MBE Challenges from Quantum Information Technologies

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Materials Issues are Essential for QI

Spin coherence times

influenced by inversion asymmetry of the material

(110) growth has promise:

control of spin coherence times with gates

Integration of magnetic and semiconducting materials

coherent transport between magnetic and nonmagnetic materials

- new spin detection and amplification methods

Control of nuclear properties in semiconductor structures

spatially-selective nuclear magnetic resonance

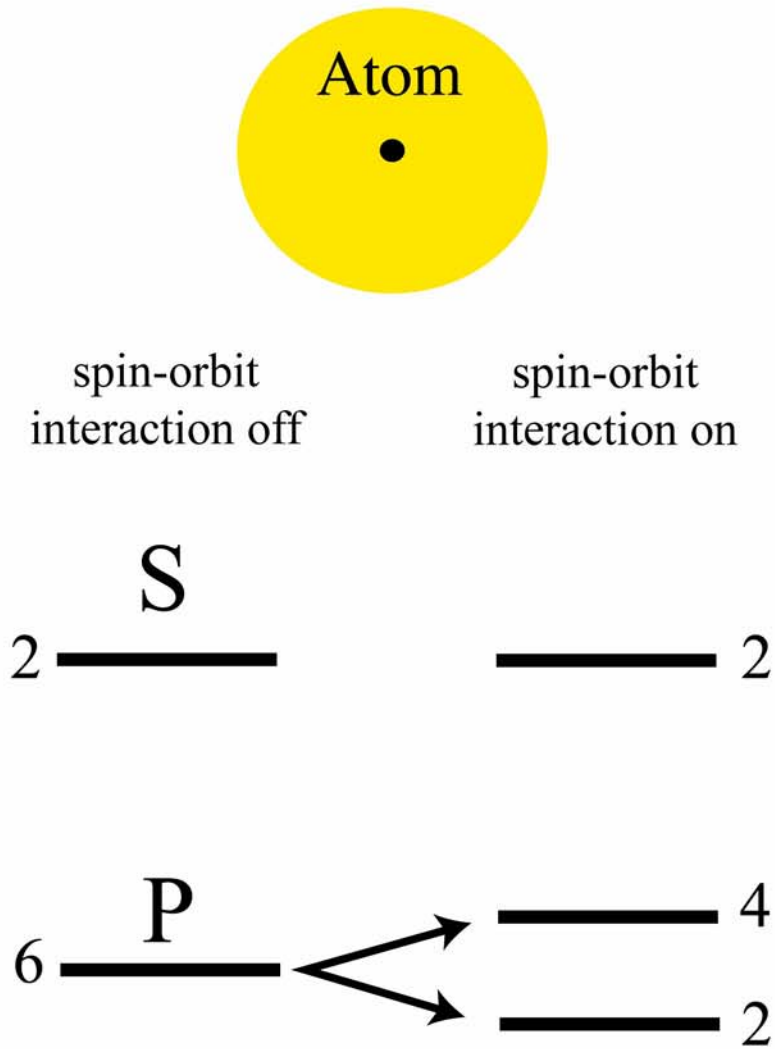
manipulation of nuclear pseudomagnetic fields

