Fundamentals of spin physics in semiconductors

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- What is spin? - General introduction
- Historical background
- Spin interactions
- Optical spin orientation and detection
- The Hanle effect
- Spin relaxation
- Spin-related transport phenomena
- The electron-nuclear spin system

General introduction

The electron spin was discovered by Gaudsmith an Uhlenbeck in 1923

Spin is the internal angular momentum of a particle

For an electron, its projection on ***any*** axis is ±1/2 (in units of $\hbar$)

$S_z = \pm 1/2$, and similar for S_x and S_y. However $\boldsymbol{S}^2 = 3/4$! Isn't this bizarre?

Associated with spin, there is a *magnetic moment*

For an electron $\mu = \dfrac{e\hbar}{2mc}$ (Bohr's magneton)

Zeeman energy: $E = \pm \mu B$

What is the origin of the electron magnetic moment?

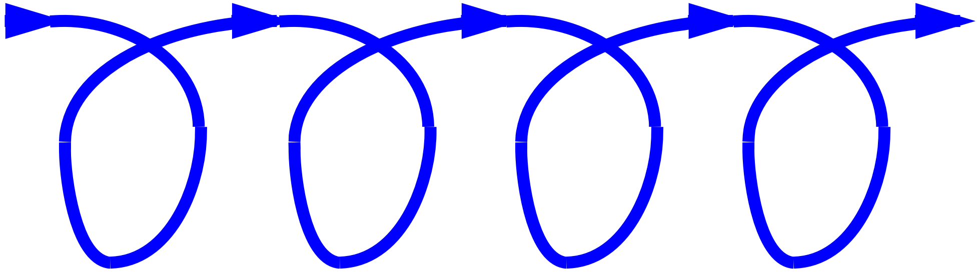
For a charged rotating sphere of radius r and velocity at equator v one finds:

$$\mu \sim \frac{erv}{c}$$

The “classical radius” of an electron is $r \sim e^2/mc \sim 10^{-13}$ cm. Then, to obtain the correct value of μ one needs a velocity v ~ *137* c *!* This is not nice...

The correct order of magnitude for μ is obtained if one assumes that charge e rotates with the speed of light c around the Compton radius $r \sim \hbar/mc \sim 10^{-10}$ cm

The fascinating picture of *Zitterbewehgung* of a ***free*** electron:



Spins and magnetic moments of other particles

The proton and the neutron also have spin 1/2

Both have magnetic moments ~ $\dfrac{e\hbar}{mc}$, where now m is the ***proton*** mass

Thus the magnetic moments of the proton, neutron, and nuclei is

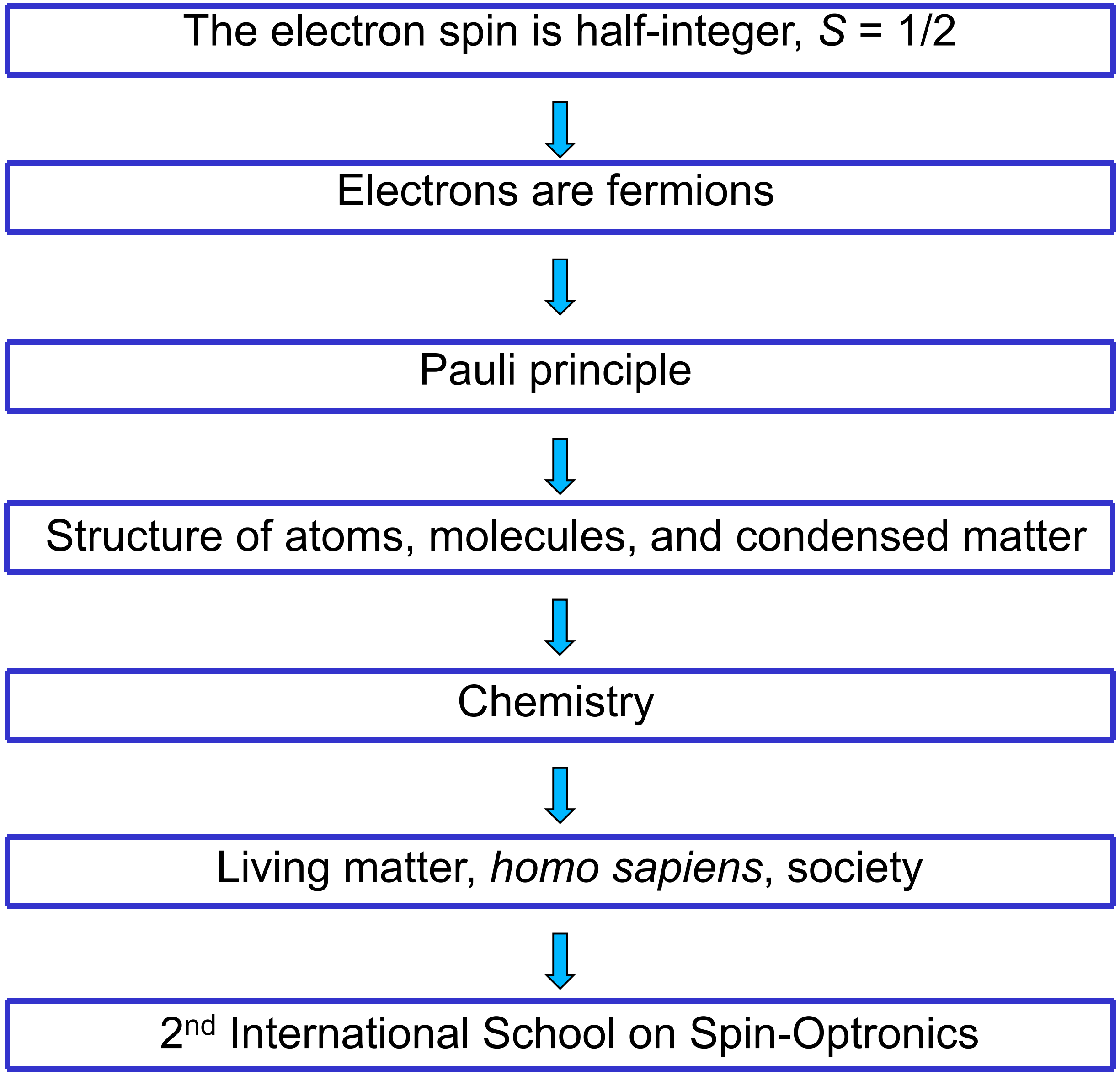
~ 2000 times smaller than the moment of an electron!

Nuclei with *even* number of protons + neutrons normally have $S = 0$ (and $\mu = 0$ too)

If the number of protons + neutrons is *odd*, the nucleus can have any half-integer spin

Examples: ^{4}He has $S = 0$, ^{3}He has $S = 1/2$, ^{113}In has $S = 9/2$

The role of spin in Nature



The electron spin is half-integer, $S = 1/2$

↓

Electrons are fermions

↓

Pauli principle

↓

Structure of atoms, molecules, and condensed matter

↓

Chemistry

↓

Living matter, *homo sapiens*, society

↓

2nd International School on Spin-Optronics

Historical background

Roots of “spintronics”

Atomic physics

Polarized luminescence (Wood, 1923)

Depolarization by magnetic field (Wood, 1923; Hanle, 1924)

Optical pumping (Kastler, Brossel, 1950)

Magnetic resonances

Nuclear magnetic resonance (Rabi, 1938)

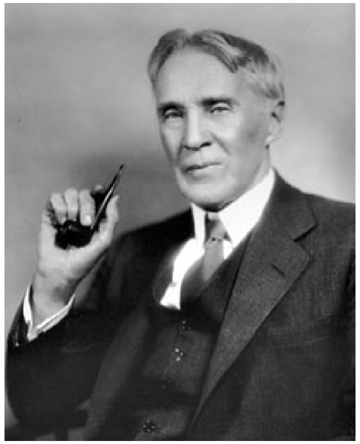
Electron spin resonance (Zavoisky, 1944)

Roots

R.W. Wood and A. Ellett

"Polarized resonance radiation in weak magnetic fields"

Phys. Rev. **24**, 243 (1924)



Robert Wood
(1868-1955)

W. Hanle

"Über magnetische Beeinflussung der Polarisation der Resonanz-Fluoreszenz"

Z. Physik **30**, 93 (1924)

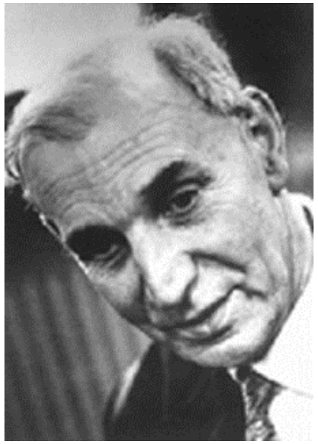
Wilhelm Hanle
(1901-1993)

Roots

J. Brossel, A. Kastler,

> “La détéction de la résonance magnétique des niveaux excités – l’effet de depolarization des radiations de résonance optique et de fluorescence”

Compt. Rend. Hebd. Acad. Sci. **229**, 1213 (1949)



Alfred Kastler
(1902-1984)

Jean Brossel
(1918-2003)

Roots

1938 - Discovery of the Nuclear Magnetic Resonance

Isidor Rabi
(1898-1988)

1944 - Discovery of the Electron Spin Resonance

Evgeny Zavoisky
(1907-1976)

First experiment on optical spin orientation of free electrons in a semiconductor

VOLUME 20, NUMBER 10 PHYSICAL REVIEW LETTERS 4 MARCH 1968

NUCLEAR DYNAMIC POLARIZATION BY OPTICAL ELECTRONIC SATURATION AND OPTICAL PUMPING IN SEMICONDUCTORS*

Georges Lampel
Ecole Polytechnique,† Paris, France

Georges Lampel 2009

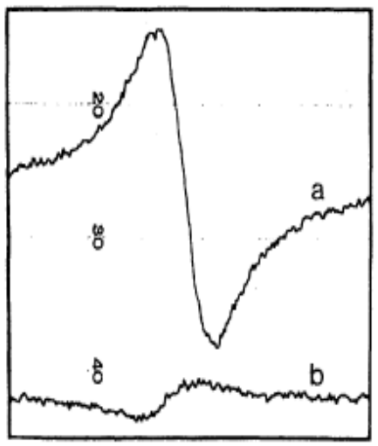


FIG. 1. Curve *a*: Signal proportional to the Si^{29} magnetization obtained in $H_0 = 1$ G after 21 h of irradiation with circularly polarized light at 77°K. Curve *b*: Signal proportional to the equilibrium Si^{29} magnetization in $H_0 = 6$ kG at 300 °K.

Spin interactions

Direct magnetic interaction – the dipole-dipole interaction between the magnetic moments of a pair of electrons. Order of magnitude $\sim \mu^2/r^3$.

Normally negligible for electrons, however important for nuclear spins

Exchange interaction – Coulomb interaction between electrons, which becomes spin-dependent because their wavefunction must be anti-symmetric.

