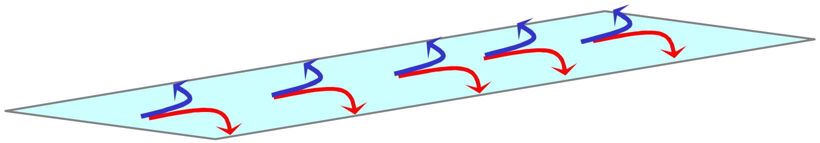
Nobel-díj 1933

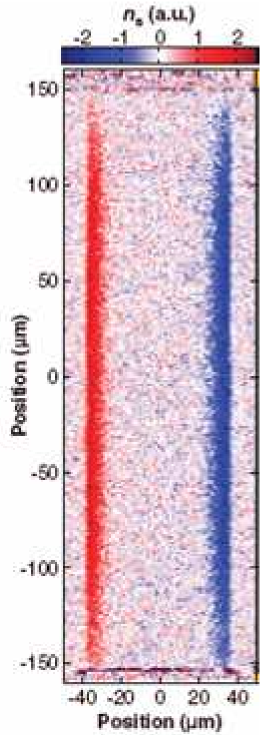
Elektron spin

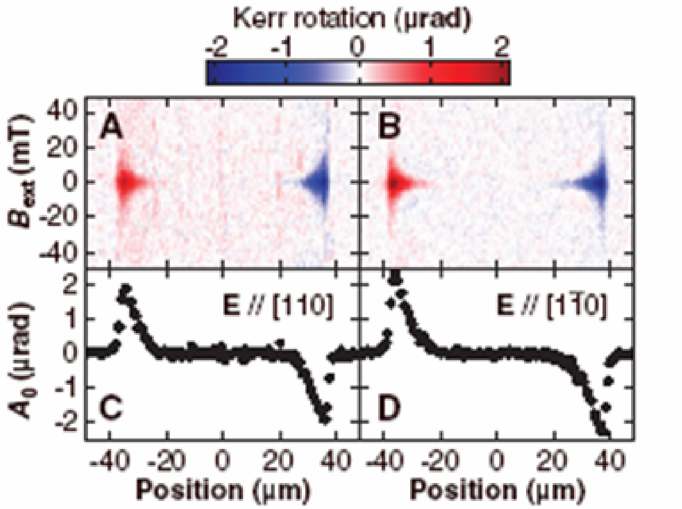


spin Hall effektus kísérleti kimutatása, 2004

spin Hall effektus
spin állapot szerint kétféle elektron, ↑↓ :
eltérő terjedés a kristályban



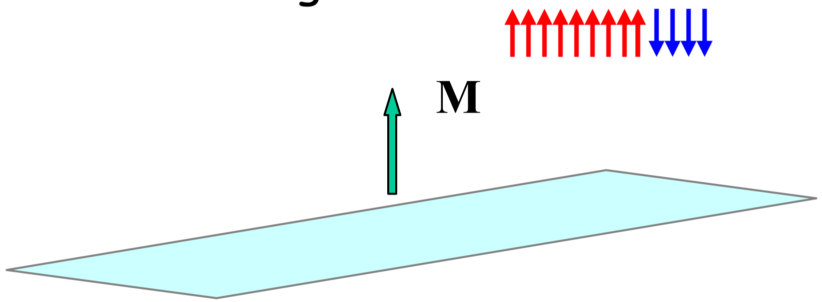




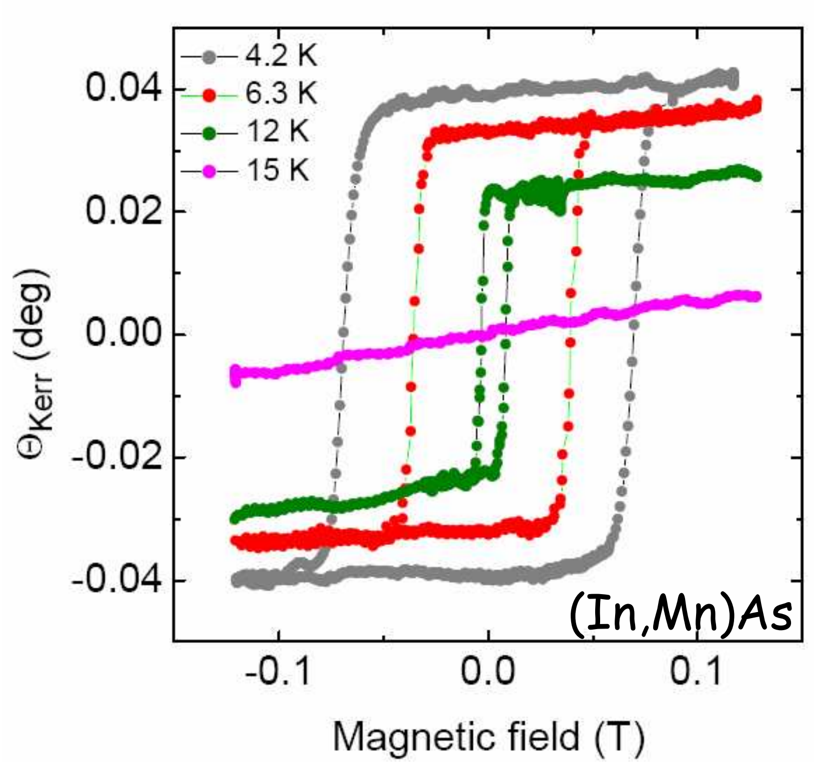
Nincs mérhető feszültség,
de a mágneses jel kimutatható

Y.K. Kato *et al.*, Science*express* 11 Nov.(2004)

