Spin filter in spin-dependent recombination and nuclear effects

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International Workshop on Physics of Excitons, Varadero, Cuba, March 30 – April 6, 2013

Motivation

Attractive ideas:

Spin of carriers and nuclei in semiconductor is supposed to be used for quantum computation and spintronics

Realization of these ideas at room temperature would certainly benefit their practical implementation

We propose using spin-dependent Shockley-Read recombination via deep paramagnetic centers
in order to achieve very high (up to 100%)
both electron and nuclear spin polarization
in nonmagnetic semiconductors
at room temperature and
zero and weak magnetic fields

Striking result

Problem:

Spin relaxation time of conduction electrons
in nonmagnetic direct-gap semiconductors

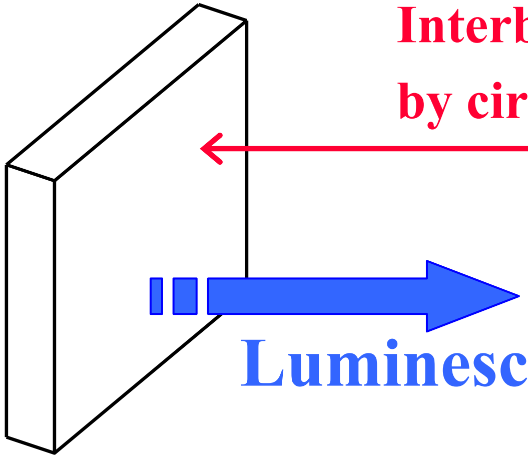
τ_s < 100 ps at T=300 K

G.E. Pikus, A.N. Titkov, Chap. 3, ***Optical orientation***, eds. F. Meier and B. Zakharchenya (North-Holland, Amsterdam, 1984).
Pil Hun Song and K.W. Kim, Phys. Rev. B **66**, 035207 (2002).

Striking result:

We have found at T=300 K
in GaAsN alloys [N]=0.6÷3.5%
spin polarization of free electrons P ~ 90 %
spin lifetime T_s > 1 ns

Optical orientation in semiconductors



Interband excitation

by circular polarized light; $\Delta m = +\hbar$ for σ^{+} light

$$P = \frac{n_{+} - n_{-}}{n_{+} + n_{-}}$$

Luminescence: $\rho \propto P$

PL circular polarization degree $\rho = \dfrac{J^{+} - J^{-}}{J^{+} + J^{-}}$

Optical orientation, eds. F. Meier and B. Zakharchenya (North-Holland, Amsterdam, 1984)

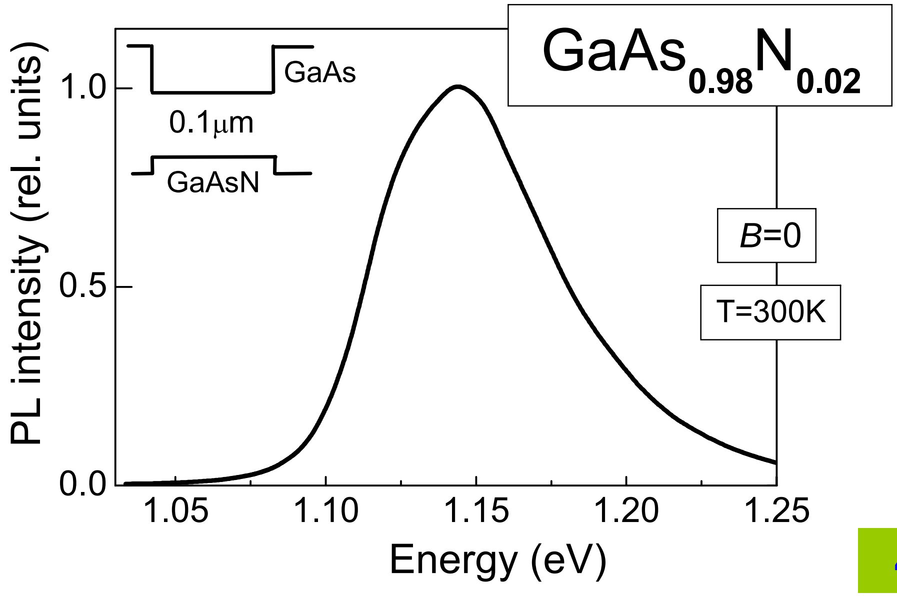
Spin Physics in Semiconductors, ed. M.I. Dyakonov (Springer, Berlin, 2008)

$GaAs_{1-x}N_x$, $x = 0.6 \div 3.5\%$

$Ga(In)As_{1-x}N_x$

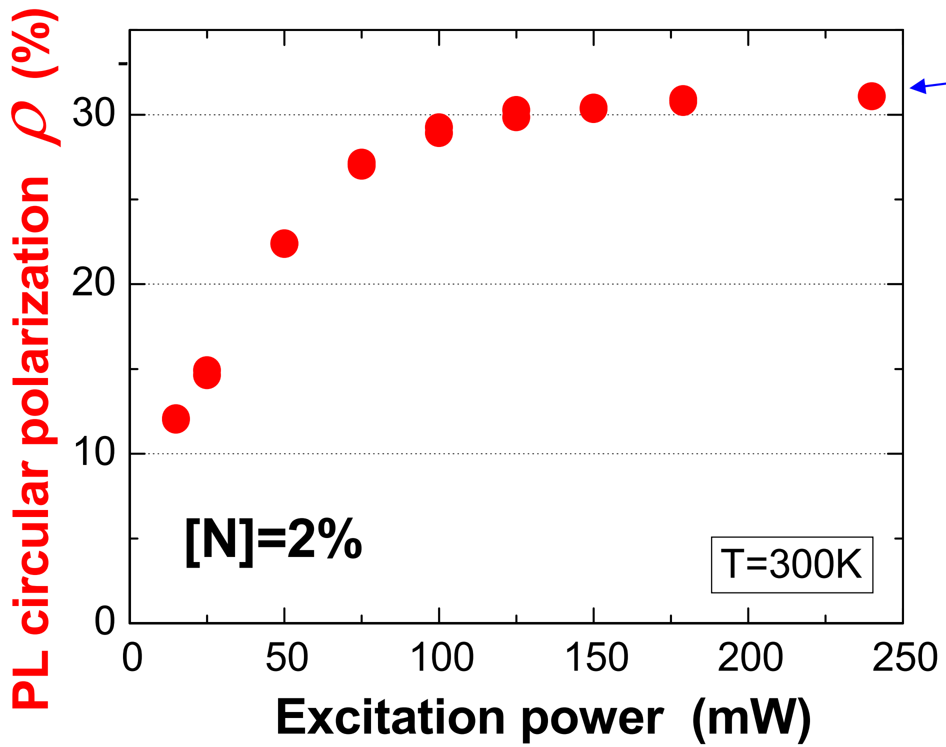
films 0.1μm

T = 300K



PL circular polarization in GaAsN

continuous-wave pumping



$P = 2\rho \sim 60\% \;>\; P_{theor} = 50\%$

electron spin polarization

$$P = \frac{n_+ - n_-}{n_+ + n_-}$$

PL circular polarization degree

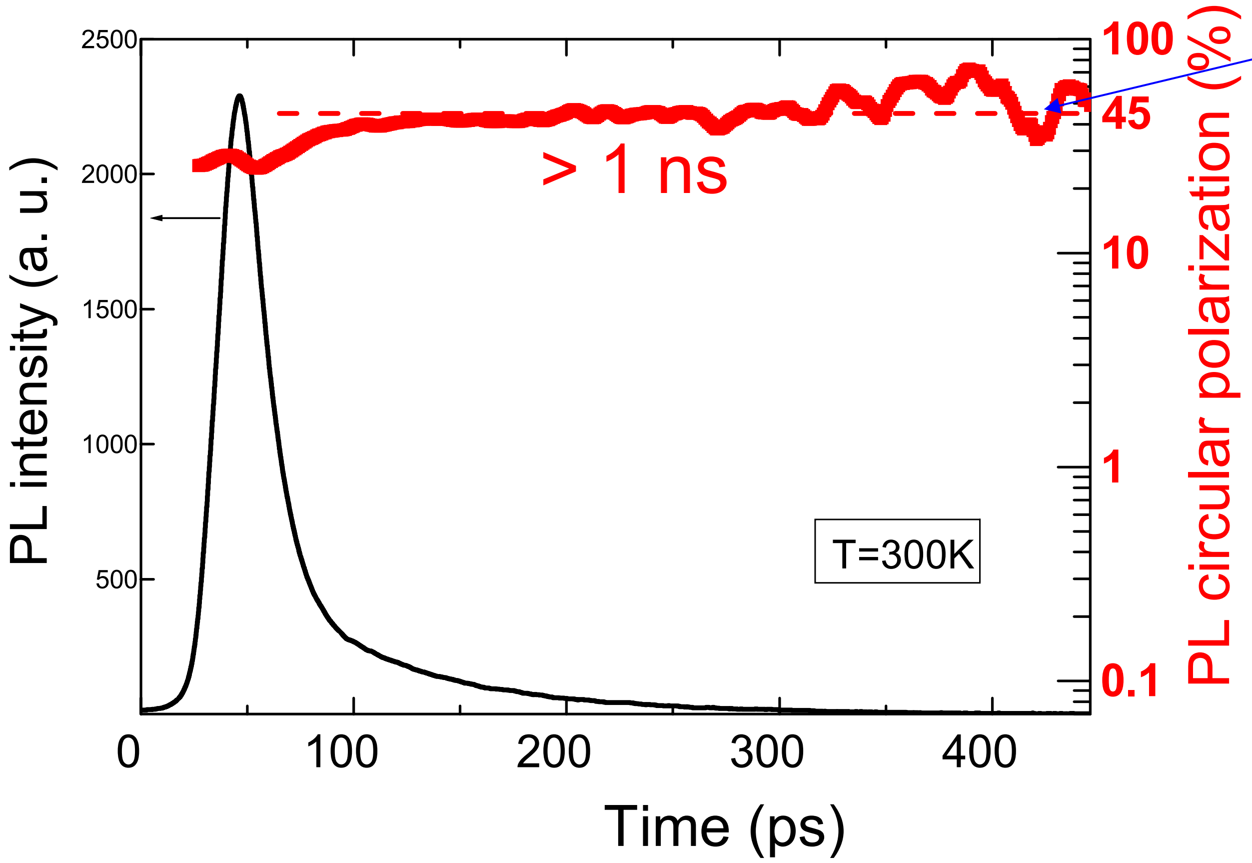
$$\rho = \frac{J^+ - J^-}{J^+ + J^-}$$

Kalevich, Ikezawa, Shiryaev, Egorov, Ustinov, and Masumoto, Meeting Abstracts of the Physical Society of Japan, Okayama, Japan, 20-23 September **2003**, v.58, iss.2, part 4, p.574.

Egorov, Kalevich, Afanasiev, Shiryaev, Ustinov, Ikezawa and Masumoto, J. Appl. Phys. **98**, 13539 (2005)

Spin dynamics in $GaAs_{0.98}N_{0.02}$

under pulse (1.5 ps) pumping



P ~ 90%

electron spin polarization

$$P = \frac{n_+ - n_-}{n_+ + n_-}$$

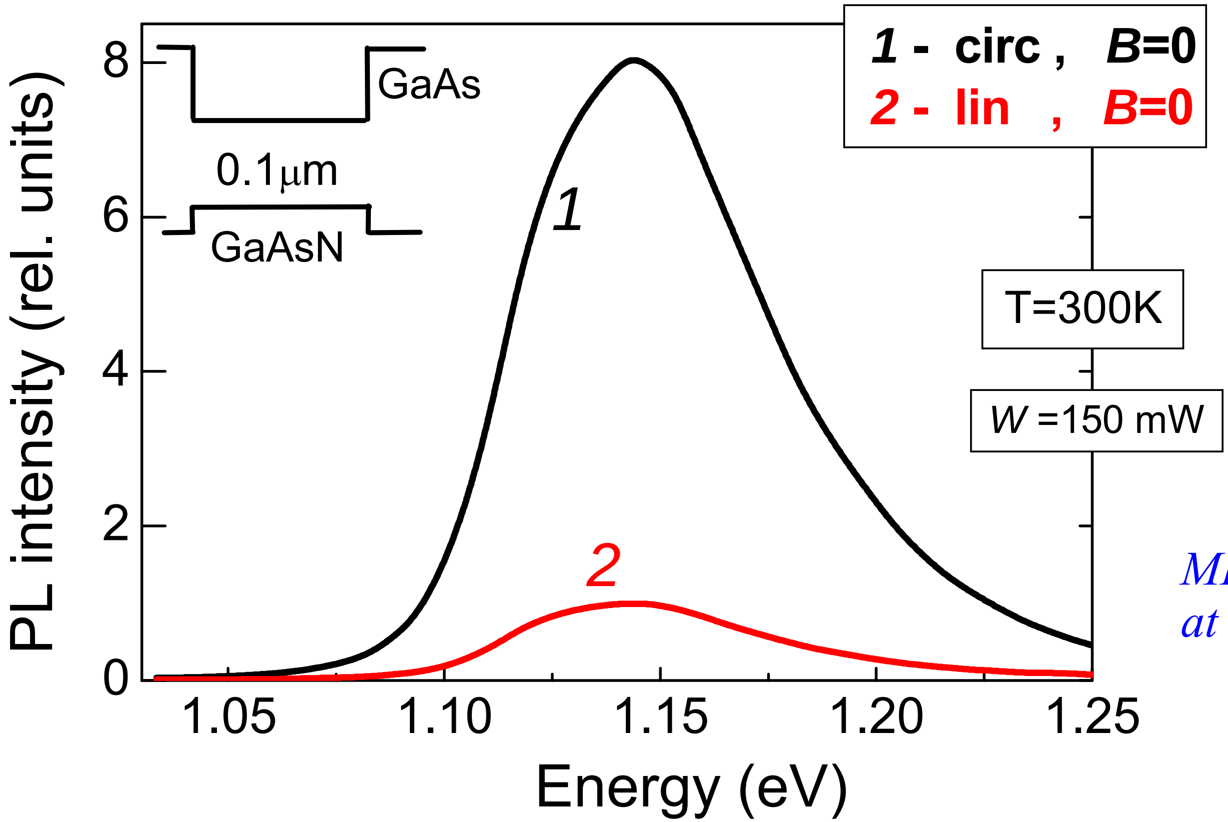
PL circular polarization degree

$$\rho = \frac{J^+ - J^-}{J^+ + J^-}$$

L. Lombez, P.-F. Braun, H. Carrère, B. Urbaszek, P. Renucci, T. Amand, X. Marie, J.C. Harmand and V.K. Kalevich, APL **87**, 252115 (2005)

Spin-dependent recombination in $GaAs_{0.98}N_{0.02}$

continuous wave pumping



MBE grown
at Ioffe Institute

Kalevich, Ivchenko, Afanasyev, Shiryaev, Egorov, Ustinov, Pal and Masumoto, JETP Lett. **82**, 455 (2005)

For a review on GaNAs properties, see e.g., *Dilute III-V Nitride Semiconductors and Material Systems*, Springer Series in Material Science Vol. 105, ed. A. Erol (Springer, Berlin, 2008)

Outline

- Introduction
- Spin-dependent recombination (SDR) as an origin of a giant electron spin-polarization:
  (a) continuous-wave pumping
  (b) pulsed pumping
- SDR model and comparison with experiment
- Spin-dependent photoconductivity and ODEMR
- Enhancement of electron spin-polarization by a longitudinal magnetic field
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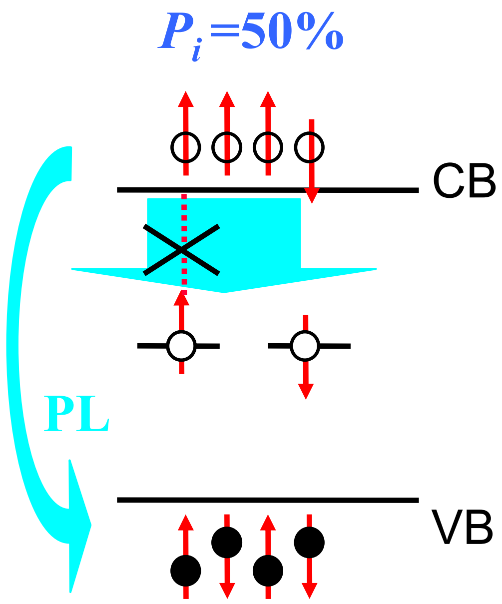
Origin of Spin-Dependent Recombination (SDR)

The source of the SDR is the Pauli exclusion principle:
new electron cannot be captured on the energy state if the state is already occupied by the other electron with the same spin orientation.