Is at the origin of ferromagnetism. Important in magnetic semiconductors

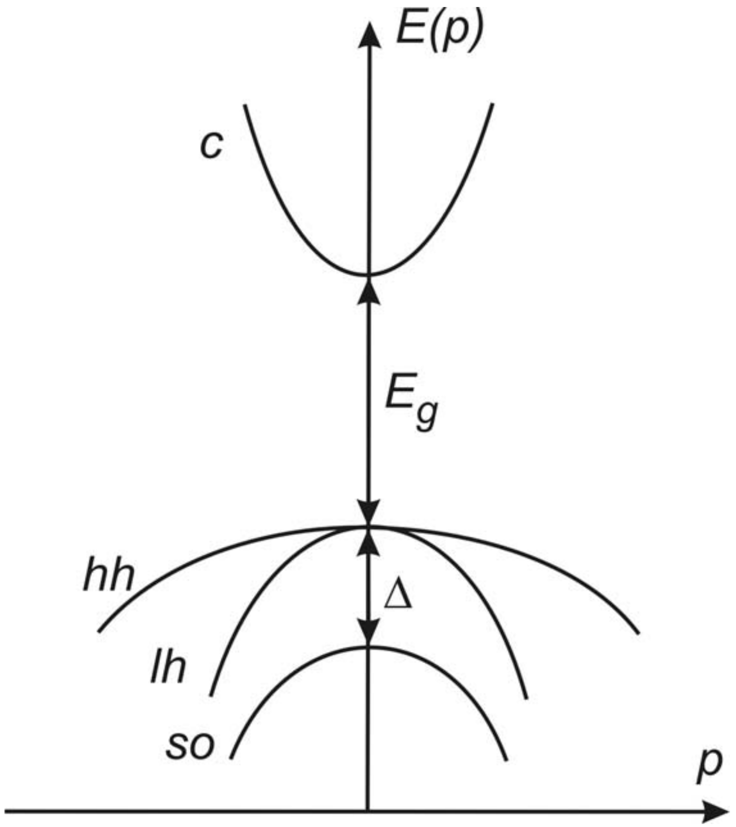
Spin-orbit interaction – If an observer moves with a velocity $\boldsymbol{v}$ in an external electric field $\boldsymbol{E}$, he will see a magnetic field $\boldsymbol{B} = (\mathbf{v}/c)\times\boldsymbol{E}$. Thus there is an effective magnetic field acting on the magnetic moment (spin) of a moving electron. Stongly enhanced for atoms with large Z.

This interaction is responsible for most of the spin-related optical and transport effects

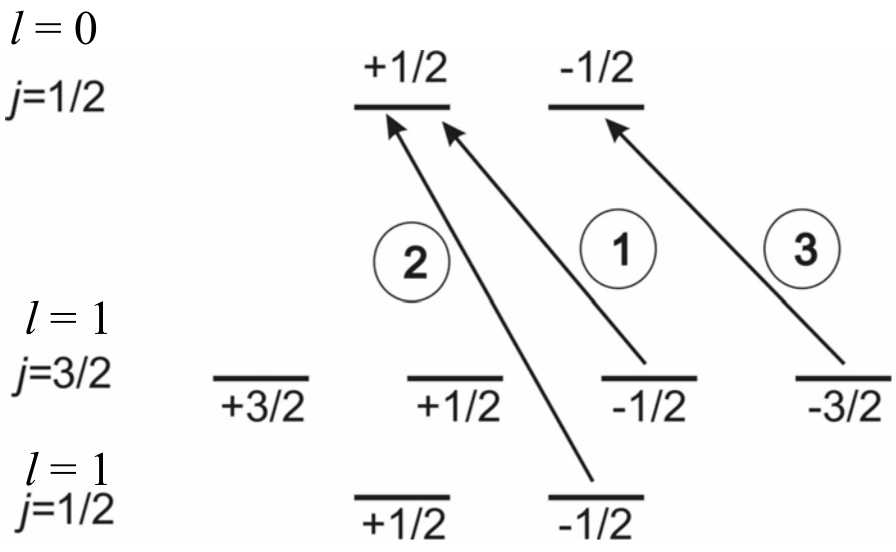
Hyperfine interaction with lattice nuclei – Magnetic interaction between the electron and nuclear magnetic moments. Important for bands originating from *s*-states in atoms with large *Z.*

Leads to spectacular phenomena in the strongly coupled electron – nuclei spin system

Optical spin orientation and detection



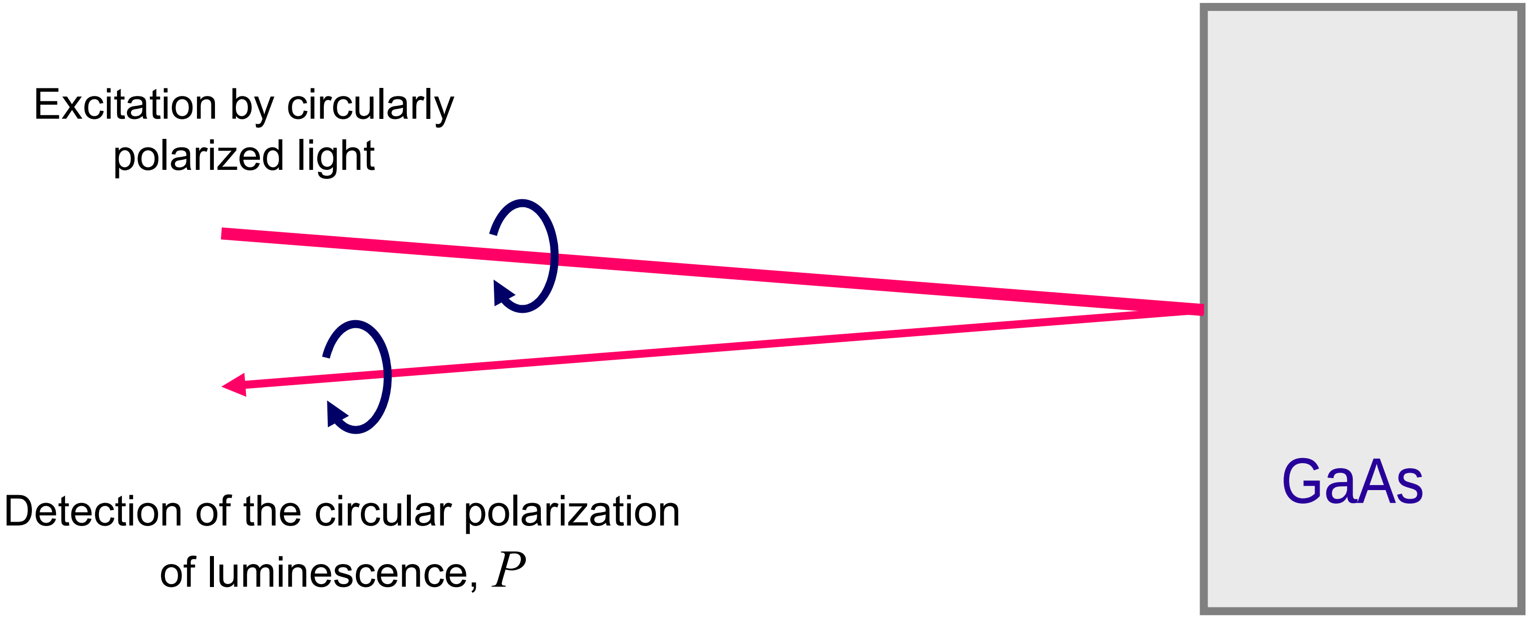
Band structure of GaAs near Γ point



Optical transitions between atomic levels with j = 3/2 and j =1/2 under absorption of a right circularly polarized photon

The ratio of the two probabilities is 3:1

Optical spin orientation and detection



Excitation by circularly polarized light

Detection of the circular polarization of luminescence, P

For recombination with non-polarized holes
$P = S$, the average spin per electron

$$P = \frac{P_0}{1+\tau/\tau_s}$$

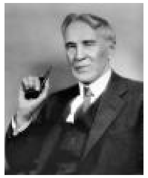
where τ is the electron lifetime,

τ_s is the spin relaxation time

The Hanle effect

depolarization of luminescence in magnetic field

"It was then observed that the apparatus was oriented in a different direction from that which obtained in earlier work, and on turning the table on which everything was mounted through ninety degrees, bringing the observation direction East and West, we at once obtained a much higher value of the polarization"



R. Wood and A. Ellett (1924)

$$P(B) = \frac{P(0)}{1 + (\Omega T)^2}$$

Ω is the spin precession frequency in magnetic field,

$1/T = 1/\tau + 1/\tau_s$ is the effective spin lifetime

(The Hanle curve)

Spin relaxation

Spin relaxation

Mistification of spin relaxation:

“The qubit (spin) gets entangled with the environment…”

“The environment is constantly trying to look at the state of a qubit, a process called decoherence”

Spin relaxation is a result of the action of fluctuating in time magnetic fields

In most cases, these are not real magnetic fields, but rather “effective” magnetic fields originating from the spin-orbit, exchange, or hyperfine interactions

Two parameters of a randomly fluctuating magnetic field:

a) Its amplitude, or the average spin precession frequency, ω, in this random field

b) Its correlation time τ_c , i.e. the time during which the field may be roughly considered as constant

Spin relaxation

IMPORTANT PARAMETER

What happens, depends on the value of the dimensionless parameter

$$\boxed{\omega\tau_c}$$

which is the typical angle of spin precession during the correlation time

Spin relaxation

TWO LIMITING CASES:

a) $\omega\tau_c << 1$ (most frequent case)

The spin vector experiences a slow angular diffusion

b) $\omega\tau_c >> 1$

This means that during the correlation time the spin will make many rotations around the direction of the magnetic field

Spin relaxation

$a)\ \omega\tau_c << 1$

Number of uncorrelated random steps during *t*: t/τ_c

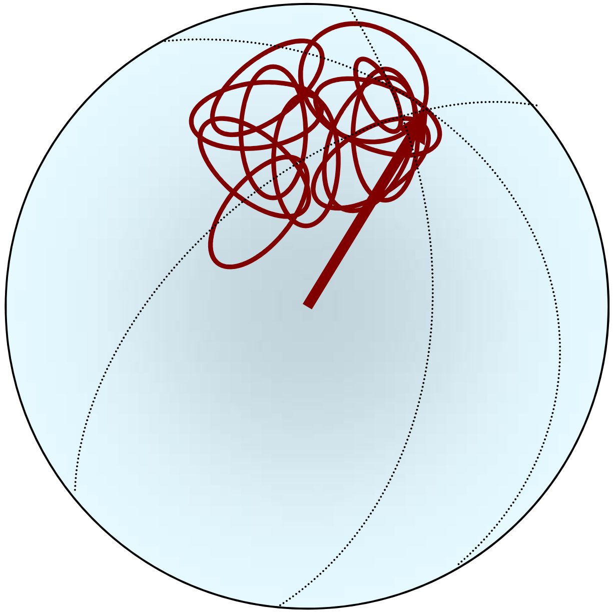
Squared precession angle for each step: $(\omega\tau_c)^2$

Total squared angle after time *t* : $(\omega\tau_c)^2\ t/\tau_c$

Spin relaxation time may be defined as the time at which this angle becomes of the order of 1:

$$1/\tau_s \sim \omega^2\tau_c$$

This is essentially a ***classical*** formula !



