Electron spins in nonmagnetic semiconductors

Yuichiro K. Kato

Institute of Engineering Innovation, The University of Tokyo

Physics of non-interacting spins

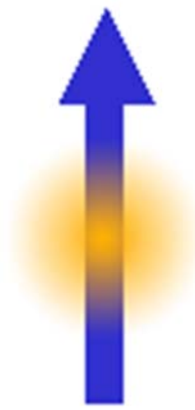
Optical spin injection and detection

Spin manipulation in nonmagnetic semiconductors

Physics of non-interacting spins

In non-magnetic semiconductors such as GaAs and Si, spin interactions are weak; To first order approximation, they behave as non-interacting, independent spins.

- Zeeman Hamiltonian
- Bloch sphere
- Larmor precession
- T_1, T_2, and T_2^*
- Bloch equation



The Zeeman Hamiltonian

Hamiltonian for an electron spin in a magnetic field

$$H = -\vec{M} \cdot \vec{B} = g\mu_{\mathrm{B}}\vec{s} \cdot \vec{B}$$

$\vec{M}$: magnetic moment

$\vec{B}$: magnetic field

magnetic moment of an electron spin

$$\vec{M} = -g\mu_{\mathrm{B}}\vec{s}$$

g: Landé g-factor (=2 for free electrons)

$\mu_{\mathrm{B}} = \frac{e\hbar}{2m}$: Bohr magneton $= 58\ \mu\mathrm{eV/T}$

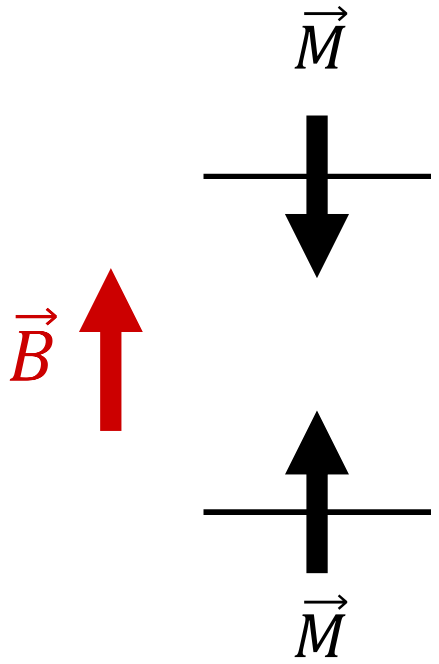
e: electronic charge

$\hbar$: Planck constant

m: free electron mass

$\vec{s} = \frac{\vec{\sigma}}{2}$: spin operator

$\vec{\sigma}$: Pauli operator



$E = +MB$

$(M = |\vec{M}|,\ B = |\vec{B}|)$

$E = -MB$

The Zeeman Hamiltonian

Hamiltonian for an electron spin in a magnetic field

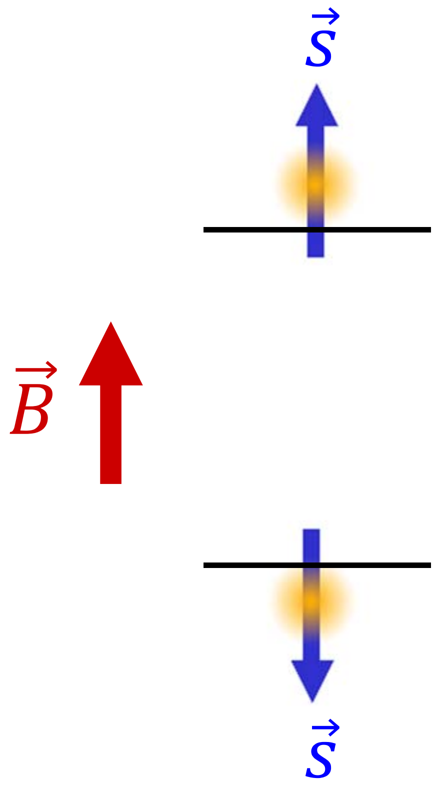
$$H = -\vec{M}\cdot\vec{B} = g\mu_{\mathrm{B}}\vec{s}\cdot\vec{B}$$

$\vec{M}$: magnetic moment

$\vec{B}$: magnetic field

magnetic moment of an electron spin

$$\vec{M} = -g\mu_{\mathrm{B}}\vec{s}$$



$$E = +\frac{g\mu_{\mathrm{B}}B}{2}$$

$$E = -\frac{g\mu_{\mathrm{B}}B}{2}$$

g: Landé g-factor (=2 for free electrons)

$\mu_{\mathrm{B}} = \frac{e\hbar}{2m}$: Bohr magneton

$= 58\ \mu\mathrm{eV/T}$

e: electronic charge

$\hbar$: Planck constant

m: free electron mass

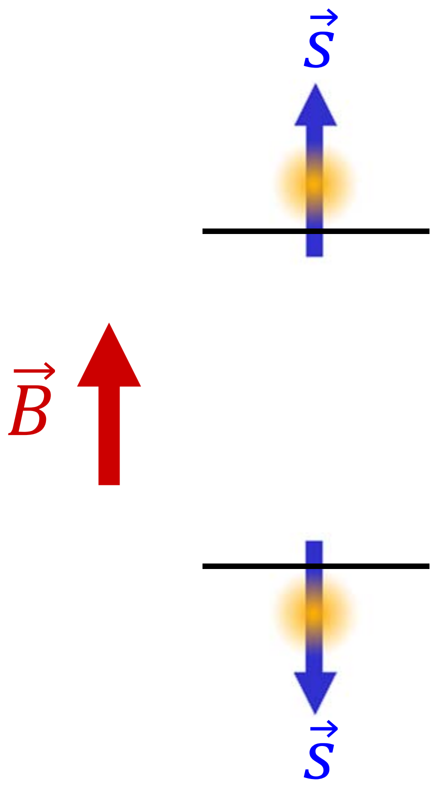
$\vec{s} = \frac{\vec{\sigma}}{2}$: spin operator

$\vec{\sigma}$: Pauli operator

The energy eigenstates

Without loss of generality, we can set the z-axis to be the direction of $\vec{B}$, i.e., $\vec{B} = (0,0,B)$

$$H = g\mu_{\mathrm{B}}\vec{s}\cdot\vec{B} = g\mu_{\mathrm{B}}B s_z$$



$$|\uparrow\rangle$$

Spin “up” $\quad s_z|\uparrow\rangle = +\frac{1}{2}|\uparrow\rangle$

$$s_z = +\frac{1}{2} \qquad E = +\frac{g\mu_{\mathrm{B}}B}{2}$$

$$|\downarrow\rangle$$

Spin “down” $\quad s_z|\downarrow\rangle = -\frac{1}{2}|\downarrow\rangle$

$$s_z = -\frac{1}{2} \qquad E = -\frac{g\mu_{\mathrm{B}}B}{2}$$

Spinor notation and the Pauli operators

Quantum states are represented by a normalized vector in a Hilbert space

➡ Spin states are represented by 2D vectors

$$|\uparrow\rangle = \begin{pmatrix} 1 \\ 0 \end{pmatrix} \qquad |\downarrow\rangle = \begin{pmatrix} 0 \\ 1 \end{pmatrix}$$

Spin operators are represented by 2x2 matrices. For example, the Pauli operators are

$$\sigma_x = \begin{pmatrix} 0 & 1 \\ 1 & 0 \end{pmatrix} \qquad \sigma_y = \begin{pmatrix} 0 & -i \\ i & 0 \end{pmatrix} \qquad \sigma_z = \begin{pmatrix} 1 & 0 \\ 0 & -1 \end{pmatrix}$$

ex. $s_z|\uparrow\rangle = +\frac{1}{2}|\uparrow\rangle$ is equivalent to

$$s_z|\uparrow\rangle = \frac{\sigma_z}{2}|\uparrow\rangle = \frac{1}{2}\begin{pmatrix} 1 & 0 \\ 0 & -1 \end{pmatrix}\begin{pmatrix} 1 \\ 0 \end{pmatrix} = \frac{1}{2}\begin{pmatrix} 1 \\ 0 \end{pmatrix} = +\frac{1}{2}|\uparrow\rangle$$

Expectation values of the Pauli vector

$$\sigma_x = \begin{pmatrix} 0 & 1 \\ 1 & 0 \end{pmatrix} \qquad \sigma_y = \begin{pmatrix} 0 & -i \\ i & 0 \end{pmatrix} \qquad \sigma_z = \begin{pmatrix} 1 & 0 \\ 0 & -1 \end{pmatrix}$$

Expectation values for the spin up state

$$\langle\uparrow|\sigma_x|\uparrow\rangle = \begin{pmatrix} 1 & 0 \end{pmatrix} \begin{pmatrix} 0 & 1 \\ 1 & 0 \end{pmatrix} \begin{pmatrix} 1 \\ 0 \end{pmatrix} = \begin{pmatrix} 1 & 0 \end{pmatrix} \begin{pmatrix} 0 \\ 1 \end{pmatrix} = 0$$

$$\langle\uparrow|\sigma_y|\uparrow\rangle = \begin{pmatrix} 1 & 0 \end{pmatrix} \begin{pmatrix} 0 & -i \\ i & 0 \end{pmatrix} \begin{pmatrix} 1 \\ 0 \end{pmatrix} = \begin{pmatrix} 1 & 0 \end{pmatrix} \begin{pmatrix} 0 \\ i \end{pmatrix} = 0$$

$$\langle\uparrow|\sigma_z|\uparrow\rangle = \begin{pmatrix} 1 & 0 \end{pmatrix} \begin{pmatrix} 1 & 0 \\ 0 & -1 \end{pmatrix} \begin{pmatrix} 1 \\ 0 \end{pmatrix} = \begin{pmatrix} 1 & 0 \end{pmatrix} \begin{pmatrix} 1 \\ 0 \end{pmatrix} = 1$$

$\langle\vec{\sigma}\rangle = (0,0,1)$ $\Rightarrow$ spin is pointing in the +z direction

Expectation values of the Pauli vector

One more example: Expectation values for a coherent superposition

$$|\varphi\rangle = \frac{1}{\sqrt{2}}(|\uparrow\rangle + |\downarrow\rangle) = \frac{1}{\sqrt{2}}\begin{pmatrix}1\\1\end{pmatrix}$$

$$\langle\varphi|\sigma_x|\varphi\rangle = \frac{1}{2}\begin{pmatrix}1 & 1\end{pmatrix}\begin{pmatrix}0 & 1\\1 & 0\end{pmatrix}\begin{pmatrix}1\\1\end{pmatrix} = \frac{1}{2}\begin{pmatrix}1 & 1\end{pmatrix}\begin{pmatrix}1\\1\end{pmatrix} = 1$$

$$\langle\varphi|\sigma_y|\varphi\rangle = \frac{1}{2}\begin{pmatrix}1 & 1\end{pmatrix}\begin{pmatrix}0 & -i\\i & 0\end{pmatrix}\begin{pmatrix}1\\1\end{pmatrix} = \frac{1}{2}\begin{pmatrix}1 & 1\end{pmatrix}\begin{pmatrix}-i\\i\end{pmatrix} = 0$$

$$\langle\varphi|\sigma_z|\varphi\rangle = \frac{1}{2}\begin{pmatrix}1 & 1\end{pmatrix}\begin{pmatrix}1 & 0\\0 & -1\end{pmatrix}\begin{pmatrix}1\\1\end{pmatrix} = \frac{1}{2}\begin{pmatrix}1 & 1\end{pmatrix}\begin{pmatrix}1\\-1\end{pmatrix} = 0$$

$\langle\vec{\sigma}\rangle = (1,0,0)$ spin is pointing in the +x direction

spin can point in any direction, but when measured along a particular axis, it can only be "up" or "down"

The Bloch sphere

In general, $|\varphi\rangle = \lambda|\uparrow\rangle + \mu|\downarrow\rangle$ where λ and μ are complex numbers.

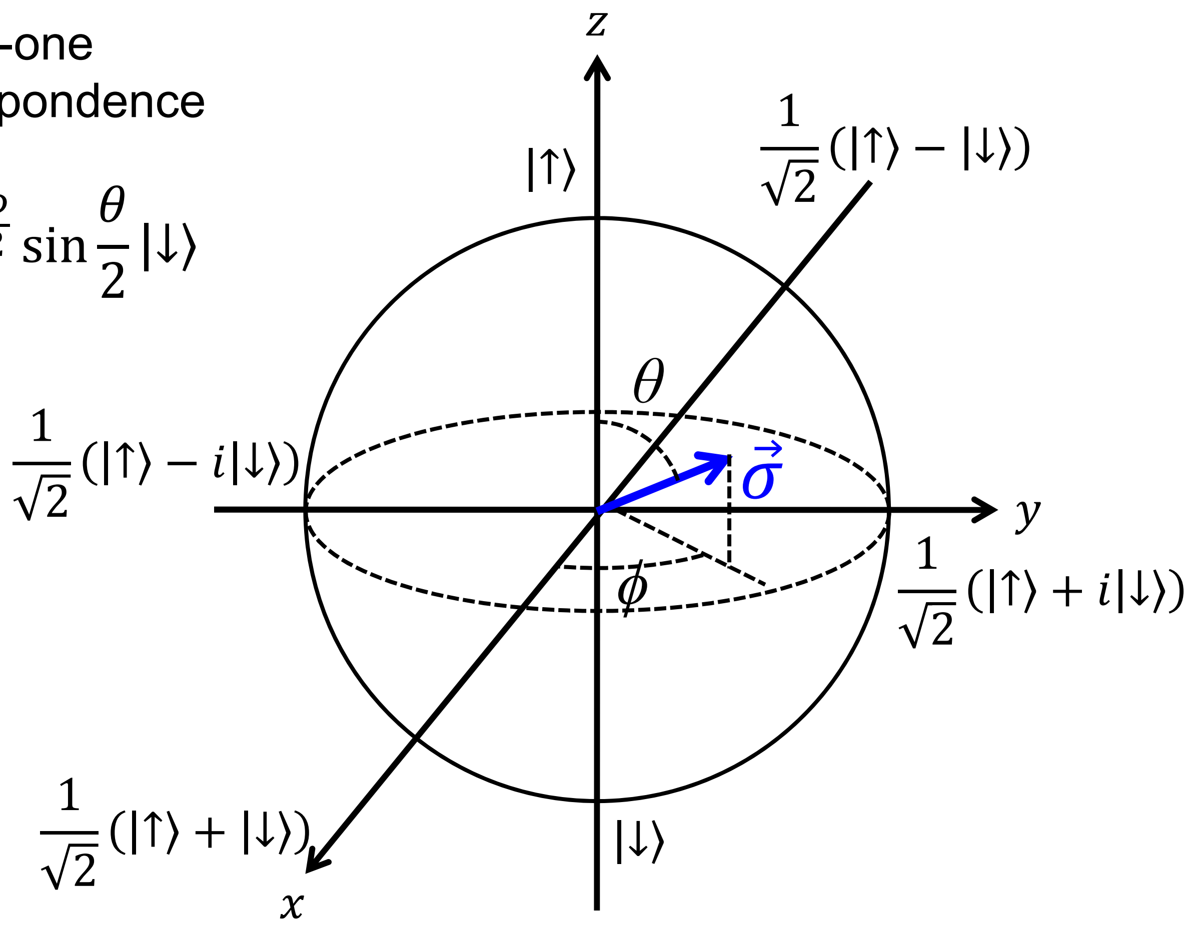
Any spin state (and any qubit) can be represented by a point on a sphere

$$\langle\vec{\sigma}\rangle = (\sin\theta\cos\phi\,, \sin\theta\sin\phi\,, \cos\theta)$$

one-to-one correspondence

$$|\varphi\rangle = e^{-i\frac{\phi}{2}}\cos\frac{\theta}{2}|\uparrow\rangle + e^{+i\frac{\phi}{2}}\sin\frac{\theta}{2}|\downarrow\rangle$$

This is the most general state. 2 complex coefficients have 4 degrees of freedom, minus normalization condition and arbitrariness of the global phase.