When electrons are polarized
electron-capture cross-section depends on their polarizations: $\sigma_e = \sigma_0(1-PP_c)$

- S. Geschwind *et al*., PRL (1959):
  ODEPR in fluorescence of Cr^{3+} excited states in Al_2O_3 .
- D. Lepine, PRB (1972):
  EPR of paramagnetic centers on the surface of crystalline silicon; observed in photoconductivity.
- T. Wosinski *et al*., phys. status solidi (1976): SDR in dislocated silicon.
- I. Solomon *et al*., Solid State Commun. (1977): SDR in amorphous silicon.

Model of Spin-Dependent Recombination

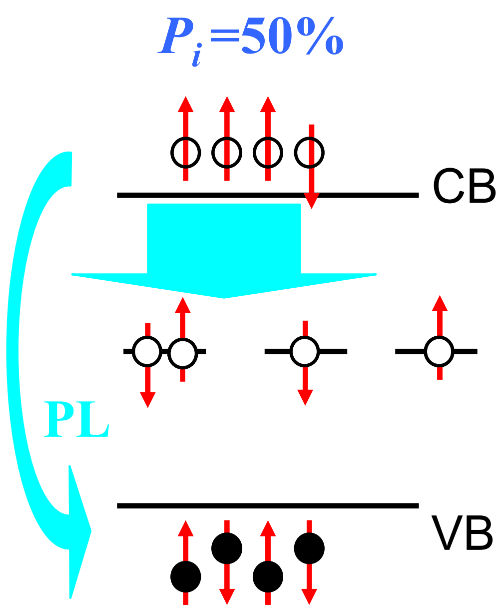


- Weisbuch and Lampel, SSC **14**, 141 (1974)
  AlGaAs epilayer, 77K
- Miller *et al*., PRB **21**, 1569 (1980)
  AlGaAs/GaAs SL, 4K
- Paget, PRB **30**, 931 (1984)
  GaAs bulk, 4K

1) deep centers are paramagnetic and unpolarized without light
2) recombination of free electrons with deep centers is dominant
3) a capture of electron with parallel spin is forbidden
4) holes are unpolarized and their capture is spin-independent
5) $\tau_{sc} >> \tau_s$

Model of Spin-Dependent Recombination

- Weisbuch and Lampel, SSC **14**, 141 (1974)



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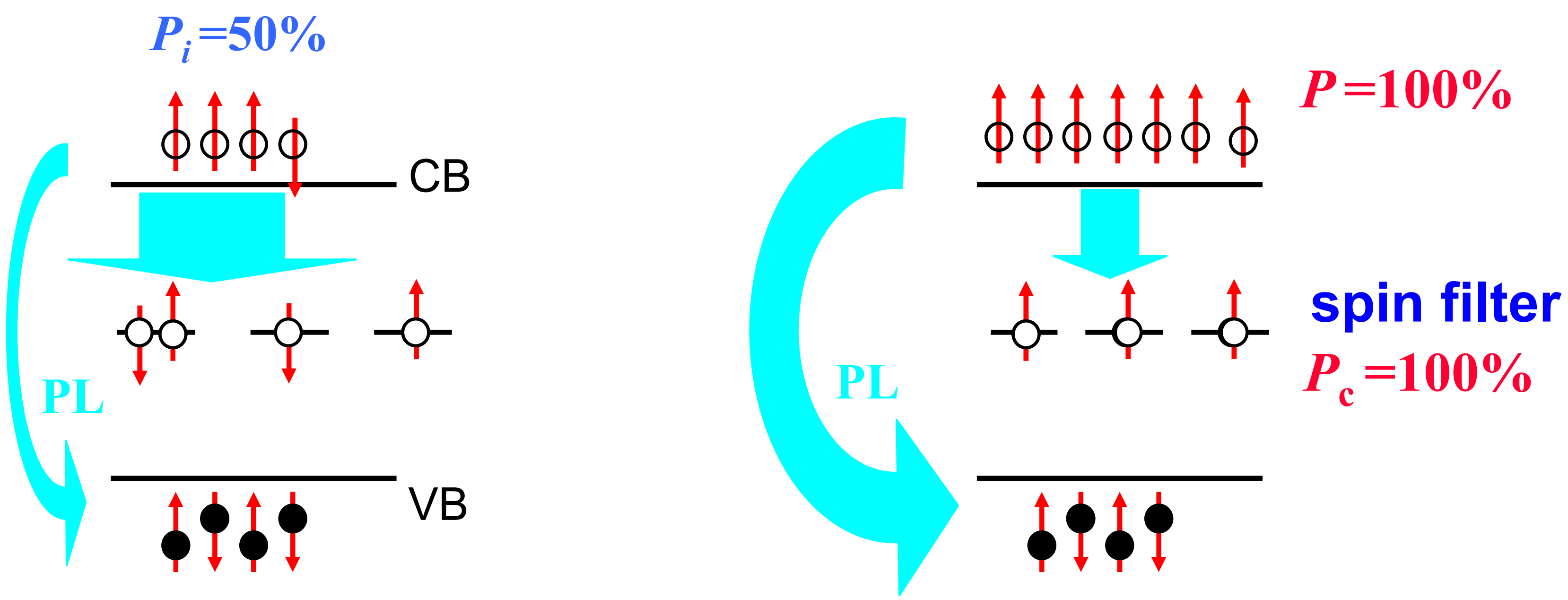
Dynamic polarization of electron spins



1) Increase of ρ and $\boldsymbol{J}$ with increasing ***pump power***

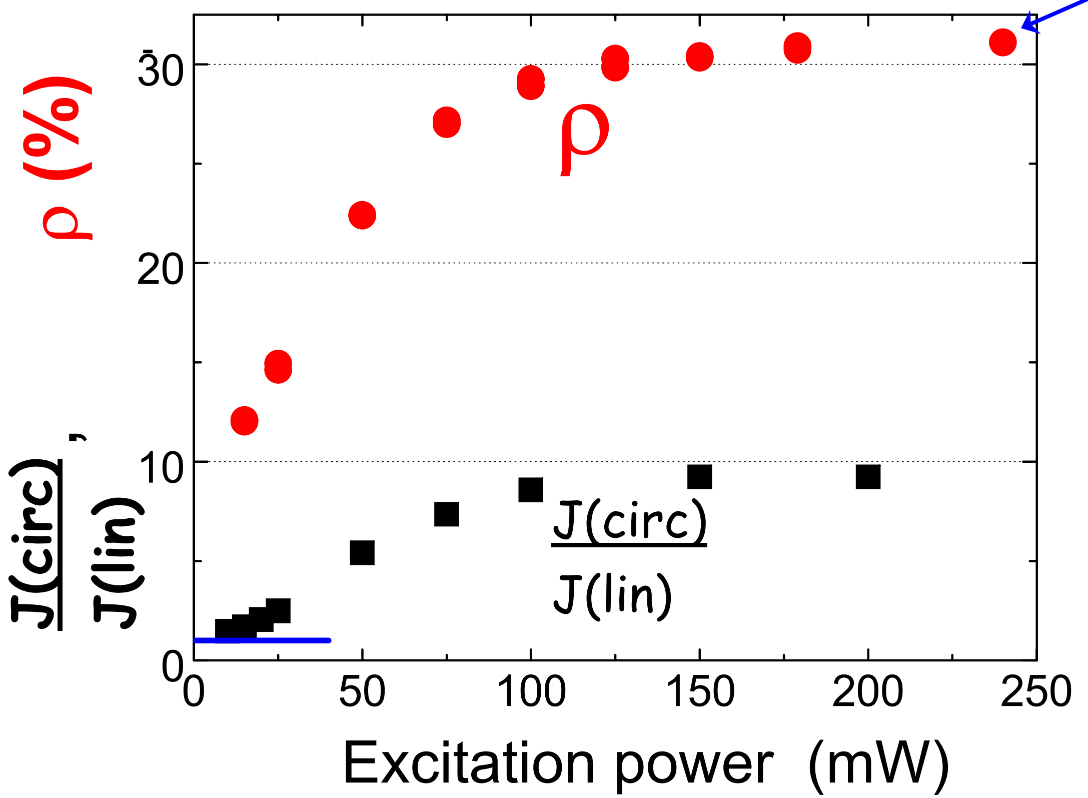
2) Decrease of $\boldsymbol{J}$: (a) **circ** $\rightarrow$**lin,** B=0

(b) **circ**, $\boldsymbol{B}_{\perp} \neq \mathbf{0}$

Spin-filtering effect vs excitation power

continuous wave pumping

$P = 2\rho \sim 60\%$

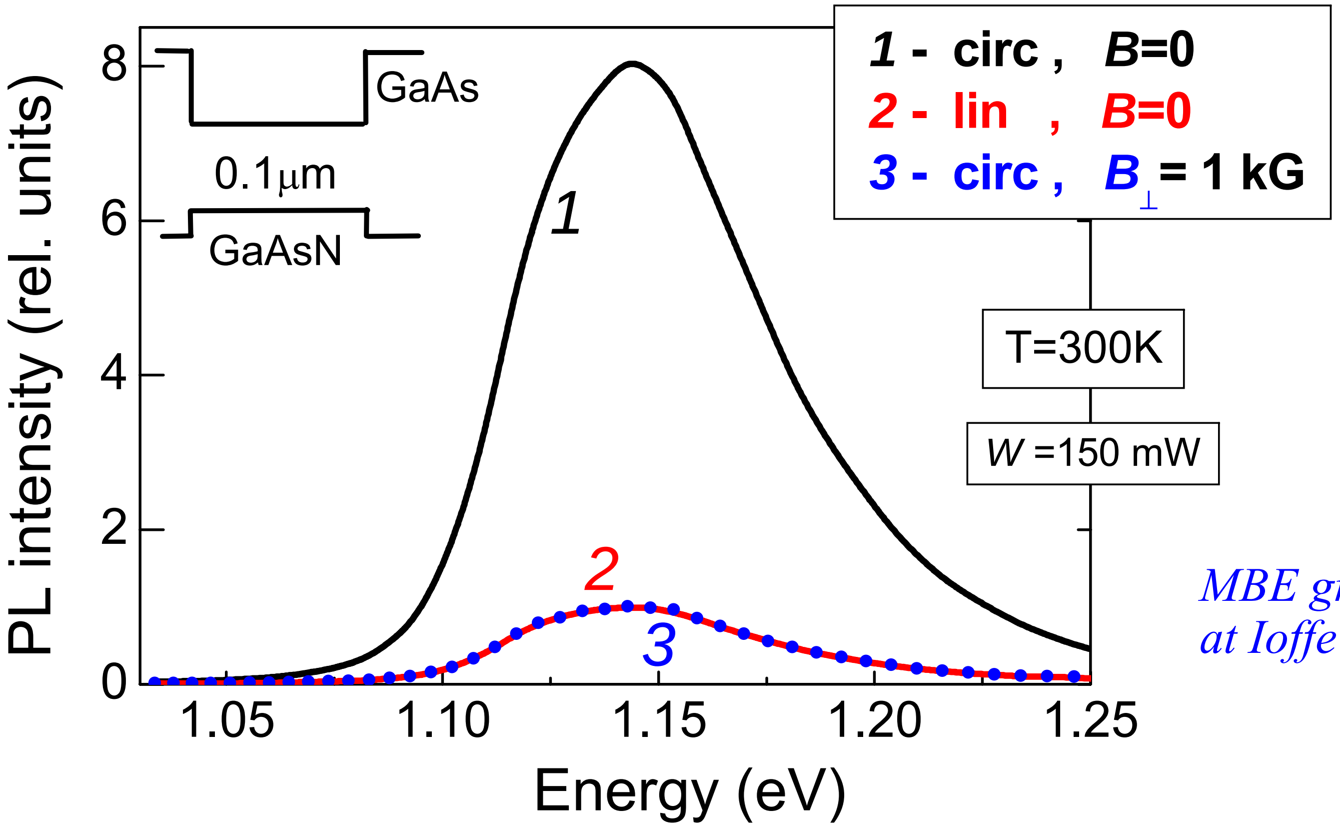


Ivchenko, Kalevich, Shiryaev, Afanasiev, Masumoto, J. Phys.: Condens. Matter **22,** 465804 (2010)

$\tau_{sc} >> \tau_s$

Spin-dependent recombination in $GaAs_{0.98}N_{0.02}$

continuous wave pumping



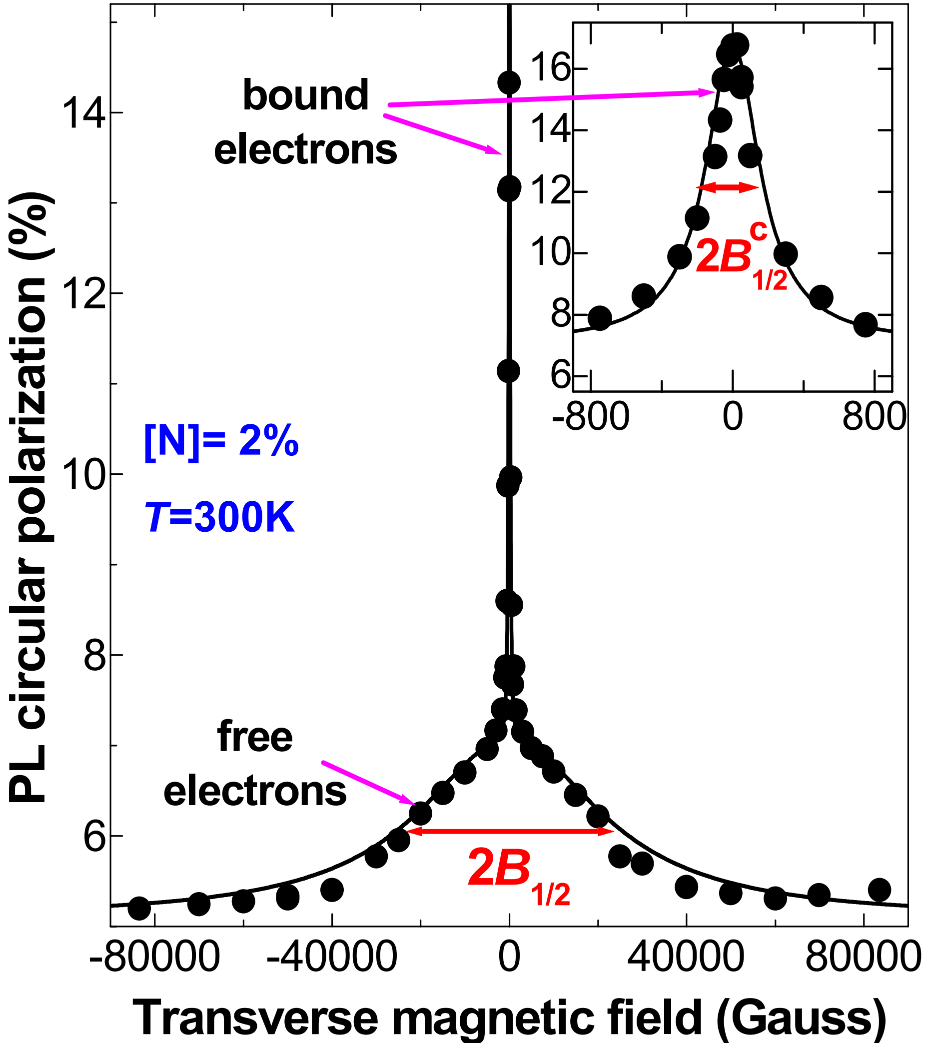
$B \perp z$

MBE grown at Ioffe Institute

$\tau_{sc} >> \tau_s$

Kalevich, Ivchenko, Afanasyev, Shiryaev, Egorov, Ustinov, Pal and Masumoto, JETP Lett. **82**, 455 (2005)