Mágneses minta

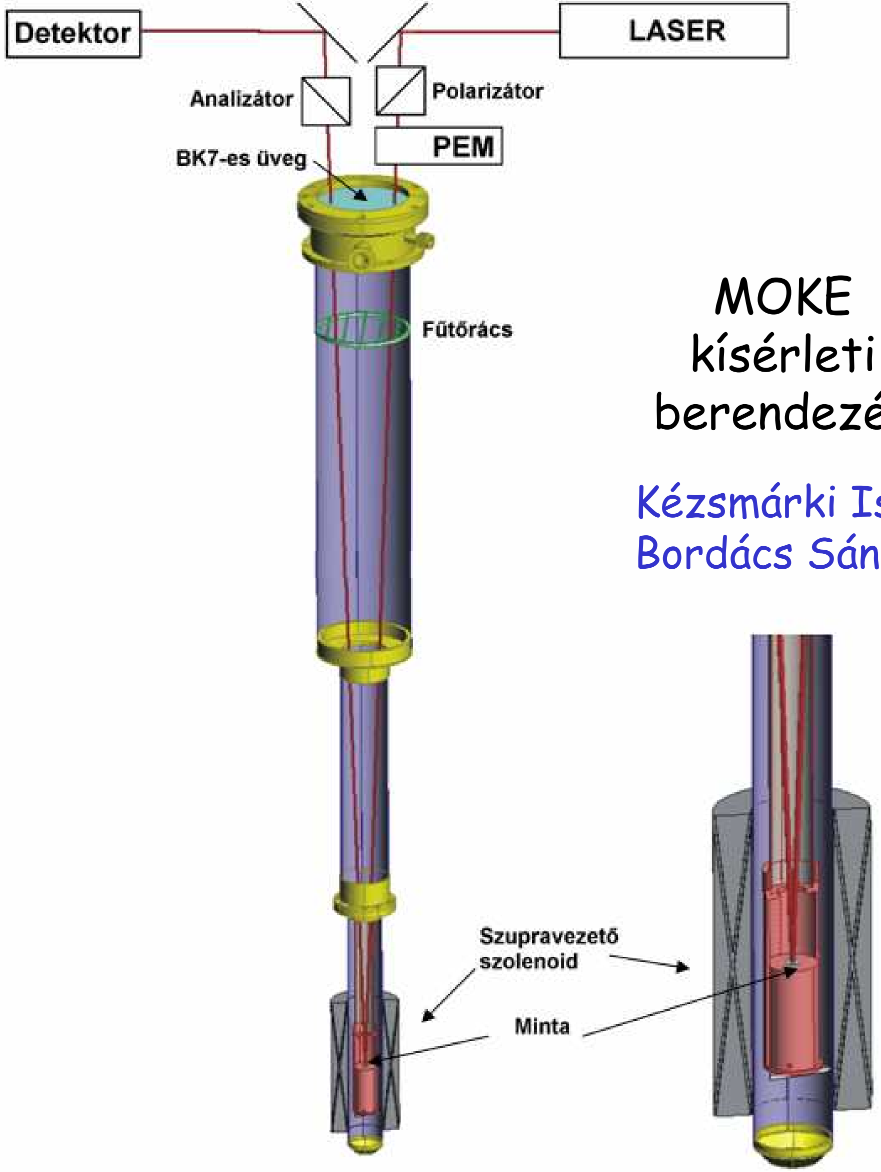


A mágnesezettség meghatározása
optikai Kerr-forgatás mérésével



Spin Hall effektus

Bordács Sándor, BME

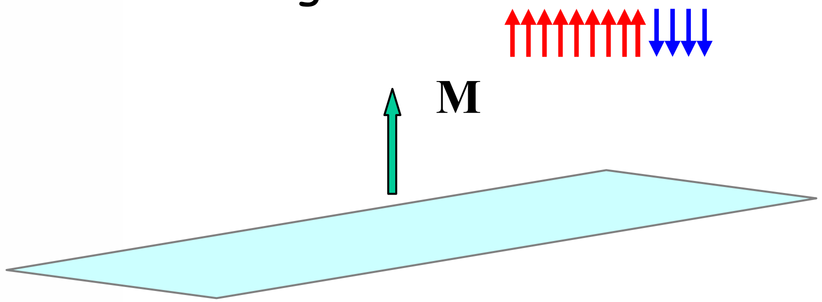


MOKE
kísérleti
berendezés

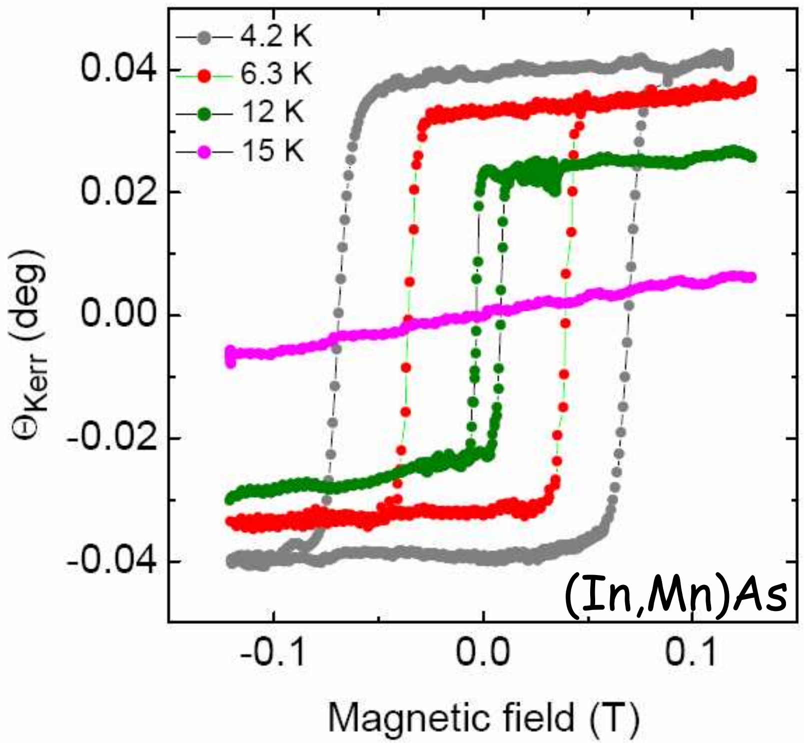
Kézsmárki István
Bordács Sándor

Szupravezető mágnes B_{max}= 14 T
Mágnesezettség felbontás ~ 5×10^{-9} emu

Mágneses minta



A mágnesezettség meghatározása optikai Kerr-forgatás mérésével



Anomális Hall effektus

Csontos Miklós, BME

spin Hall effektus
spin állapot szerint kétféle elektron, ↑↓ :
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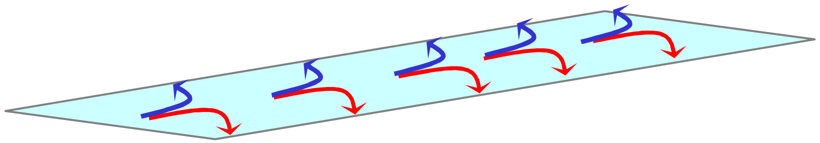
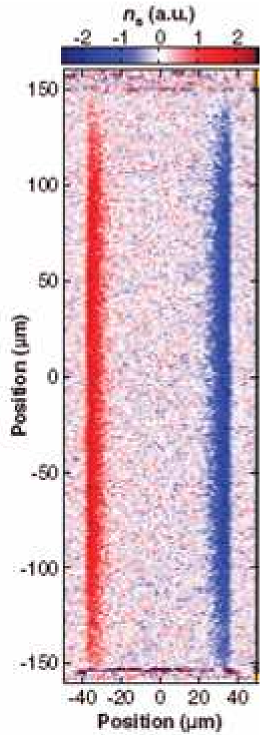
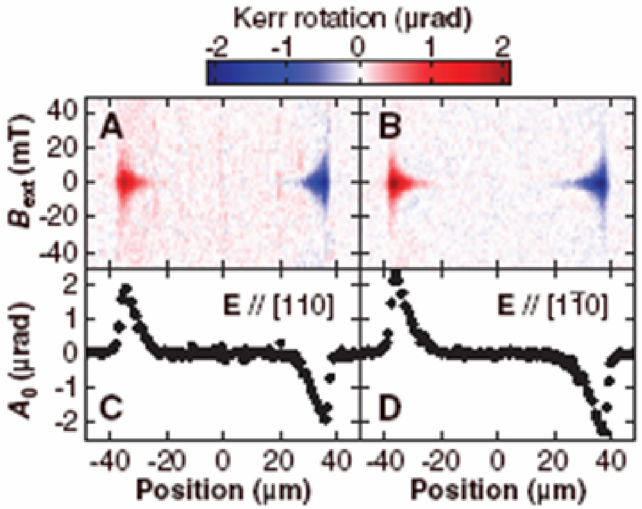


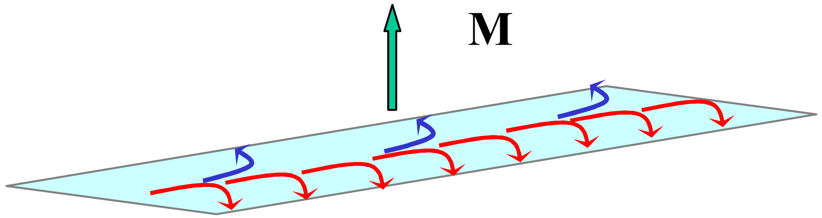


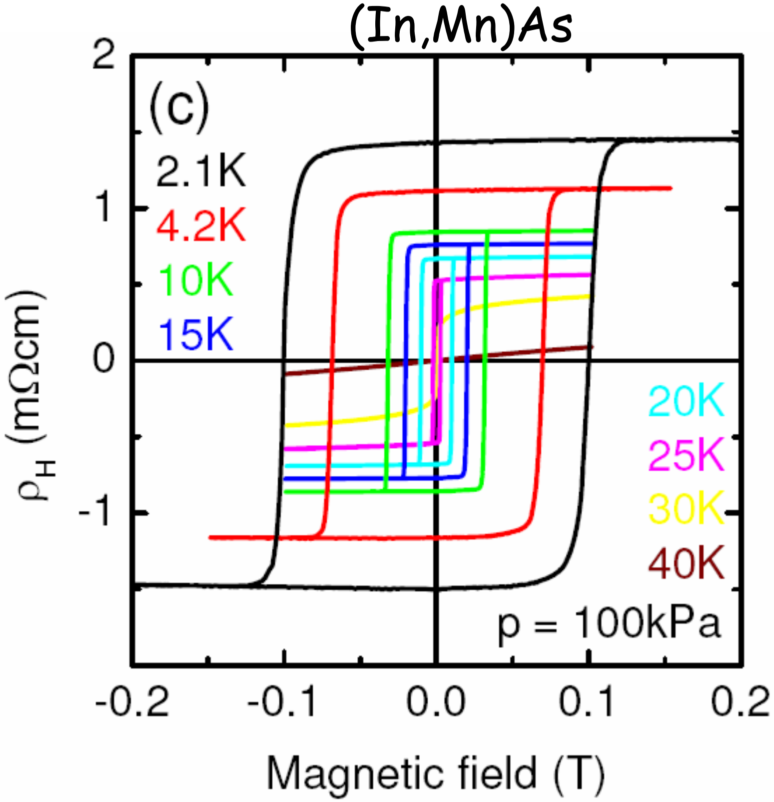


Nincs mérhető feszültség,
de a mágneses jel kimutatható

Y.K. Kato *et al.*, Science*express* 11 Nov.(2004)