Time evolution of spin states

How does a spin state that is perpendicular to magnetic field evolve with time?

Initial state: $|\varphi(t=0)\rangle = \frac{1}{\sqrt{2}}(|\uparrow\rangle + |\downarrow\rangle)$

1. Obtain the time-evolution operator

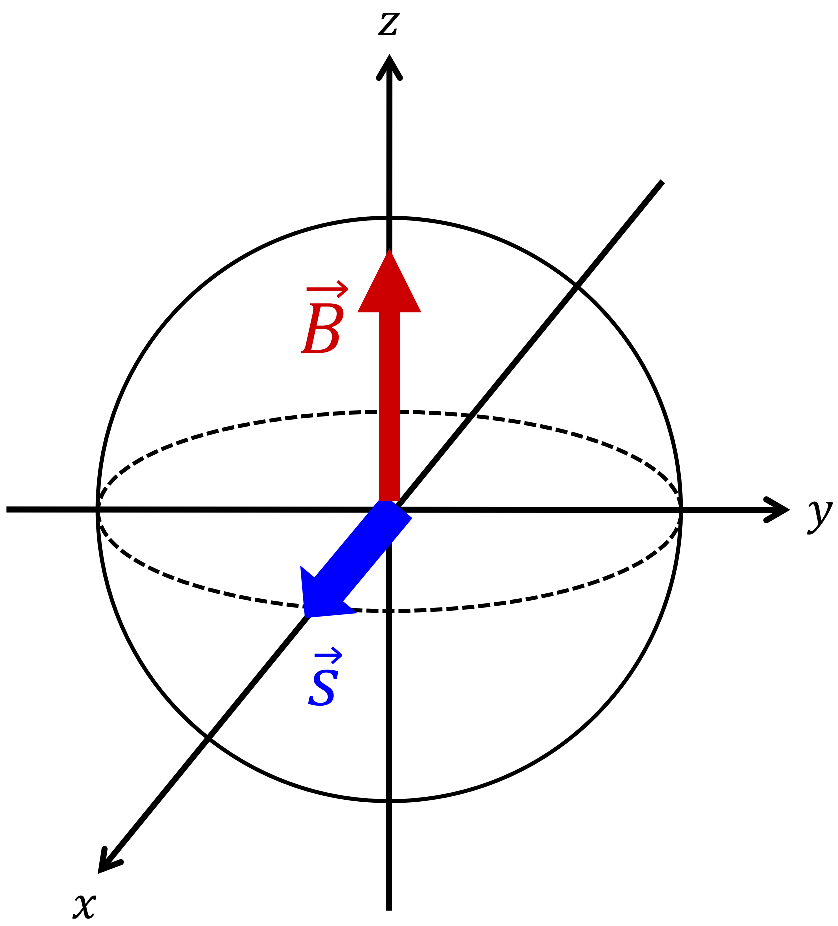
$$U(t) = \exp\left(\frac{Ht}{i\hbar}\right)$$

2. Compute the state at time t

$$|\varphi(t)\rangle = U(t)|\varphi(0)\rangle$$

3. Calculate the expectation value of $\vec{\sigma}$

$$\langle\varphi(t)|\vec{\sigma}|\varphi(t)\rangle$$



Time-evolution operator

1. Time-evolution operator is given by

$$U(t) = \exp\left(\frac{Ht}{i\hbar}\right) \quad \text{where} \quad H = g\mu_{\mathrm{B}} B s_z = \frac{g\mu_{\mathrm{B}} B}{2}\begin{pmatrix} 1 & 0 \\ 0 & -1 \end{pmatrix}$$

so

$$U(t) = \begin{pmatrix} \exp\left(-i\dfrac{g\mu_{\mathrm{B}} B t}{2\hbar}\right) & 0 \\ 0 & \exp\left(+i\dfrac{g\mu_{\mathrm{B}} B t}{2\hbar}\right) \end{pmatrix} = \begin{pmatrix} \exp\left(-i\dfrac{\Omega t}{2}\right) & 0 \\ 0 & \exp\left(+i\dfrac{\Omega t}{2}\right) \end{pmatrix}$$

where $\Omega = \dfrac{g\mu_{\mathrm{B}} B}{\hbar}$ is the Larmor frequency $\left(\dfrac{\mu_{\mathrm{B}}}{2\pi\hbar} = 14\ \mathrm{GHz/T}\right)$

2. The state at time t is obtained by applying $U(t)$ on the initial state

$$|\varphi(0)\rangle = \frac{1}{\sqrt{2}}(|\uparrow\rangle + |\downarrow\rangle) = \frac{1}{\sqrt{2}}\begin{pmatrix} 1 \\ 1 \end{pmatrix}$$

$$|\varphi(t)\rangle = U(t)|\varphi(0)\rangle = \frac{1}{\sqrt{2}}\begin{pmatrix} \exp(-i\Omega t/2) & 0 \\ 0 & \exp(+i\Omega t/2) \end{pmatrix}\begin{pmatrix} 1 \\ 1 \end{pmatrix} = \frac{1}{\sqrt{2}}\begin{pmatrix} \exp(-i\Omega t/2) \\ \exp(+i\Omega t/2) \end{pmatrix}$$

Larmor precession

3. Expectation value of $\vec{\sigma}$

$$\langle\varphi(t)|\sigma_x|\varphi(t)\rangle = \frac{1}{2}\begin{pmatrix} e^{+\frac{i\Omega t}{2}} & e^{-\frac{i\Omega t}{2}} \end{pmatrix}\begin{pmatrix} 0 & 1 \\ 1 & 0 \end{pmatrix}\begin{pmatrix} e^{-\frac{i\Omega t}{2}} \\ e^{+\frac{i\Omega t}{2}} \end{pmatrix}$$

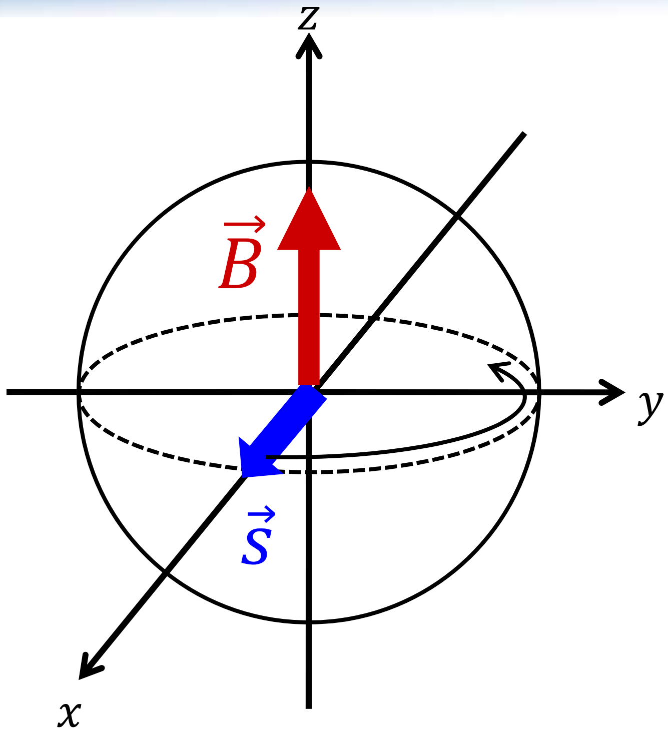
$$= \frac{1}{2}\left(e^{+i\Omega t} + e^{-i\Omega t}\right)$$

$$= \cos \Omega t$$

$$\langle\varphi(t)|\sigma_y|\varphi(t)\rangle = \frac{1}{2}\begin{pmatrix} e^{+\frac{i\Omega t}{2}} & e^{-\frac{i\Omega t}{2}} \end{pmatrix}\begin{pmatrix} 0 & -i \\ i & 0 \end{pmatrix}\begin{pmatrix} e^{-\frac{i\Omega t}{2}} \\ e^{+\frac{i\Omega t}{2}} \end{pmatrix}$$

$$= -\frac{i}{2}\left(e^{+i\Omega t} - e^{-i\Omega t}\right)$$

$$= \sin \Omega t$$



spin precession in the xy plane at an angular frequency $\Omega = g\mu_{\mathrm{B}}B/\hbar$

$$\langle\varphi(t)|\sigma_z|\varphi(t)\rangle = \frac{1}{2}\begin{pmatrix} e^{+\frac{i\Omega t}{2}} & e^{-\frac{i\Omega t}{2}} \end{pmatrix}\begin{pmatrix} 1 & 0 \\ 0 & -1 \end{pmatrix}\begin{pmatrix} e^{-\frac{i\Omega t}{2}} \\ e^{+\frac{i\Omega t}{2}} \end{pmatrix} = 1 - 1 = 0$$

Heisenberg picture of Larmor precession

More intuitive semi-classical picture can be obtained

$$H = g\mu_{\mathrm{B}} \vec{s} \cdot \vec{B} = g\mu_{\mathrm{B}}\left(B_x s_x + B_y s_y + B_z s_z\right)$$

$$\frac{ds_x}{dt} = \frac{1}{i\hbar}[s_x, H] = \frac{g\mu_{\mathrm{B}}}{i\hbar}\{[s_x, s_y]B_y + [s_x, s_z]B_z\}$$

using commutation relations: $[s_x, s_y] = is_z,\ [s_y, s_z] = is_x,\ [s_z, s_x] = is_y$

$$\left.\begin{aligned}
\frac{ds_x}{dt} &= \frac{g\mu_{\mathrm{B}}}{\hbar}\{s_z B_y - s_y B_z\} \\
\frac{ds_y}{dt} &= \frac{g\mu_{\mathrm{B}}}{\hbar}\{s_x B_z - s_z B_x\} \\
\frac{ds_z}{dt} &= \frac{g\mu_{\mathrm{B}}}{\hbar}\{s_y B_x - s_x B_y\}
\end{aligned}\right\}$$

combined into one vector equation

$$\boxed{\frac{d\vec{s}}{dt} = \vec{\Omega} \times \vec{s}}$$

where $\vec{\Omega} = \dfrac{g\mu_{\mathrm{B}}}{\hbar}\vec{B}$

Semi-classical equation of motion

$$\boxed{\frac{d\vec{s}}{dt} = \vec{\Omega} \times \vec{s}}$$

$$\vec{\Omega} = \frac{g\mu_{\mathrm{B}}}{\hbar}\vec{B}$$

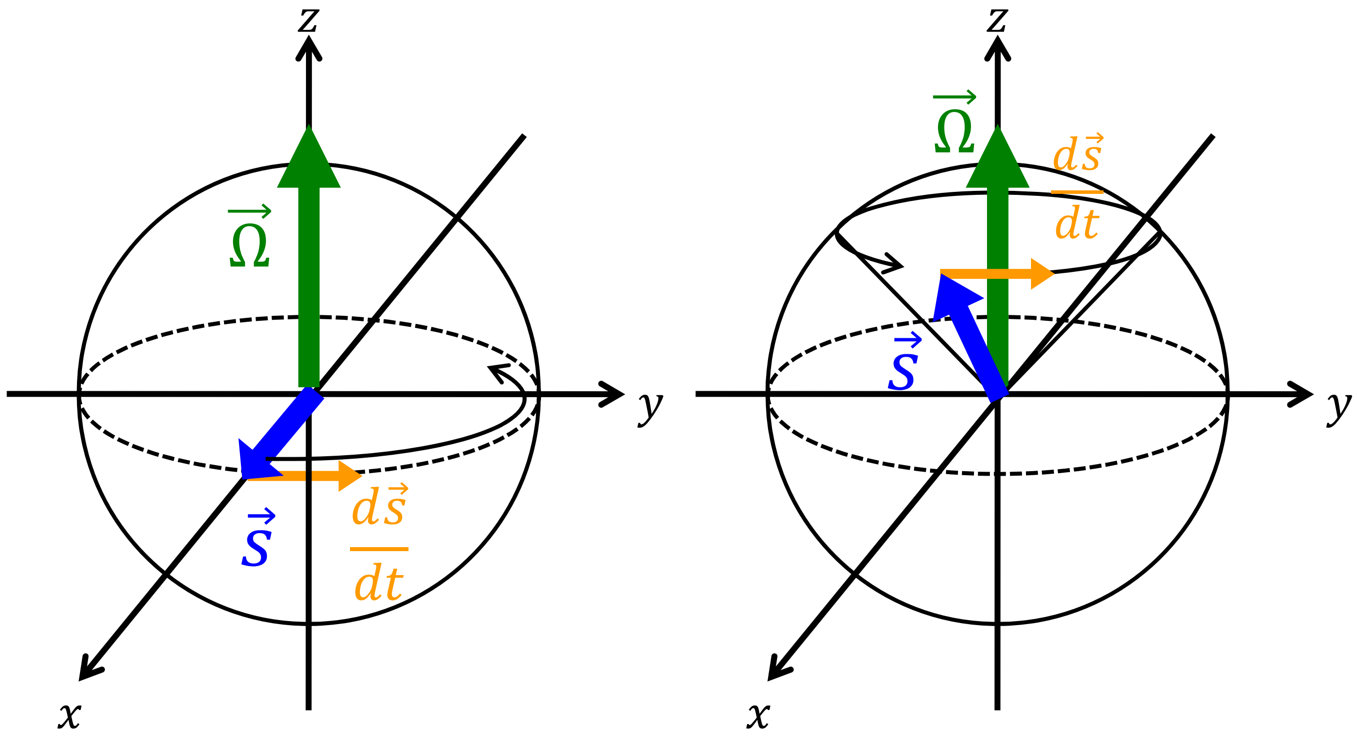
in terms of magnetization $\vec{M} = -g\mu_{\mathrm{B}}\vec{s}$
and spin angular momentum $\vec{S} = \hbar\vec{s}$

$$\frac{d\vec{S}}{dt} = \vec{M} \times \vec{B}$$

(agrees with classical result!)