Hanle effect under SDR



$$\boldsymbol{B} \perp \mathbf{z}\,, \qquad \Omega = g\,\mu_B\,\boldsymbol{B}/\hbar$$

$$\frac{\rho(B)}{\rho(0)} = \frac{1}{1+(\Omega T_s)^2} = \frac{1}{1+(B/B_{1/2})^2}$$

$$\boxed{B_{1/2} = \frac{\hbar}{g\mu_B T_s}}\,, \qquad \frac{1}{T_s} = \frac{1}{\tau_s} + \frac{1}{\tau}$$

$$\tau_{sc} >> \tau_s$$

$$\tau_c >> \tau$$

$$T_{sc} >> T_s \quad \Rightarrow \quad B^{c}_{1/2} << B_{1/2}$$

$$\boxed{B^{c}_{1/2} = 100\text{G}} \qquad \boxed{B_{1/2} = 25000\text{G}}$$

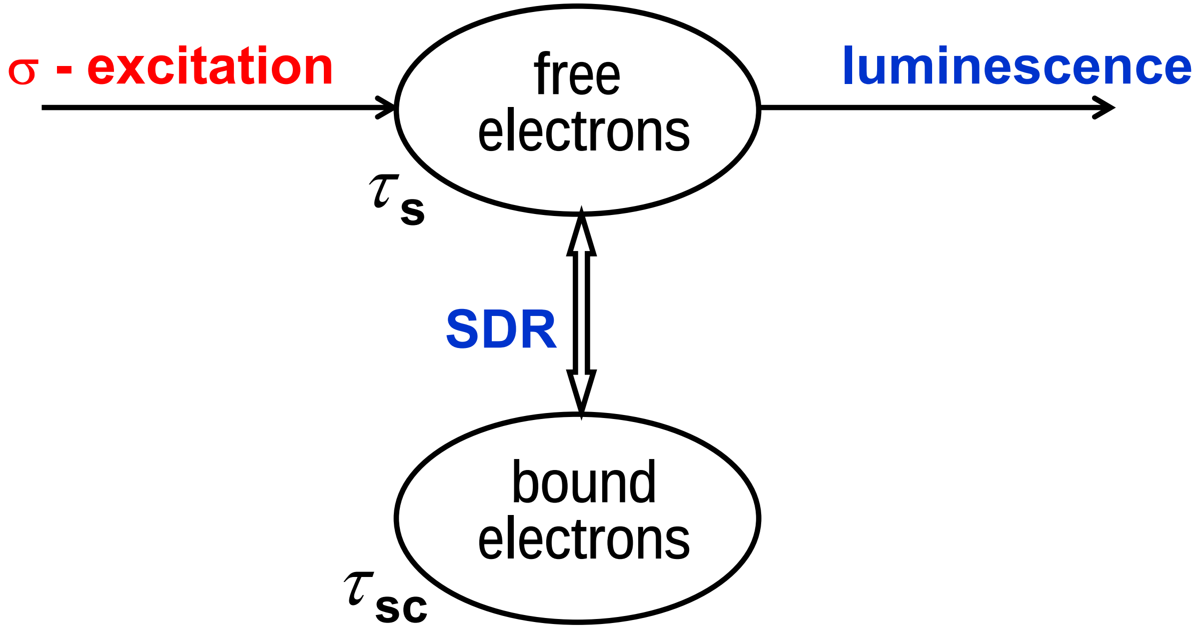
$$\downarrow\ \boldsymbol{g_c = +2} \qquad \downarrow\ \boldsymbol{g = +1}$$

$$\boxed{T_{sc} \sim 1\text{ ns}} \qquad \boxed{T_s \sim 1\text{ ps}}$$

$$\boxed{\tau_{sc} \sim 1\text{ns}} \qquad \boxed{\tau \sim 1\text{ps}}$$

Kalevich, Ivchenko, Shiryaev, Afanasiev, Egorov, Ikezawa, Masumoto, Semicond. Sci. Technol. **23**, 114008 (2008)

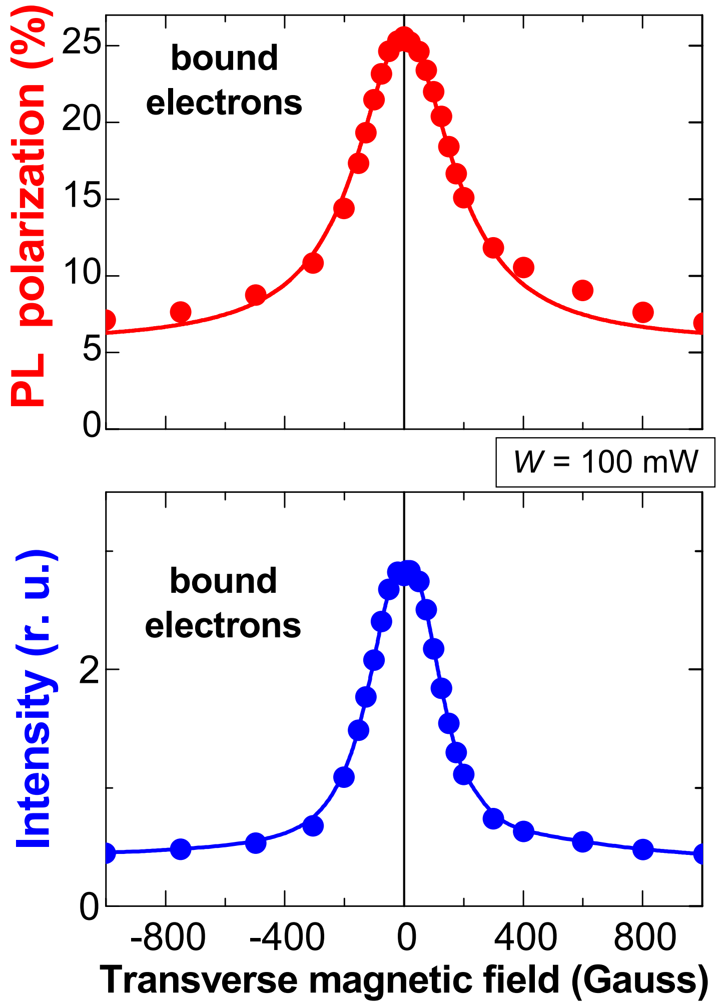
Nonlinear strongly coupled spin-system of free and bound electrons

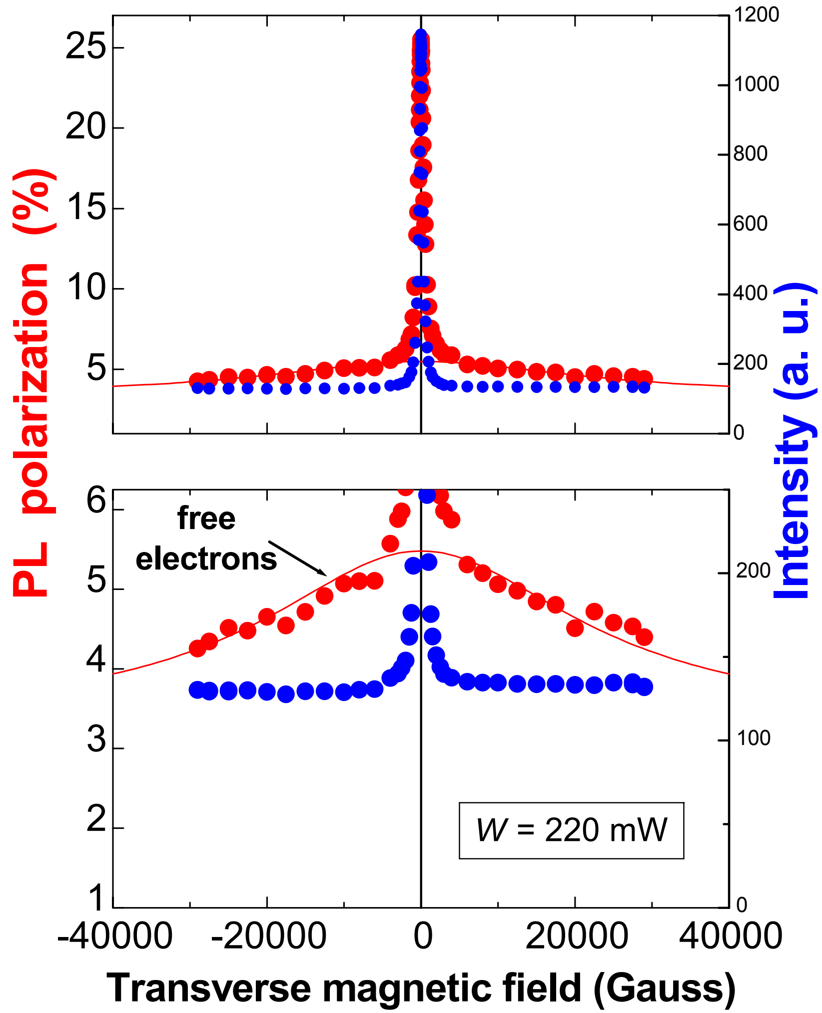


Spin stability of the coupled system of spin-polarized free and bound electrons is controlled by the long spin relaxation time of bound electrons $\tau_{sc} \sim 1\text{ns} \gg \tau_s \sim 100\text{ps}$

Hanle effect in intensity

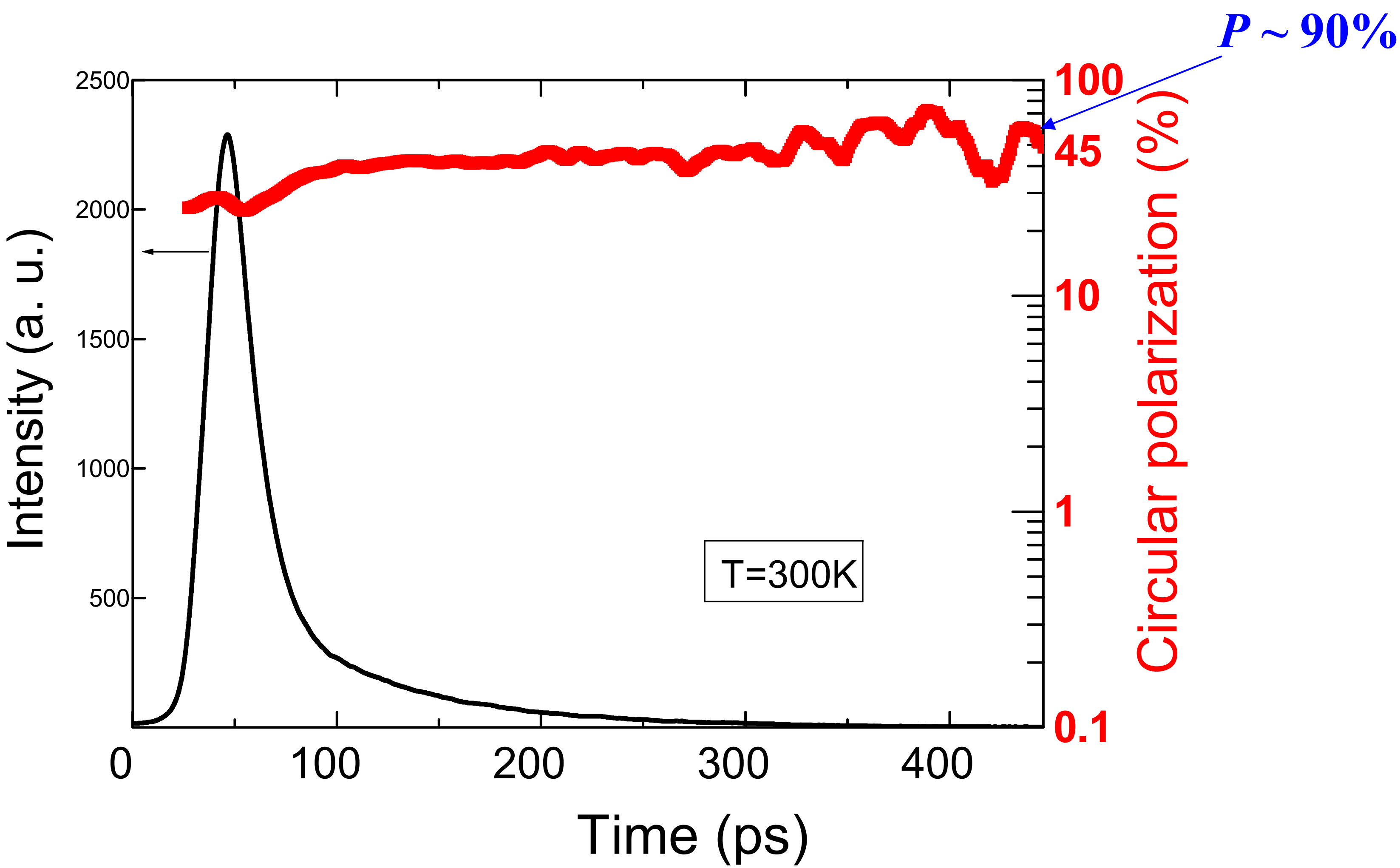
continuous wave pumping





Spin dynamics in $GaAs_{0.98}N_{0.02}$

under pulse (1.5 ps) pumping



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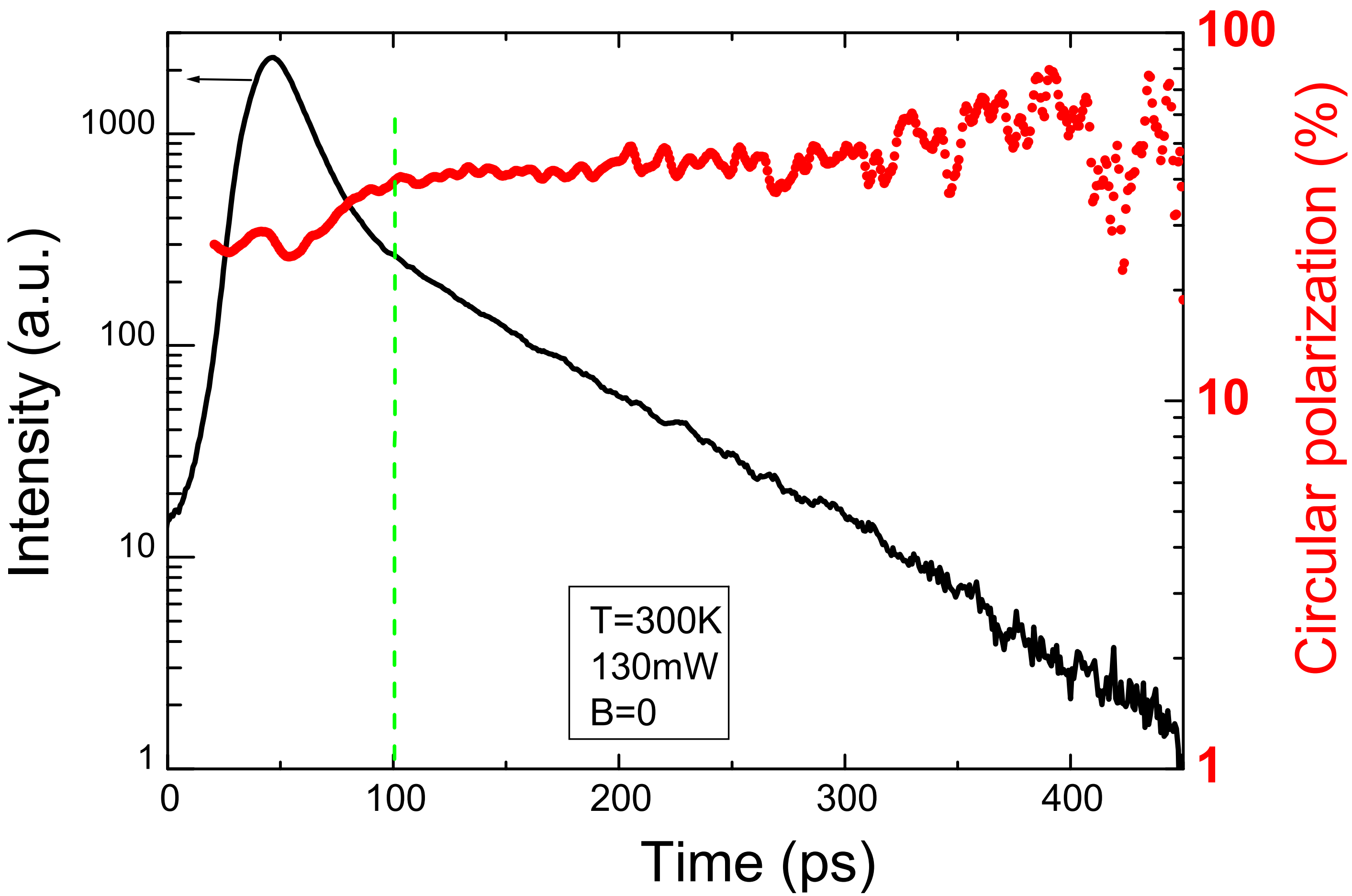
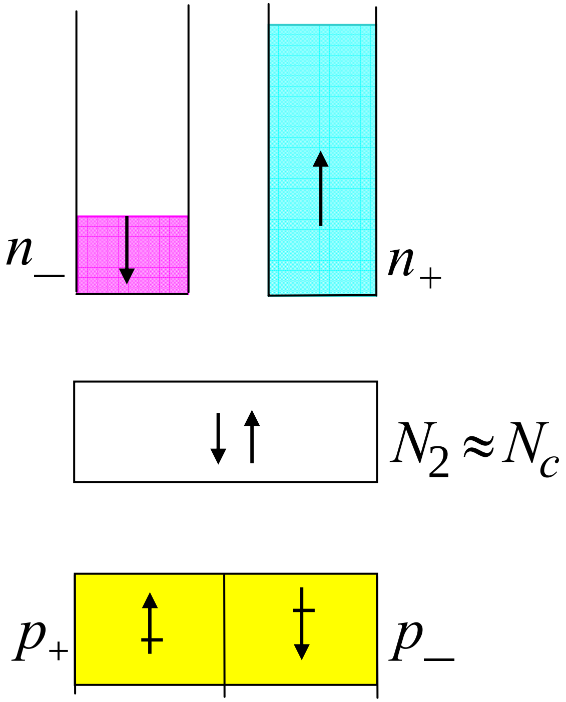