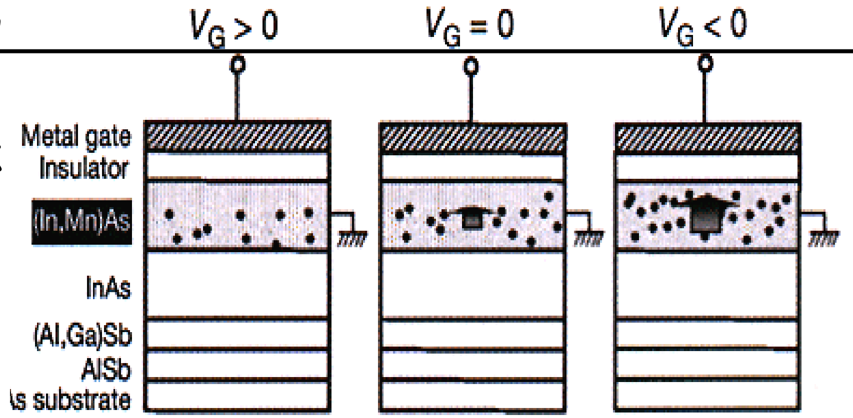
Mágneses minta
nem egyforma spin-betöltés:
keresztirányú feszültség mérhető

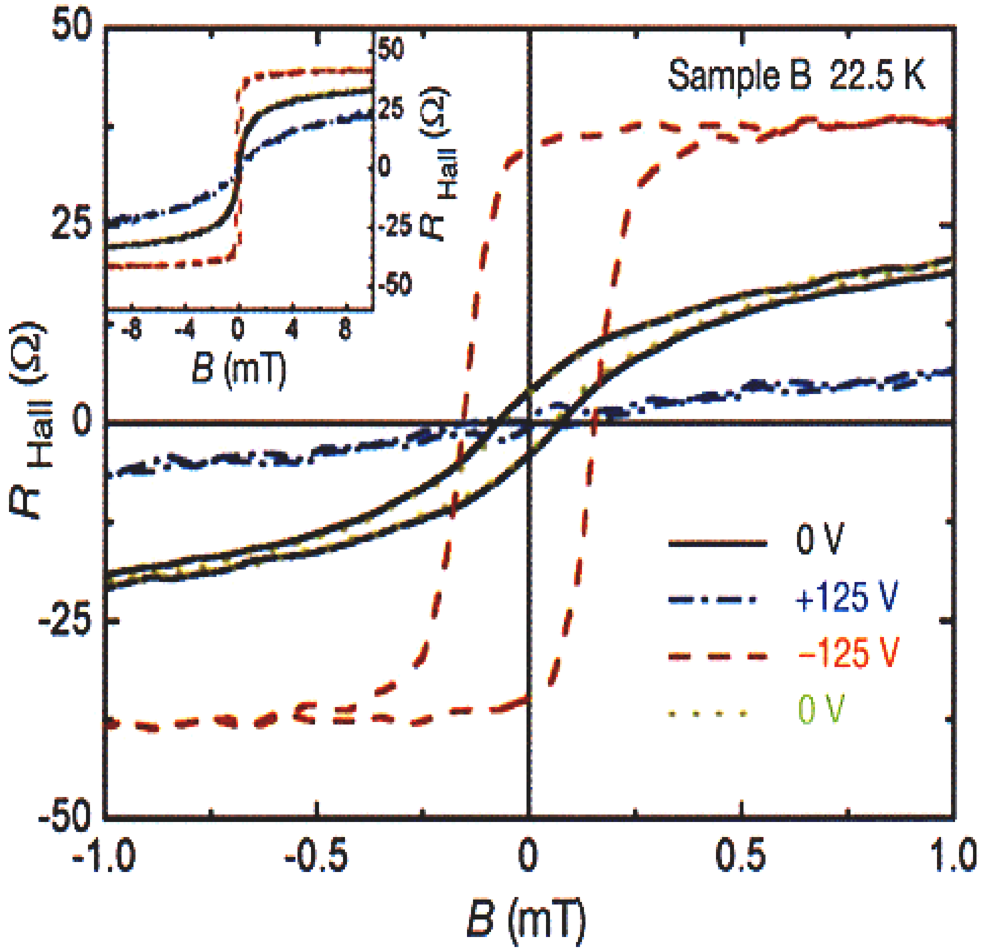




Elektromos térrel kontrollált mágnesség

1. a mágneses csatolást a lyukak közvetítik
2. a lyukak száma FET szerkezetben változtatható

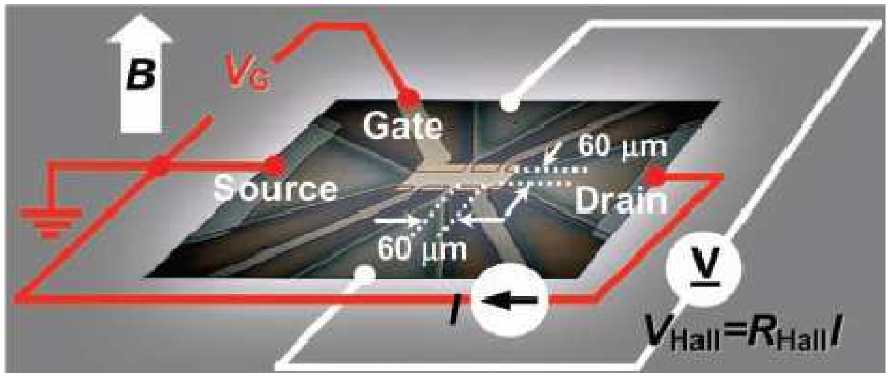




H. Ohno *et al.*, Nature **408**, 944(2000)

Elektromosan vezérelt mágneses memória

Kontroll -- kapufeszültség
Detektálás -- anomális Hall



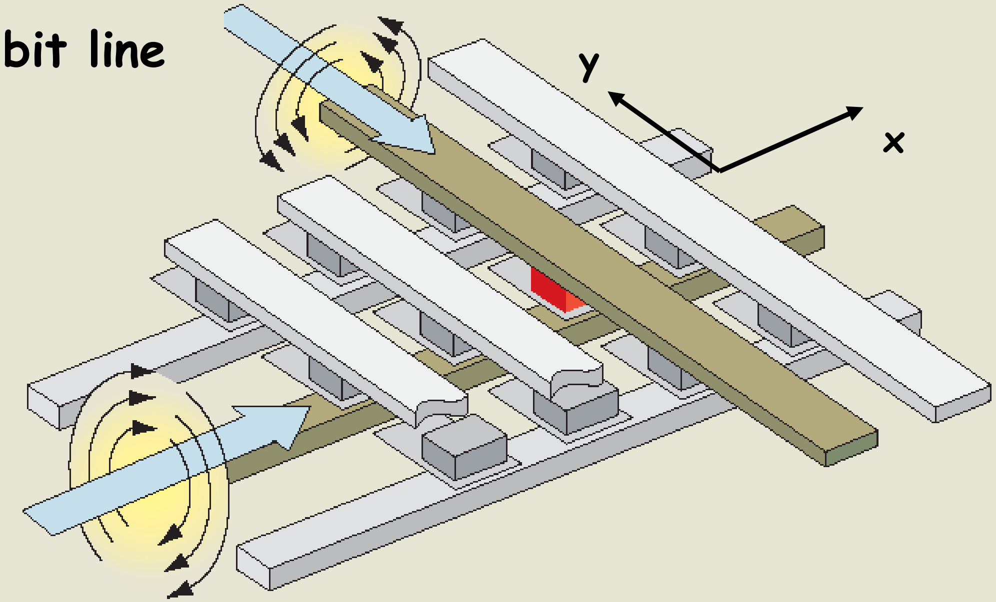
D. Chiba *et al.*, Science **301**, 943 (2003)