Random walk of the spin vector

Spin relaxation

$b)\ \omega\tau_c >> 1$

During time ~ $1/\omega$ the spin projection transverse to the random magnetic field is (on the average) completely destroyed, while its projection along the direction of the field is conserved

After time τ_c the magnetic field changes its direction, and the initial spin polarization will disappear. Thus for this case

$$\tau_s \sim \tau_c\ ,$$

i.e. the spin relaxation time is on the order of the correlation time

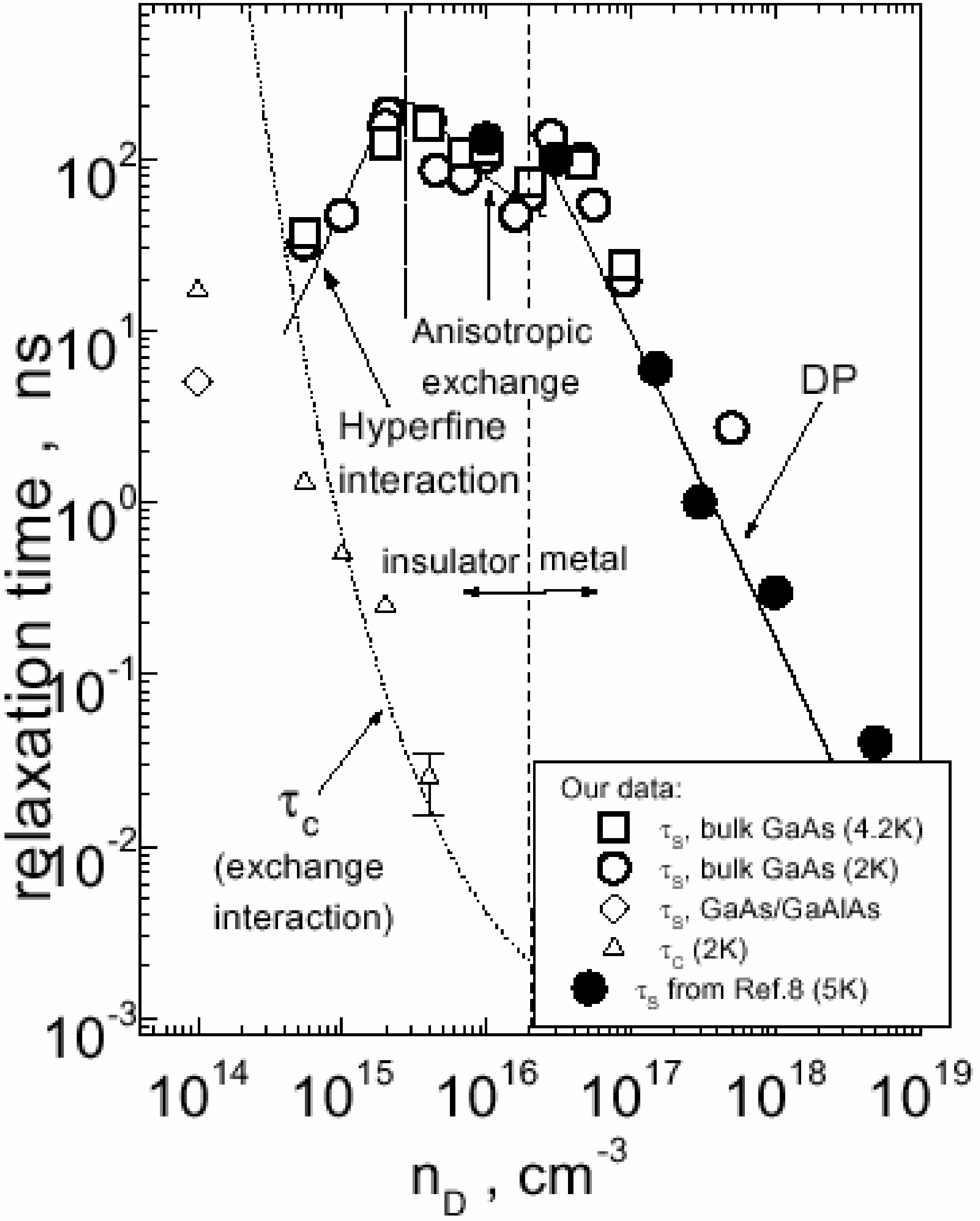
This consideration is quite general
It applies to any mechanism of spin relaxation!

Spin relaxation

Low-temperature spin relaxation
in n-type bulk GaAs

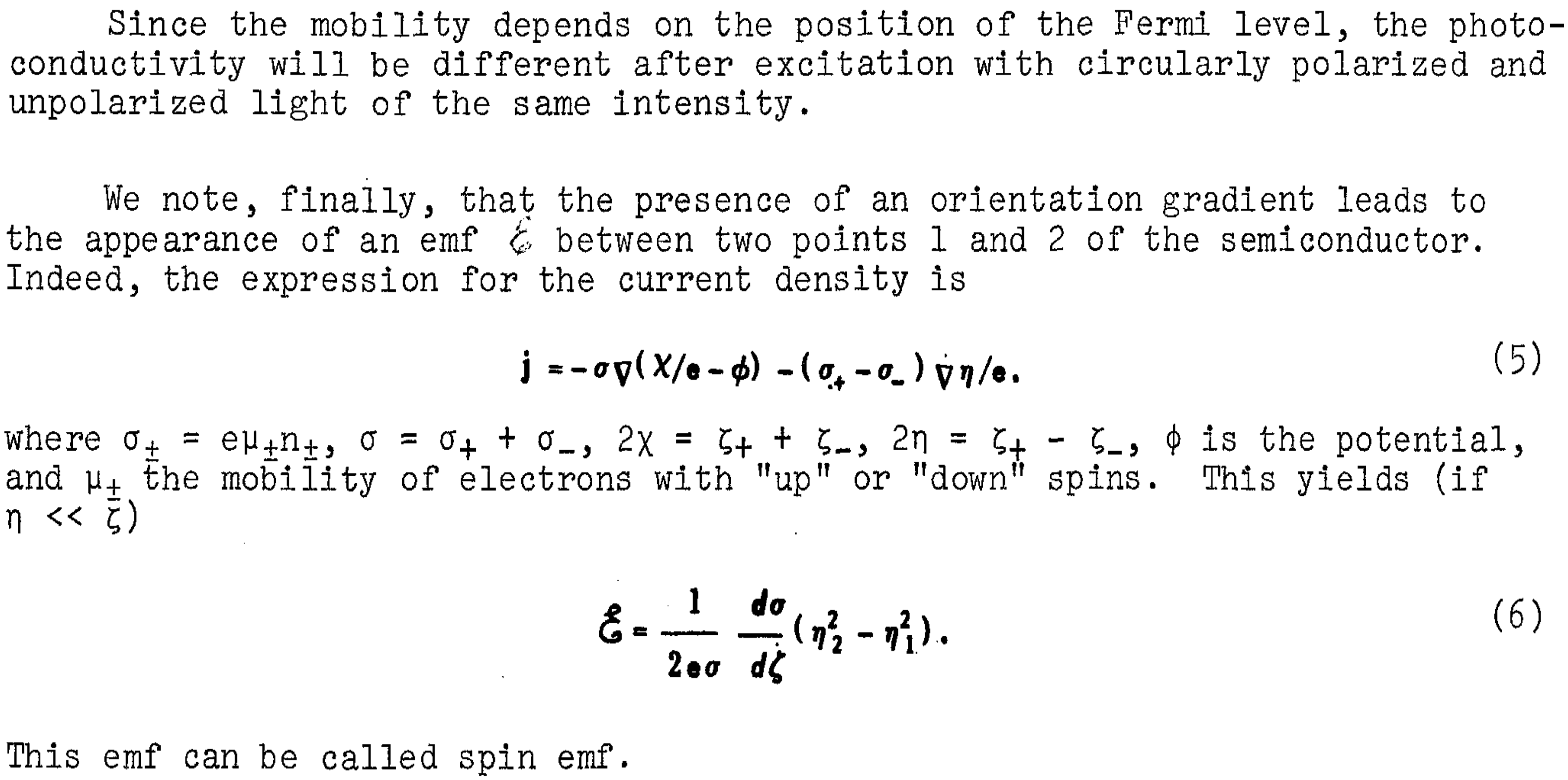
R. Dzhioev et al,

Phys. Rev. **B66**, 245204 (2002)



Spin-related transport phenomena

Spin emf



Since the mobility depends on the position of the Fermi level, the photoconductivity will be different after excitation with circularly polarized and unpolarized light of the same intensity.

We note, finally, that the presence of an orientation gradient leads to the appearance of an emf $\mathcal{E}$ between two points 1 and 2 of the semiconductor. Indeed, the expression for the current density is

$$j = -\sigma\nabla(\chi/e - \phi) - (\sigma_+ - \sigma_-)\nabla\eta/e. \tag{5}$$

where $\sigma_\pm = e\mu_\pm n_\pm$, $\sigma = \sigma_+ + \sigma_-$, $2\chi = \zeta_+ + \zeta_-$, $2\eta = \zeta_+ - \zeta_-$, ϕ is the potential, and $\mu_\pm$ the mobility of electrons with "up" or "down" spins. This yields (if $\eta \ll \zeta$)

$$\mathcal{E} = \frac{1}{2e\sigma}\frac{d\sigma}{d\zeta}(\eta_2^2 - \eta_1^2). \tag{6}$$

This emf can be called spin emf.