PL kinetics under strong SDR

pulse pumping : $\boldsymbol{n, p >> N_c}$, $\boldsymbol{n, p \approx 30N_c}$

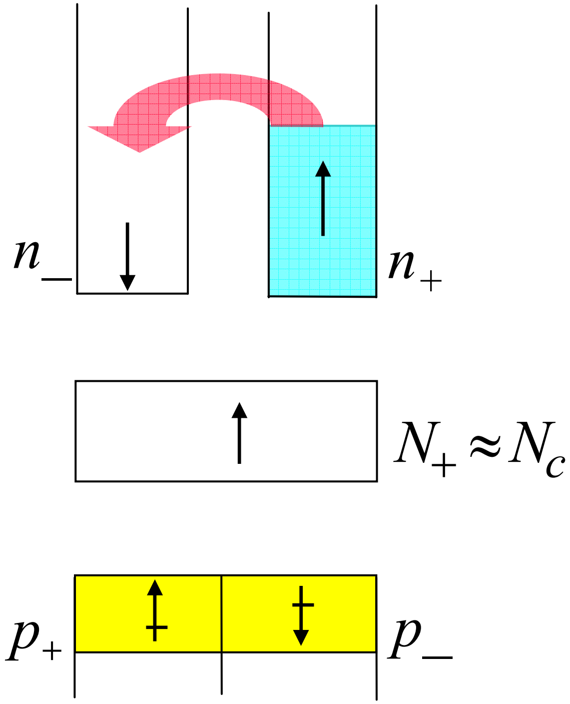
Fast decay: τ_h



$$n, p \propto \exp(-t/\tau_h)$$

$$J \propto np \propto \exp(-2t/\tau_h)$$

Slow decay: τ_s

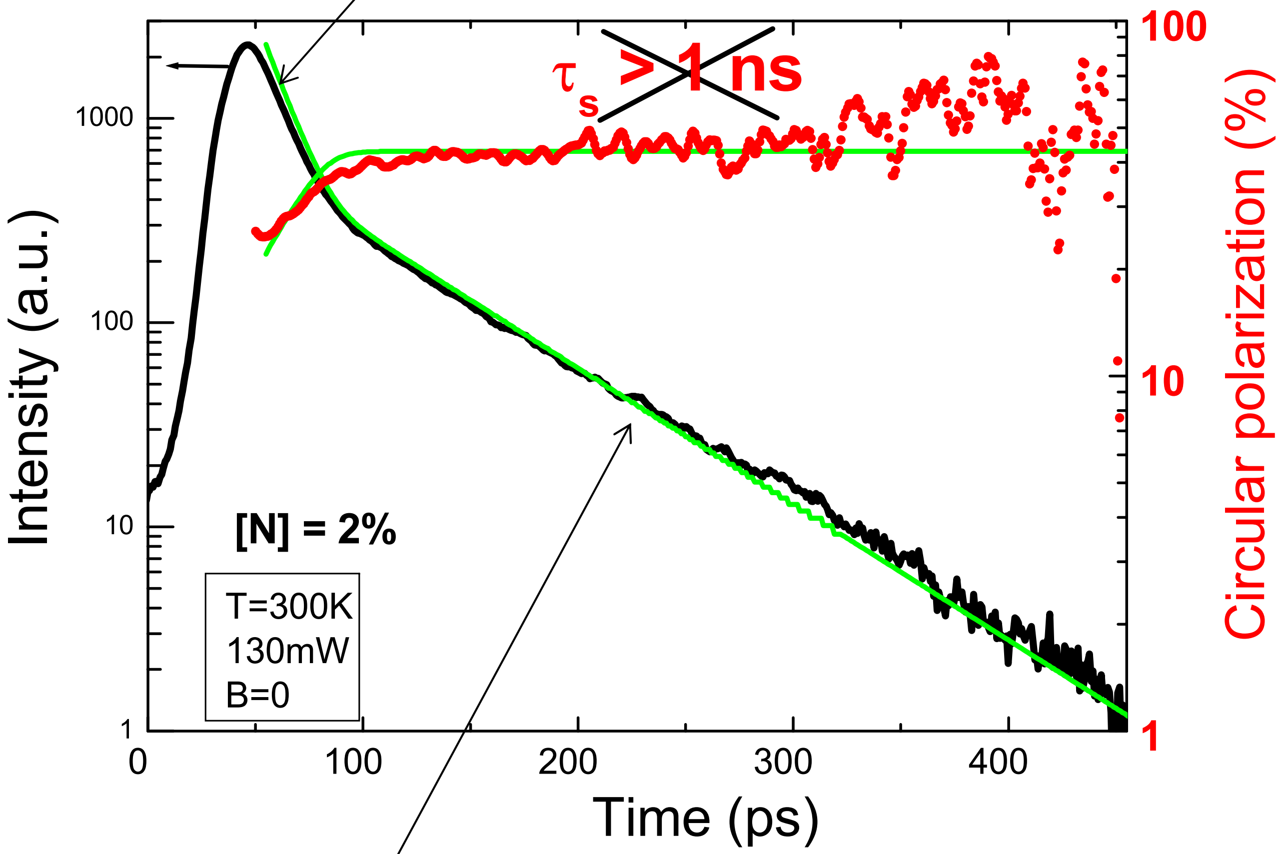


$$n, p \propto \exp(-t/\tau_s)$$

$$J \propto np \propto \exp(-2t/\tau_s)$$

Measurement of τ_s from PL decay

$\tau_{h\ min}$= (30±1) ps ⇒ $R_h N_c = 1/\tau_{h\ min}$= 0.033 ps^{-1}



τ_s= (140±4) ps

Kalevich, Ivchenko, Shiryaev, Egorov, Lombez, Lagarde, Marie and Amand, JETP Lett. **85**, 174 (2007)

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SDR model for the arbitrary excitation intensity and magnetic field

$$\frac{dn_\pm}{dt} = G_\pm - R_e n_\pm N_\mp - \frac{n_\pm - n_\mp}{2\tau_s} + \cancel{\gamma n_\pm p}$$

$$\frac{dN_\pm}{dt} = \frac{R_h}{2} p N_2 - R_e n_\mp N_\pm - \frac{N_\pm - N_\mp}{2\tau_{sc}}$$

$$p = n + N_2$$

$$n = n_+ + n_- , \qquad N_1 = N_+ + N_- , \qquad N_c = N_1 + N_2$$

n, S are the total free-electron density and spin, $S = (n_+ - n_-)/2$

G is the photogeneration rate of free electrons; $G = G_+ + G_-$, $G = W/V$

p is the free-hole density,

N_c is the total density of deep centers,

N_1, S_c are the density and total spin of centers with 1 electrons, $S_c = (N_+ - N_-)/2$

R_e, R_h are the recombination constants of free electrons and holes,

τ_s, τ_{sc} are the spin relaxation times of free and bound electrons

SDR model for the arbitrary excitation intensity and magnetic field

$$\frac{dn}{dt} = G - \frac{R_e}{2}(nN_1 - 4\vec{S}\vec{S}_c)$$

$$\frac{dp}{dt} = G - R_h(N_c - N_1)p$$

$$p = n + N_c - N_1$$

$$\frac{d\vec{S}}{dt} = \vec{S}_i + \frac{R_e}{2}(\vec{S}_c n - \vec{S}N_1) - \frac{\vec{S}}{\tau_s} + (\vec{\Omega}\times\vec{S})$$

$$\frac{d\vec{S}_c}{dt} = \frac{R_e}{2}(\vec{S}N_1 - \vec{S}_c n) - \frac{\vec{S}_c}{\tau_{sc}} + (\vec{\Omega}_c \times \vec{S}_c)$$

$$\frac{1}{\tau} = \frac{R_e N_1}{2}(1 - \vec{P}\vec{P}_c)$$

$$\vec{S}_i = \frac{nP_i}{2}\vec{o}_z$$

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

$$\Omega_c = g_c\mu_B B/\hbar$$

P_i

N_c

R_e, R_h

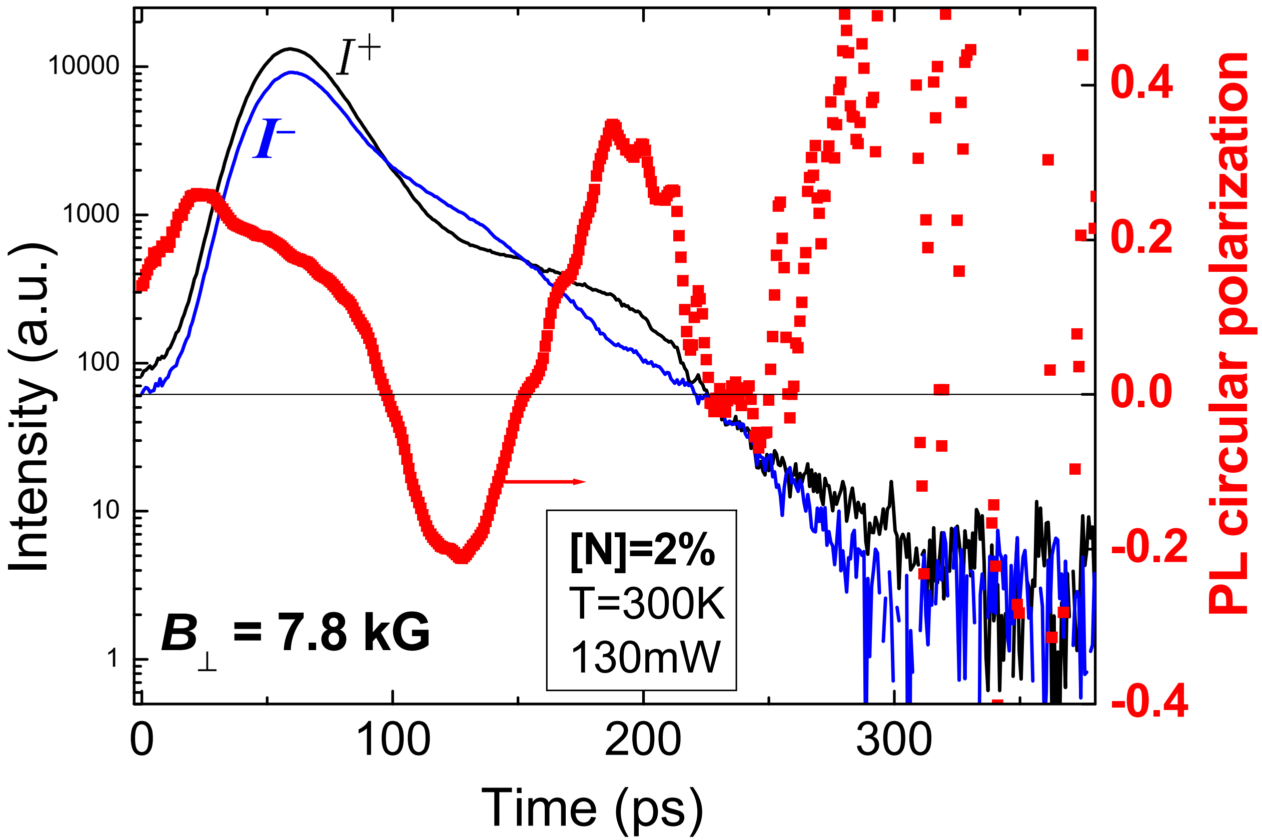
τ_s, τ_{sc}

g, g_c

Ivchenko, Kalevich, Shiryaev, Afanasiev, Masumoto, J. Phys.: Condens. Matter **22,** 465804 (2010)

Polarization oscillations in a transverse magnetic field

pulse (1.5 ps) pumping



$|g| \approx 1$

Kalevich, Ivchenko, Shiryaev, Egorov, Lombez, Lagarde, Marie and Amand, JETP Lett. **85**, 174 (2007)

Measured and estimated parameters

g = +1 (from polarization oscillations; sign from the Hanle effect)

g_c = +2 (measured by ODMR; sign from the Hanle effect)

τ_s = 140 ps (from PL kinetics)

τ_{sc} = 700 ps (from the Hanle effect)

$R_e N_c = 2/\tau_{min} = 1\ ps^{-1}$, τ_{min} = 2 ps (from the Hanle effect)

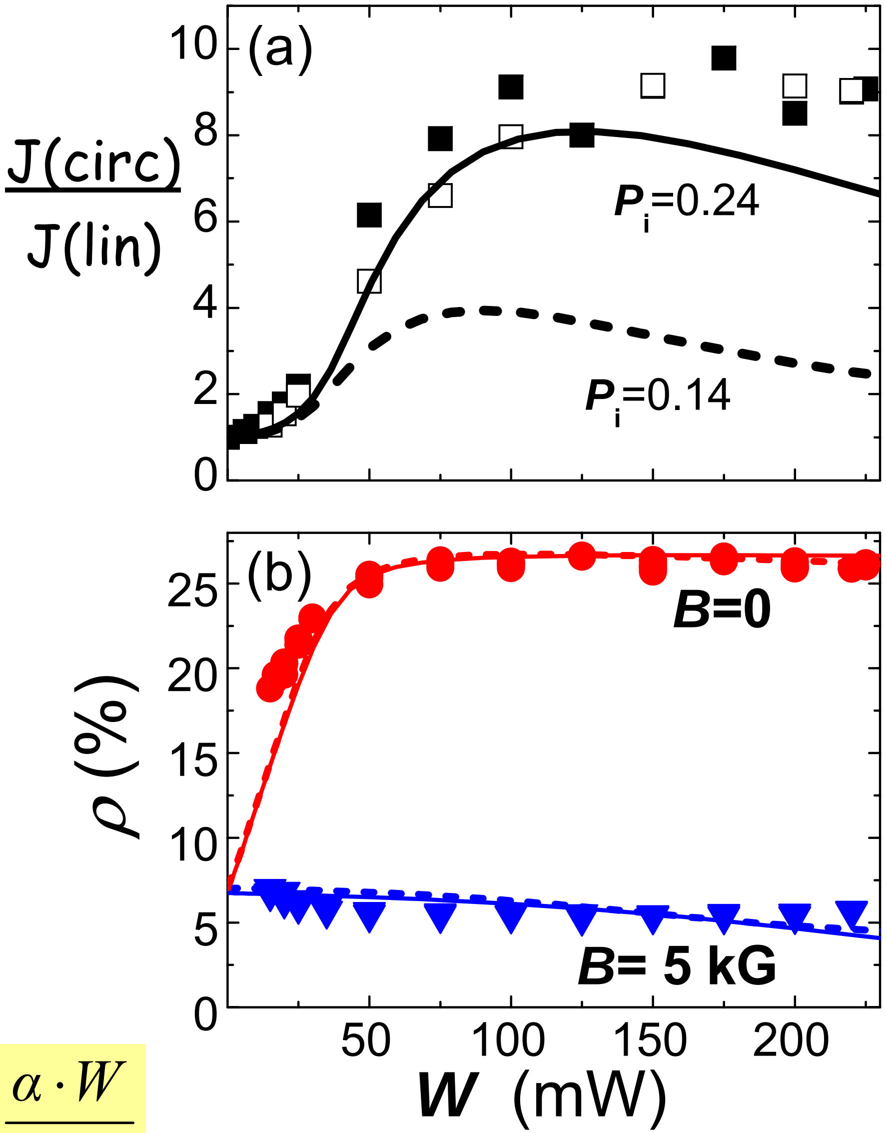
$R_h N_c = 1/\tau_{h\ min} = 0.033\ ps^{-1}$, $\tau_{h\ min}$ = 30 ps, (from PL kinetics)

N_c = ?

P_i = ?