Spintronika – Nobel díj 2007
A.Fert, P. Grünberg

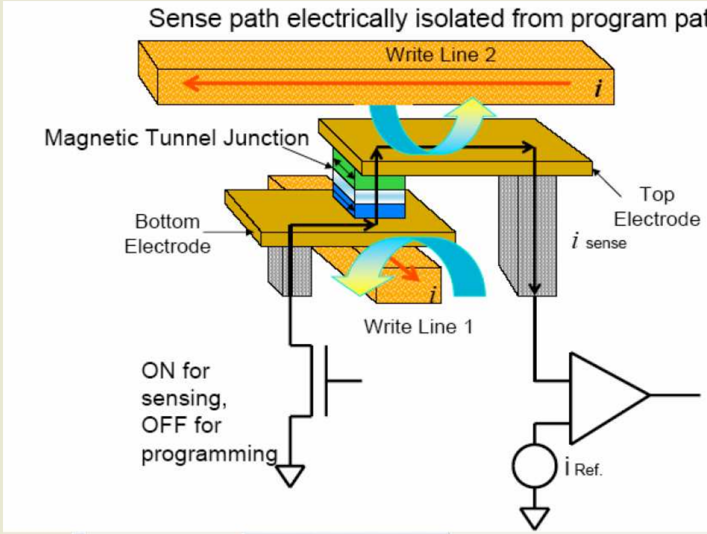
MRAM
(Magnetic Random Acces Memory)

non-volatile
1000-szer gyorsabb írás, mint a flash memory-ban
adatok elérése 1/10000 része, mint a HDD-ben

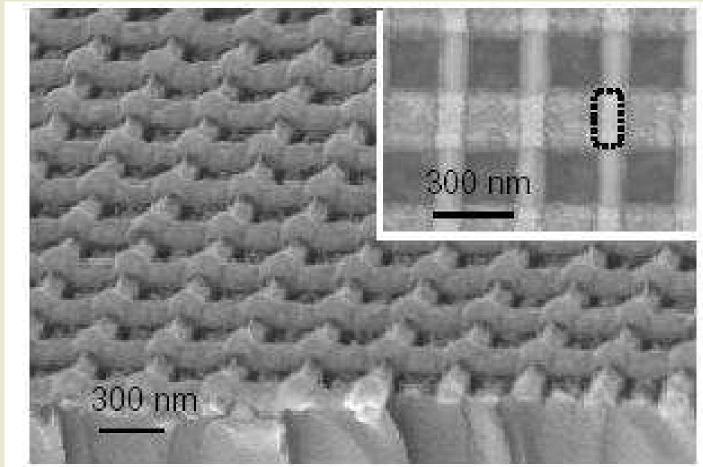
bit line



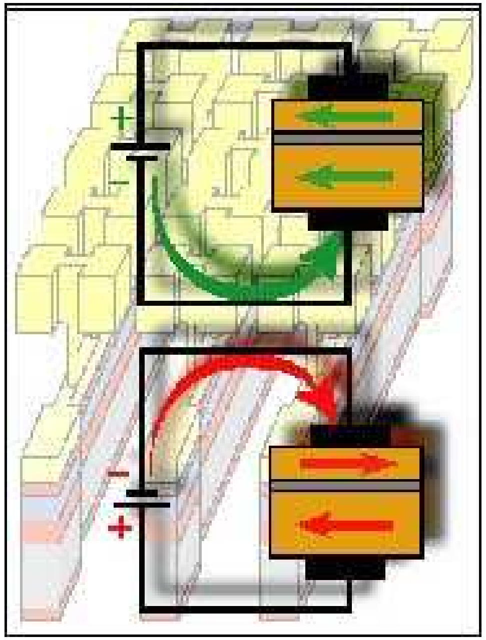
word line

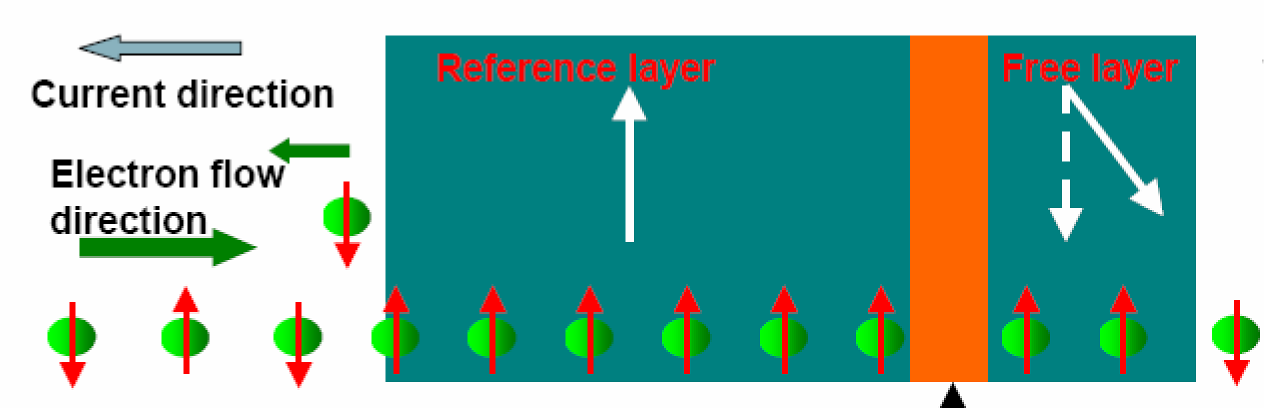


A „bit line” áramszintje alacsonyabb, mint ami szabad réteg mágnesezettségének átfordításához szükséges kivéve, ha a „word line”-ra kapcsolt áram tere

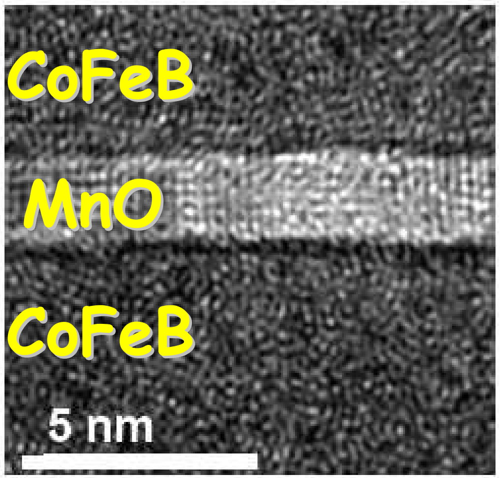


Spin fogatónyomaték

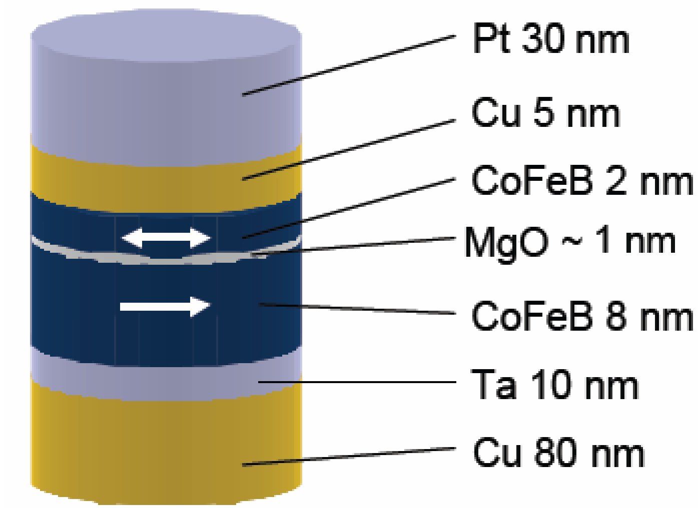




Mágneses áram !!!