M.I. D'yakonov and V.I. Perel'

ZhETF Pis. Red. 13, No. 4, 206 - 208 (20 February 1971)

Anomalous Hall effect

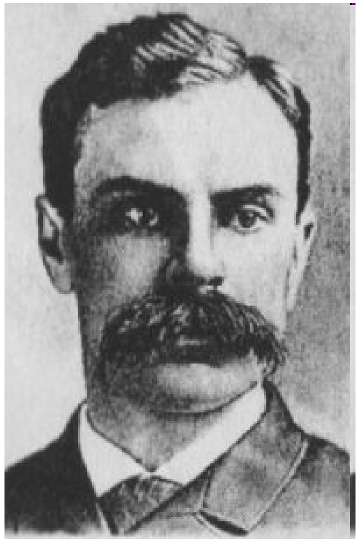
- 1879 Hall Effect $\rho_{xy} = R_H B$

- 1881 Anomalous Hall Effect

  in ferromagnets:

$$\rho_{xy} = R_H B + R_{AH} \cdot 4\pi M$$

$$\boxed{R_{AH} > R_H}$$



Edwin Hall

Explanation (spin-orbit interaction!):

J. Smit (1951,1955)

R. Karplus, J.M. Luttinger (1954)

Robert Karplus

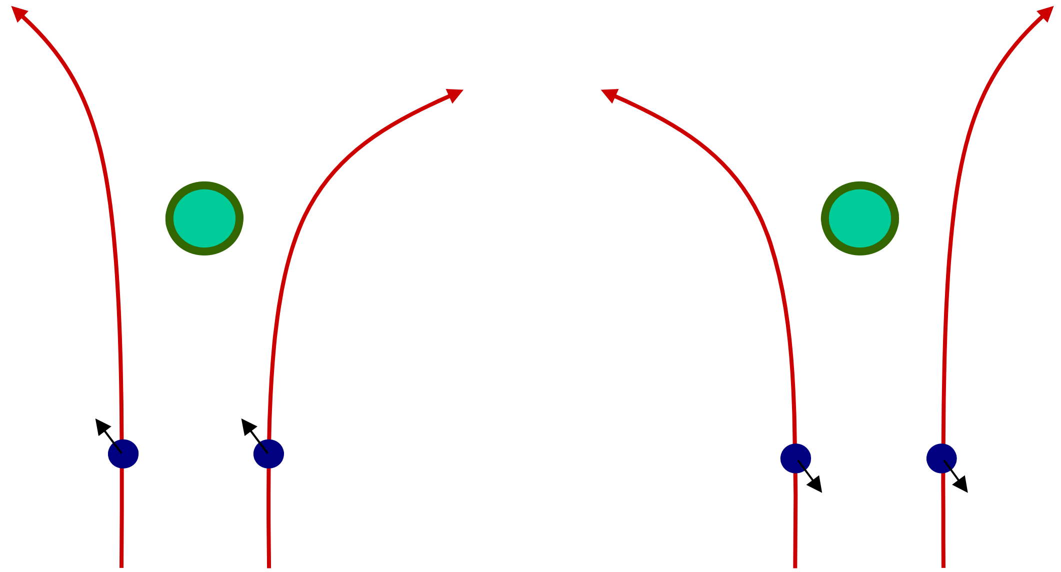
Joaquin Mazdak Luttinger

Magnus effect and Mott scattering

Magnus effect

A spinning tennis ball deviates from a straight path to the right or to the left, depending on the sense of rotation (first noted by Newton?)

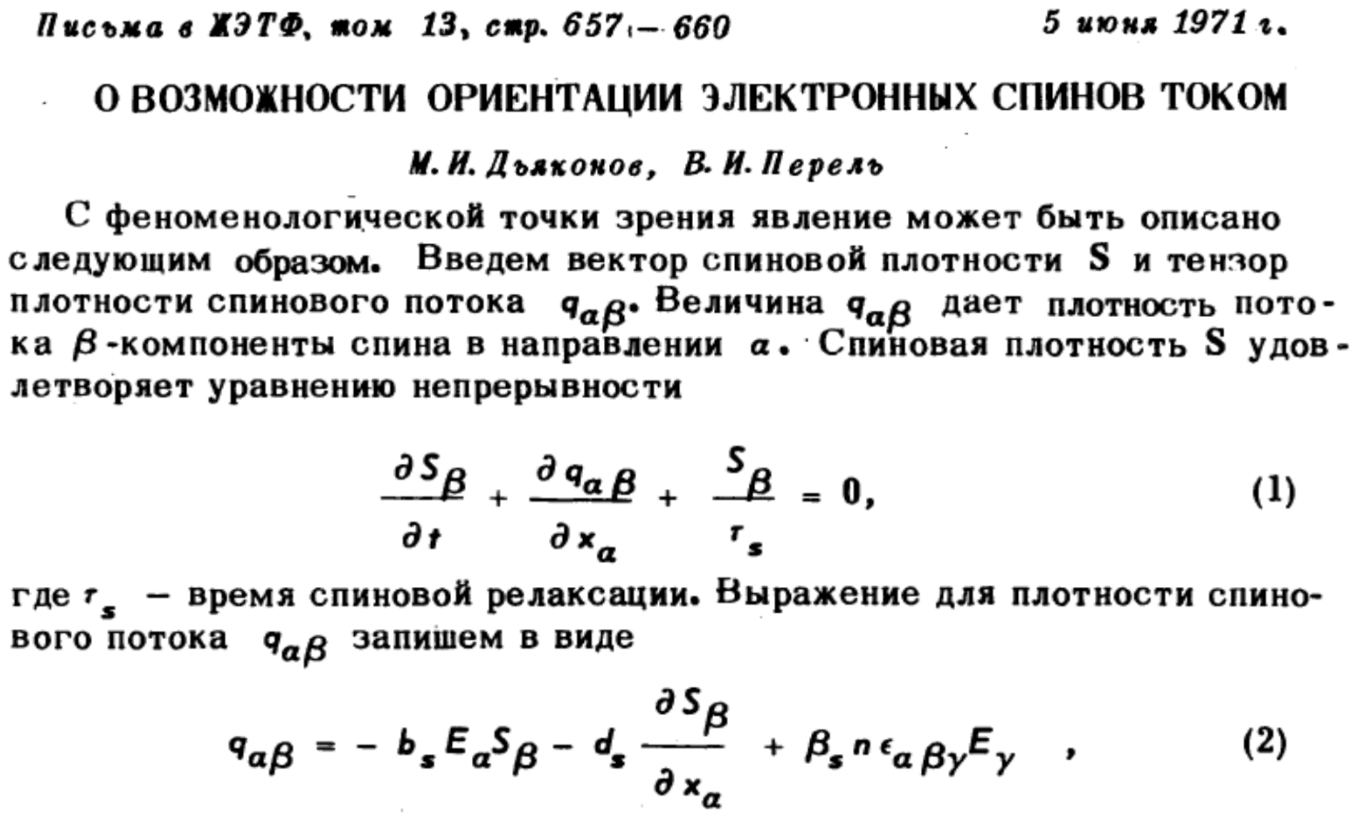
Schematic illustration of spin-dependent asymmetry in scattering



Neville Mott

Skew scattering or the Mott effect (1929)

Current-induced spin accumulation (Spin Hall Effect)



Письма в ЖЭТФ, том 13, стр. 657 – 660 *5 июня 1971 г.*

О ВОЗМОЖНОСТИ ОРИЕНТАЦИИ ЭЛЕКТРОННЫХ СПИНОВ ТОКОМ

М. И. Дьяконов, В. И. Перель

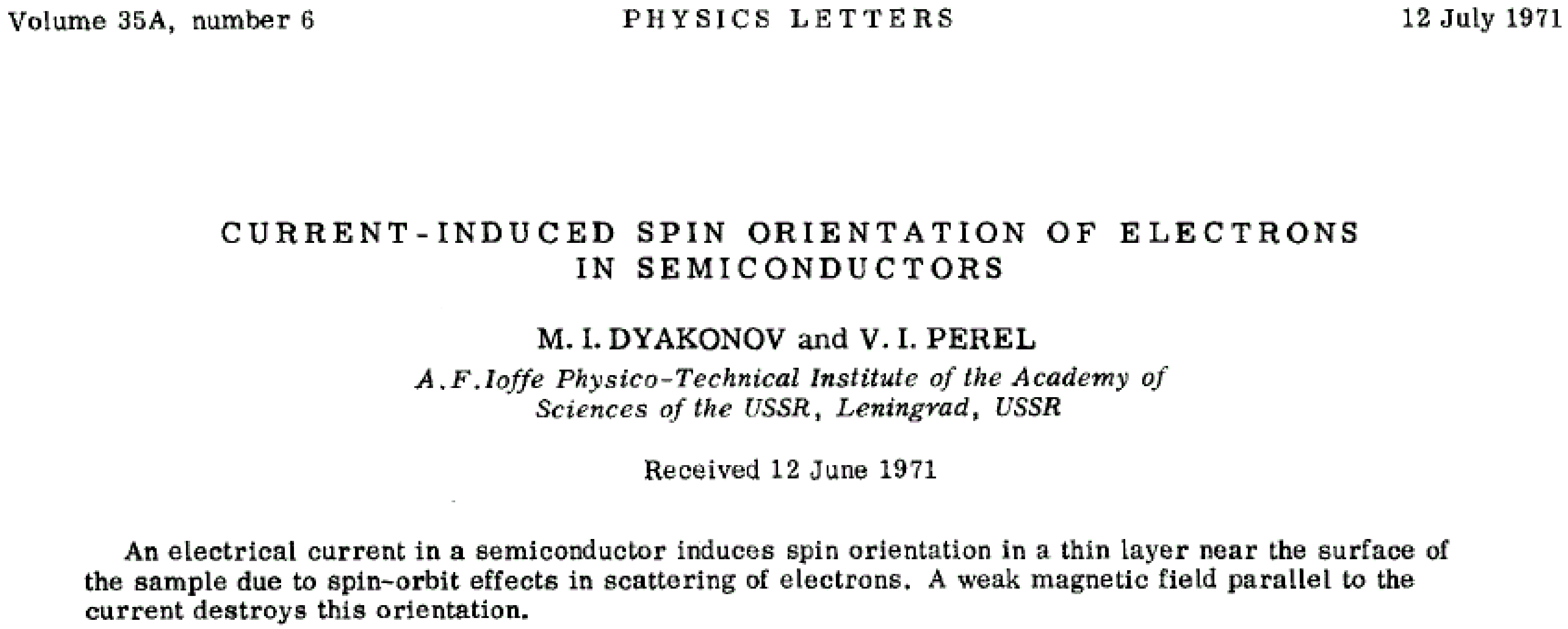
С феноменологической точки зрения явление может быть описано следующим образом. Введем вектор спиновой плотности **S** и тензор плотности спинового потока $q_{\alpha\beta}$. Величина $q_{\alpha\beta}$ дает плотность потока β-компоненты спина в направлении α. Спиновая плотность **S** удовлетворяет уравнению непрерывности

$$\frac{\partial S_\beta}{\partial t} + \frac{\partial q_{\alpha\beta}}{\partial x_\alpha} + \frac{S_\beta}{\tau_s} = 0, \qquad (1)$$

где τ_s – время спиновой релаксации. Выражение для плотности спинового потока $q_{\alpha\beta}$ запишем в виде

$$q_{\alpha\beta} = -b_s E_\alpha S_\beta - d_s \frac{\partial S_\beta}{\partial x_\alpha} + \beta_s n \epsilon_{\alpha\beta\gamma} E_\gamma \quad , \qquad (2)$$

Leningrad 1976



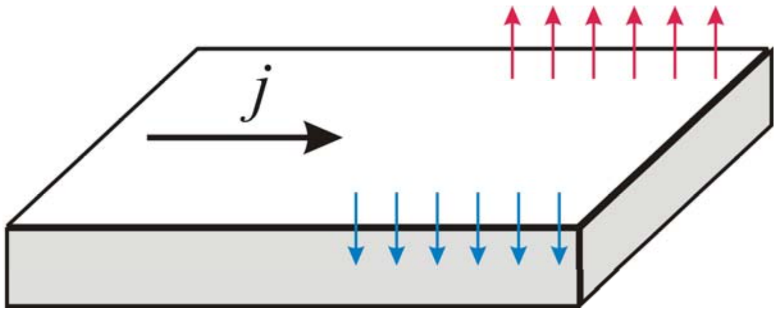
Volume 35A, number 6 PHYSICS LETTERS 12 July 1971

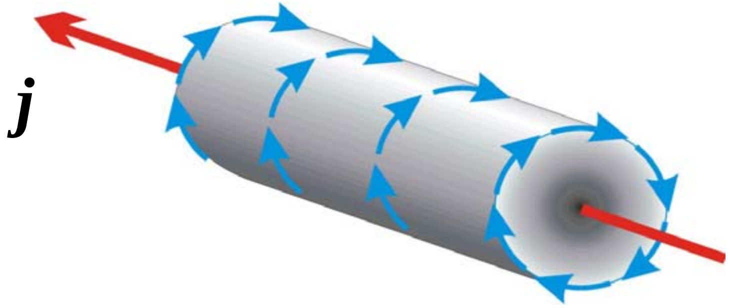
CURRENT-INDUCED SPIN ORIENTATION OF ELECTRONS IN SEMICONDUCTORS

M. I. DYAKONOV and V. I. PEREL
A.F.Ioffe Physico-Technical Institute of the Academy of Sciences of the USSR, Leningrad, USSR

Received 12 June 1971

An electrical current in a semiconductor induces spin orientation in a thin layer near the surface of the sample due to spin-orbit effects in scattering of electrons. A weak magnetic field parallel to the current destroys this orientation.