Ivchenko, Kalevich, Shiryaev, Afanasiev, Masumoto, J. Phys.: Condens. Matter **22,** 465804 (2010)

Estimation of N_c and P_i



P_i = 24%

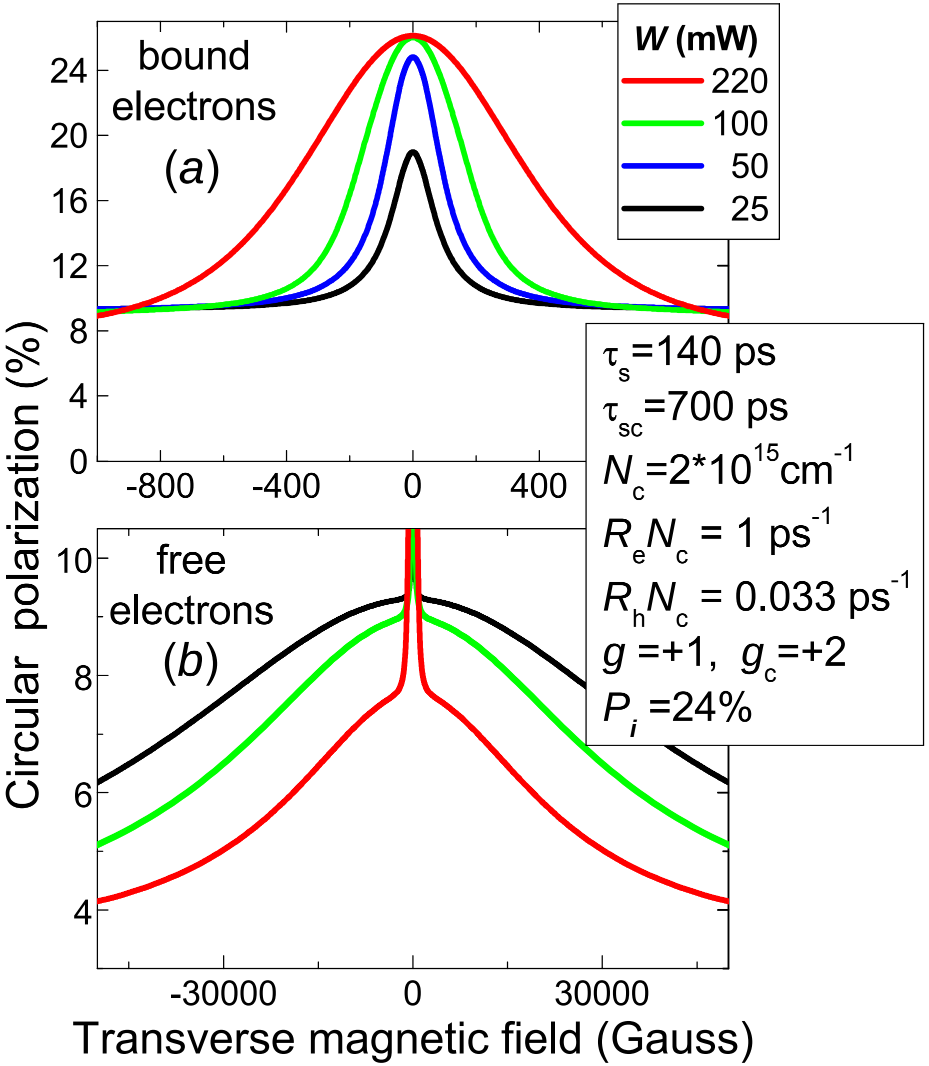
$N_c = 3{\cdot}10^{15}$ cm^{-3}

$$G = \frac{\alpha \cdot W}{E_{ph}\Sigma}$$

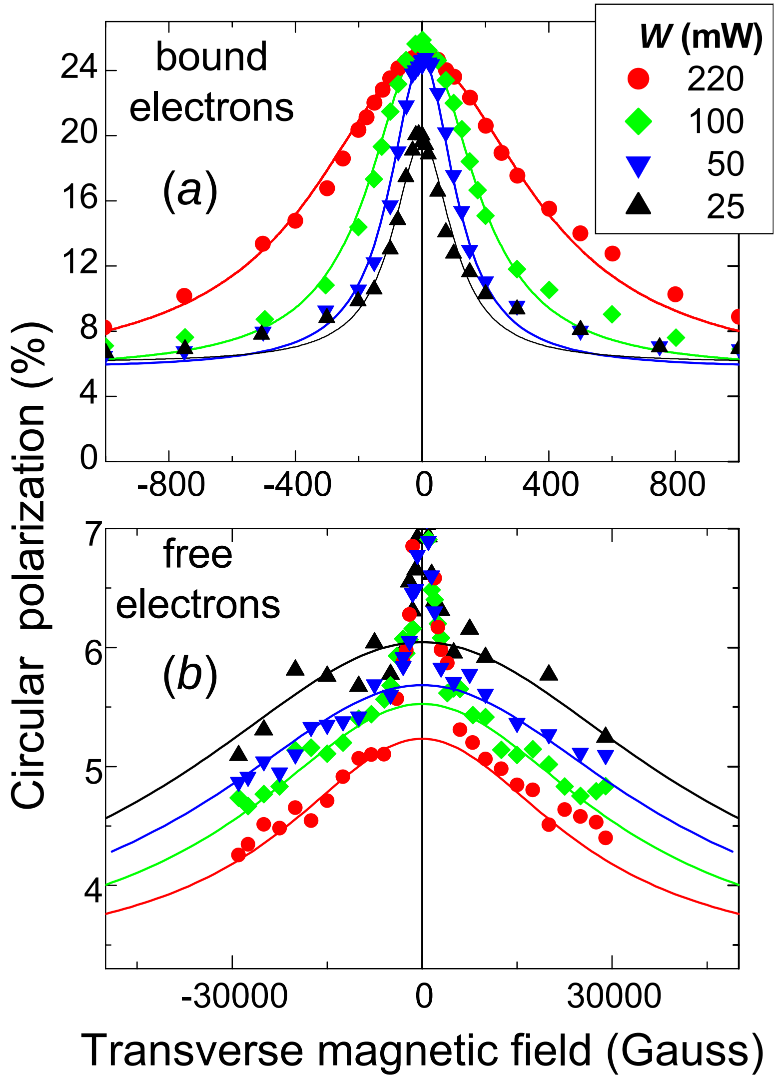
Ivchenko, Kalevich, Shiryaev, Afanasiev, Masumoto, J. Phys.: Condens. Matter **22,** 465804 (2010)

Calculated Hanle effect

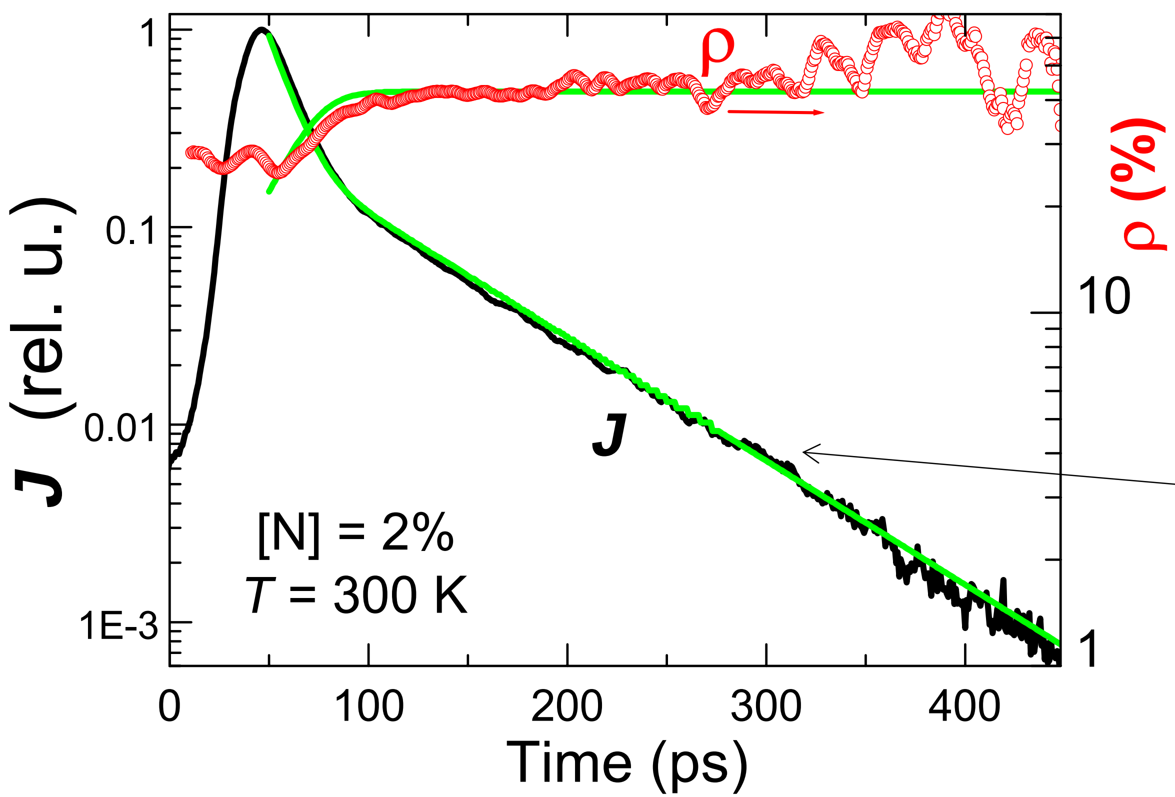
computation



experiment



Kinetics of J and ρ



τ_s= (140±4) ps

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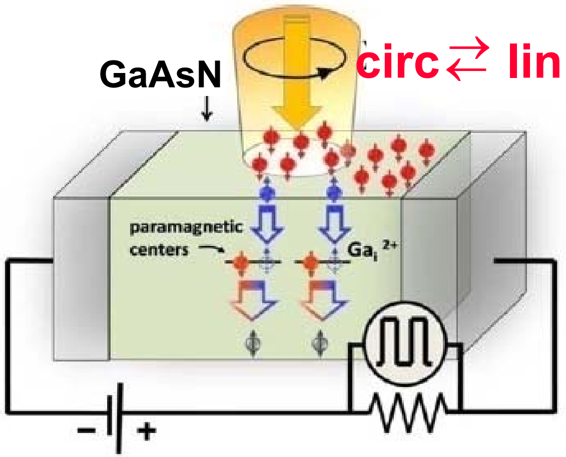
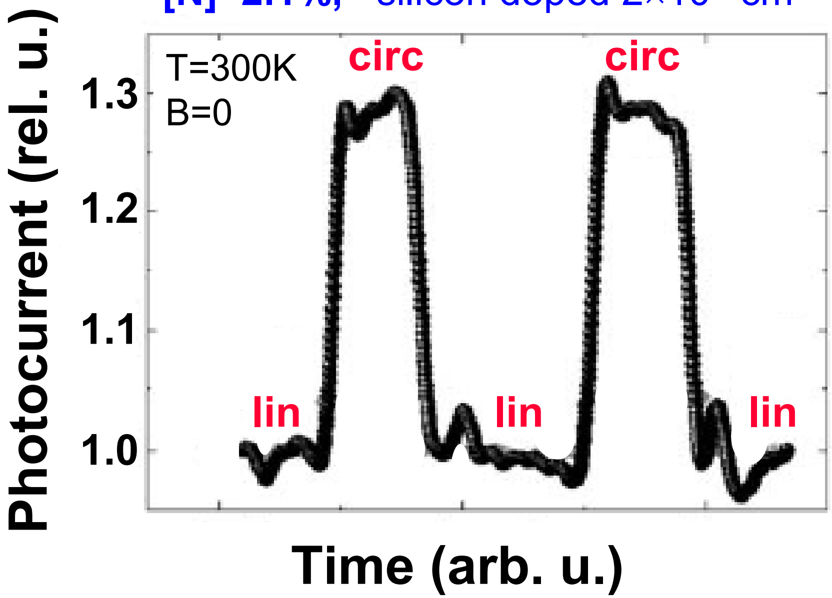
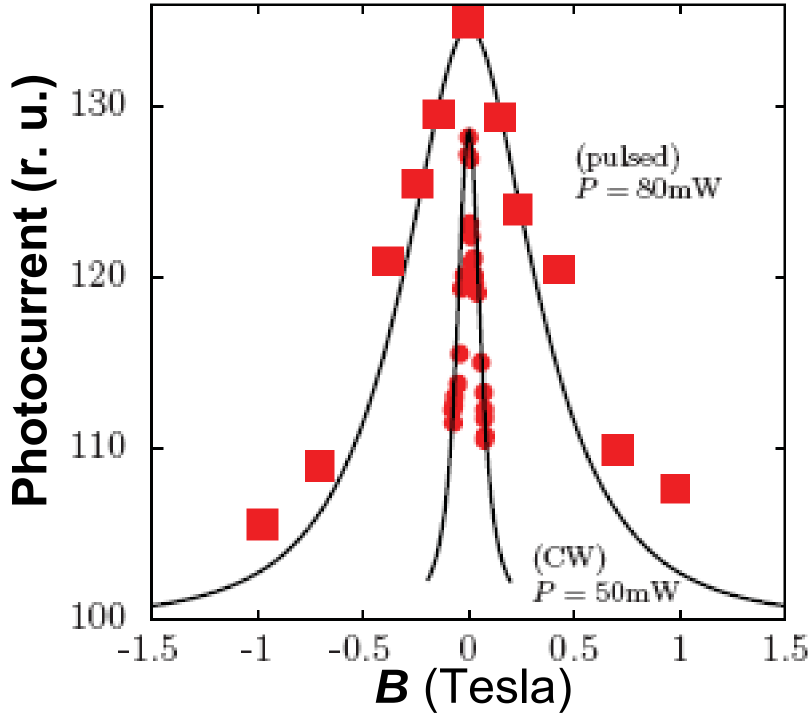
Spin-dependent photoconductivity in GaAsN



[N]=2.1%, silicon doped 2×10^{18}cm^{-3}



Hanle effect
in photoconductivity



F. Zhao, A. Balocchi, A. Kunold, J. Carrey, H. Carrère, T. Amand, N.B. Abdallah, J.C. Harmand, X. Marie, APL**95**, 241904 (2009)

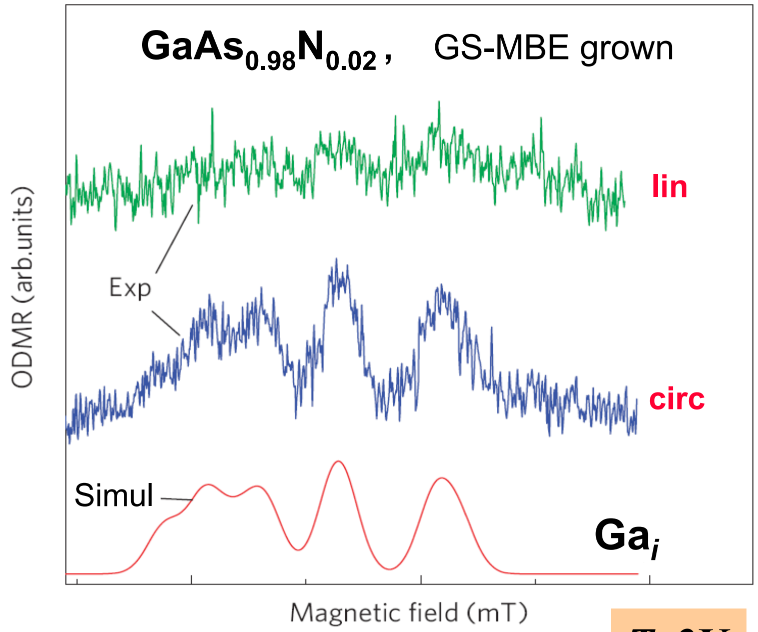
A. Kunold, A. Balocchi, F. Zhao, T. Amand, N. Ben Abdallah, J.C. Harmand, X. Marie, Phys. Rev. B **83**, 165202 (2011)

What is the nature of paramagnetic centers?