Yousa *et al.*, Nature Materials **3**, 868 (2004)



Toshiba develops new MRAM device which opens the way to giga-bits capacity

06 November, 2007

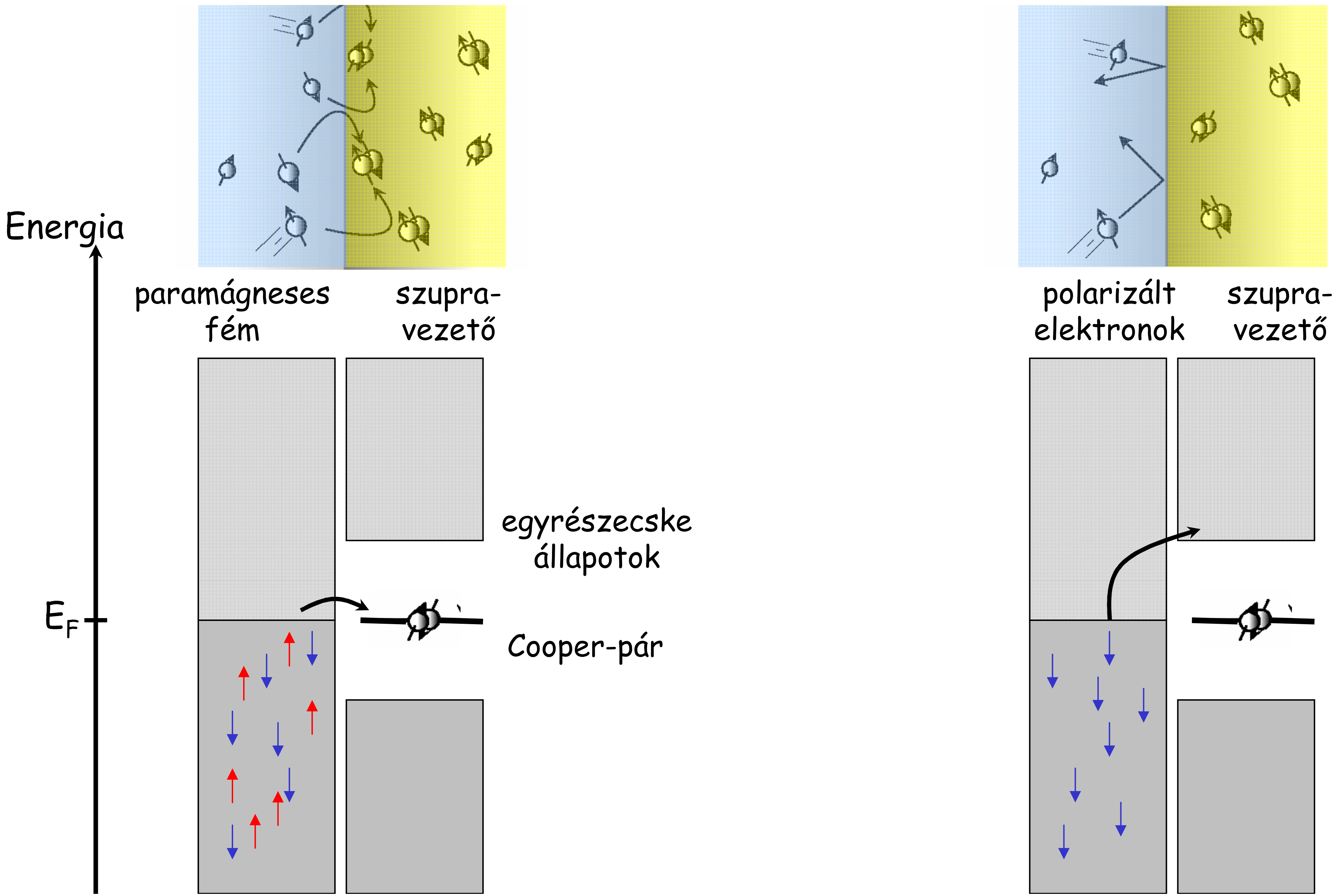
World's first perpendicular magnetic anisotropy MTJ device

Tokyo--Toshiba Corporation today announced important breakthroughs in key technologies for magnetoresistive random access memory (MRAM), a promising, next-generation semiconductor memory device. The company has successfully fabricated a MRAM memory cell integrating the new technologies and verified its stable performance.

Spin transfer switching uses the properties of electron spin to invert magnetization and writes data at very low power levels. It is widely regarded as a major candidate among next-generation principles for new memory devices.

Andrejev spektroszkópia – az elektronok spin polarizációjának mérése

Normal elektron → Cooper pár konverzió



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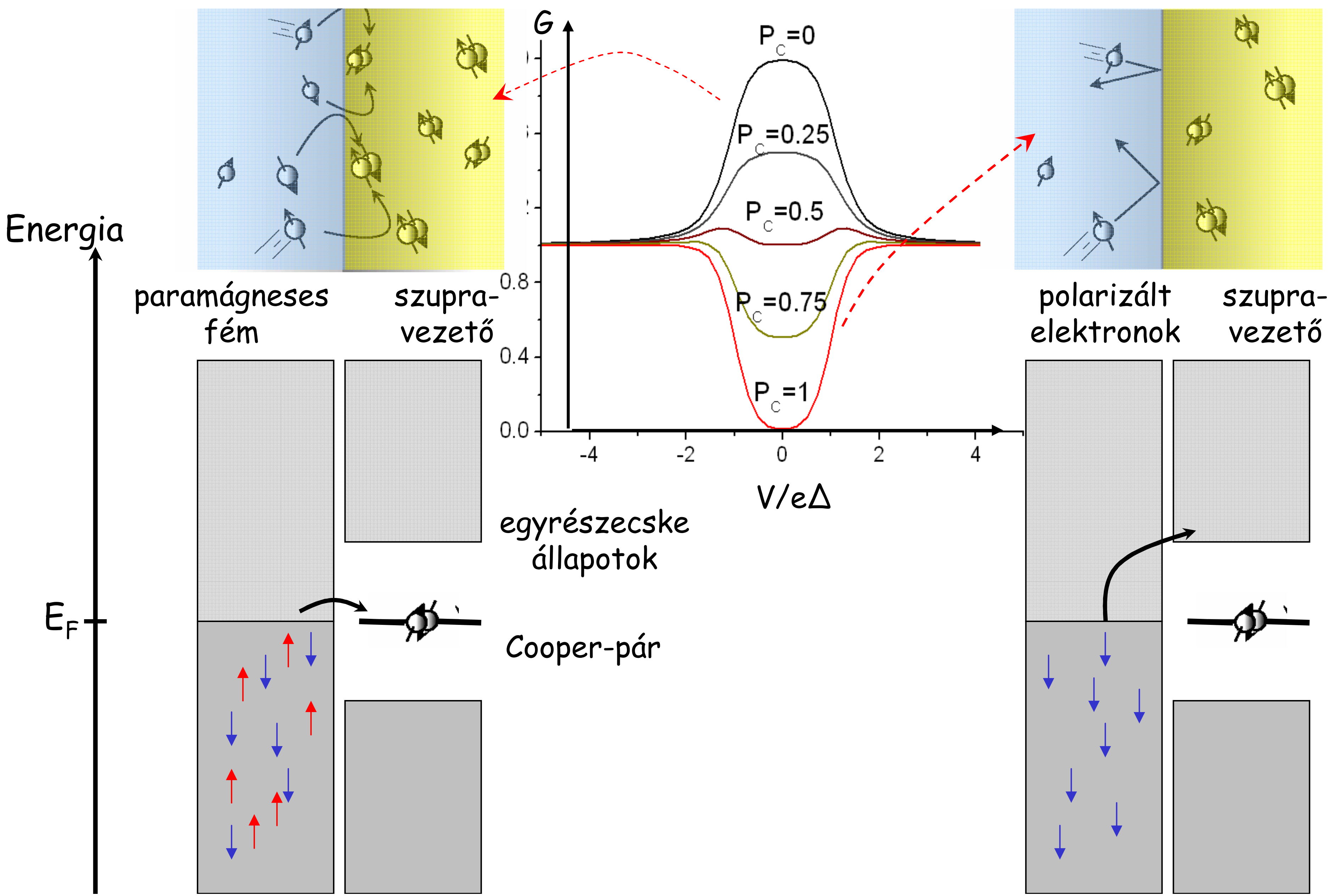
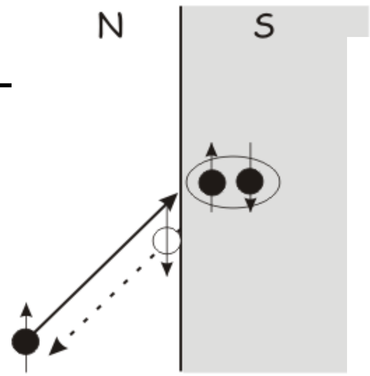
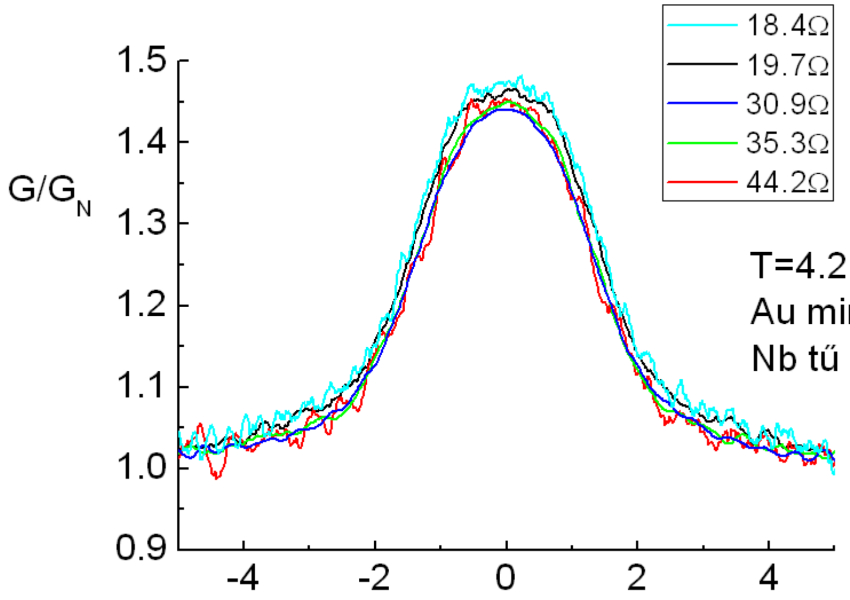