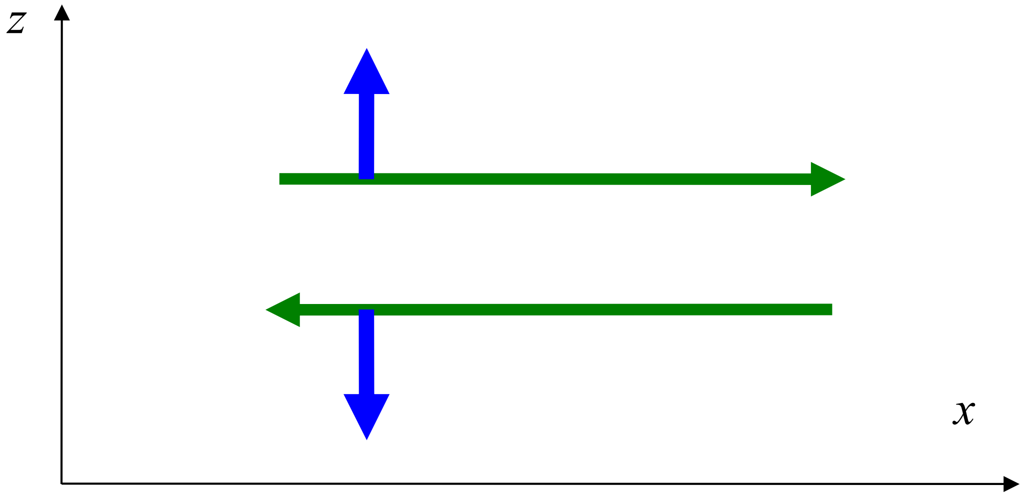


Spin and charge currents

q_{xz} - z component of spin is flowing in the x direction

Generally: q_{ij}

Here the spin current is accompanied by a charge current q_x (electric current $\boldsymbol{j} = -\mathbf{q}/e$)



Now there is a *pure* spin current q_{xz}

The charge current is zero: $\mathbf{q}=0$

Coupling of spin and charge currents

Charge flow density: $\boldsymbol{q} = -\boldsymbol{j}/e$ ($\boldsymbol{j}$ – electric current density)

Spin polarization flow density tensor: q_{ij} (flow of the j-component of spin in direction i)

Spin polarization density: $\boldsymbol{P} = 2\boldsymbol{S}$, where $\boldsymbol{S}$ is the spin density vector.

Without taking account of spin-orbit interaction:

$\boldsymbol{q}^{(0)} = -\mu n \boldsymbol{E} - D \nabla n$ – normal expression with drift and diffusion

$q_{ij}^{(0)} = -\mu E_i P_j - D \dfrac{\partial P_j}{\partial x_i}$ – similar expression (spins carried by drift and diffusion)

Spin-orbit interaction couples the two currents:

$$\boxed{\begin{aligned} q_i &= q_i^{(0)} + \gamma \varepsilon_{ijk} q_{ij}^{(0)} \\ q_{ij} &= q_{ij}^{(0)} - \gamma \varepsilon_{ijk} q_k^{(0)} \end{aligned}}$$

Here γ is a dimensionless coupling parameter proportional to the spin-orbit interaction

ε_{ijk} is the unit antisymmetric tensor

M.I. Dyakonov, Phys. Rev. Lett. **99**, 126601 (2007)

Phenomenological equations

(Dyakonov, Perel, 1971)

Anomalous Hall Effect

Inverse Spin Hall Effect

$$\boldsymbol{j}/e = \mu n \boldsymbol{E} + D \nabla n + \beta n \boldsymbol{E} \times \boldsymbol{P} + \delta \,\mathrm{curl}\, \boldsymbol{P}$$

$$q_{ij} = -\mu E_i P_j - D \frac{\partial P_j}{\partial x_i} + \varepsilon_{ijk} \left(\beta n E_k + \delta \frac{\partial n}{\partial x_k} \right)$$

Spin Hall Effect

Diffusive counterpart of SHE

$$\beta = \gamma \mu, \ \delta = \gamma D.$$

First observation of the Inverse Spin Hall Effect ($\boldsymbol{j} \sim \mathrm{curl}\, \boldsymbol{P}$)

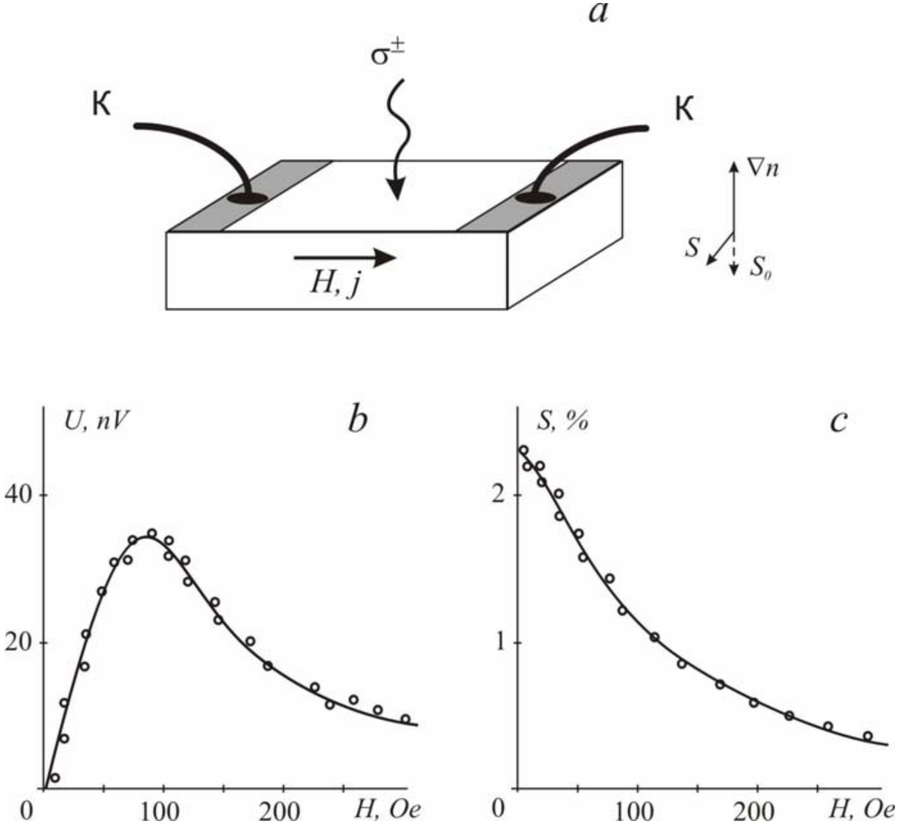
Proposal: N.S. Averkiev and M.I. Dyakonov, *Sov. Phys. Semicond.* **17**, 393 (1983)

Experiment: A.A. Bakun, B.P. Zakharchenya, A.A. Rogachev, M.N. Tkachuk, and V.G. Fleisher, *Sov. Phys. JETP Lett.* **40**, 1293 (1984)

Circularly polarized light creates spin polarization $\boldsymbol{P}$, however $\mathrm{curl}\, \boldsymbol{P} = 0$

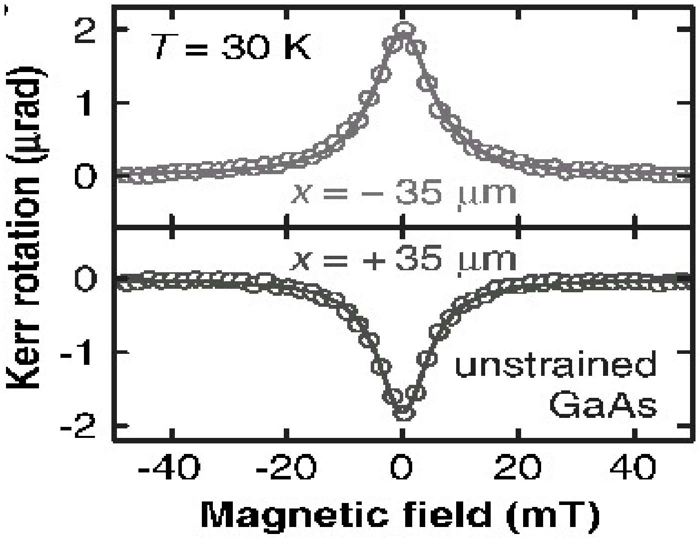
By applying a magnetic field parallel to the surface, one creates the *y* component of $\boldsymbol{P}$.

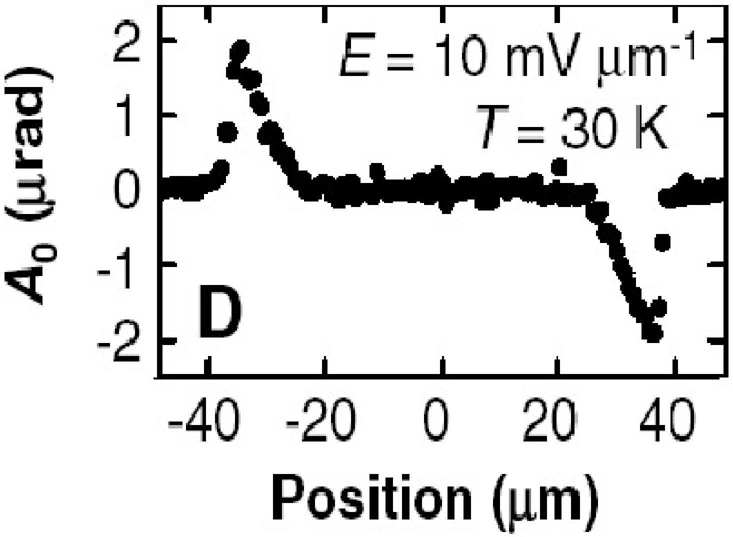
This makes a non-zero $\mathrm{curl}\, \boldsymbol{P}$ and hence an electric current in the *x* direction



First observations of the Spin Hall effect

Y.K. Kato, R.C. Myers, A.C. Gossard, and D.D. Awschalom, *Science* 306, 1910 (2004)





Y.K. Kato, R.C. Myers, A.C. Gossard, and D.D. Awschalom, *Science* **306**, 1910 (2004)