rate of change for angular momentum

torque exerted by magnetic field



- Torque is perpendicular to both magnetic field and spin
- Parallel component of spin is conserved
- Perpendicular component precesses

Spin precesses in a cone at frequency Ω

Spin relaxation and the Bloch equation

In a real world, interaction with the environment will eventually randomize spin

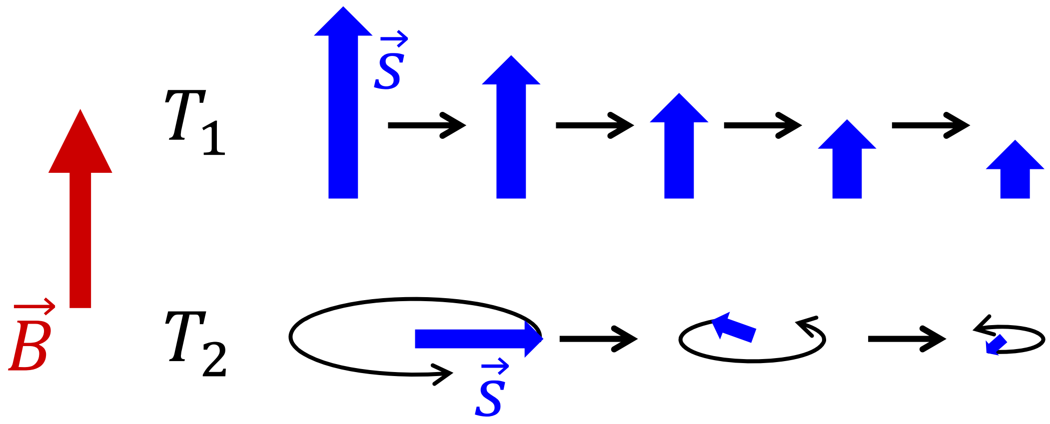
1. Longitudinal spin relaxation (T_1)

    Requires energy relaxation

2. Transverse spin relaxation (T_2)

    Phase relaxation is enough

    For an ensemble, Inhomogeneous dephasing (T_2^*)



$$\boxed{\frac{d\vec{s}}{dt} = \vec{\Omega} \times \vec{s} - \frac{(\vec{s}\cdot\hat{\Omega})\hat{\Omega}}{T_1} - \frac{\vec{s} - (\vec{s}\cdot\hat{\Omega})\hat{\Omega}}{T_2^*}}$$

$$\hat{\Omega} = \frac{\vec{\Omega}}{|\vec{\Omega}|}$$

Bloch equation

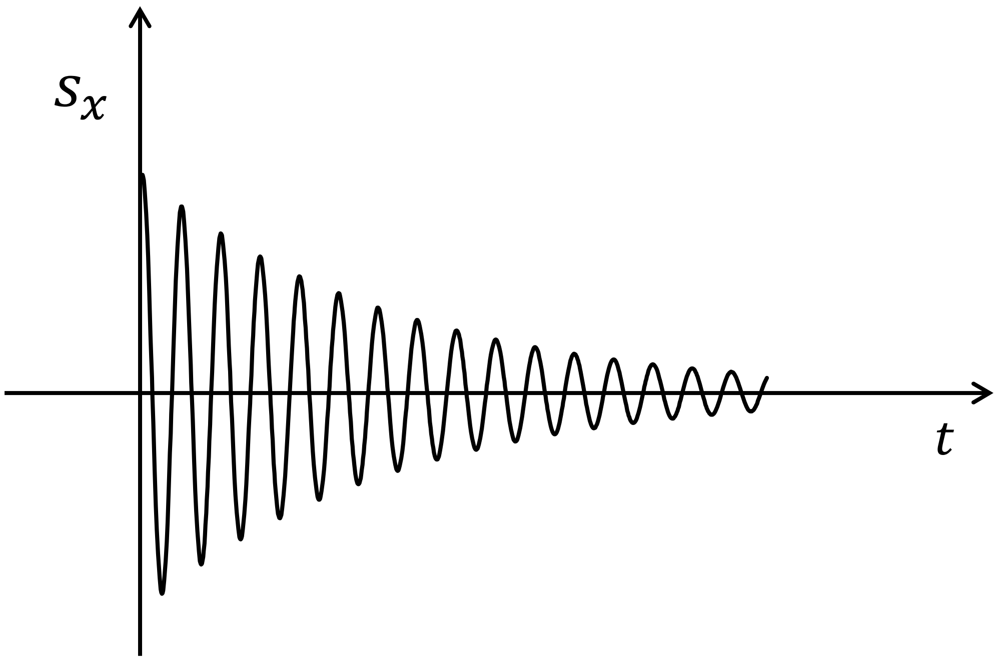
$$\frac{d\vec{S}}{dt} = \vec{M} \times \vec{B} - \frac{(\vec{S}\cdot\hat{B})\hat{B}}{T_1} - \frac{\vec{S} - (\vec{S}\cdot\hat{B})\hat{B}}{T_2^*}$$

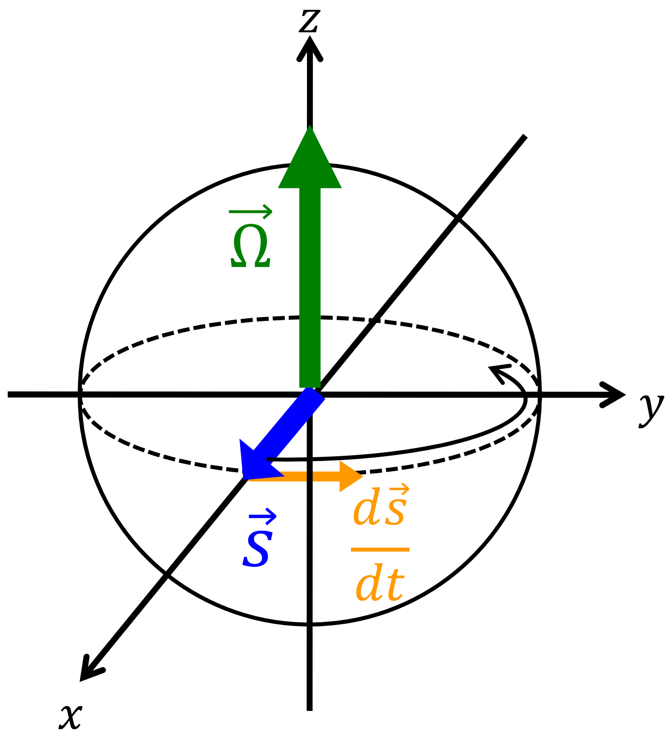
$$\hat{B} = \frac{\vec{B}}{|\vec{B}|}$$

Larmor precession revisited

For spins initially pointing along x in a magnetic field along z, the solution for spin component along x is given by

$$s_x(t) = \frac{1}{2}\exp\left(-\frac{t}{T_2^*}\right)\cos\Omega t$$



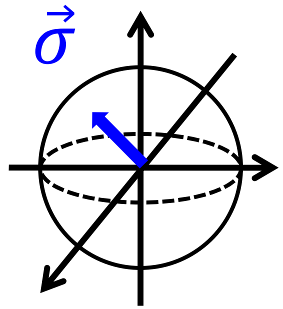


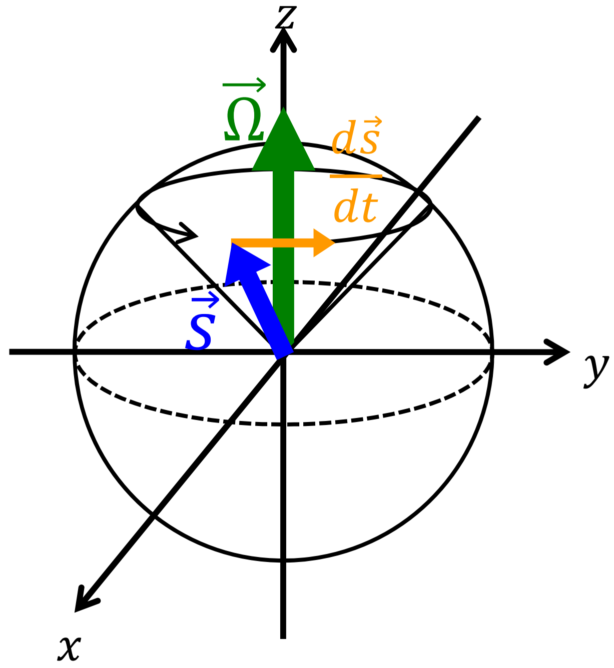
Summary: physics of non-interacting spins

- Zeeman Hamiltonian

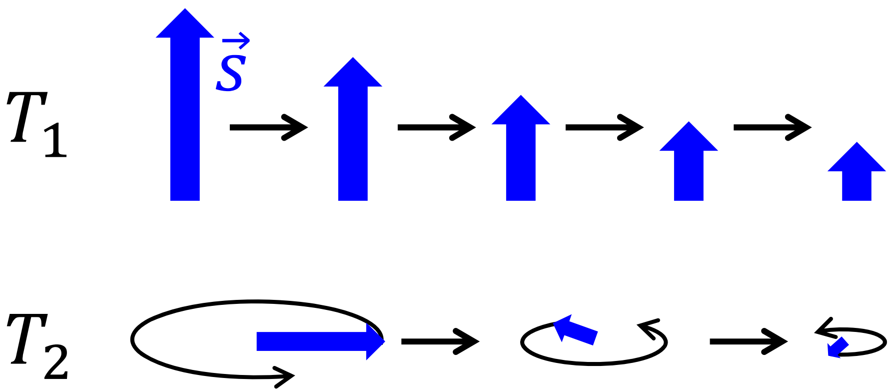
$$H = g\mu_{\mathrm{B}}\vec{s} \cdot \vec{B}$$

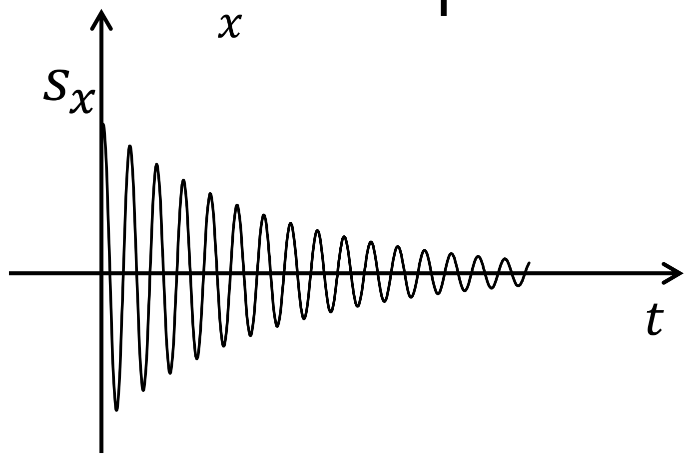
- Bloch sphere





- Larmor precession
- T_1, T_2, and T_2^*
- Bloch equation



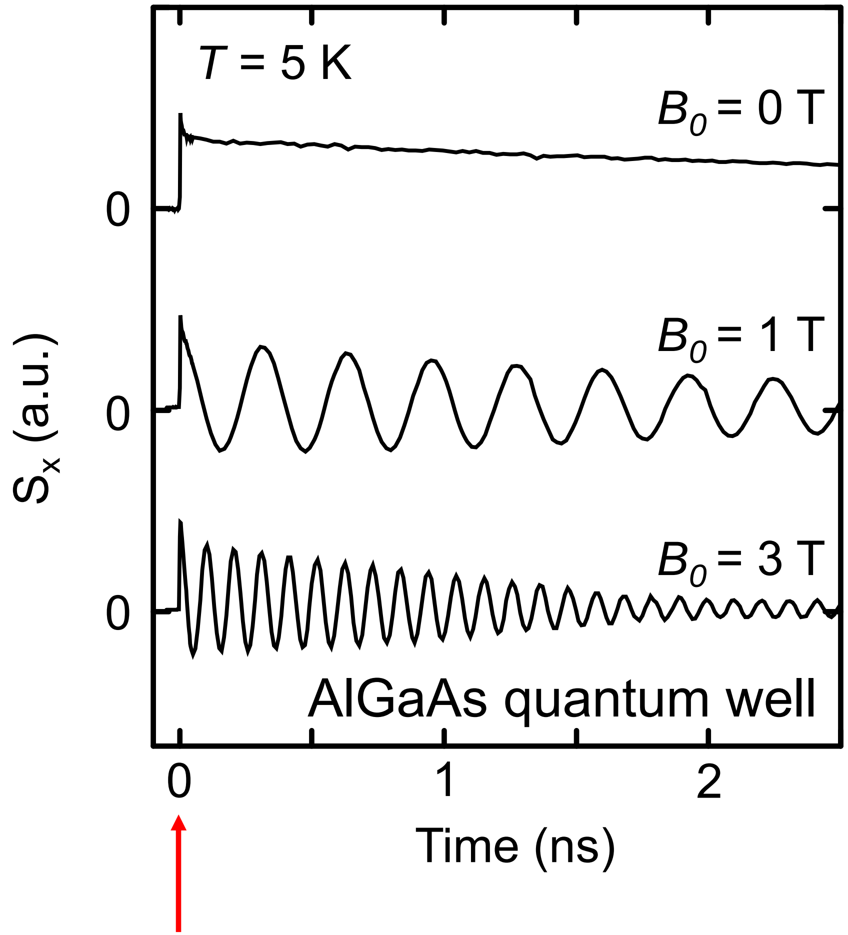


Optical spin injection and detection

In direct gap nonmagnetic semiconductors, Larmor precession can be directly observed in the time domain