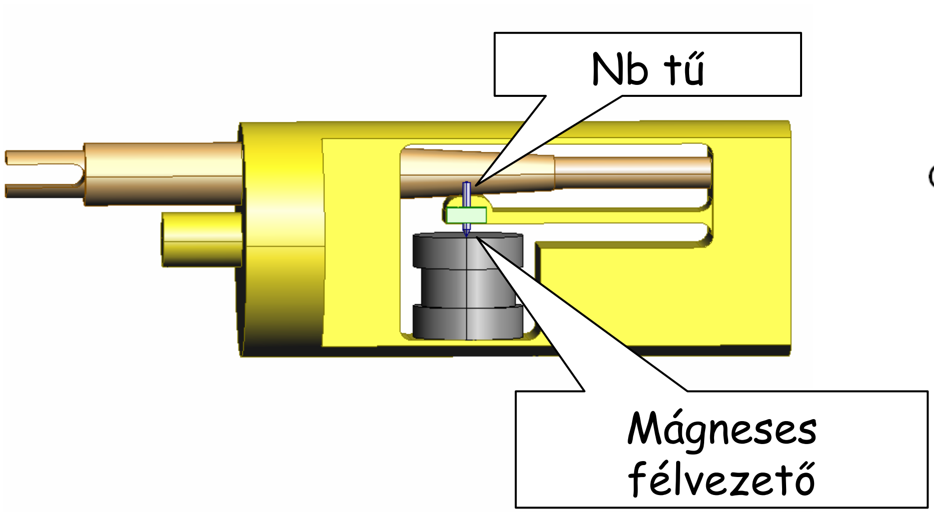
Andrejev reflexió

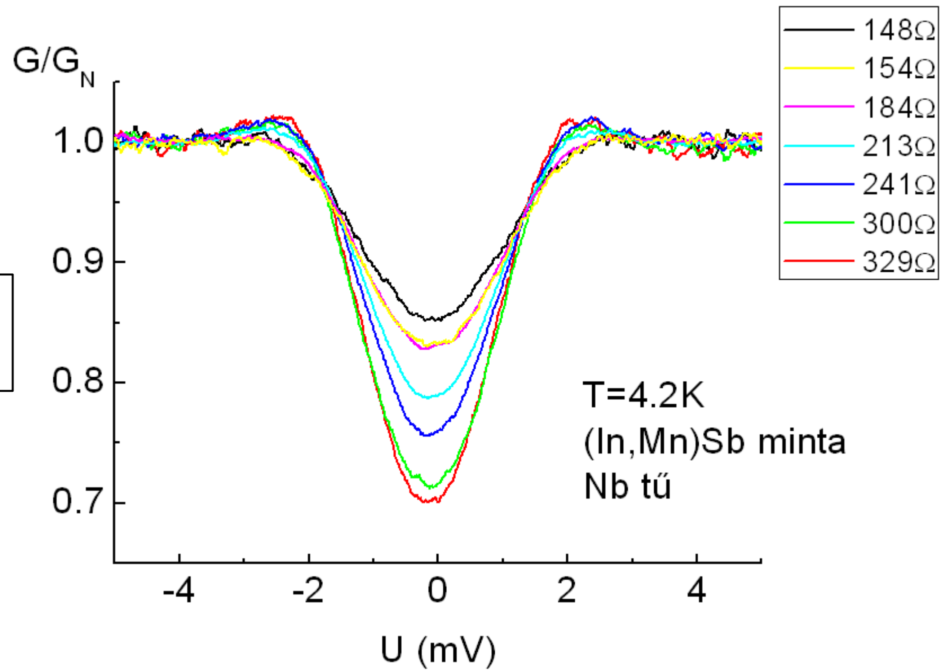
A.F. Andrejev:
JETP 19 1228 (1964)