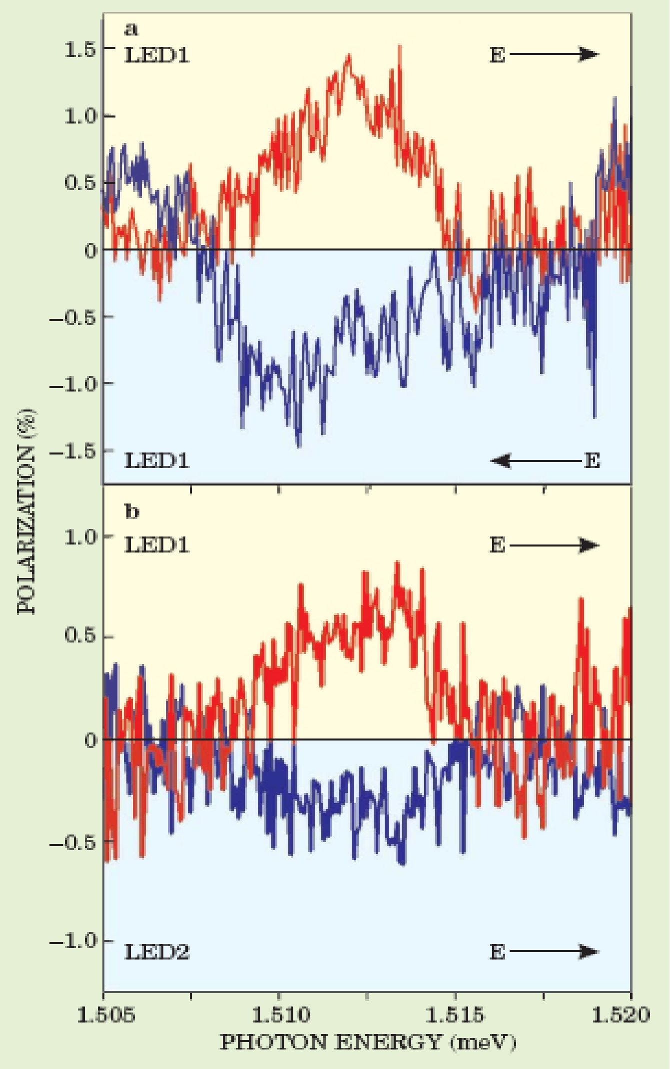
Science: **33-Year Hunt for Proof of Spin Current Now Over**

Spin Hall Effect Observed !

First observations of the Spin Hall effect

Experiment

Two-dimensional gas of holes in AlGaAs/GaAs heterostructure (optical registration)



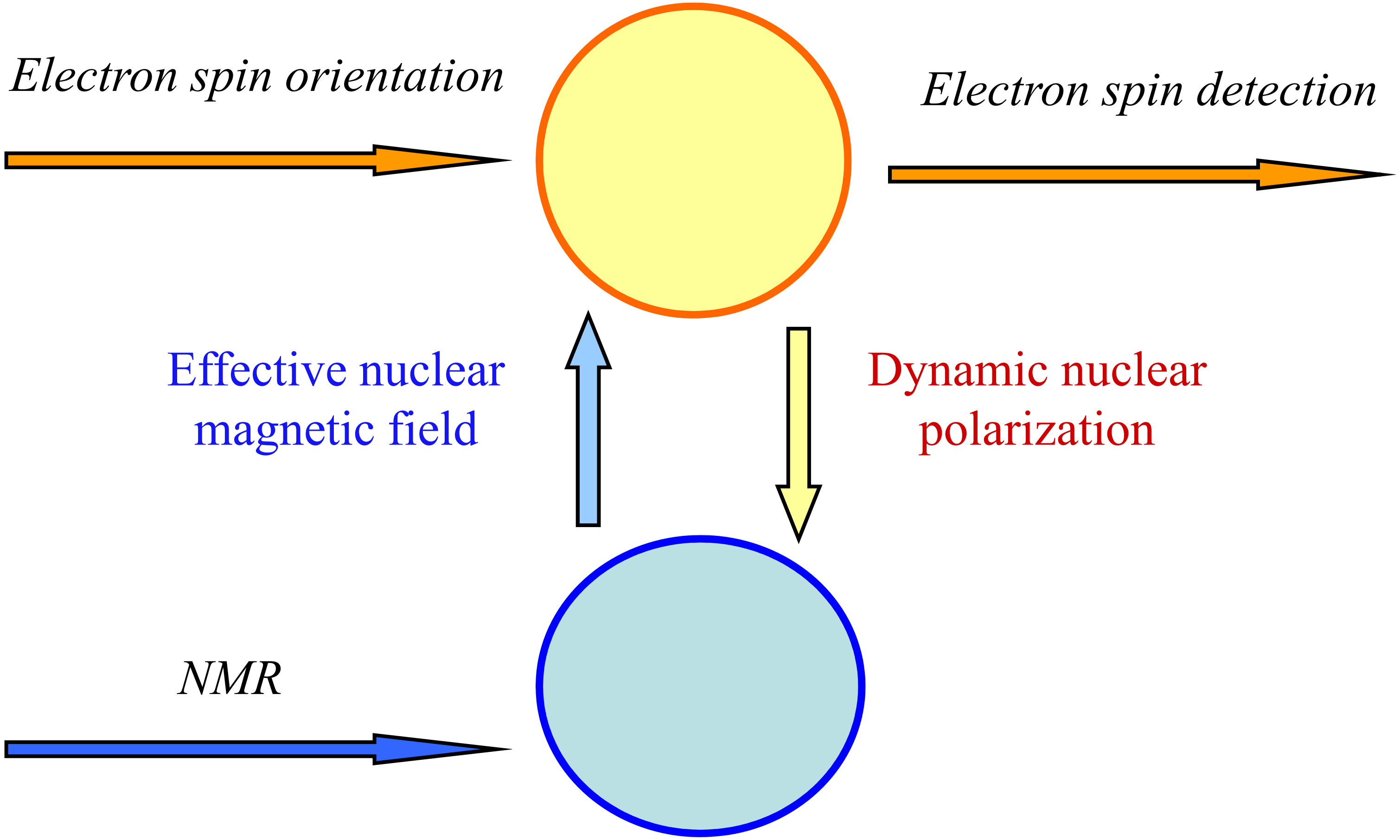
Polarization reversal when the current direction is changed

Polarization at opposite edges of the sample

J. Wunderlich, B. Kaestner, J. Sinova, and T. Jungwirth, PRL, **94**, 047204 (2005)

The electron-nuclear spin system

The electron-nuclear spin system



Electron spin system

Electron spin orientation

Electron spin detection

Effective nuclear magnetic field

Dynamic nuclear polarization

NMR

Nuclear spin system

The electron-nuclear spin system

The physics is governed by three basic interactions:

a) Hyperfine interaction between electron and nuclear spins

Fermi contact interaction: $V = A\mathbf{IS}$ (for an electron in *s*-state)

$\mathbf{I}$ - nuclear spin, $\mathbf{S}$ - electron spin

Consequences:

(i) Nuclear spin relaxation (electron spin system in equilibrium)

(ii) Dynamic nuclear polarization (electron spin system out of equilibrium)

Time scale: from seconds to minutes, to hours

(iii) Effective *nuclear magnetic field* acting on electron spins

The field of 100% polarized nuclei in GaAs would be about 6 Tesla !

The electron-nuclear spin system

b) Dipole-dipole interaction between nuclear spins.

Can be characterized by the *local magnetic field*, B_L **~** several Gauss
and a precession period of a nuclear spin in this field, $\tau_N \sim 10^{-4}\ s$

This interaction leads to *nuclear spin diffusion* (Bloembergen)

Diffusion coefficient: $D_N \sim a^2/\tau_N \sim 10^{-12}\ cm^2/s$

So, spin diffusion on a distance of 100 Å takes ~ 1*s*
and several hours for a distance of 1 μm

c) Zeeman interaction of electron and nuclear spins with the external magnetic field

$$\mu_N / \mu_B \sim 10^{-3}$$

The electron-nuclear spin system

Nuclear spin temperature

The time $\tau_N \sim 10^{-4}$ *s* (also called T_2) gives a characteristic time scale for the nuclear spin system, which is much shorter than the spin-lattice relaxation time T_1

During time ~ τ_N *thermal equilibrium* within this system is established, with a *nuclear spin temperature* Θ, which may be very different from the crystal temperature, for example, something like 10^{-6} *K*

The average nuclear spin is given by the thermodynamical formula:

$$\mathbf{I}_{av} = \frac{I+1}{3}\frac{\mu\mathbf{B}}{k\Theta}$$

always along ***B*** *!*

Calculation of the spin temperature (Dyakonov, Perel, 1974) gives :

$$\mathbf{B}_N = B_0 \frac{\mathbf{B}(\mathbf{BS})}{B^2+B_L^2}$$

Yet to discover: **dynamic nuclear self-polarization** (Dyakonov, Perel, 1972)

The oblique Hanle effect

(manifestation of nuclear magnetic field in the oblique Hanle effect)