- Optical selection rules
- Time-resolved Kerr/Faraday rotation
- Hanle effect

Time-resolved Kerr rotation data



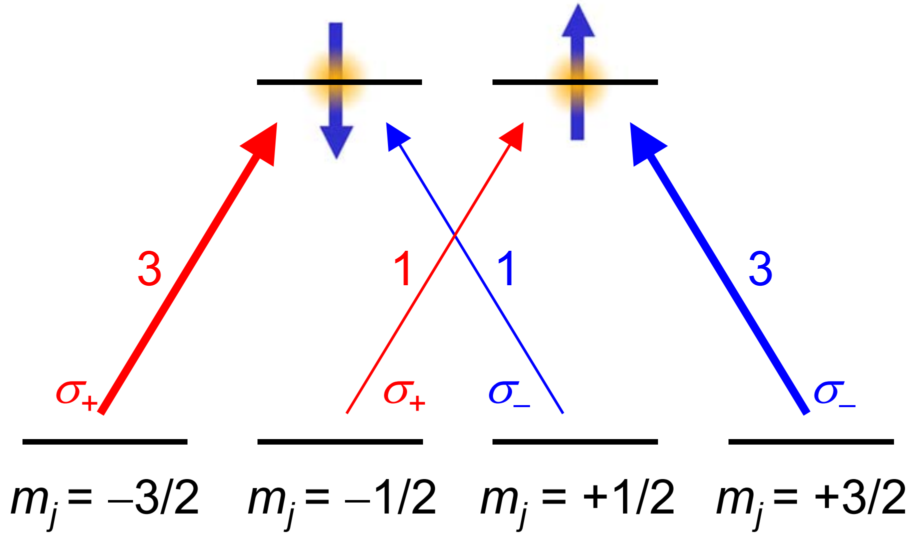
Electron spins are optically injected at t=0

Optical selection rules

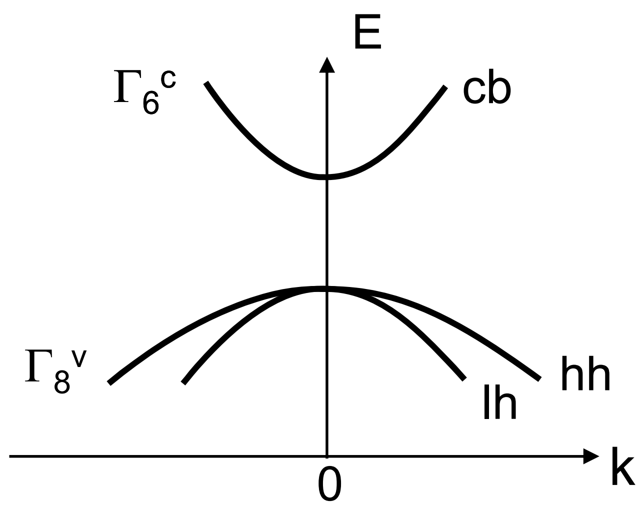
left circularly polarized photons carry angular momentum of +1
right circularly polarized photons carry angular momentum of -1
(in units of ħ)