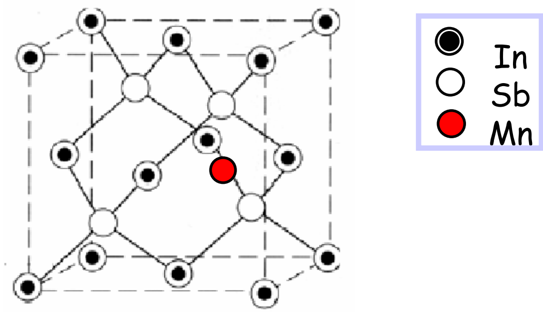
Néhány nanométeres kontaktus

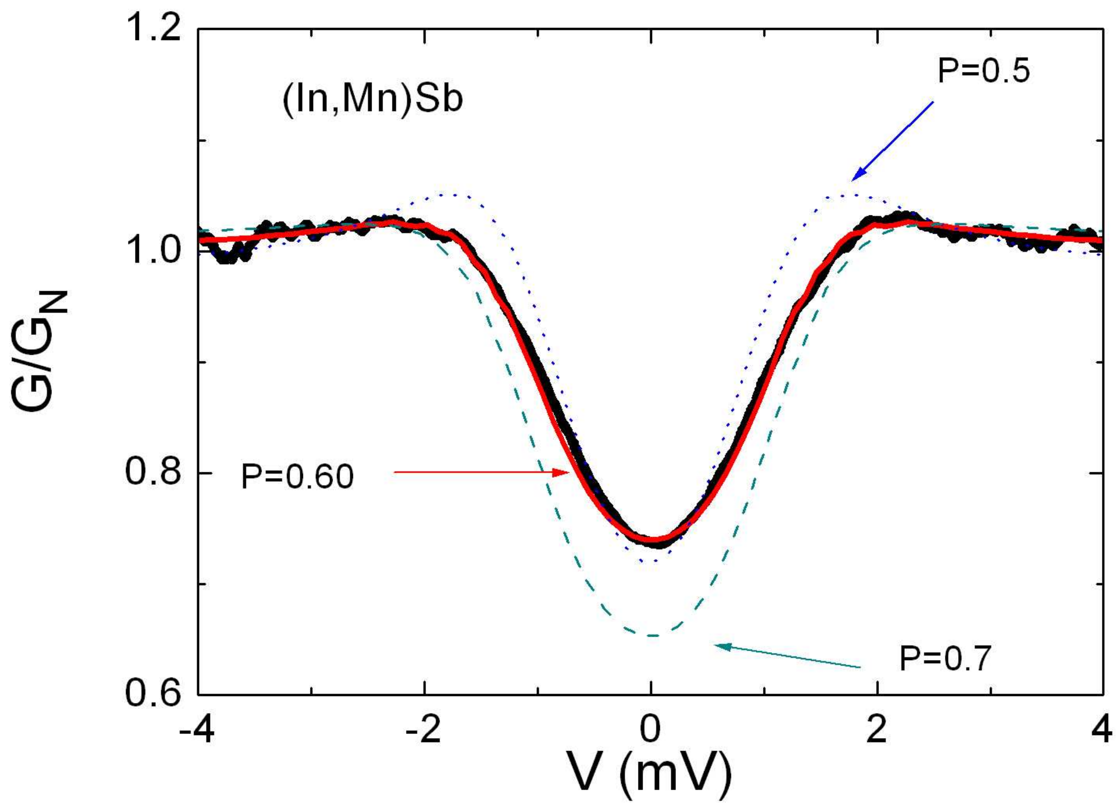


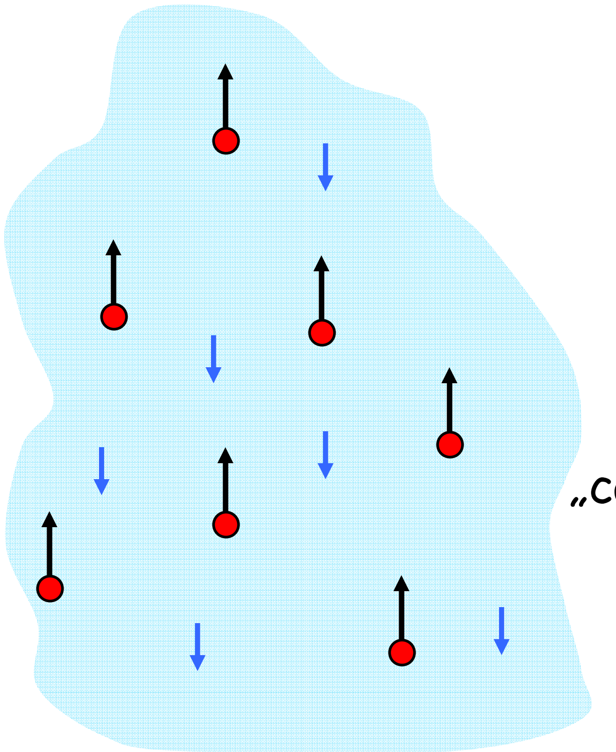


Halbritter András
Geresdi Attila

Spin-polarizáció (In,Mn)Sb mágneses félvezetőben



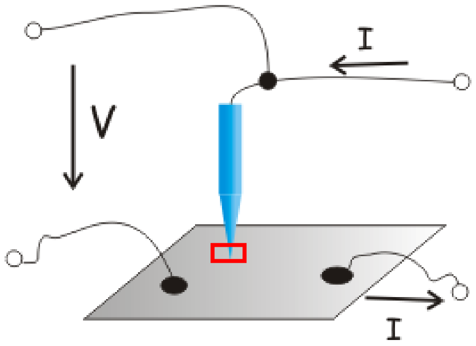




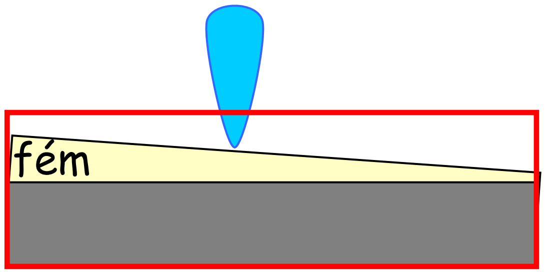
„carrier mediated magnetic coupling"

M. Csontos *et al.*, Nature Materials **4**, 447 (2005)
M. Csontos *et al.*, Phys. Rev. Lett. **95**, 227203 (2005)
A. Geresdi *et al.*, Nano Letters (2008)
G. Mihály *et al.*, Phys. Rev. Lett, March (2008)

Mágneses mikroszkópia

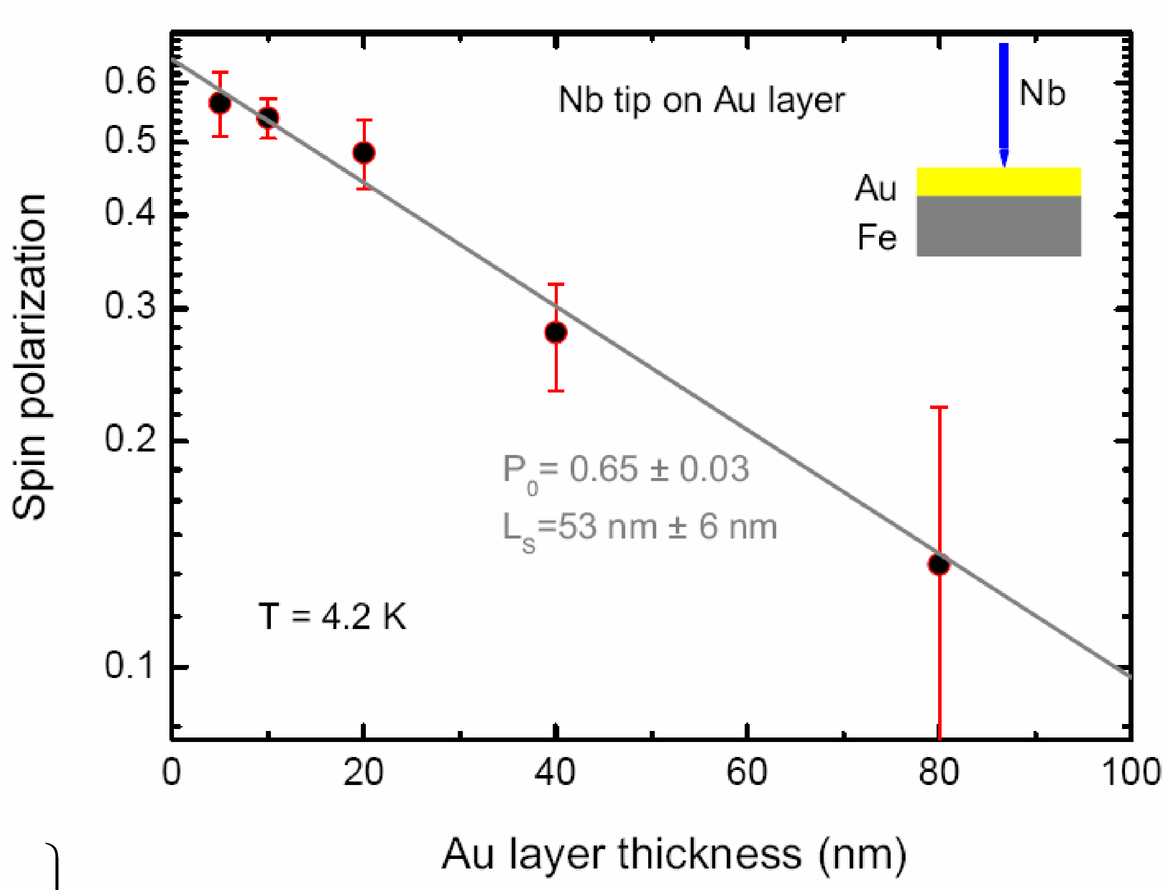


Spin diffúziós hossz

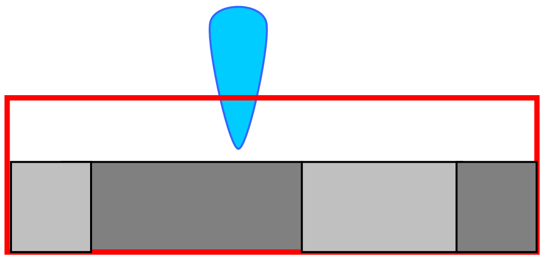


Mágneses fém

$$P = P_o \exp\left\{-\frac{l}{\sqrt{D\tau_s}}\right\}$$



Geresdi Attila, BME



Mágneses szerkezetek meghatározása nanométeres méretskálán

Konklúzió

A klasszikus gondolatment alapján megértettnek hitt jelenség (pl. Hall effektus) igazi magyarázata már kvantumfizikai szemléletet feltételez.