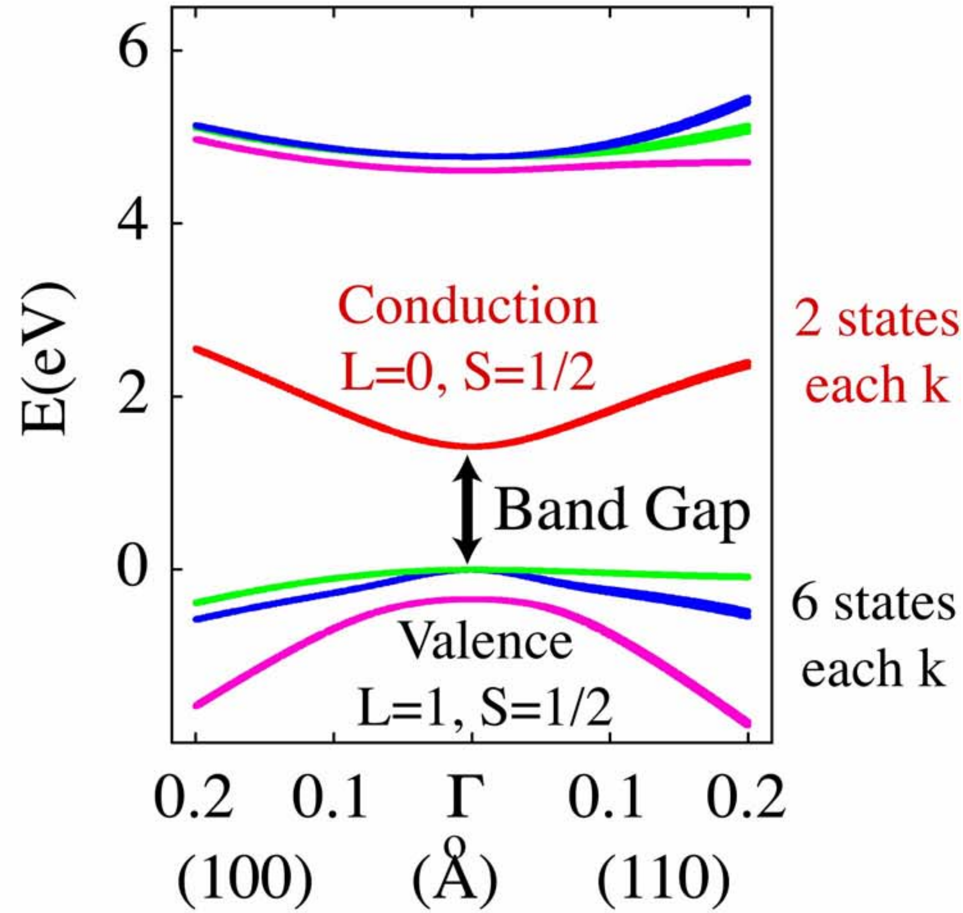
Spin manipulation and detection in quantum dots

importance of dot shape for selection rules for AC Stark effect and photoluminescence