selection rules from angular momentum conservation

conduction band



valence band

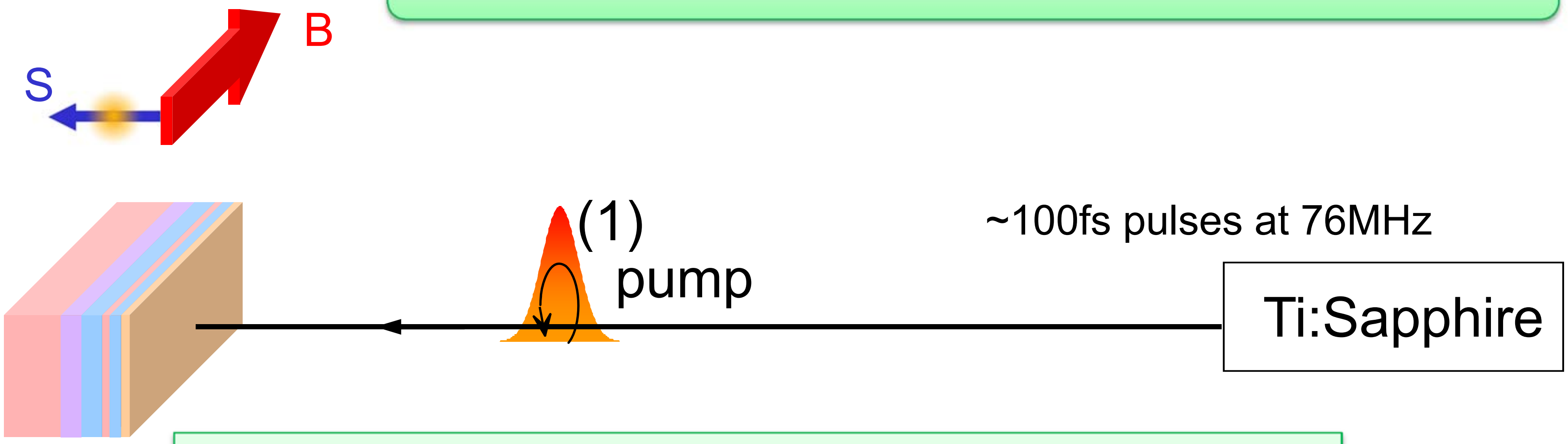


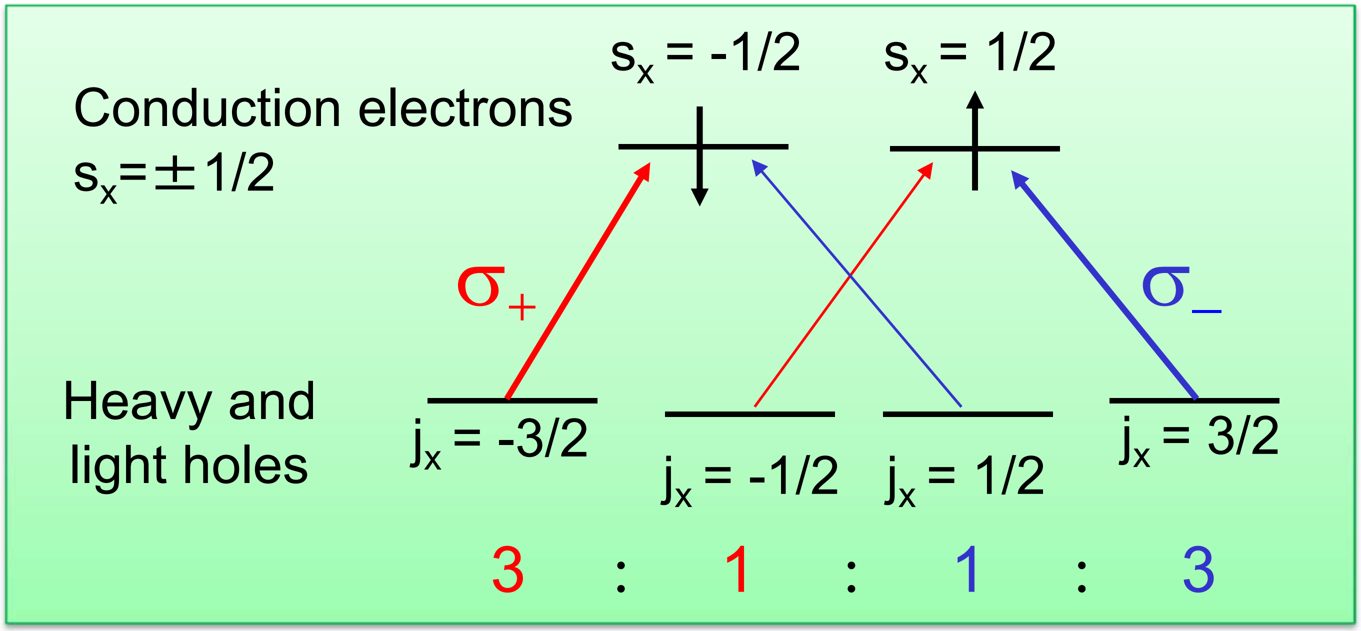
Zinc-blende: 50% polarization

Wurtzite and quantum wells: 100% polarization

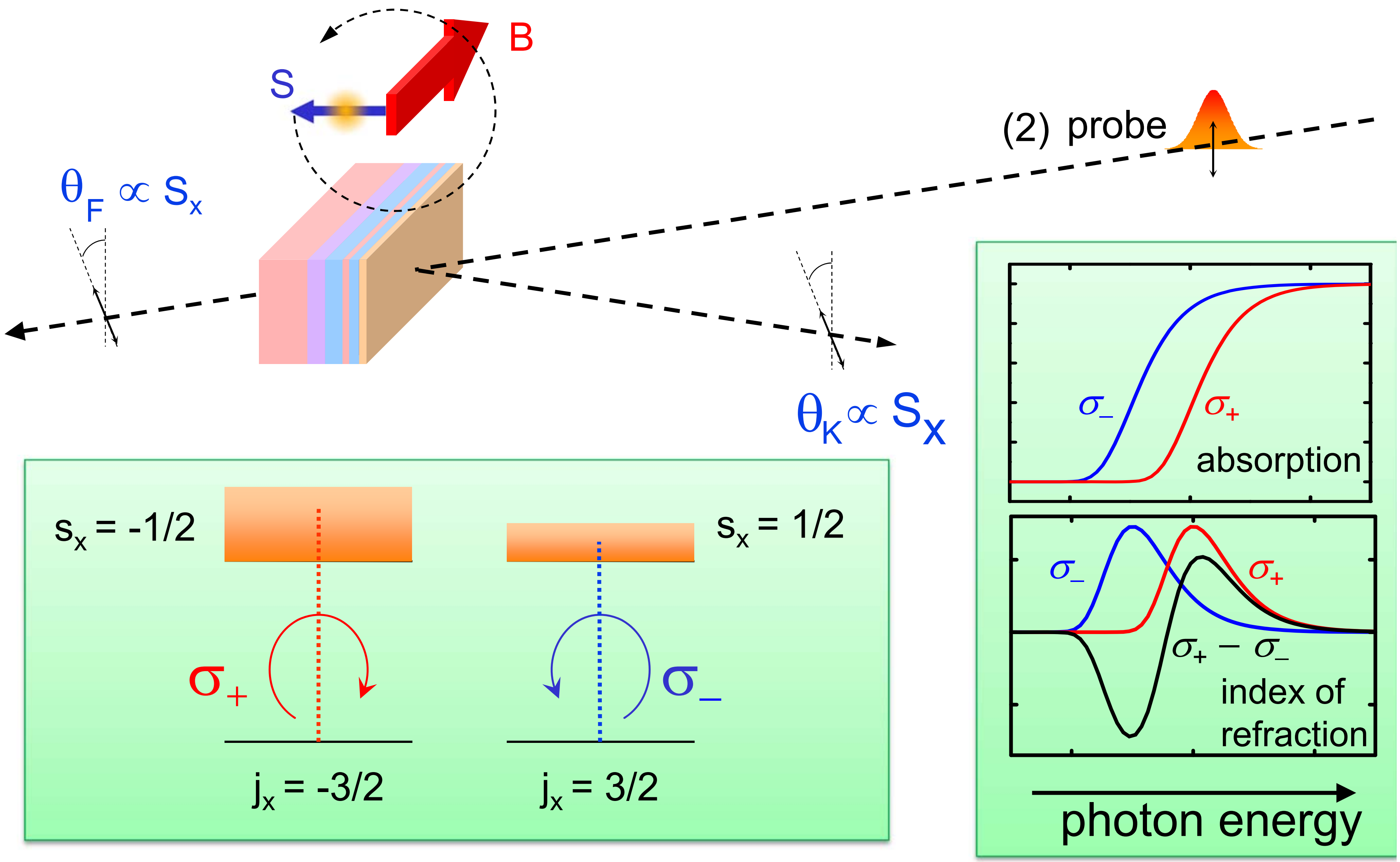
Time-resolved Faraday (Kerr) rotation

1. Circularly polarized pump creates spin population

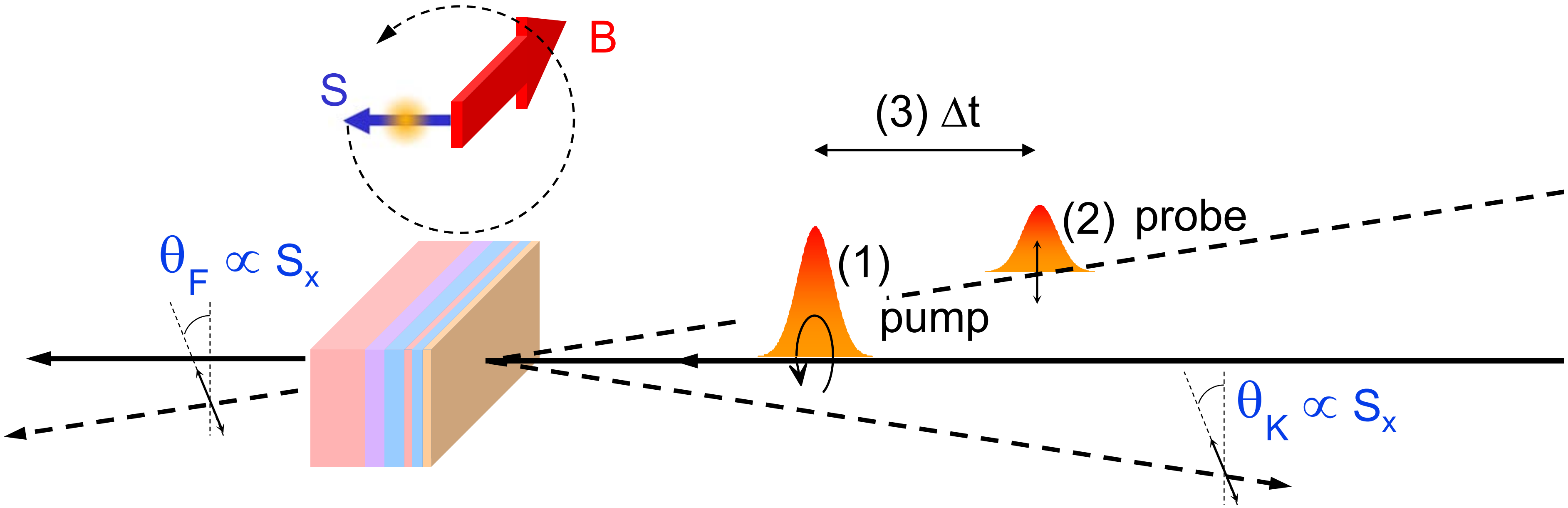


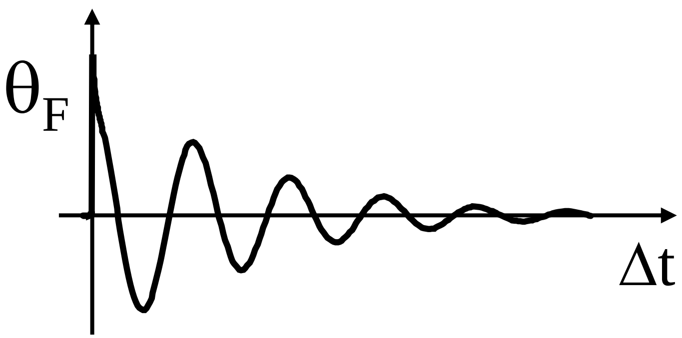


1. Circularly polarized pump creates spin population
2. Linearly polarized probe measures S_x



1. Circularly polarized pump creates spin population
2. Linearly polarized probe measures S_x
3. Δt is scanned and spin precession is mapped out





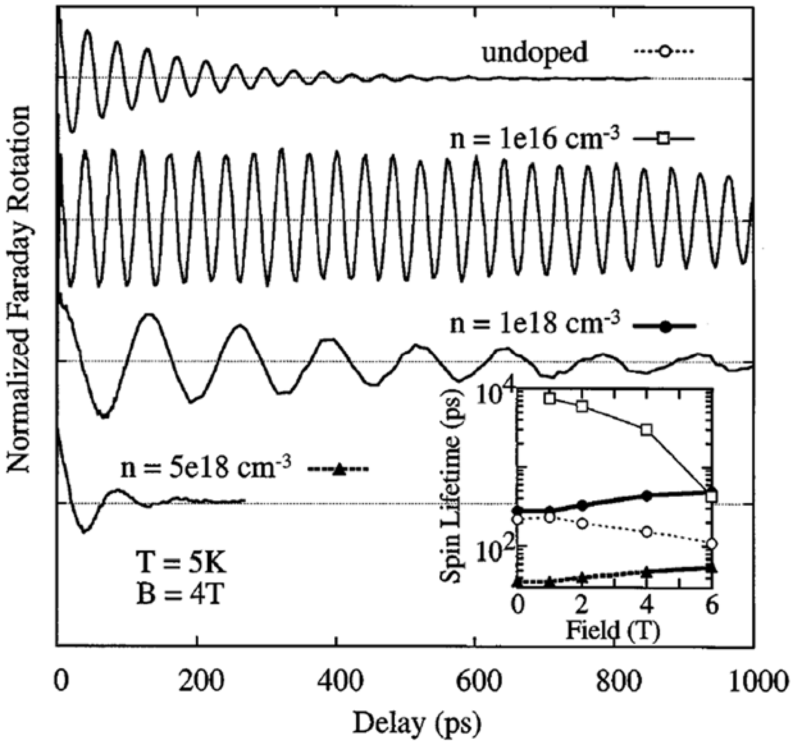
$$\theta_F = Ae^{-\Delta t/T_2^*}\cos(\Omega\Delta t)$$

$$\Omega = g\mu_B B/\hbar$$

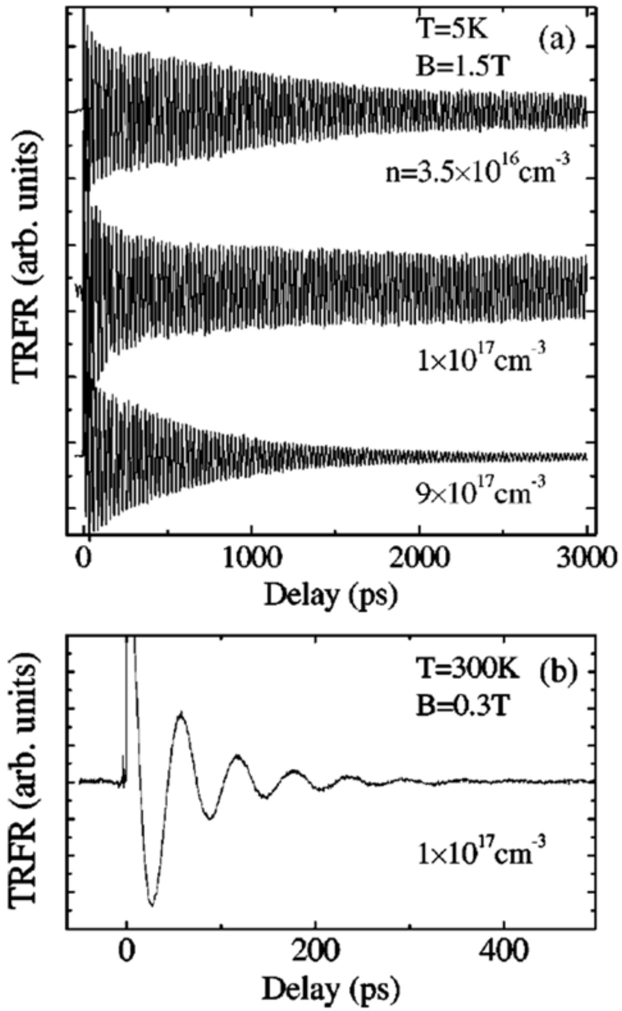
S. Crooker et al., *PRB* **56**, 7574 (1997)

TRFR in bulk semiconductors

GaAs
PRL 80, 4313 (1998)

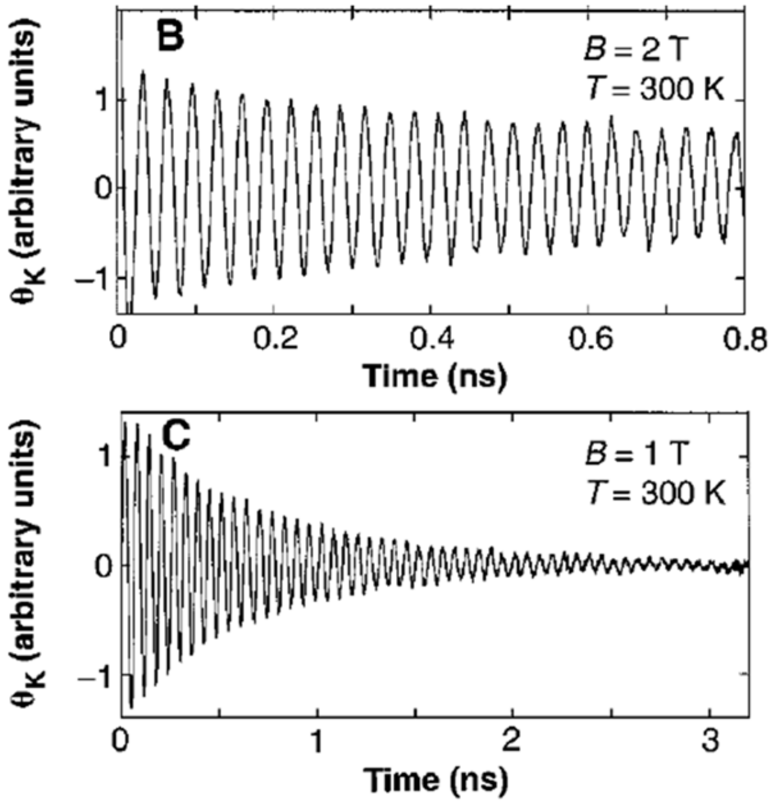


GaN
PRB 63, 121202 (2001)

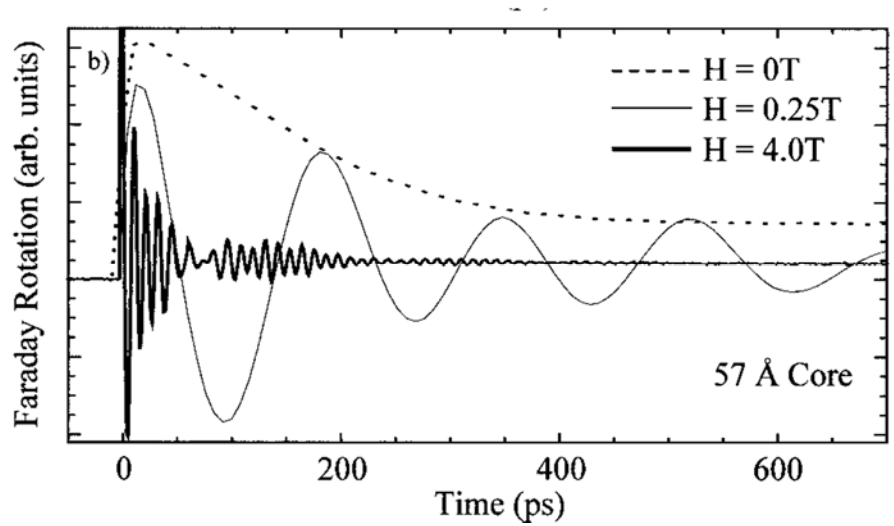


TRFR in quantum wells and quantum dots

ZnCdSe quantum well
Science 277, 1284 (1997)



CdSe quantum dots
PRB 59, 10421 (1999)



Hanle effect

In DC measurements, magnetic field dependence of the spin polarization becomes Lorentzian.

$$\int_0^\infty dt\left[S_0\exp\left(-\frac{t}{T_2^*}\right)\cos(\Omega t)\right]=\frac{\rho_{\mathrm{el}}}{\left(\Omega T_2^*\right)^2+1}$$

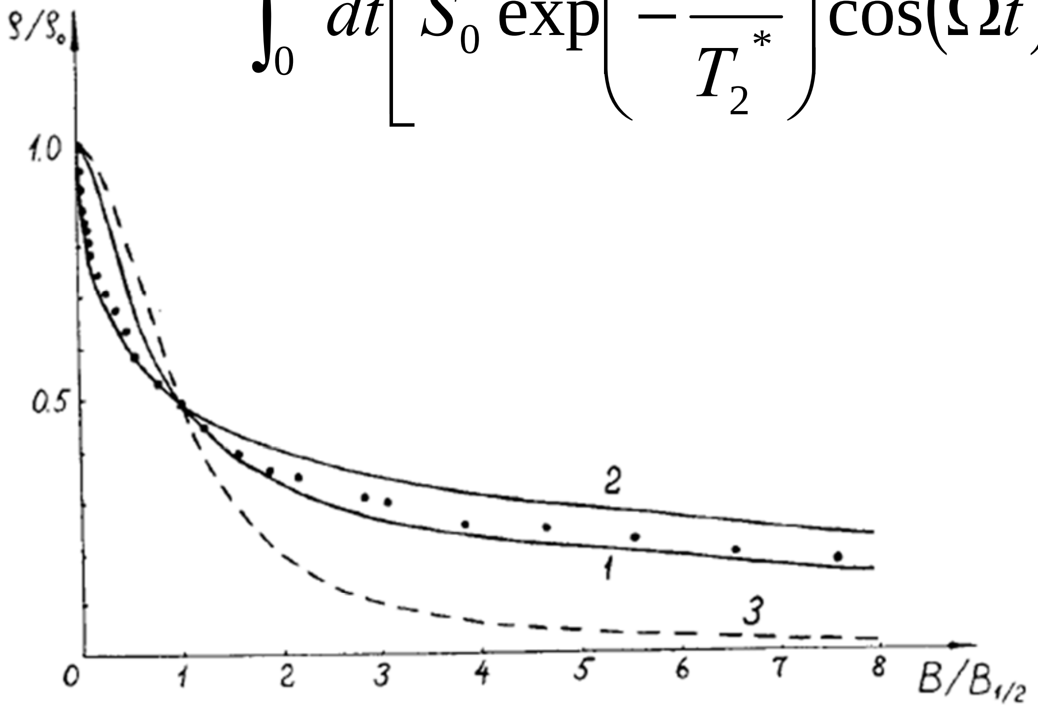
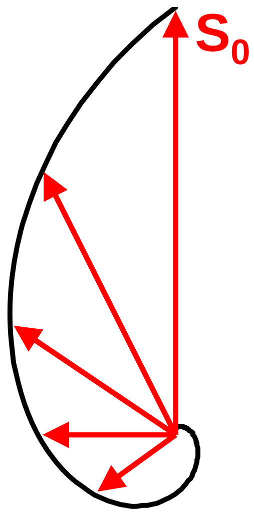


Fig. 14. The Hanle effect in an n-$Ga_{0.8}Al_{0.2}As$ crystal at 4.2 K for the A-band presented in fig. 10 (Vekua et al. 1976). Curves 1 and 2 were calculated according to eqs. (63) and (64) respectively, curve 3 is the Lorentz contour with halfwidth $B_{1/2}=6$ G equal to the halfwidth of the experimental Hanle curve.