Optically detected electron magnetic resonance (ODEMR) of **self-interstitial defect Ga^{2+}**

- strong under circular pumping / *as grown*
- absent under linear pumping / *after RTA*

$$\mathrm{Ga}_i^{2+} \xrightarrow{\text{photo-excitation}} \mathrm{Ga}_i^{2+} + \mathrm{e} + \mathrm{h} \xrightarrow{\text{e capture}} \mathrm{Ga}_i^{1+} + \mathrm{h} \xrightarrow{\text{h capture}} \mathrm{Ga}_i^{2+}$$

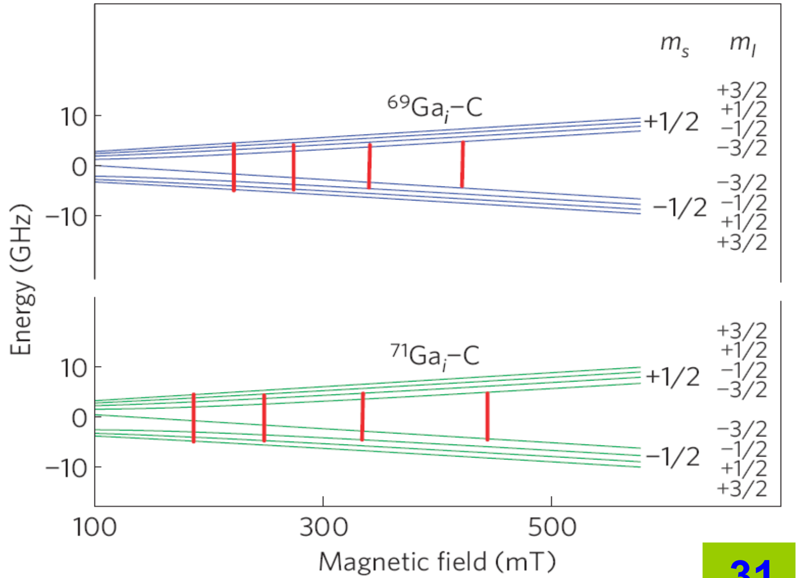


***T*=3K**

$$H = \mu_B g \mathbf{B} \cdot \mathbf{S} + A \mathbf{S} \cdot \mathbf{I}$$

$\Psi_e(r)$: *s* – shape

~ 20% localized on nucleus of center



Linköping University, Sweden

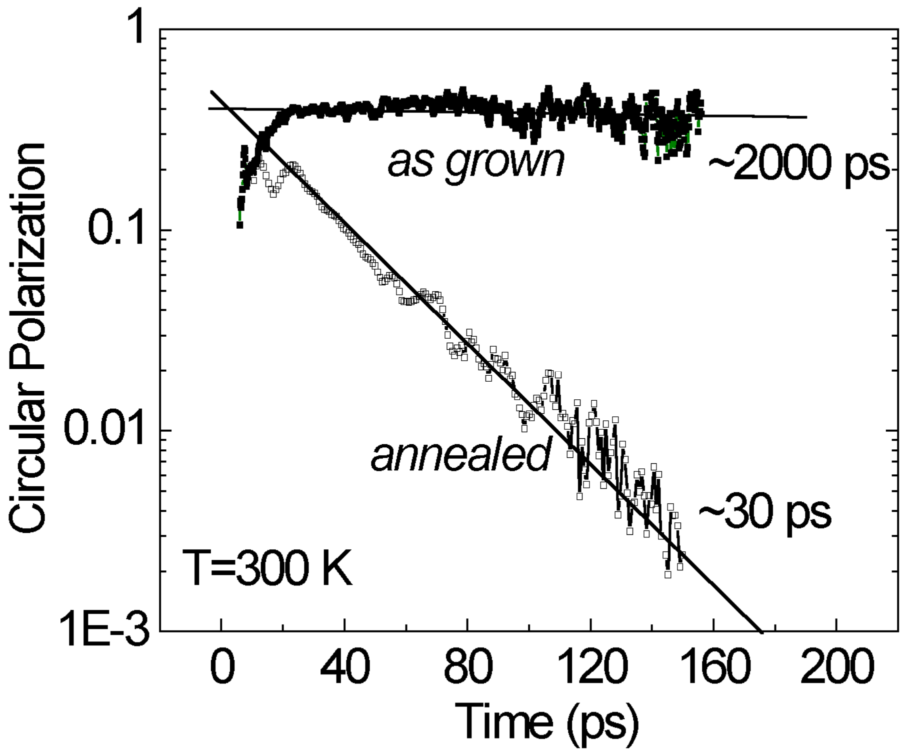
Wang, Buyanova, Zhao, Lagarde, Balocchi, Marie, Tu, Harmand, W. Chen, Nature Materials **8**, 198 (2009)

Wang, Puttisong, Tu, Ptak, Kalevich, Egorov, Geelhaar, Riechert, W. Chen, I. Buyanova, Appl. Phys. Lett. **95**, 241904 (2009)

Effect of rapid thermal annealing on spin dynamics in Ga(In)AsN /GaAs

10s, 850°C, halogen lamp, N_2 flow

$In_{0.33}Ga_{0.67}As_{0.092}N_{0.008}$/GaAs 70Å-thick QW



Post-growth rapid thermal annealing
reduces strongly the density of paramagnetic centers

L. Lombez, P.-F. Braun, H. Carrère, B. Urbaszek, P. Renucci, T. Amand, X. Marie, J.C. Harmand and V.K. Kalevich, APL **87**, 252115 (2005)

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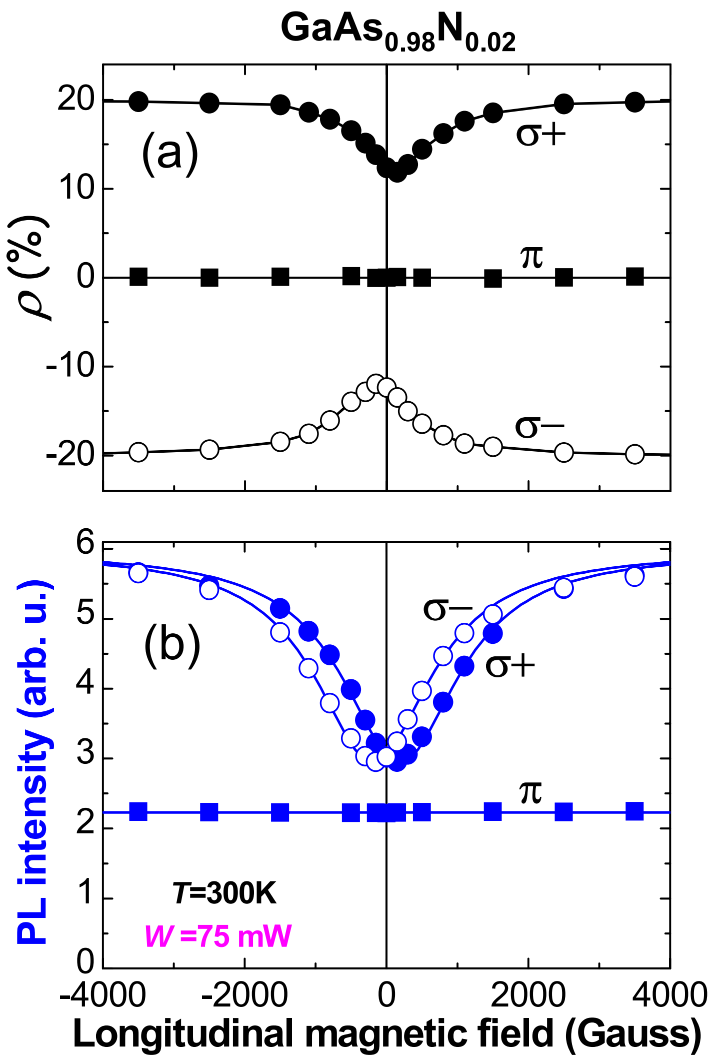
Enhancement of spin-filtering by magnetic field

Faraday geometry, B || z

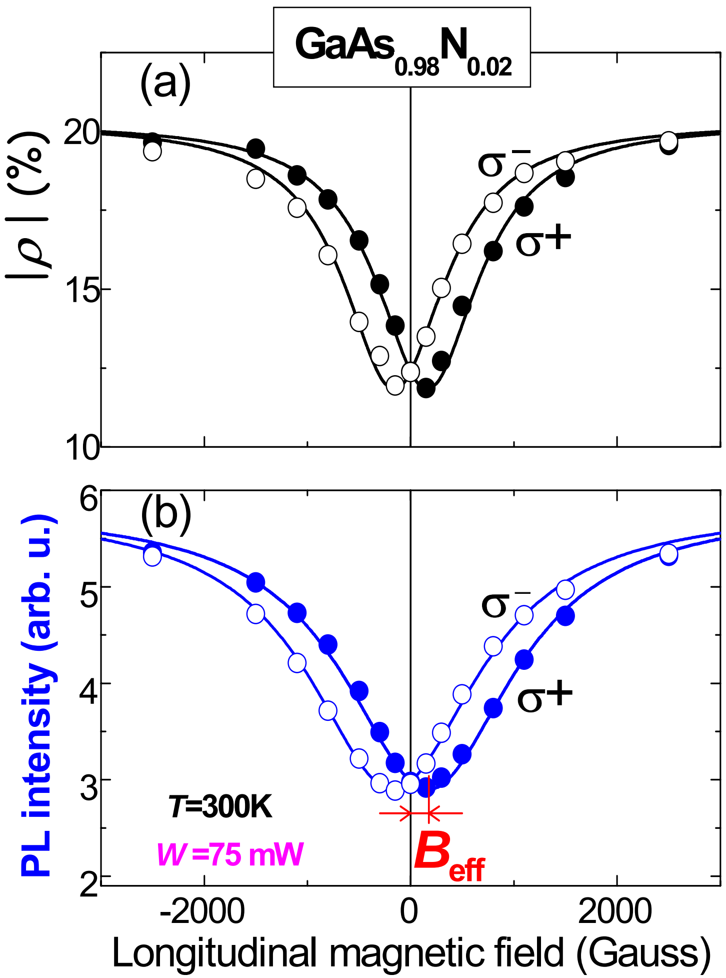


1) Increase of ρ and $\boldsymbol{J}$

Kalevich, Afanasiev, Shiryaev, Egorov,
Phys. Rev. B **85**, 035205 (2012)

Enhancement of spin-filtering by magnetic field

Faraday geometry, B || z



$$y(B) = y_{max} + (y_{min} - y_{max}) / [1 + (B - B_{eff})^2/B^2_{1/2}]$$

$$y_{min} = y(B = B_{eff}), \quad y_{max} = y(B \rightarrow \infty)$$

1) Increase of ρ and $\boldsymbol{J}$

2) Shift $|\boldsymbol{B}_{eff}|$ ~ 200 G

reverses sign with $\sigma^+ \rightarrow \sigma^-$

Suppression of spin relaxation
of bound electrons
by a longitudinal magnetic field

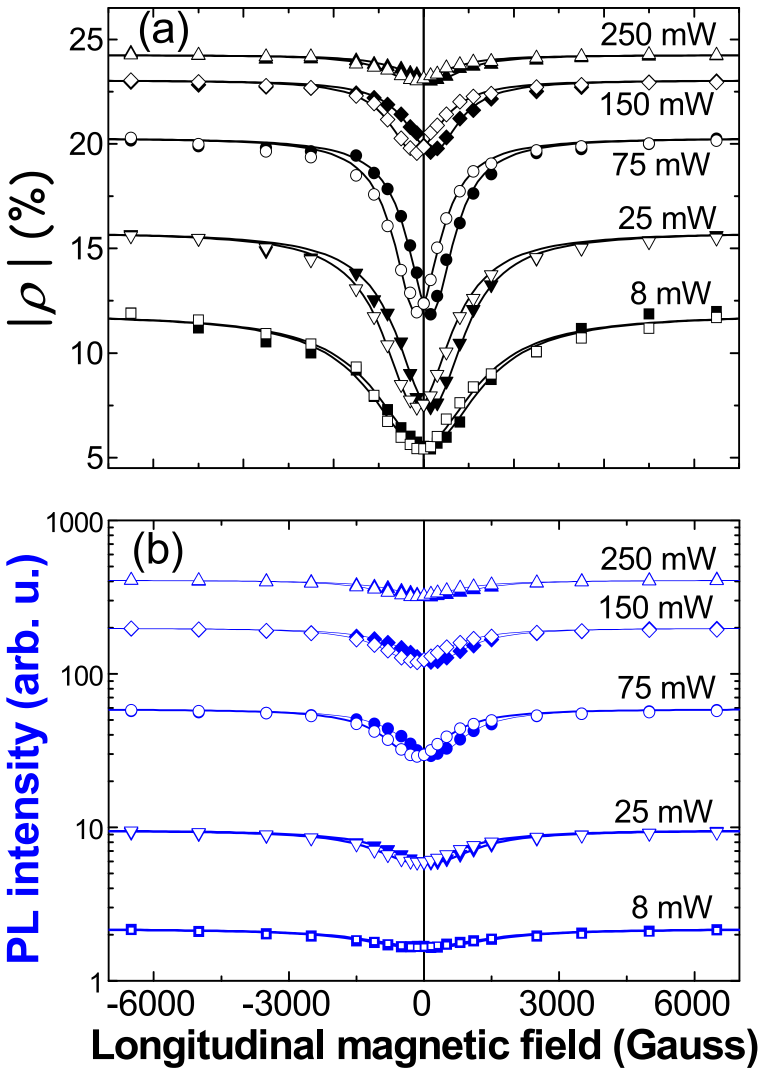
$$\frac{1}{\tau_{sc}(B)} = \frac{\frac{2}{3}\omega_f^2\tau_{cor}}{1+\omega^2\tau_{cor}^2} = \frac{1}{\tau_{sc}(0)}\frac{1}{1+(B/B^{\parallel}_{1/2})^2}$$

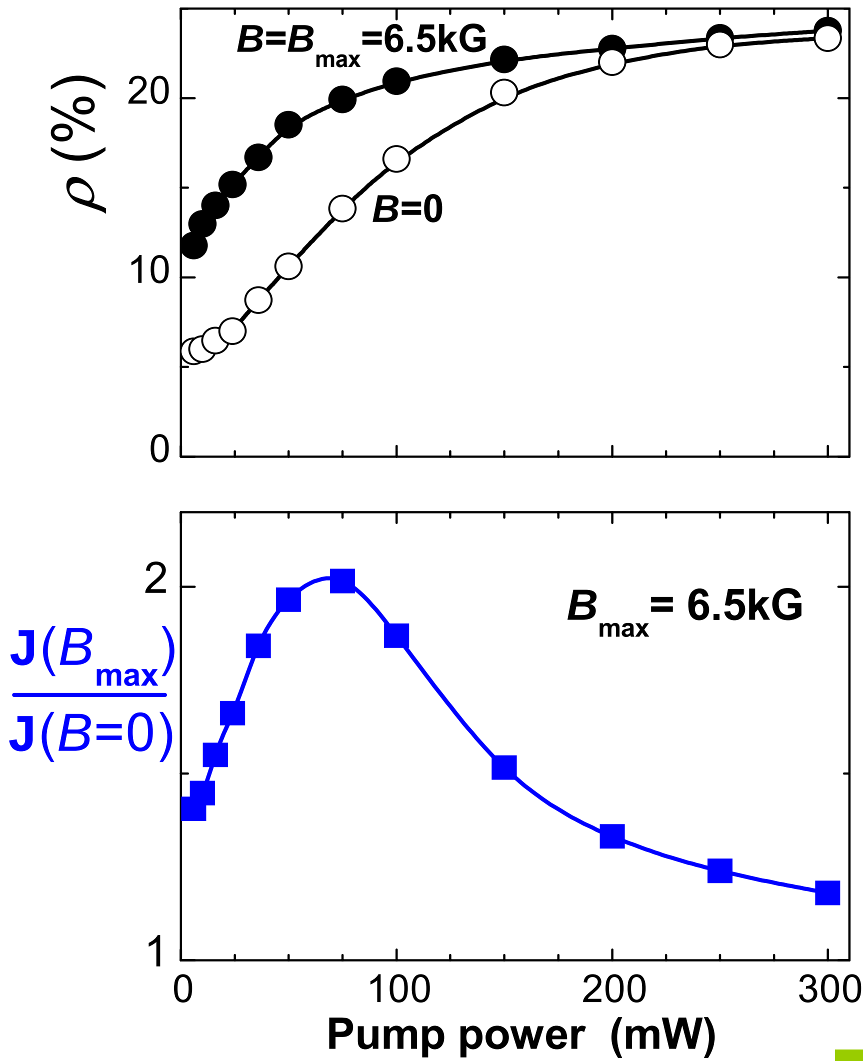
Dyakonov and Perel, JETP **38**, 177 (1974)

Suppression of the nuclear field fluctuations

Spin-filter amplification vs pump power

$$\frac{1}{\tau_{sc}(B)} = \frac{1}{\tau_{sc}^{*}} + \frac{1}{\tau_{sc}^{(1)}} \frac{1}{1+(B/B_{1/2})^2}$$