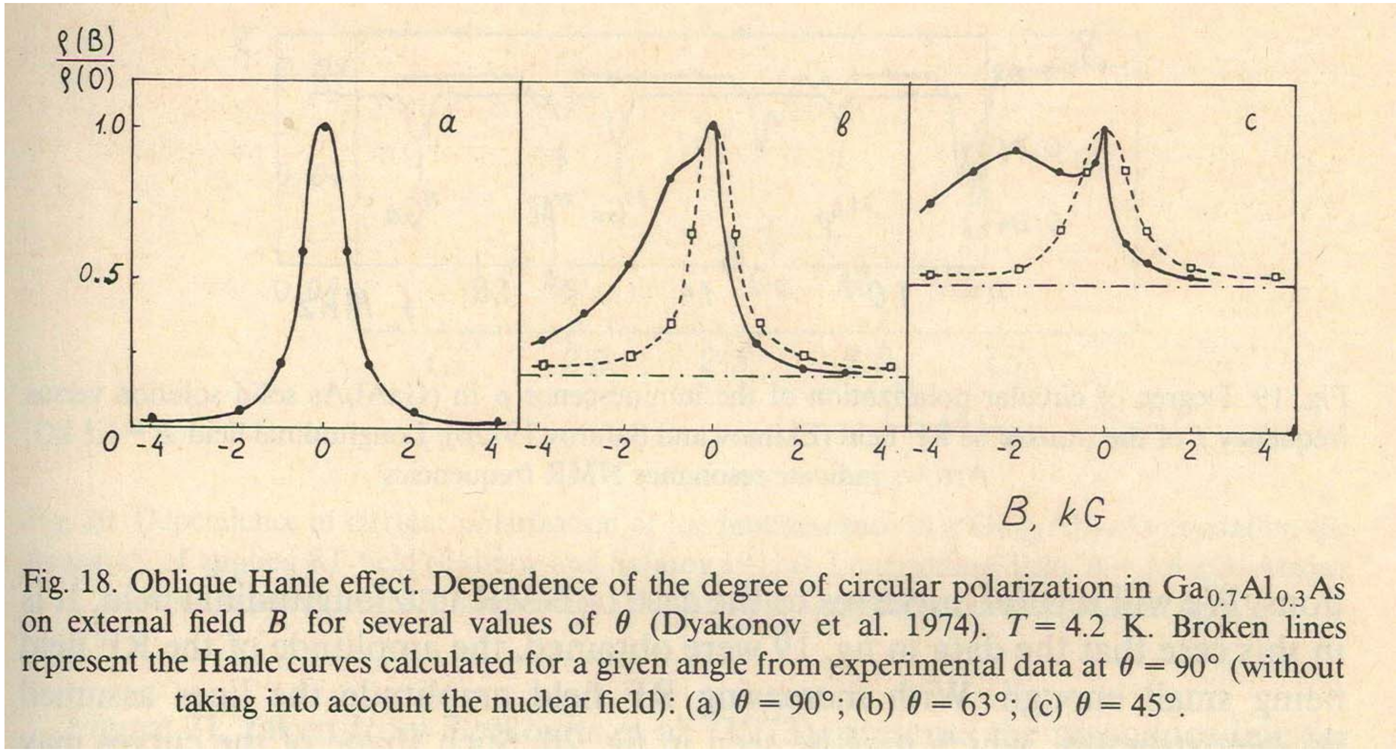


Fig. 18. Oblique Hanle effect. Dependence of the degree of circular polarization in $Ga_{0.7}Al_{0.3}As$ on external field B for several values of θ (Dyakonov et al. 1974). $T = 4.2$ K. Broken lines represent the Hanle curves calculated for a given angle from experimental data at $\theta = 90°$ (without taking into account the nuclear field): (a) $\theta = 90°$; (b) $\theta = 63°$; (c) $\theta = 45°$.

Dyakonov, Perel, Ekimov, Safarov (1974)

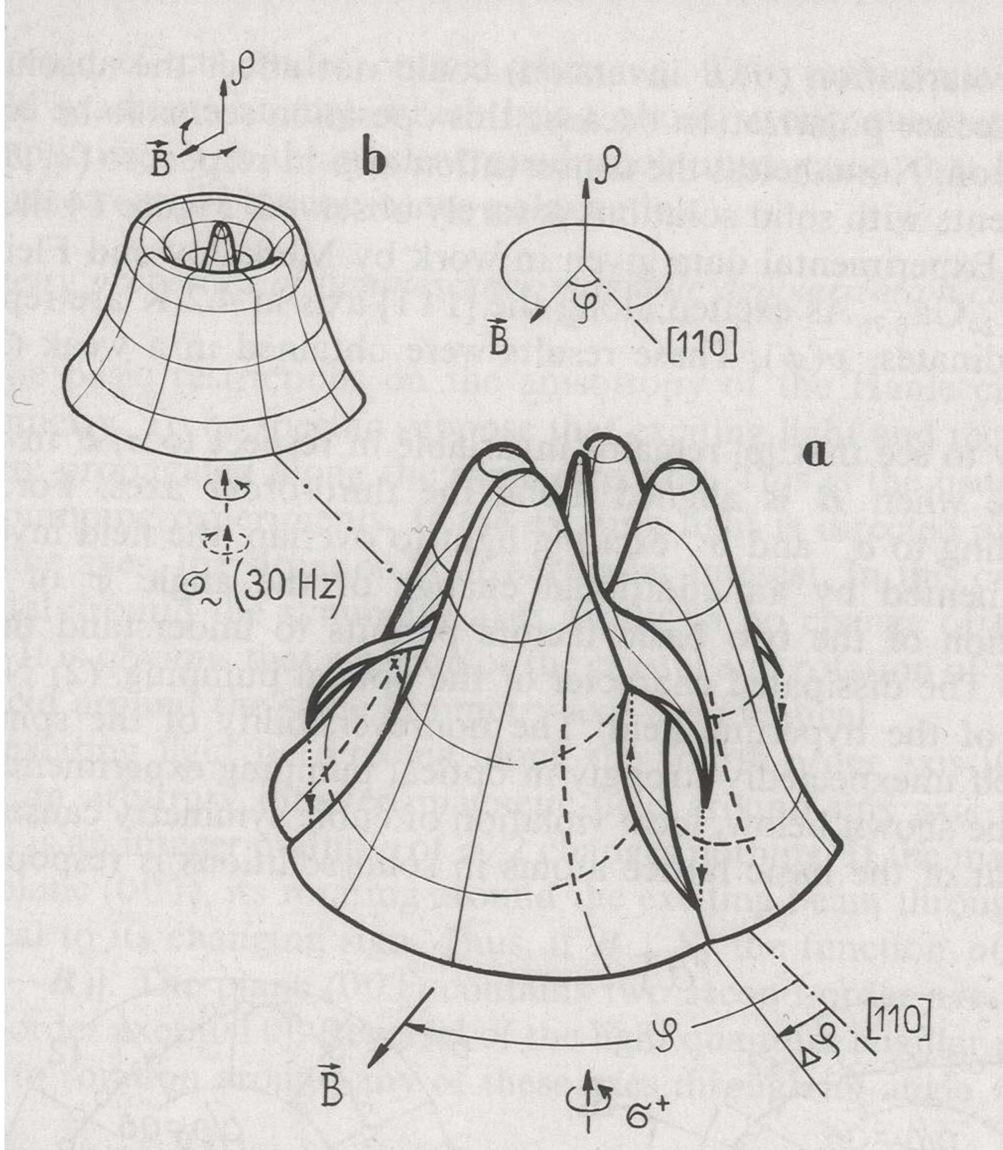
The nuclei always get polarized so that ***I*** **~** (***SB***)***B***

Hence ***B*** must be neither parallel, nor perpendicular to ***S !***

The electron-nuclear spin system

(welcome to the nuclear spin Zoo)

Circular polarization of luminescence in AlGaAs in perpendicular magnetic field for different field orientation with respect to crystal axes



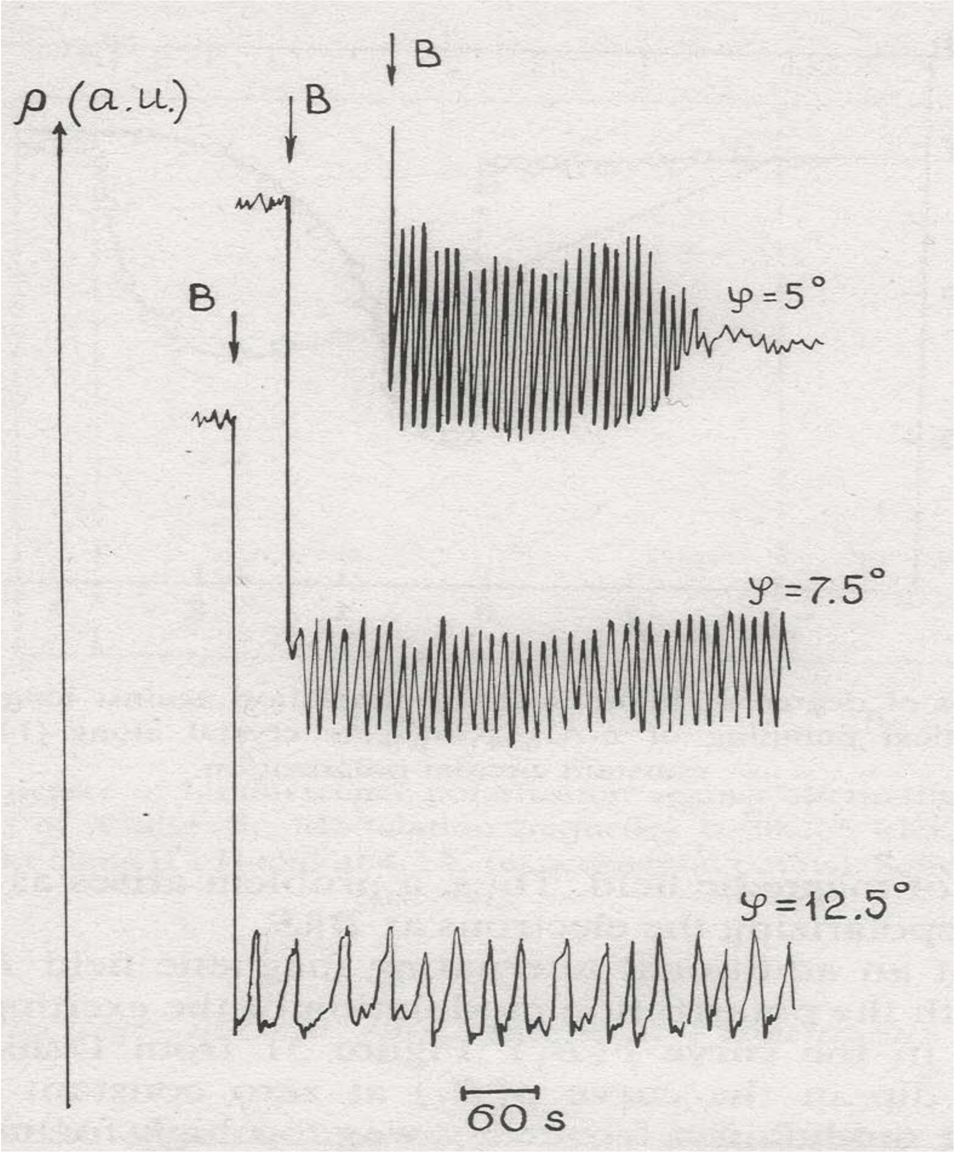
V.A. Novikov and V.G. Fleisher,

Sov. Phys. JETP, 44, 410 (1976)

The electron-nuclear spin system

(welcome to the nuclear spin Zoo)

Self-sustained oscillations of the circular polarization of the luminescence in AlGaAs appearing after application of transverse magnetic field B=60 G for different angles with [110]



V.A. Novikov and V.G. Fleisher,
Sov. Phys. JETP, 47, 539 (1978)

The electron-nuclear spin system

(welcome to the nuclear spin Zoo)

Oblique Hanle effect in GaAs

- θ = 83°
- θ = 87°
- θ = 90°

B.P. Zakharchenya, V.G. Fleisher et al,
Sov. Phys. Solid State **23**, 810 (1981)