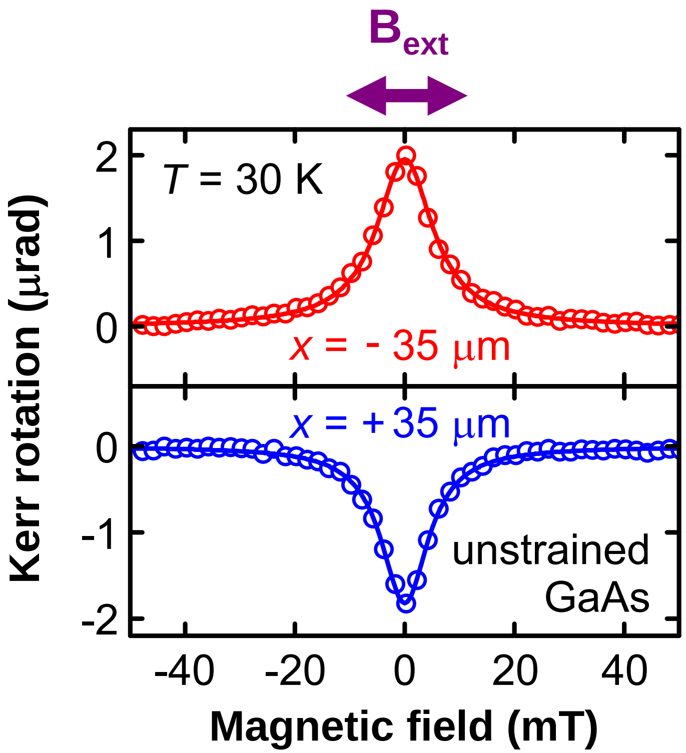


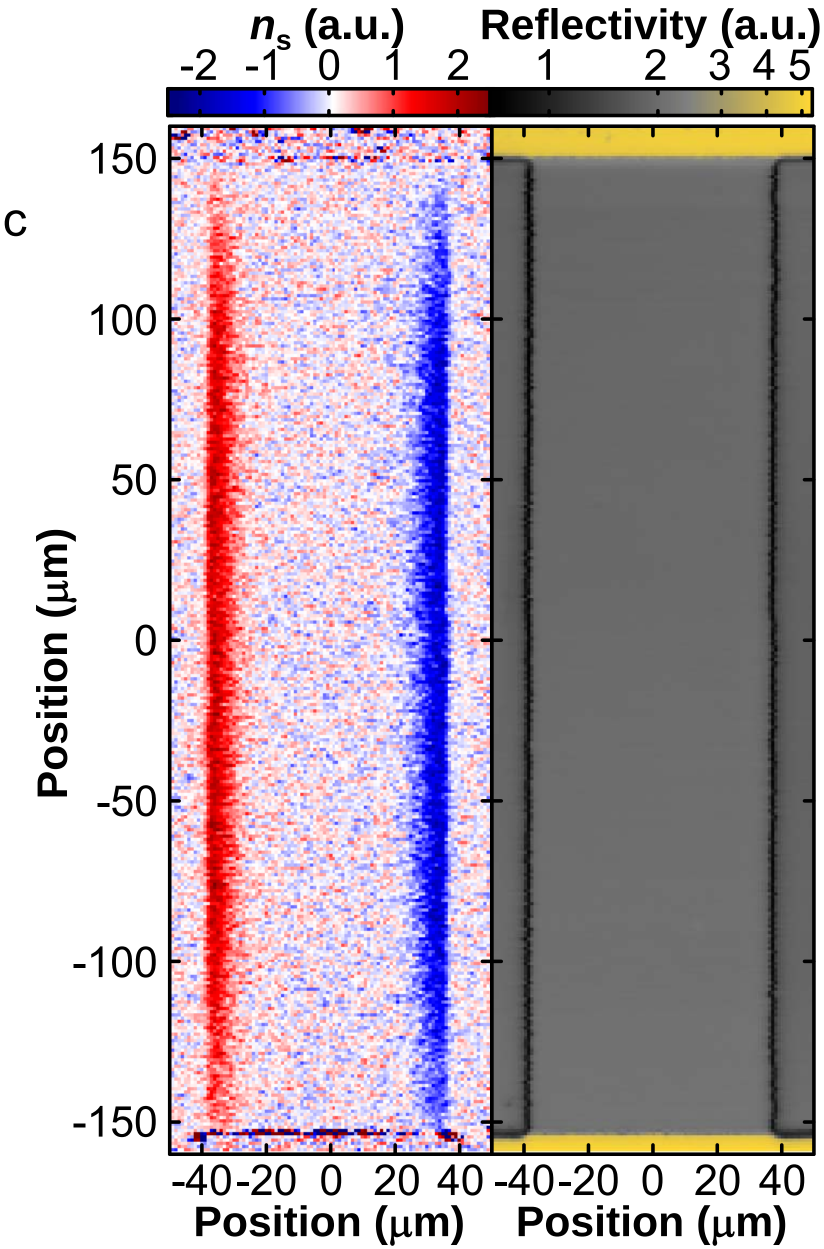
“Optical Orientation” (Elsevier, 1984)

Imaging the spin accumulation due to spin Hall effect

Science 306, 1910 (2004)

Spin accumulation at the edges are imaged by modulating the externally applied magnetic field and measuring the signal at the second harmonic frequency





Spin manipulation in nonmagnetic semiconductors

There are many interactions in nonmagnetic semiconductors that allow spin manipulation

- g-factor engineering
- spin-orbit interaction
- hyperfine interaction
- AC Stark effect

g-factor engineering

$$H = g\mu_B \, \mathbf{B}\cdot\mathbf{S}$$

g: material dependent effective g-factor
B: magnetic field

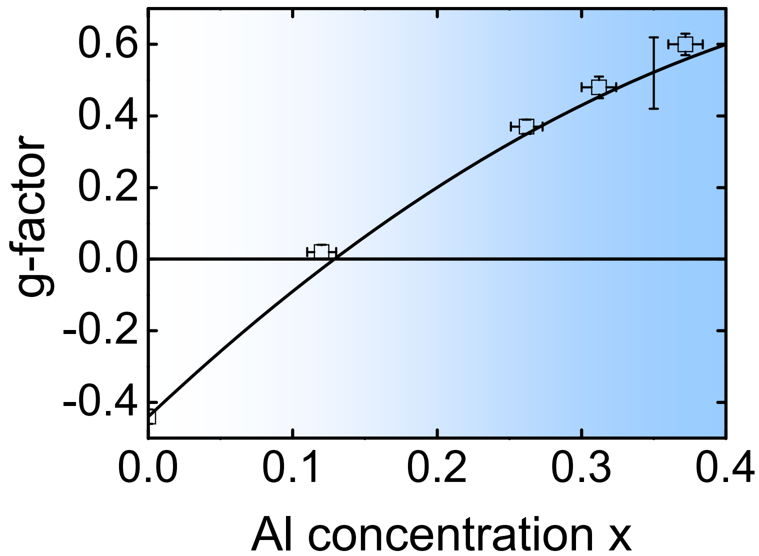
g= -0.44 in GaAs
g= -14.8 in InAs
g= 1.94 in GaN

Change g in a static, global B!

move electrons into different materials using electric fields

Control the g-factor through material composition in semiconductor heterostructures

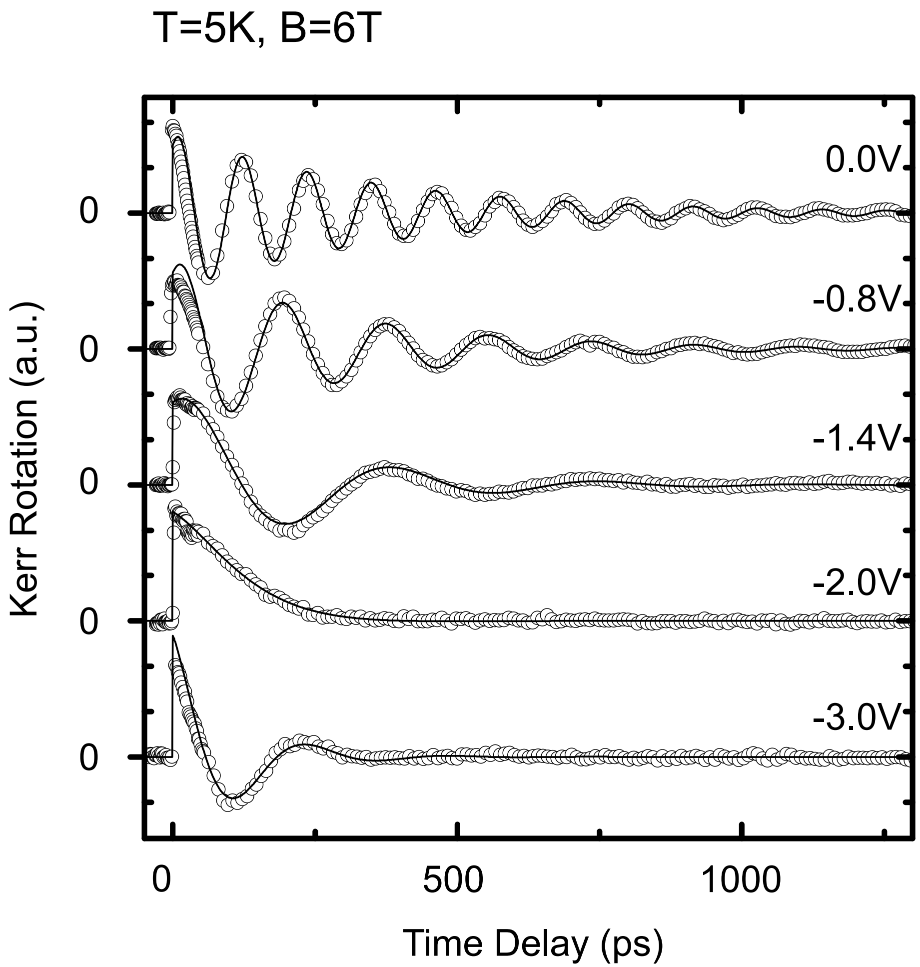
g-factor in $Al_xGa_{1-x}As$

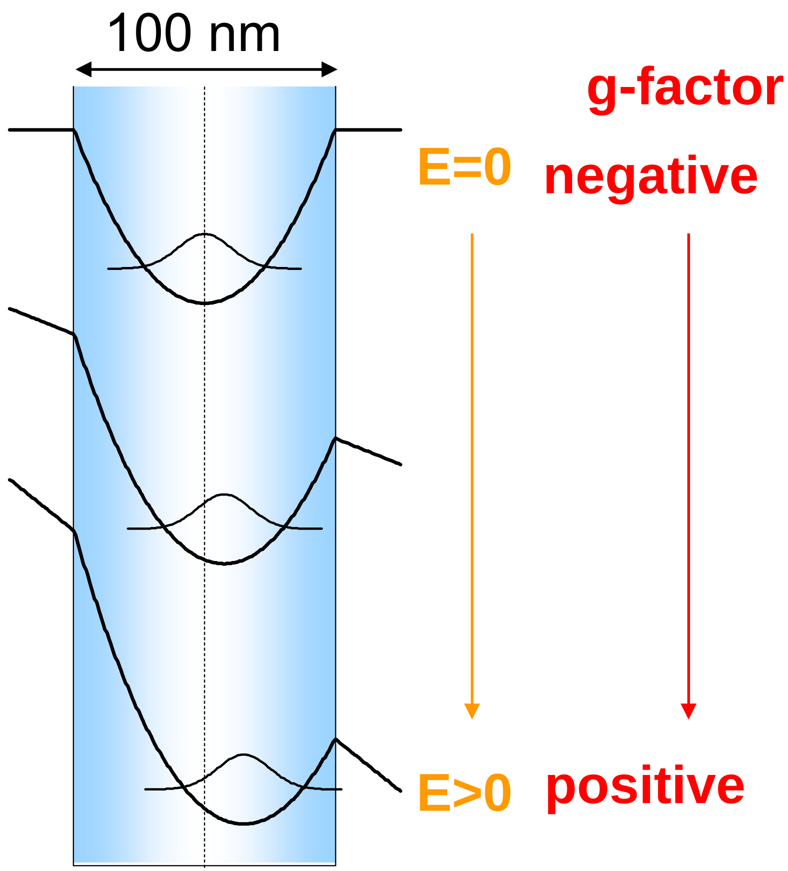


Weisbuch et al., PRB **15**, 816 (1977)

Quasi-static electrical tuning of g-factor

Nature **414,** 619 (2001)