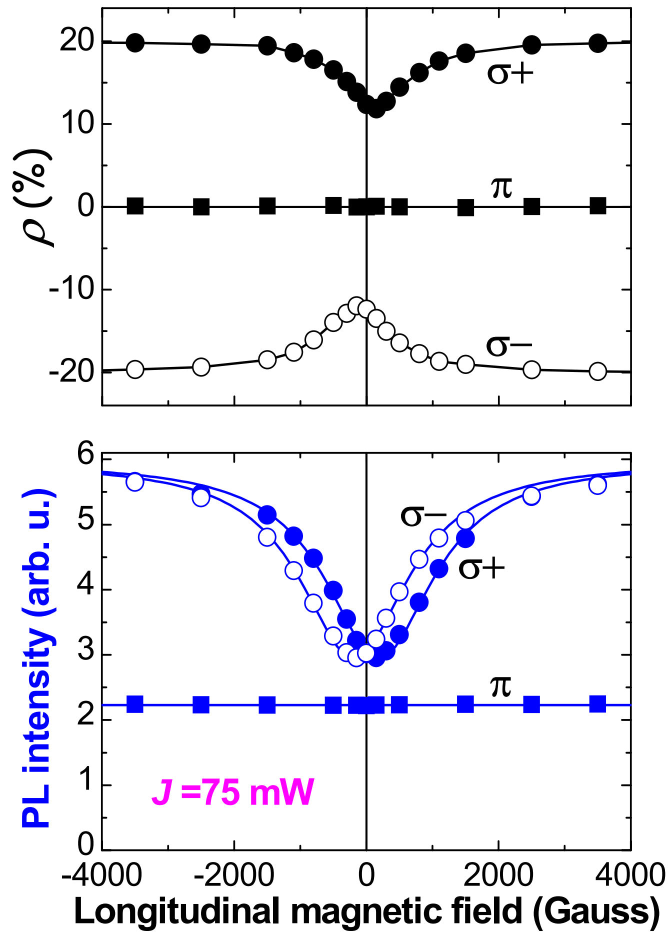




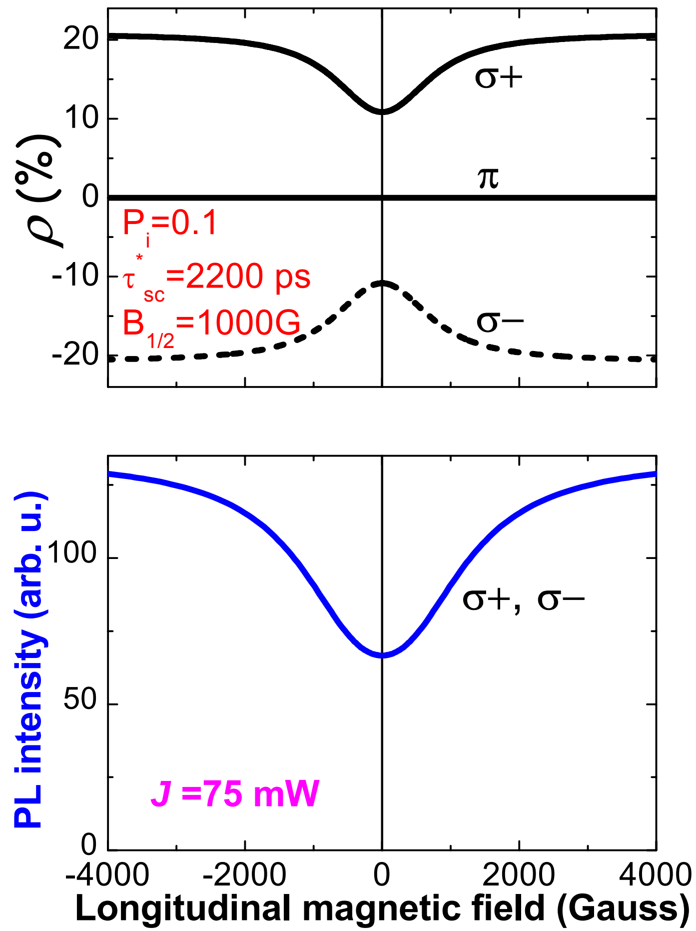
Amplification of spin-filtering by magnetic field

$$\frac{1}{\tau_{sc}(B)} = \frac{1}{\tau_{sc}^{*}} + \frac{1}{\tau_{sc}^{(1)}} \frac{1}{1+(B/B_{1/2})^2}$$

experiment



computation

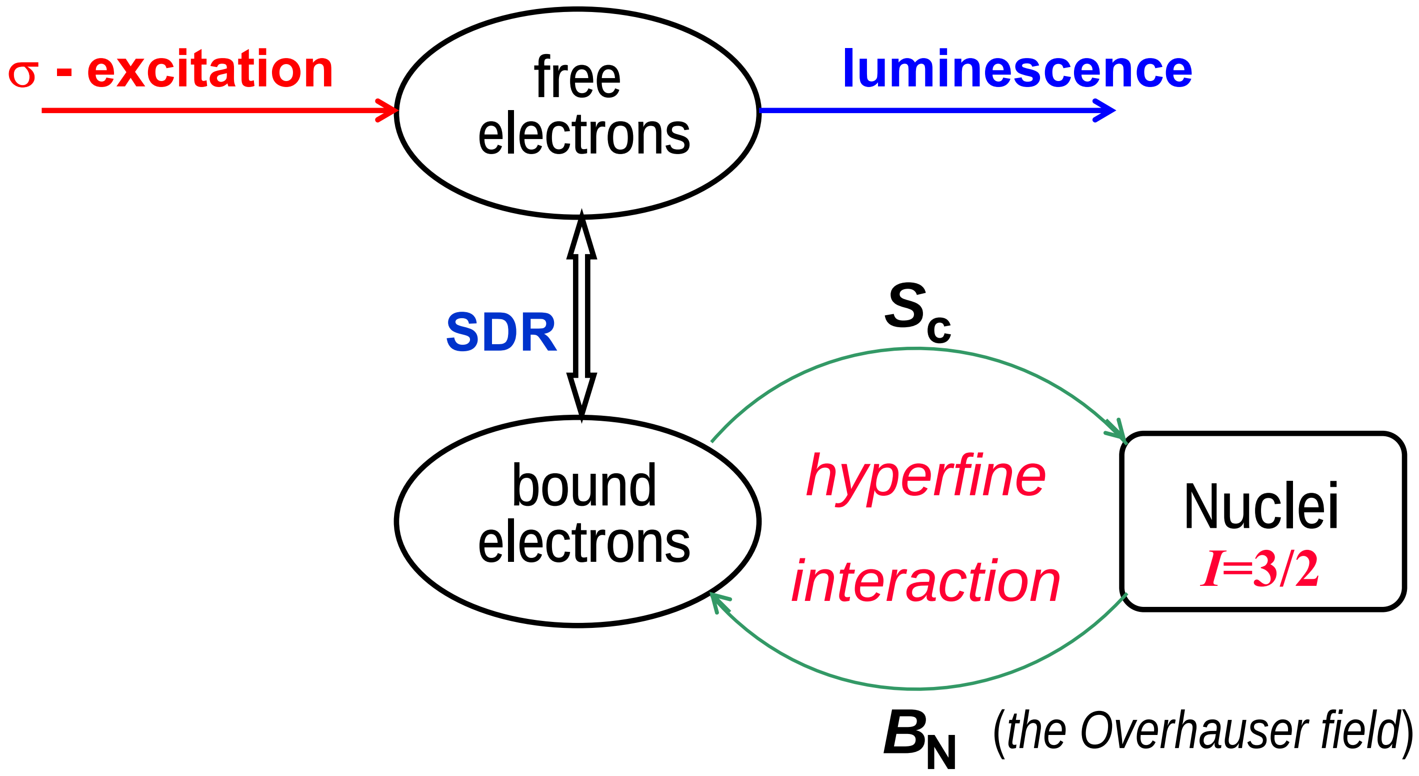


Kalevich, Afanasiev, Shiryaev, Egorov,
Phys. Rev. B **85**, 035205 (2012)

Outline

- Introduction
- Spin-dependent recombination (SDR) as an origin of a giant electron spin-polarization:
  (a) continuous-wave pumping
  (b) pulsed pumping
- SDR model and comparison with experiment
- Spin-dependent photoconductivity and ODEMR
- Enhancement of electron spin-polarization by a longitudinal magnetic field
- Dynamic nuclear spin-polarization and hyperfine nuclear magnetic fields
- Summary

Nonlinear strongly coupled electron-nuclear spin-system



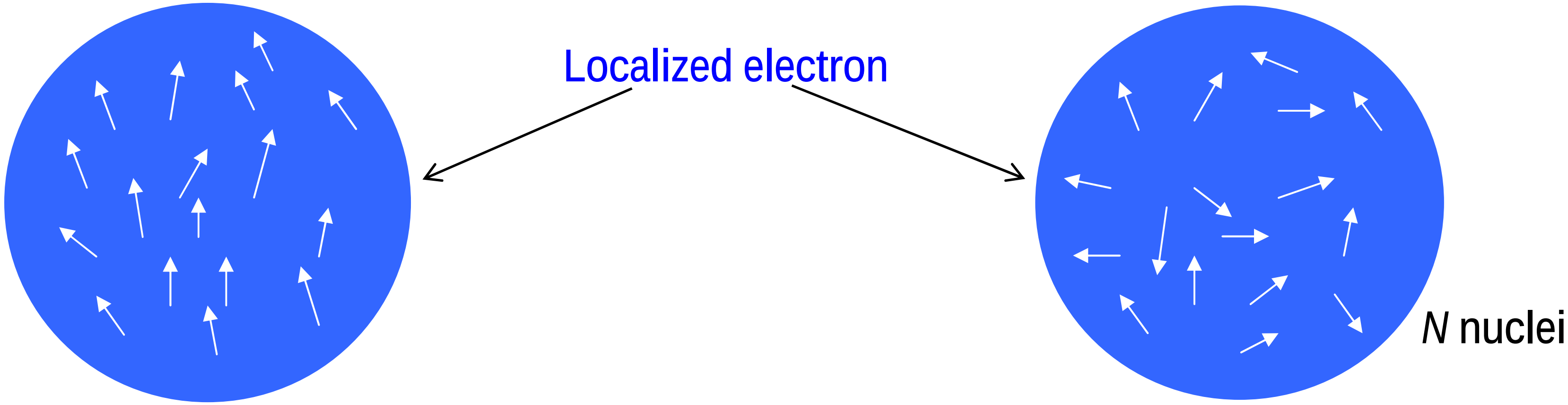
$$\hat{H}_{hf} = \sum_n a_n \left(\vec{s} \cdot \vec{I}_n\right) = \sum_n a_n \left[s_z I_z + \tfrac{1}{2}\left(s_+ I_- + s_- I_+\right)\right]$$

$$a_n = A v_0 \left|\Psi\left(\vec{r}_n\right)\right|^2, \qquad A \approx 100\ \mu\text{eV}$$

Nuclear spin fields acting on a localized electron

$$\hat{H}_{hf} = \sum_n a_n \left(\vec{s}\cdot\vec{I}_n\right) = \sum_n a_n \left[s_z I_z + \tfrac{1}{2}\left(s_+ I_- + s_- I_+\right)\right]$$

$$a_n = A v_0 \left|\Psi\left(\vec{r}_n\right)\right|^2 , \qquad A \approx 100 \text{ µeV}$$



a) Polarized nuclear spins

$$\vec{B}_N = \frac{A}{\mu_B g_e}\left\langle \vec{I} \right\rangle$$

$$B_{N\,\max}^{\text{GaAs}} \approx 53\,\text{kG}$$

$$\vec{B}_{total} = \left(\vec{B} + \vec{B}_N\right)$$

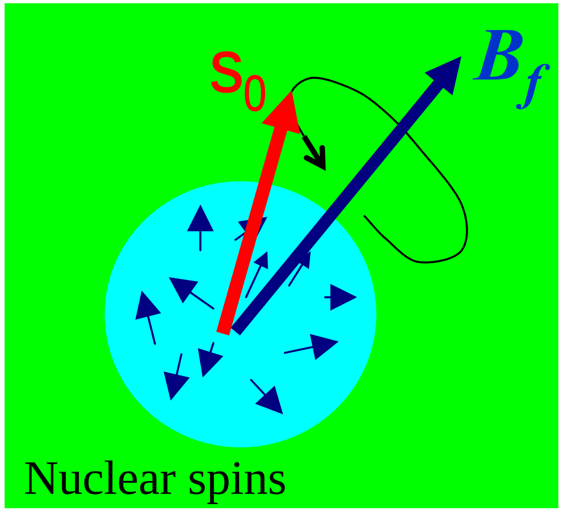
b) Disordered nuclear spins

$$\left\langle B_f^2 \right\rangle = \frac{v_0^2 \sum_n \left|\Psi\left(\vec{r}_N\right)\right|^4 A_n^2 I_n^2 \left(I_n + 1\right)^2}{\left(\mu_B g_e\right)^2} \approx$$

$$\approx \frac{B_{N\,\max}^2}{N}$$

Electron spin relaxation on nuclei

Merkulov, Efros, Rosen, PRB **65**, 205309 (2002)



$$\langle S \rangle = \frac{\langle S_0 \rangle}{3}$$

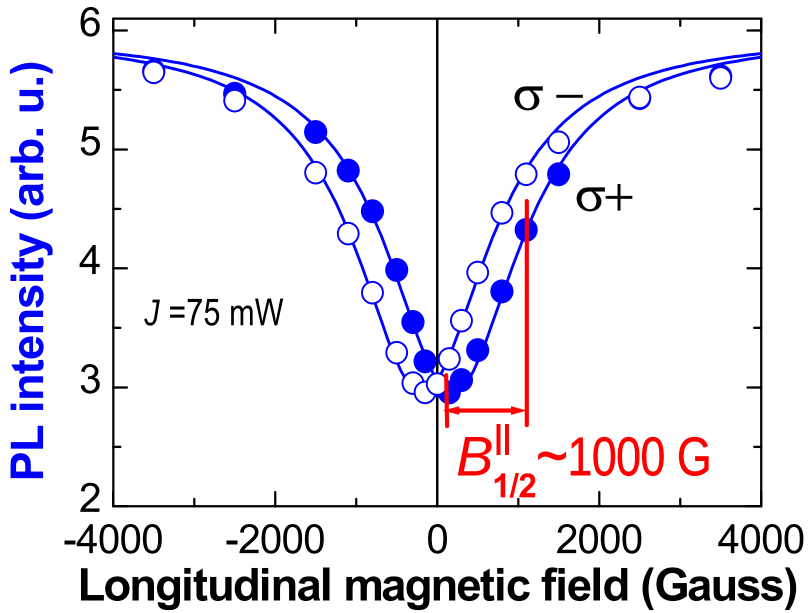
$T_2 \sim 10^{-4}$s

GaAs

$N \sim 10^5$

$B_f \sim 50$ G

$B_{N\,\max}^{GaAs} \approx 53$ kG



$$B_f \approx \frac{B_{N\,\max}}{N} \cdot \sqrt{N} = \frac{B_{N\,\max}}{\sqrt{N}}$$

$$A\langle I \rangle S \;=\; -\mu_e B_N \,, \qquad \mu_e = g_e \mu_B S$$

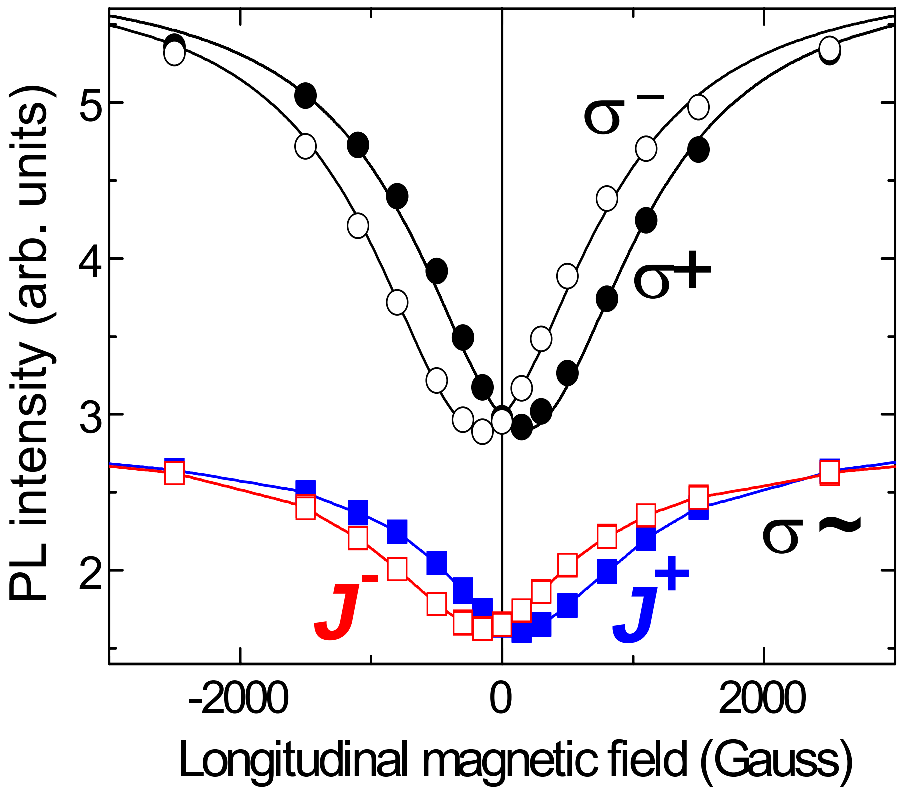
$$B_N = A\langle I \rangle / g_e \mu_B \,, \qquad A \sim 100\,\mu\text{eV}$$