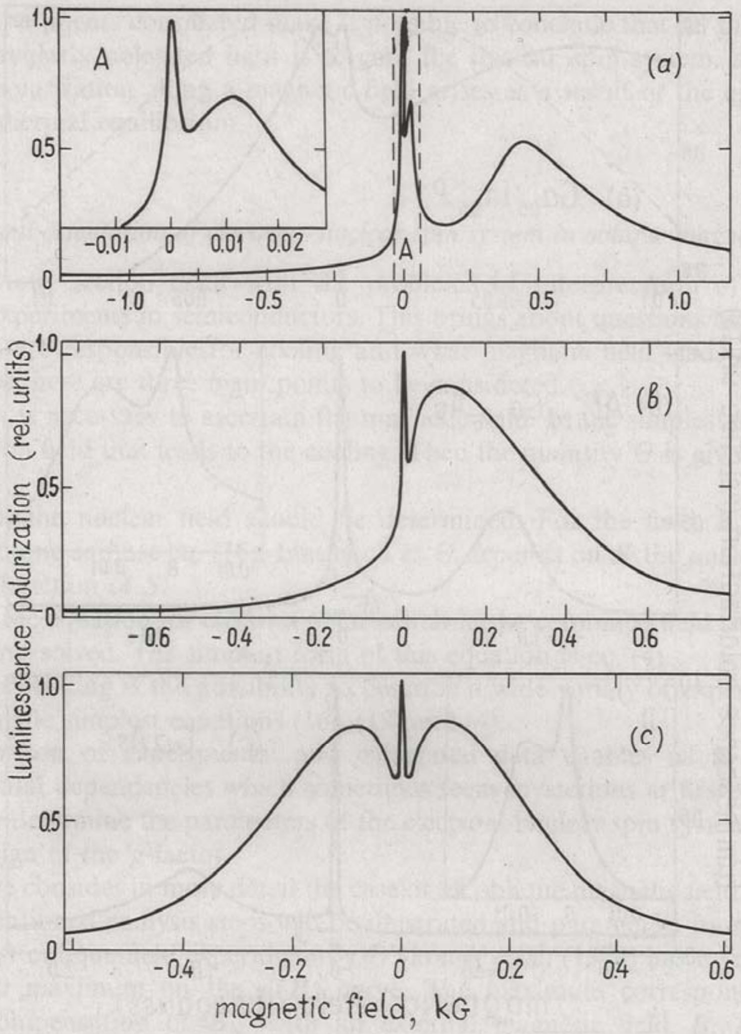


Fig. 7. Magnetic depolarization of luminescence of GaAs-crystal in oblique field near critical angle $\theta_c \simeq 87°$: (a) $\theta = 83°$; (b) $\theta = 87°$; (c) $\theta = 90°$.

Spintronics?

“Spintronics: a spin-based electronics vision of the future”,
S.A. Wolf, D.D. Awschalom, et al, *Science* **294**, 1488 (2001)

“ .. spin-based electronics, where it is not the electron charge but the electron spin that carries information, and this offers opportunities for a new generation of devices combining standard microelectronics with spin-dependent effects...”

Spintronics mantras:

“**Spintronics** is one of the most promising new technologies, where the spin degrees of freedom of electrons in semiconductors are manipulated and utilized for functions such as memory, operation, and communication”

“The electron spin, which has been largely ignored in a charge-based electronics, has now become the focus of research due to the **emerging field of spintronics**”

(repeated with small variations in ~10^4 publications by ~ 10^3 authors)

Skip the bla-bla

Replace:

Spintronics is one of the most promising new technologies, where the spin degrees of freedom of electrons in semiconductors are manipulated and utilized for functions such as memory, operation, and communication.

In the emerging fields of spintronics and quantum information, it is important to explore (**check one**):

☐ decoherence of spin qubits in quantum dots
☐ hyperfine interactions
☐ spin injection
☐ Berry phase
☐ spin-dependent tunneling
☐ rare earth impurities in A^3B^5 semiconductors
☐ influence of spin on weak localization
☐……..

In this paper, we study…

by a suitable symbol, for example: $

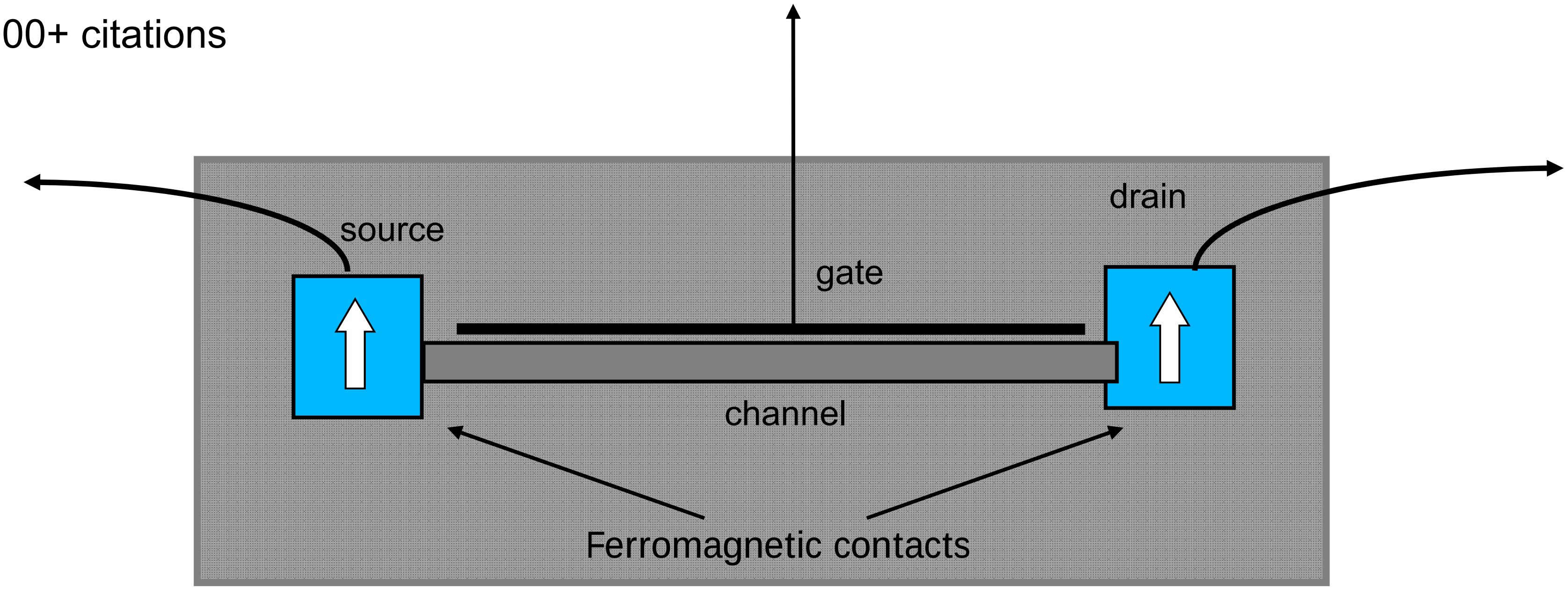
Write simply: **$** In this paper we study...

Datta-Das spin transistor

the wonderful spintronic device

S. Datta and B. Das,
Electronic analog of the electro-optic modulator
Appl. Phys. Lett. **56**, 665 (1990)

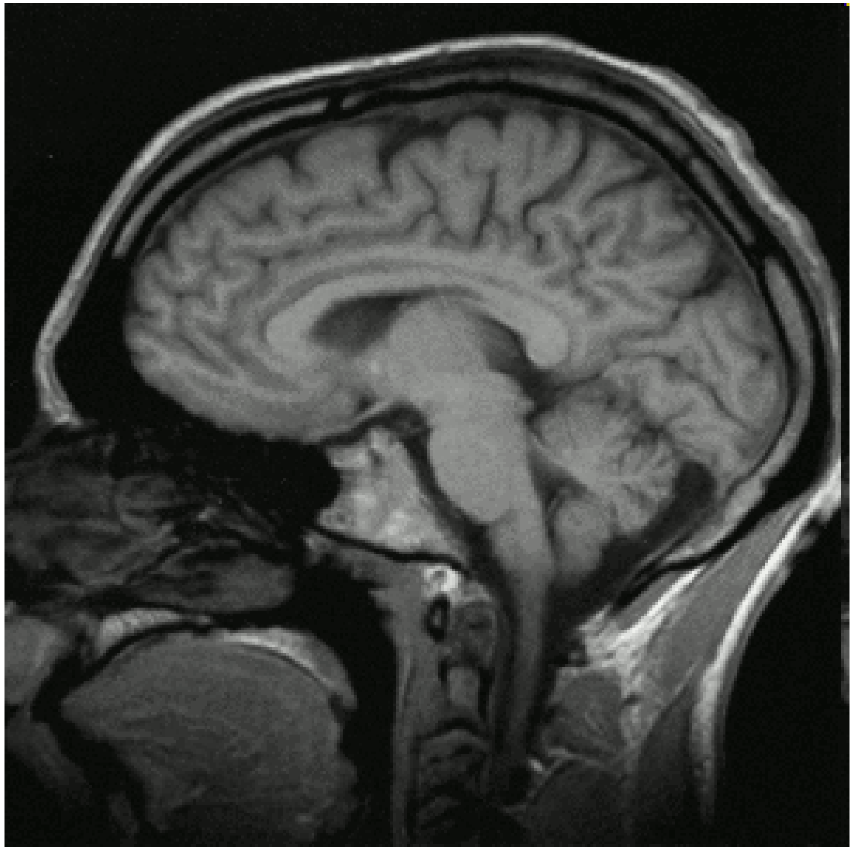
2000+ citations



No advantages compared to the normal Field Effect Transistor!

But many **severe drawbacks** ...

Applications come unexpected!



Human brain scanned by NMR

Conclusions

- First, it is beautiful and interesting (for those who find it interesting)

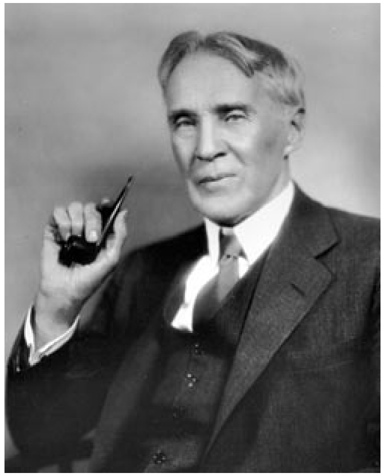
- In my opinion, some applications of spin phenomena in semiconductors can be expected in combination with ferromagnetism (switching/displacement of magnetic domains, etc)

- So far, there are no clear ideas for applications of pure semiconductor spin physics

- Only the future will tell us what physical results will become practically useful and which ones will remain simply amusing

THANK YOU

The founding fathers

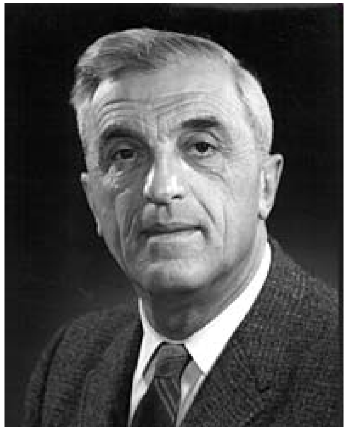


Robert Wood
(1868-1955)

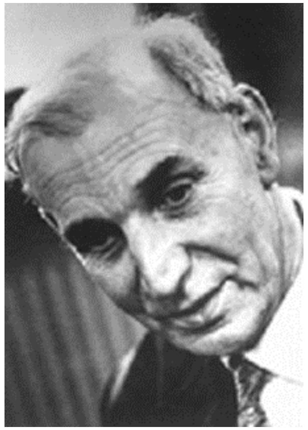
Wilhelm Hanle
(1901-1993)

Isidor Rabi
(1898-1988)

Evgeny Zavoisky
(1907-1976)



Felix Bloch
(1905-1983)



Alfred Kastler
(1902-1984)

Jean Brossel
(1918-2003)

Nicolaas Bloembergen
(1920)