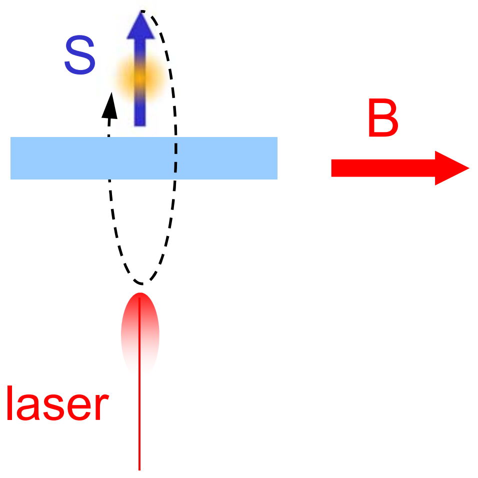


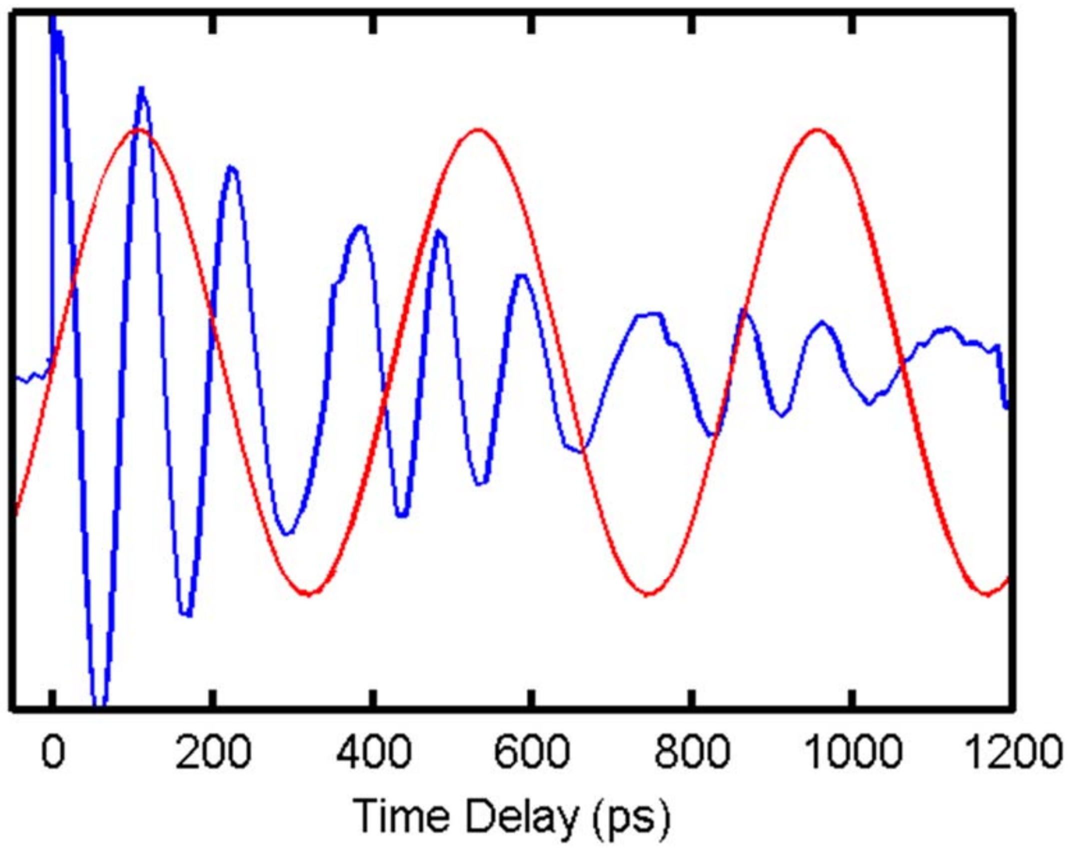
☑ g-factor is electrically tuned

Frequency modulated spin precession

Time dependent voltage

$V(t)=V_0+V_1 \sin(2\pi\nu t)$





Blue: Kerr Rotation
Red: microwave voltage

Fits well to equation :

$$Ae^{-\frac{t}{\tau_1}} \cos\left(\omega_0 t + \frac{\omega_1}{\omega_\mu}\cos(\omega_\mu t + \phi_\mu)\right)$$

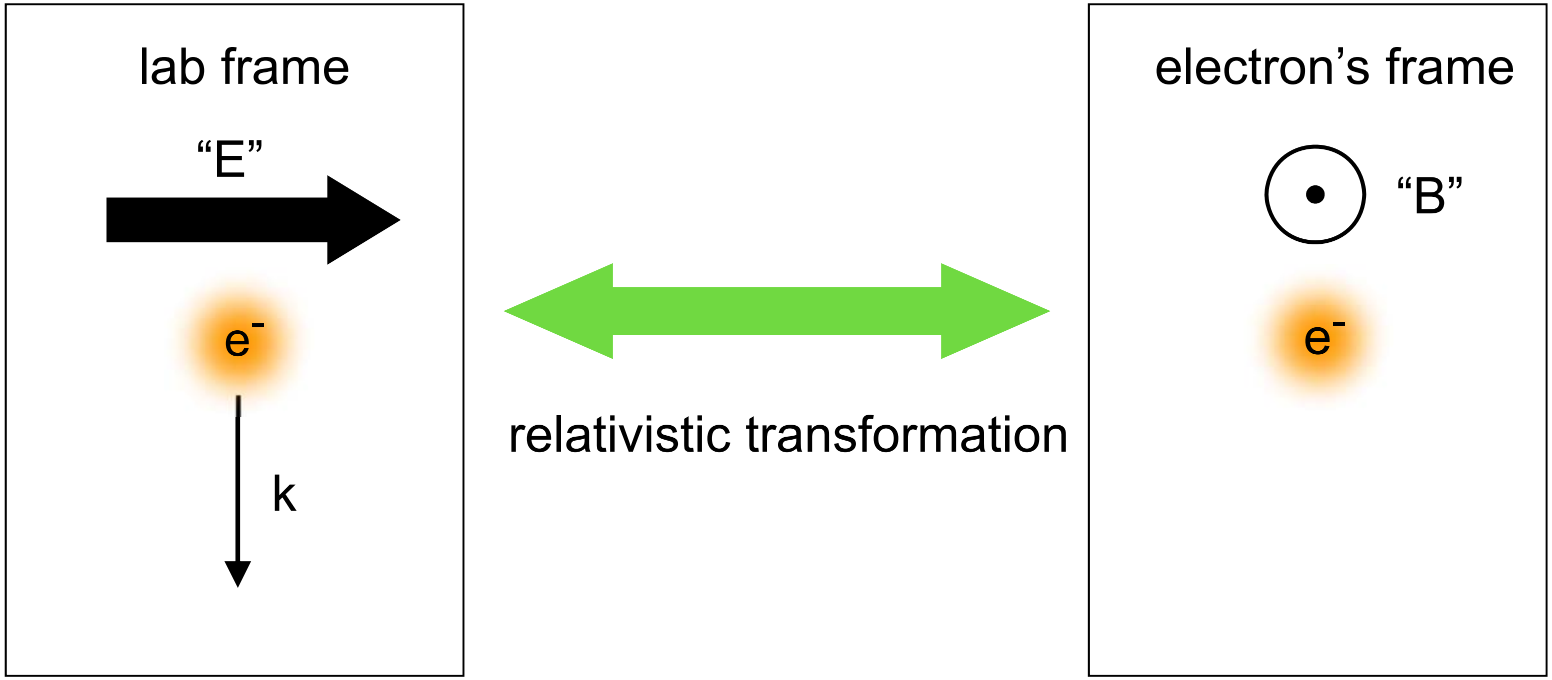
Science **299**, 1201 (2003)

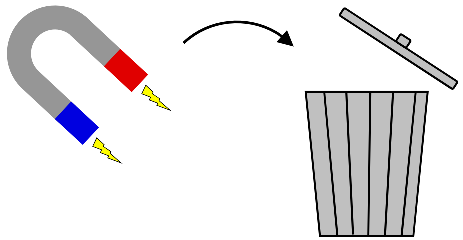
Spin precession is frequency modulated

☑ g-factor tuning at GHz frequency range

Spin-orbit interaction

$$H = \hbar/(4m^2c^2)\,(\nabla V(\mathbf{r}) \times \mathbf{p})\cdot\boldsymbol{\sigma}$$





Allows zero-magnetic field spin manipulation by electric field through control of k

Rashba and Dresselhaus effects

time-reversal symmetry (i.e., at zero magnetic field) $E(k,\uparrow) = E(-k,\downarrow)$ Kramers degeneracy

inversion symmetry $E(k,\uparrow) = E(-k,\uparrow)$ → Zero-magnetic-field spin splitting requires asymmetry

Rashba effect: structural inversion asymmetry (SIA) of quantum wells
Sov. Phys. Solid State 2, 1109 (1960)

$$\vec{\Omega}(\vec{k}) = \alpha(k_y, -k_x)$$

Dresselhaus effect: bulk inversion asymmetry (BIA) of zinc-blende crystal
Phys. Rev. 100, 580 (1955)

$$\vec{\Omega}(\vec{k}) = 2\gamma\{k_x(k_y^2 - k_z^2), k_y(k_z^2 - k_x^2), k_z(k_x^2 - k_y^2)\}$$

In a (001) quantum well

$$\vec{\Omega}(\vec{k}) = 2\gamma\langle k_z^2\rangle(k_x, -k_y)$$

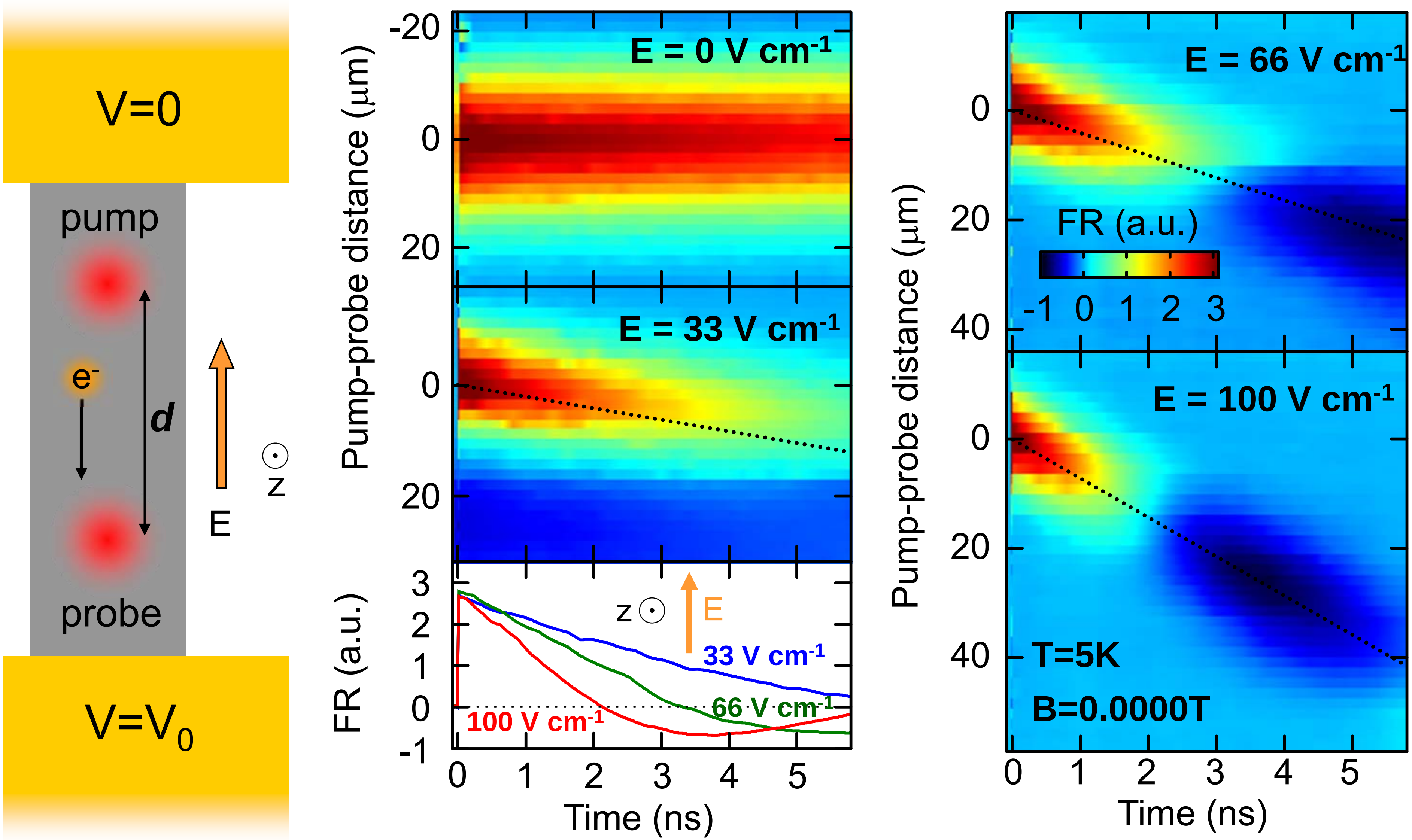
Strain-induced terms

$$\overrightarrow{\Omega_3}(\vec{k}) \propto \{(\varepsilon_{yy} - \varepsilon_{zz})k_x, (\varepsilon_{zz} - \varepsilon_{xx})k_y, (\varepsilon_{xx} - \varepsilon_{yy})k_z\}$$

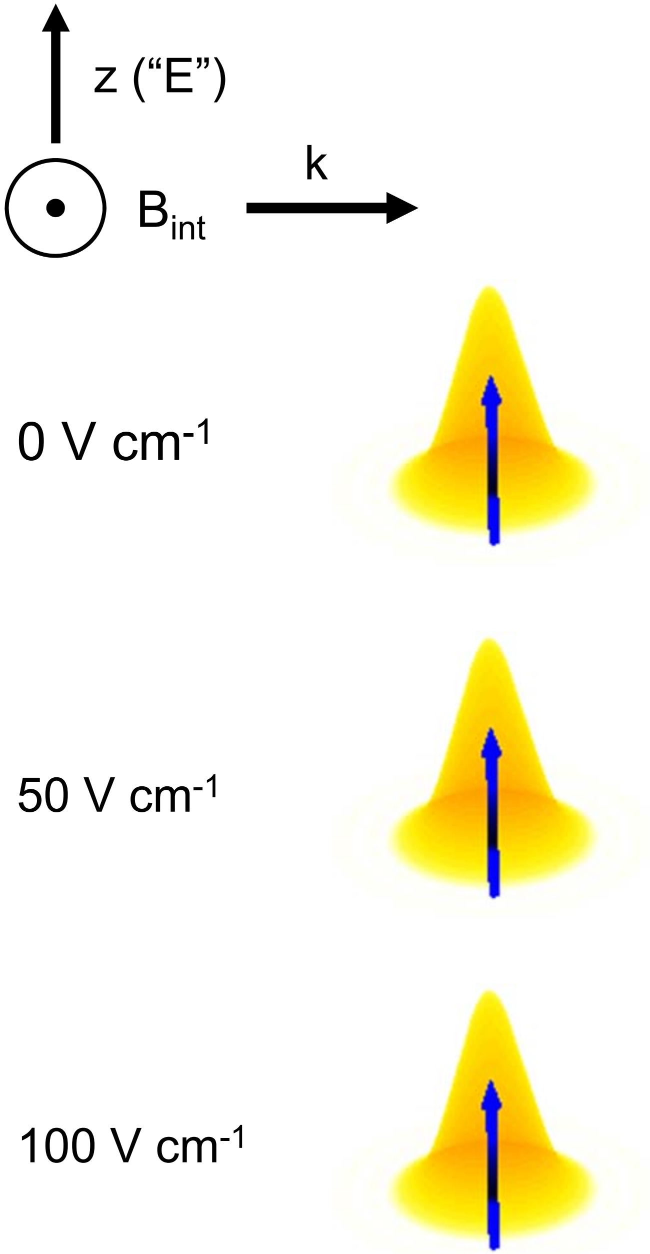
$$\overrightarrow{\Omega_4}(\vec{k}) \propto (\varepsilon_{zx}k_x - \varepsilon_{xy}k_y, \varepsilon_{xy}k_y - \varepsilon_{yz}k_z, \varepsilon_{yz}k_z - \varepsilon_{zx}k_x)$$