$$g_e = 2, \qquad B_{N\,\max}^{GaAsN} \approx 13\,\text{kG}$$

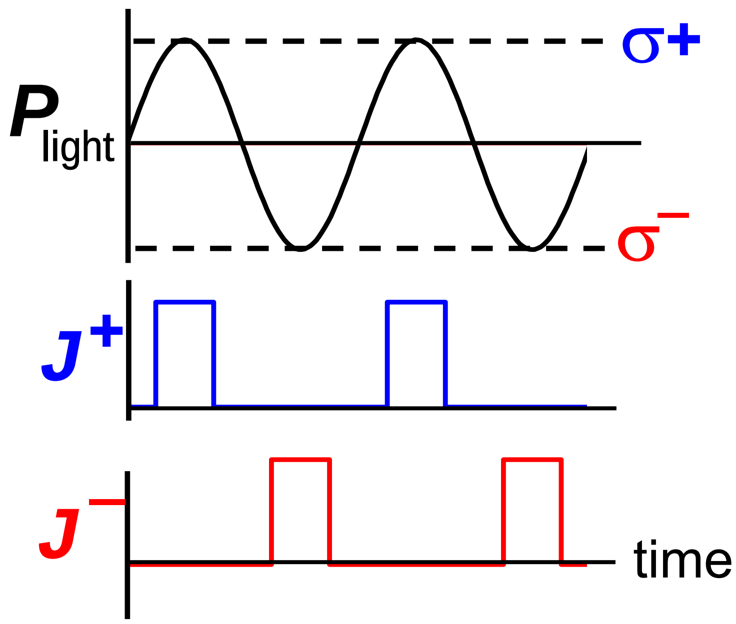
$$\boldsymbol{B_f} \sim \boldsymbol{B}^{||}_{1/2} \sim 1000\,\text{G} \quad \rightarrow \quad \boldsymbol{N} < 100$$

$$\boldsymbol{a_B} < 7\,\text{Å}$$

Extremely fast polarization of nuclei by electrons



Alternating circular pumping



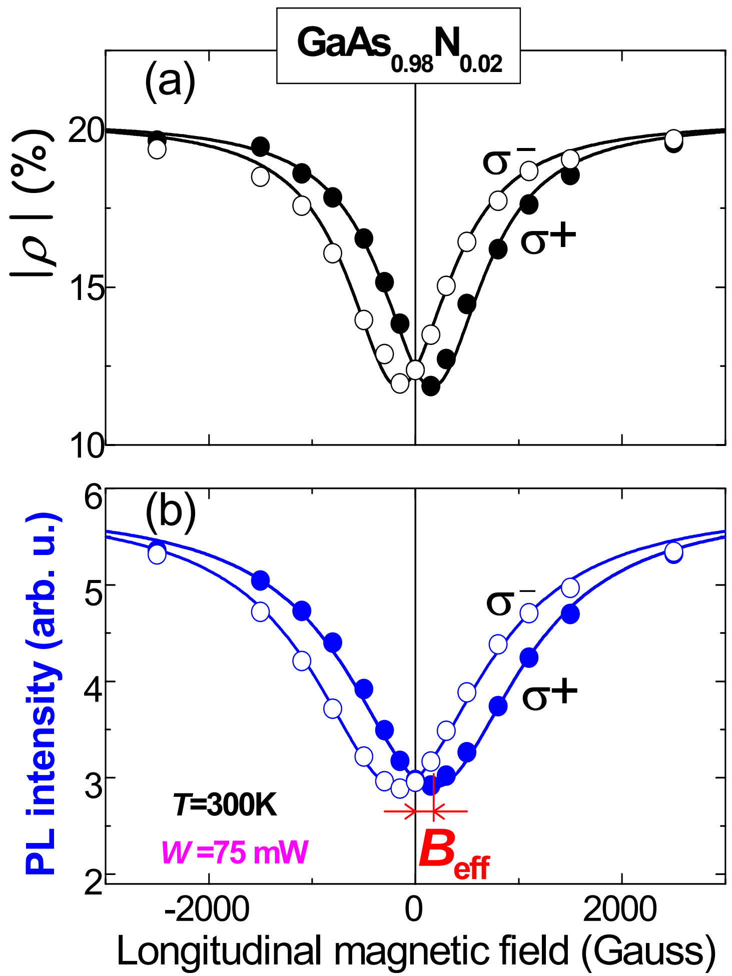
f_{mod}=35 kHz

The time required to polarize nuclei by electrons $\equiv$

Nuclei spin-relaxation time by electrons $T_{1e} < 15\ \mu s$

Enhancement of spin-filtering by magnetic field

Faraday geometry, B || z



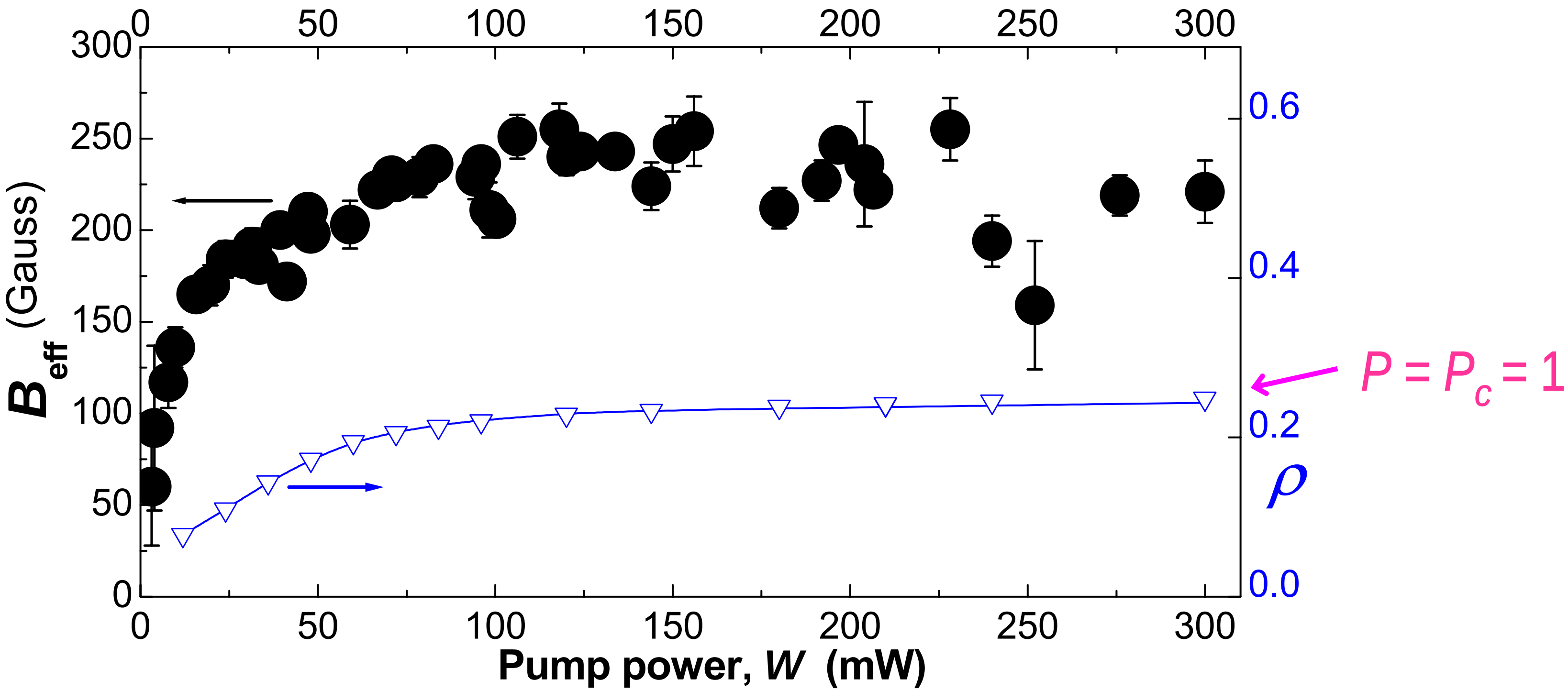
$$y(B) = y_{max} + (y_{min} - y_{max}) / [1 + (B - B_{eff})^2/B^2_{1/2}],$$

$$y_{min} = y(B = B_{eff}), \quad y_{max} = y(B \rightarrow \infty)$$

Hyperfine *vs* Exchange

Hyperfine : $H_{hf} = A\mathbf{s}_c\mathbf{I} \quad \rightarrow \quad B_N \propto \langle I \rangle \propto P_c = const$

Exchange : $H_{ex} = Q\mathbf{s}_c\mathbf{S} \quad \rightarrow \quad B_{ex} \propto S = Pn/2 \propto W$

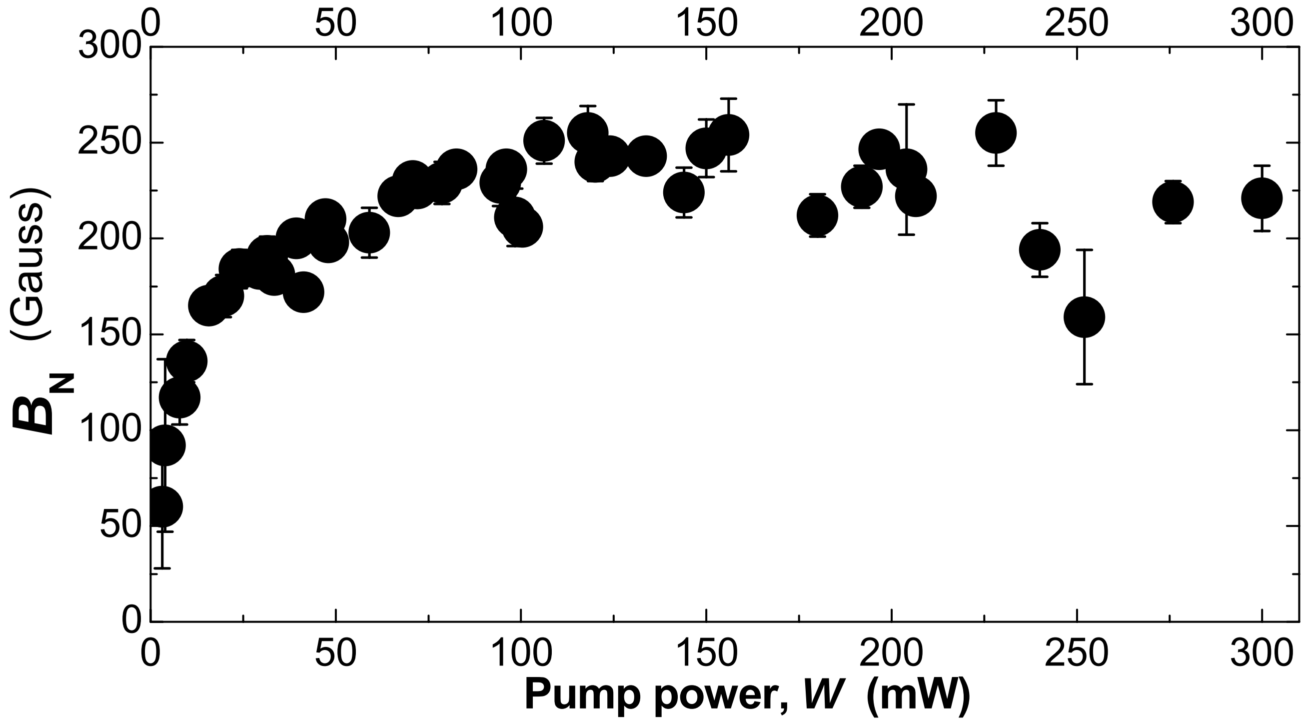


Kalevich, Afanasiev, Shiryaev, Egorov, JETP Lett. **96**, 567 (2012)

The field $\boldsymbol{B}_{\mathbf{eff}}$ is created by nuclear polarization

$\boldsymbol{B}_{\mathbf{eff}} \equiv \boldsymbol{B}_{\mathbf{N}}$

Degree of nuclear polarization ?



One electron – one nucleus

Dyakonov, Perel, ZhETP **63**, 1883 (1972)

$$\hat{H} = A\mathbf{S}\cdot\mathbf{I} + g_c\mu_B\mathbf{S}\cdot\mathbf{B}$$

1) $\mathrm{B}=0: \quad \vec{F}=\vec{S}+\vec{I}, \quad S=I=1/2, \quad F=\begin{pmatrix}1\\0\end{pmatrix}, \quad E=\begin{pmatrix}A/4\\-3A/4\end{pmatrix}$

triplet : $F_z = \begin{pmatrix}+1\\0\\-1\end{pmatrix} = \begin{pmatrix}\uparrow\Uparrow\\ \uparrow\Downarrow+\downarrow\Uparrow\\ \downarrow\Downarrow\end{pmatrix}$

mixing

singlet : $F_z = (0) = (\uparrow\Downarrow - \downarrow\Uparrow)$

2) $g_c\mu_B m_\mathbf{s} B >> A$

$$E = g_c\mu_B m_\mathbf{s} B + A m_\mathbf{s} m_\mathbf{I}\,, \qquad m_\mathbf{s} = \pm 1/2,\ m_\mathbf{I} = \pm 1/2$$

Mixing time $\hbar/A \sim 1\text{ps} << \tau_c \qquad (\tau_c > 50\text{ps})$

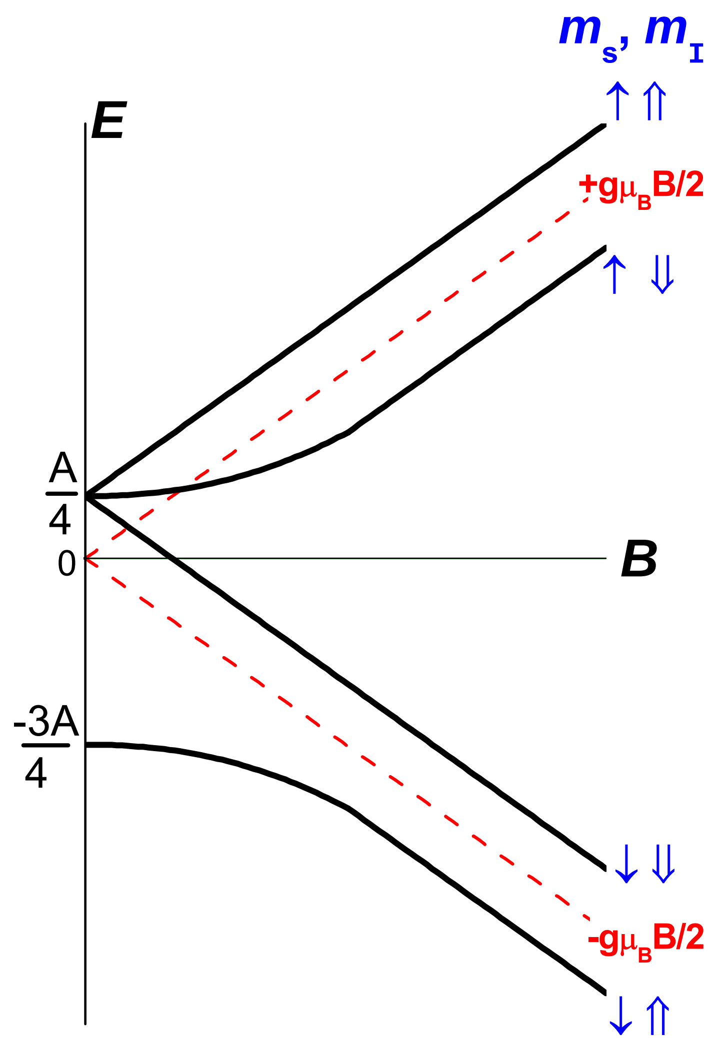
$\langle \mathrm{S}\rangle/\langle \mathrm{S}_0\rangle = 1/2,\ 3/8,\ 1/3$ for $I=1/2,\ 3/2,\ I>>1$

$$\frac{\langle \mathrm{S}\rangle}{\langle \mathrm{S}_0\rangle} = 1-\frac{0.5}{1+(g_c\mu_B B/A)^2}, \qquad g_c\mu_B B \sim \delta, \qquad \delta_{\exp} \sim 10\mu\text{eV}$$

Nuclear polarization

$$\langle I\rangle = \langle S_0\rangle \nu_{1e}/(\nu_{1e}+\nu_1)\,, \qquad \nu_{1e} = f/2$$

$$\nu_{1e} = (f/2)/[1+(g_c\mu_0 B/A)^2]$$



SUMMARY

- ✓ **Spin-dependent recombination via deep paramagnetic centers is an effective mechanism to create very high (up to 100%) spin polarization of**
  free electrons in conduction band,
  paramagnetic centers and
  nuclei
  in a nonmagnetic semiconductor
  at room temperature and
  zero or weak magnetic field

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