Optically creating spin-polarized carriers

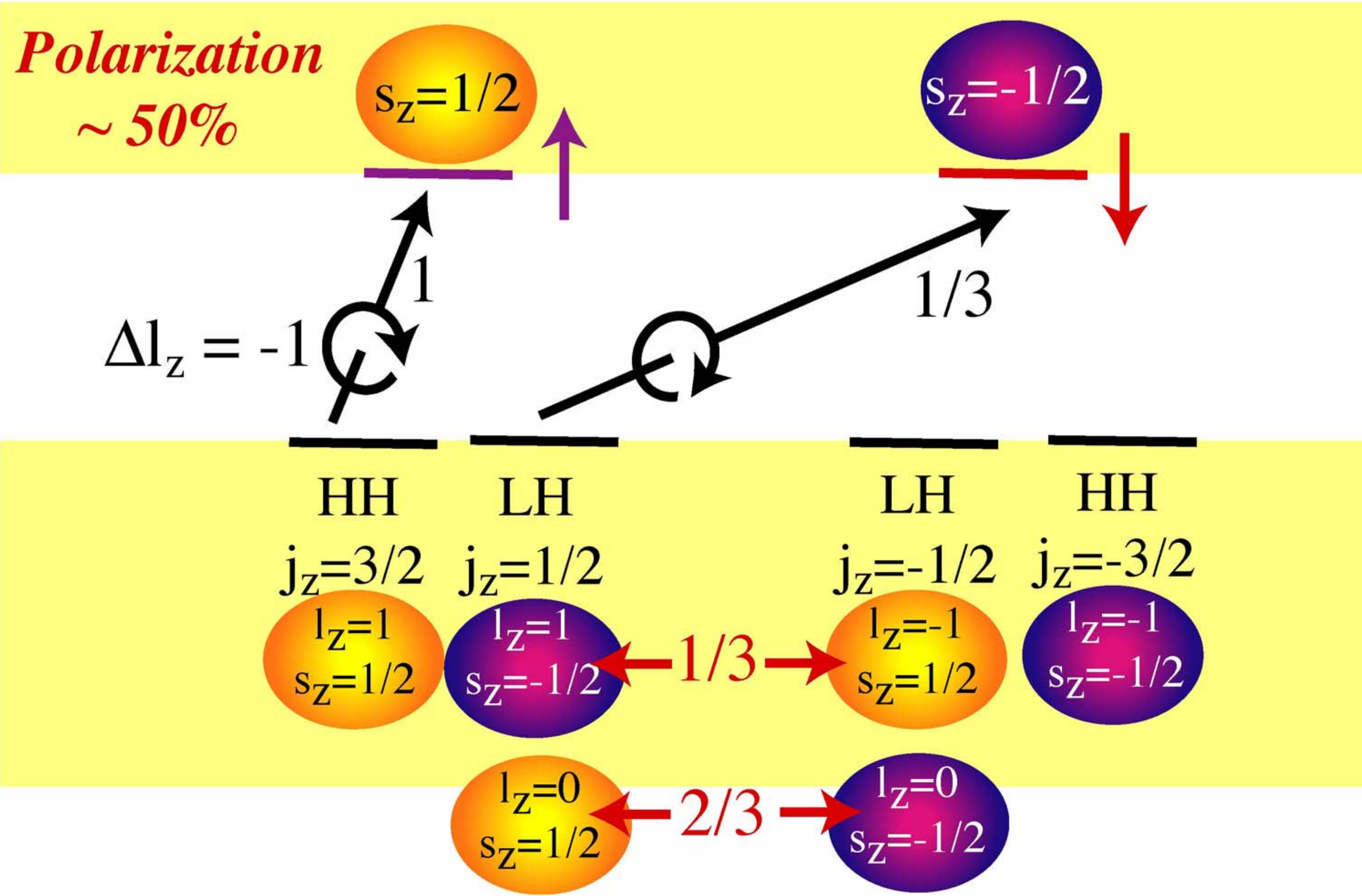
Electronic structure of GaAs



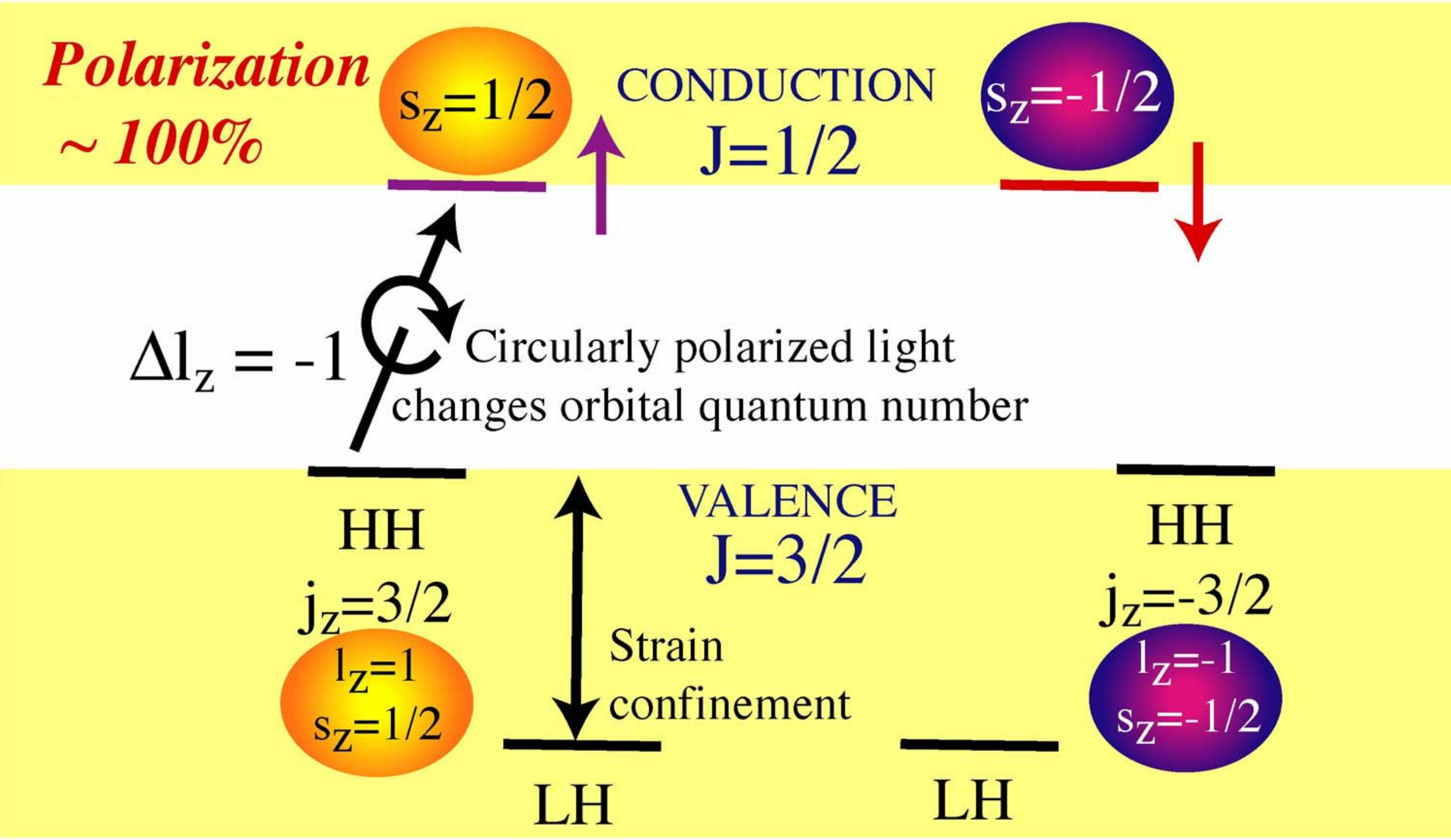


Optical transitions are vertical

Optical excitation of spin-polarized distributions

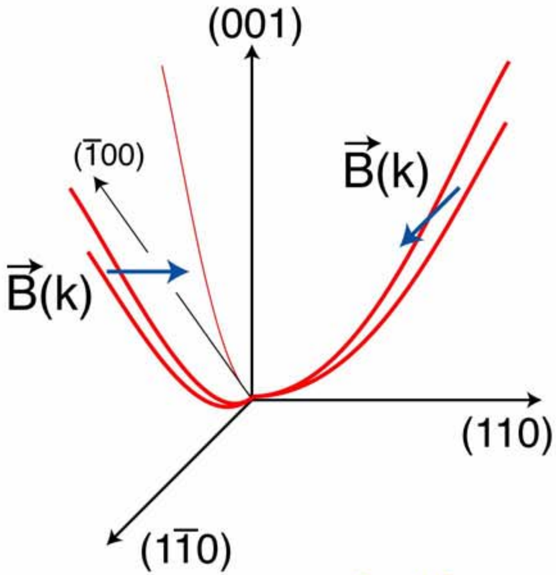


Optical excitation of spin-polarized distributions



Low-dimensional structures (e.g. quantum wells)

Precessional Decoherence