Az alacsony hőmérsékleteken tapasztalt meglepő jelenségek (szupravezetés, kvantum Hall effektus) megértése sokszor egyszerűbb, mint a megszokott tulajdonságok korrekt leírása.

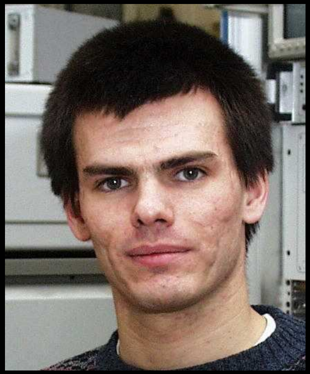
Az újonnan megfigyelt spin-függő jelenségek (pl. az anomális Hall-effektus mágneses félvezetőkben), igen gyorsan a spintronikai eszközök működési elvévé válnak.

Az Andrejev kísérletek felfedik az áram „mágnességét". Ez a mennyiség meghatározó a nanoméretű mágneses memóriák írásánál – spin-forgatónyomaték.

http://dept.phy.bme.hu/egzotikus.pdf

Munkatársak

Kézsmárki
István



Halbritter
András

Csonka
Szabolcs

Csontos
Miklós

Demkó
László

Bordács
Sándor

Makk
Péter

Geresdi
Attila

Ideális vezetés

Shcrödinger egyenlet

$$-\frac{\hbar^2}{2m}\nabla^2\psi = \varepsilon\psi$$

síkhullám

$$\psi(\mathbf{r}) = \frac{1}{\sqrt{V}}e^{i\mathbf{kr}}$$

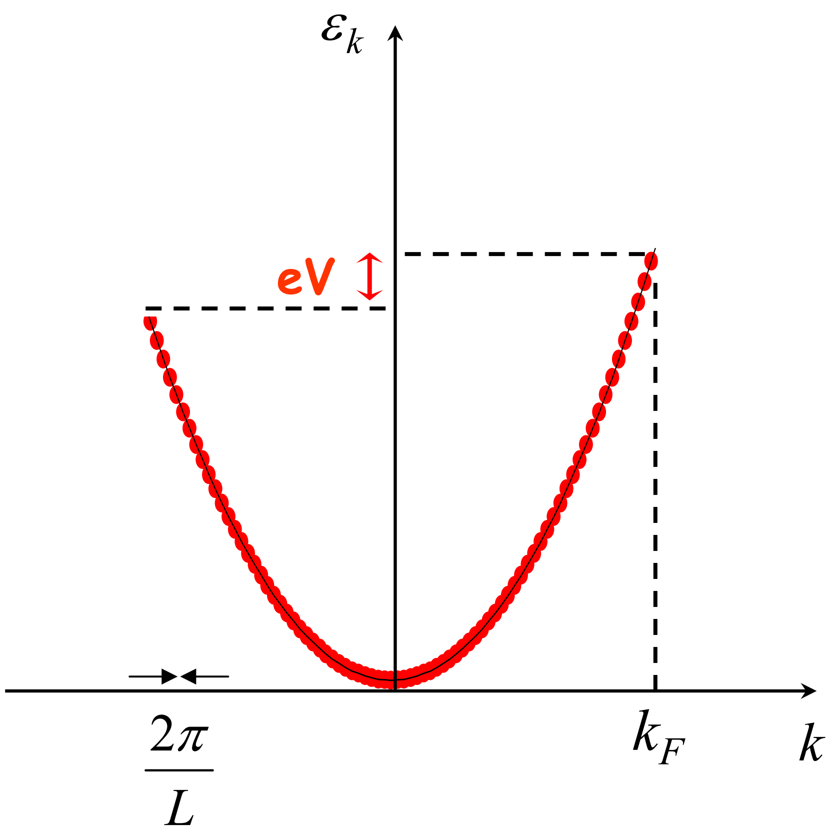
energia $\varepsilon(\mathbf{k}) = \frac{\hbar^2\mathbf{k}^2}{2m}$

impulzus $\mathbf{p} = \hbar\mathbf{k}$

Áram $\mathbf{j} = ne\mathbf{v}$

Sebesség $\mathbf{v} = \frac{\mathbf{p}}{m} = \frac{\hbar\mathbf{k}}{m} = \frac{1}{\hbar}\frac{\partial\varepsilon}{\partial\mathbf{k}}$

Elektronok sűrűsége $n = 2\left(\frac{1}{L}\right)\frac{eV}{\frac{\partial\varepsilon}{\partial\mathbf{k}}}\left(\frac{L}{2\pi}\right)$



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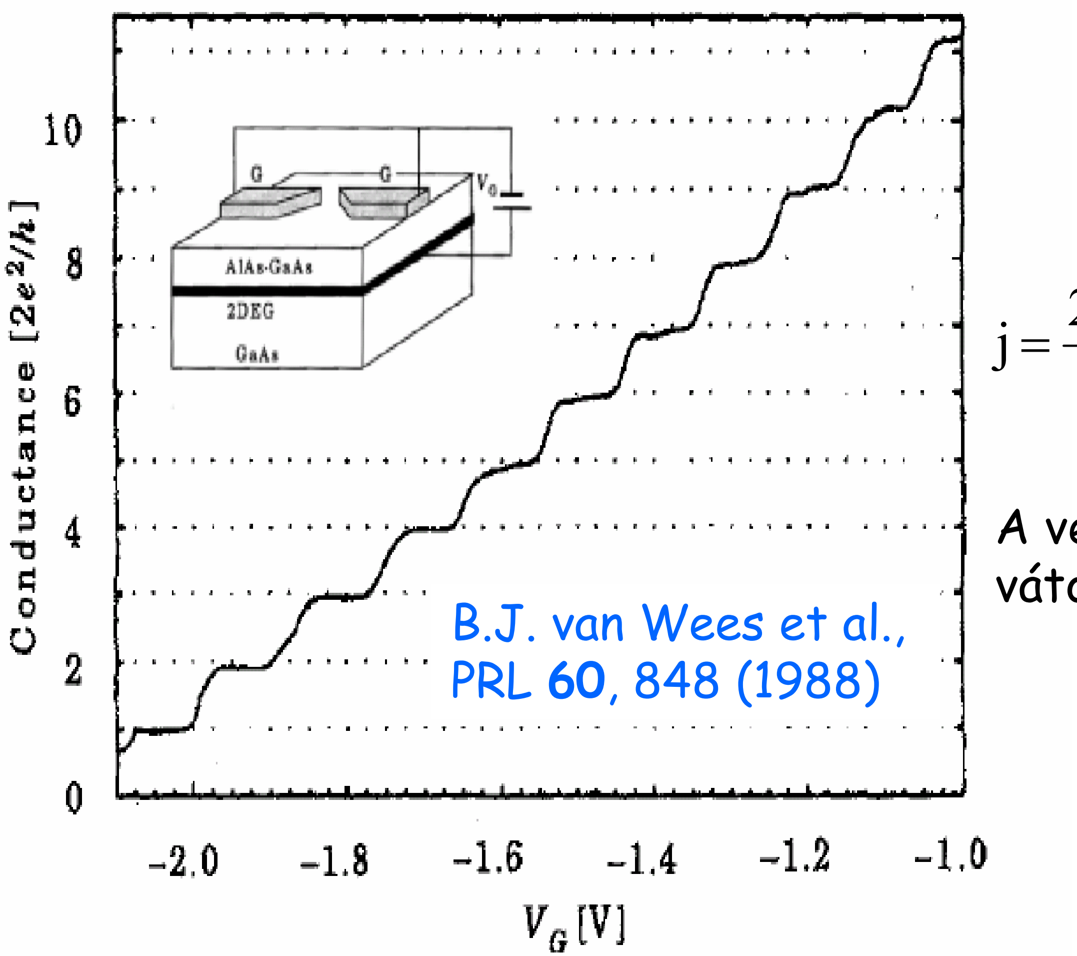

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A vezetési csatornák száma lépésekben vátozik a keresztmetszet növelésével