Spatiotemporal evolution of spin packet in strained GaAs

Nature **427**, 50 (2004)

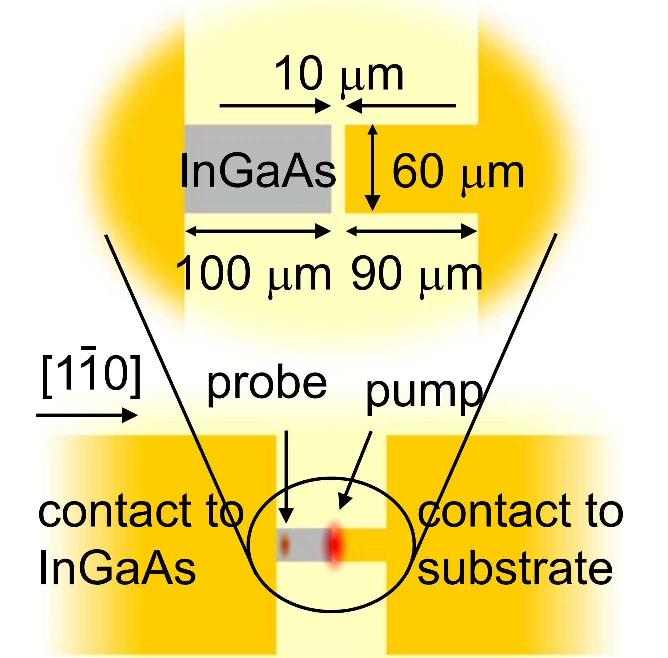


☑ Spin precession at zero magnetic field!

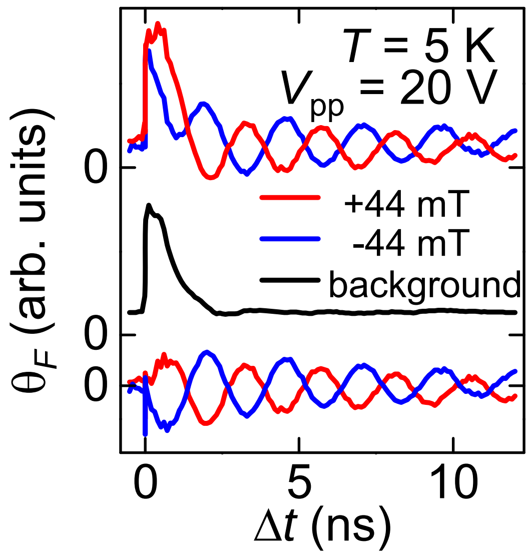

z ("E")
k
B_{int}
0 V cm^{-1}
50 V cm^{-1}
100 V cm^{-1}

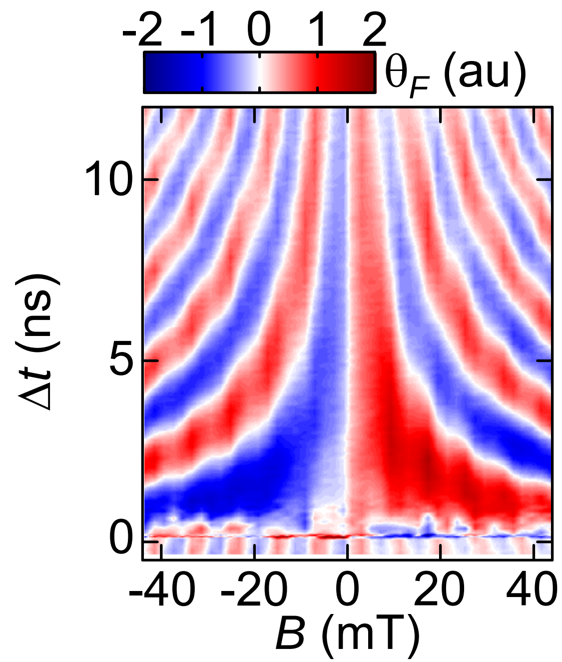
Coherent spin population excited with electrical pulses

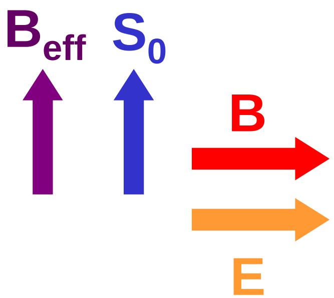
Phys. Rev. Lett. 93, 176601 (2004)



semi-insulating GaAs substrate







Precession at electron Larmor frequency of InGaAs

→ Faraday rotation signal due to electrons

The signal shows sign change with magnetic field

→ spins excited in the plane of the sample (along the effective magnetic field)

☑ Electron spins are generated using picosecond electrical pulses

Hyperfine interaction

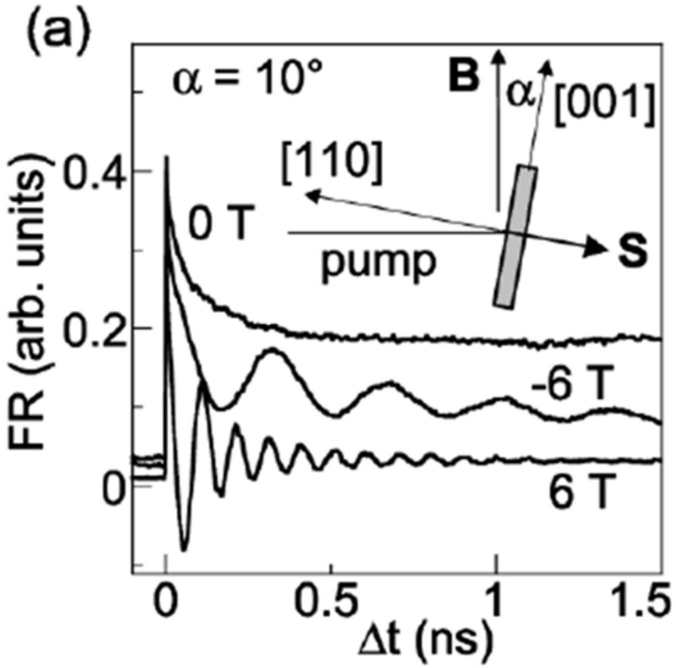
$$H = A\vec{I}\cdot\vec{S}$$

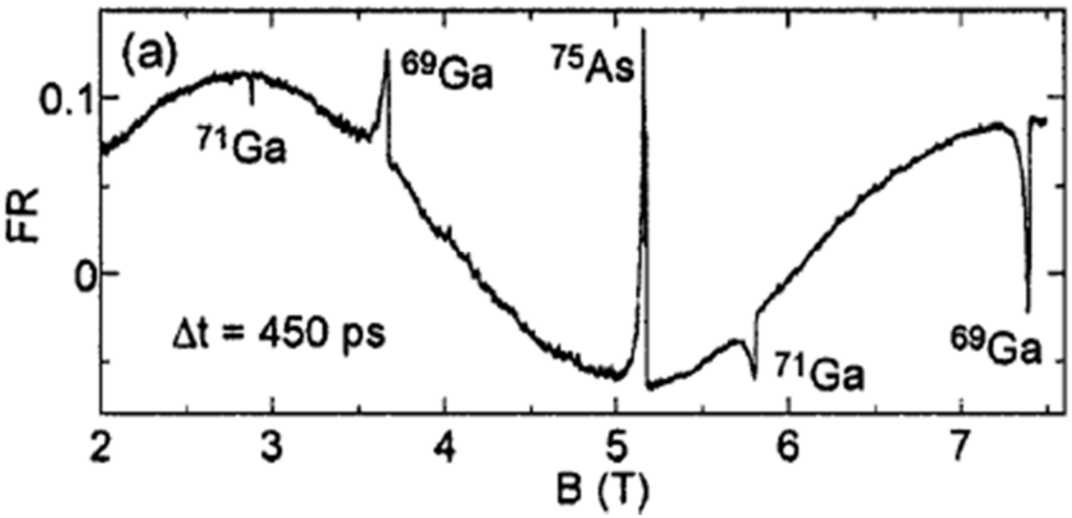
$\vec{I}$: nuclear spin

$\vec{S}$: electron spin

Nuclear spin polarization acts as an effective magnetic field for electron spins

Dynamic nuclear polarization:
spin injection causes nuclear spin polarization
Lampel, PRL 20, 491 (1968)

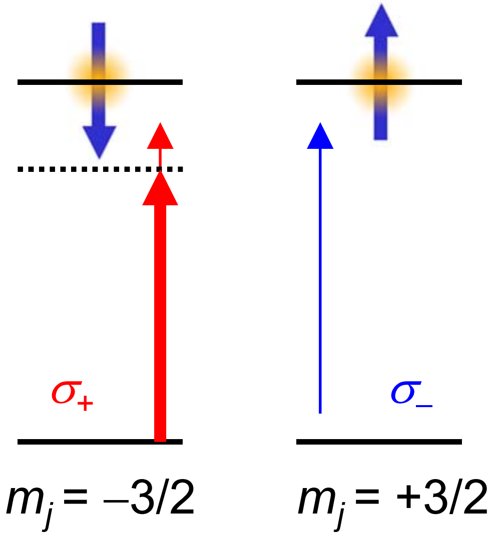


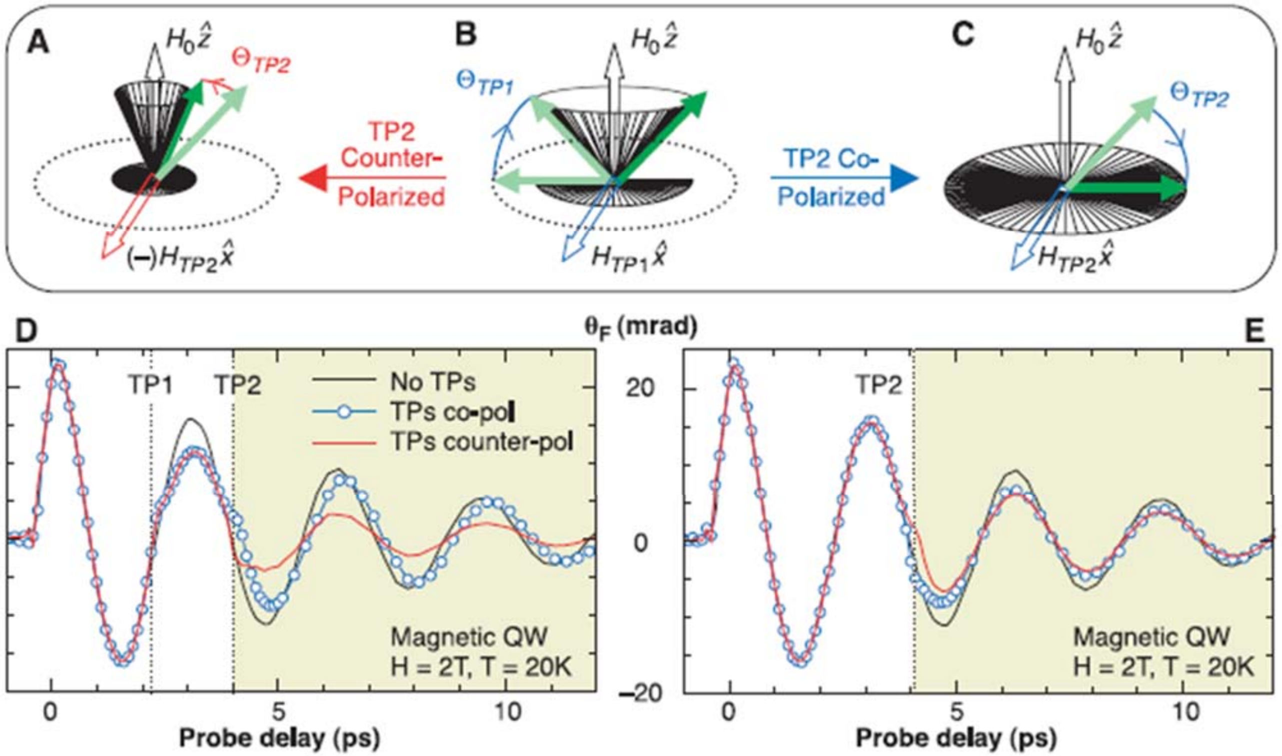


PRL 56, 2677 (2001)

AC Stark effect

Optical pulse below bandgap shifts the band gap (AC Stark effect)
Circularly polarized pulse shifts one of the spin subbands, causing spin splitting





Science 292, 2458 (2001)

Topics covered in this talk

- Zeeman Hamiltonian
- Bloch sphere
- Larmor precession
- T_1, T_2, and T_2^*
- Bloch equation

- Optical selection rules
- Time-resolved Kerr/Faraday rotation
- Hanle effect

- g-factor engineering
- spin-orbit interaction
- hyperfine interaction
- AC Stark effect