For a crystal with inversion asymmetry and spin-orbit coupling there is a (very small) effective field:

$$\mathbf{B}(\mathbf{k}) = -\mathbf{B}(-\mathbf{k})$$

Average of crystal magnetic field vanishes

however each spin precesses in this field

population of k

$S(k,\tau)$

dephasing....

orbital scattering loses k-information

... decoherence

even if the spin splitting ~ 1 meV, precession frequency ~ 1ps

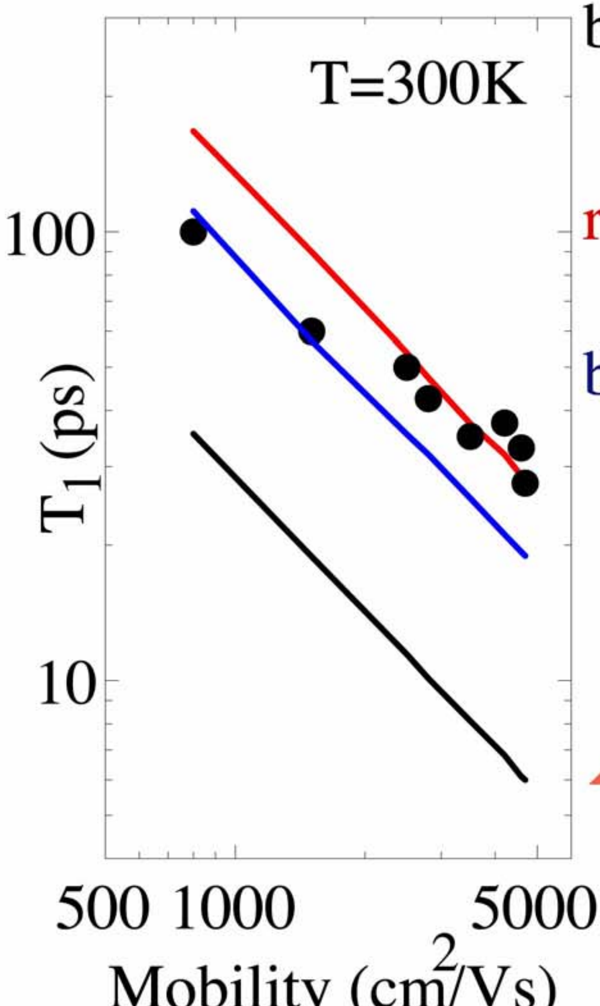
symmetry of crystal magnetic field determined by crystal symmetry

7.5 nm (001)-grown GaAs/AlGaAs MQW

PRB Rapid Comm. **64**, *161301 (2001).*

● experiment

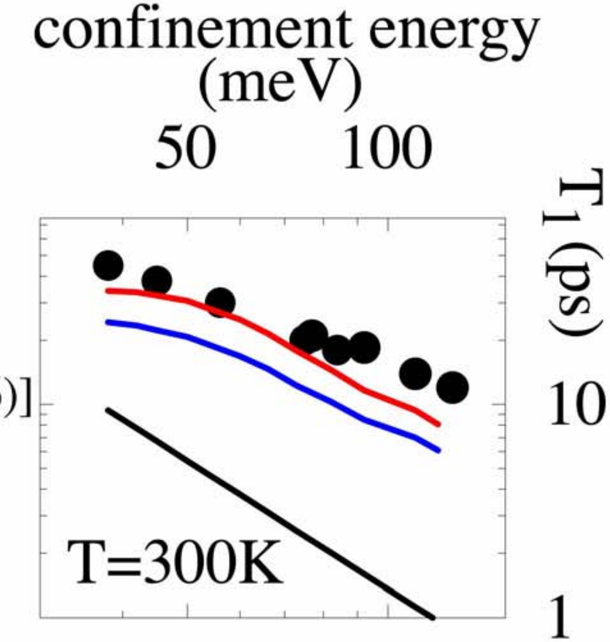
Terauchi, et al., Jpn. J. Appl. Phys. 38, 2549 (1999)

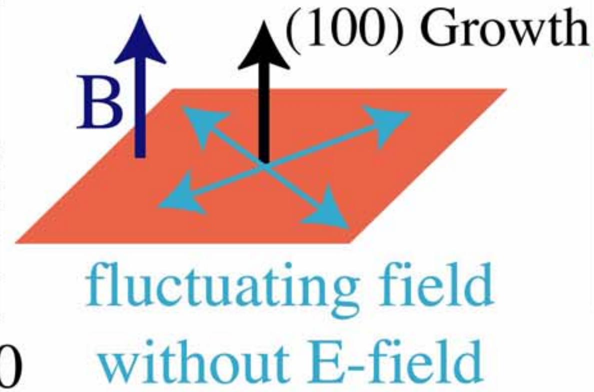


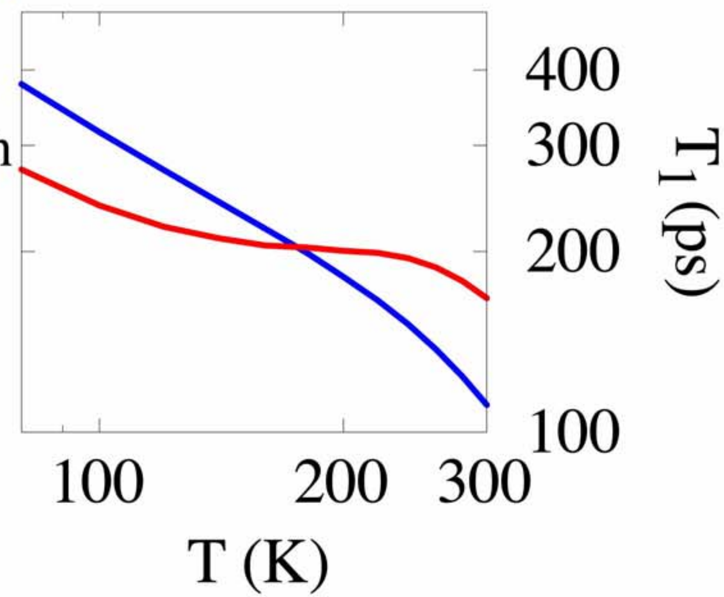
black - D'yakonov-Kachorovskii (DK) theory [Sov. Phys. Semicond. 20, 110 (1986)]

red - optical phonon scattering

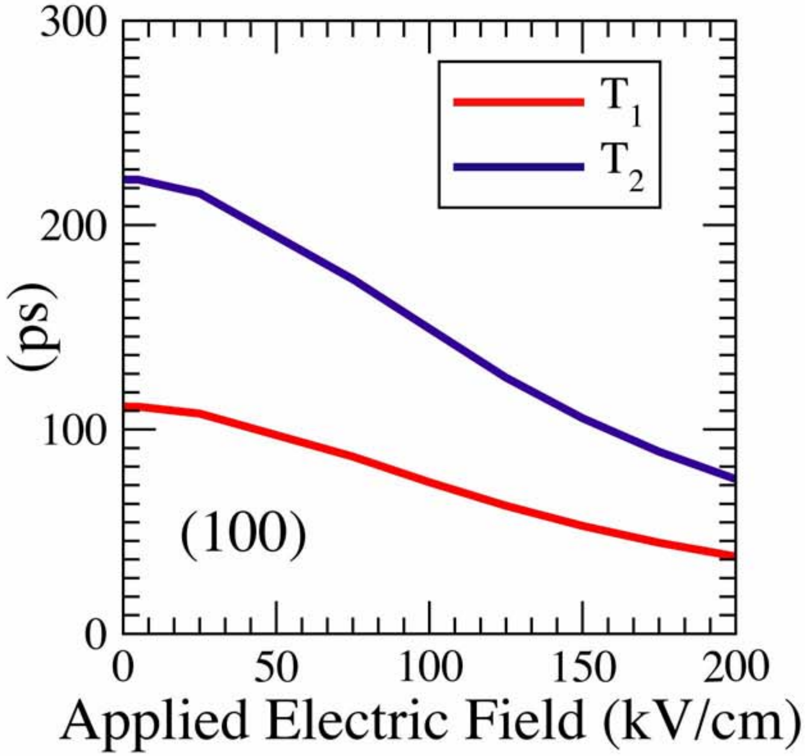
blue - neutral impurity scattering

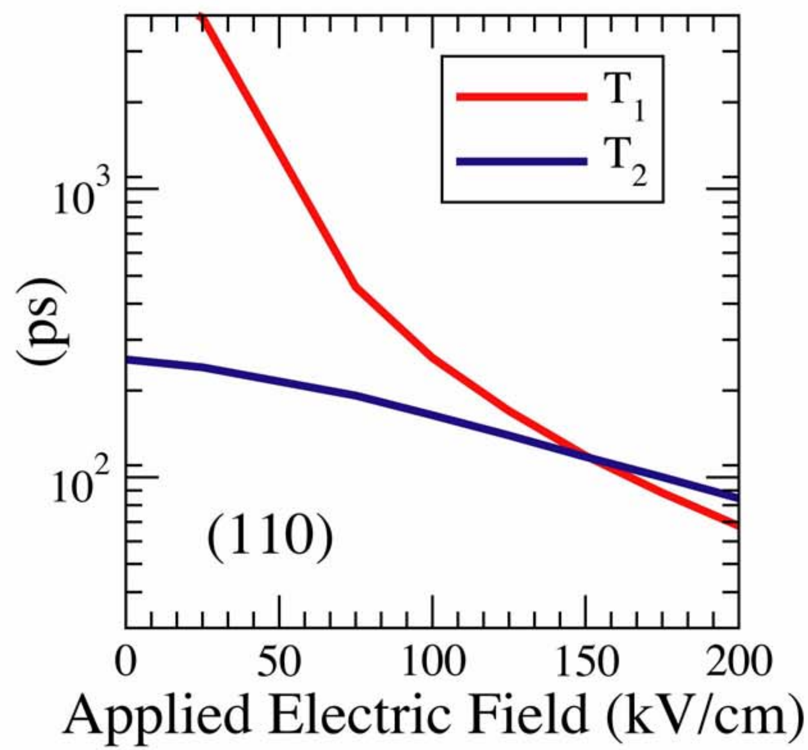


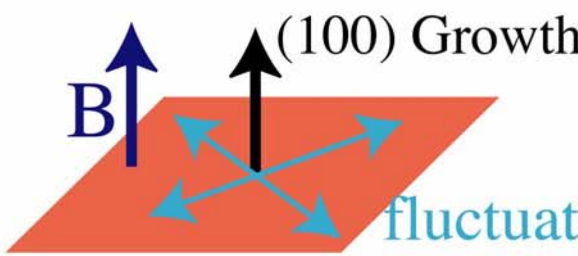


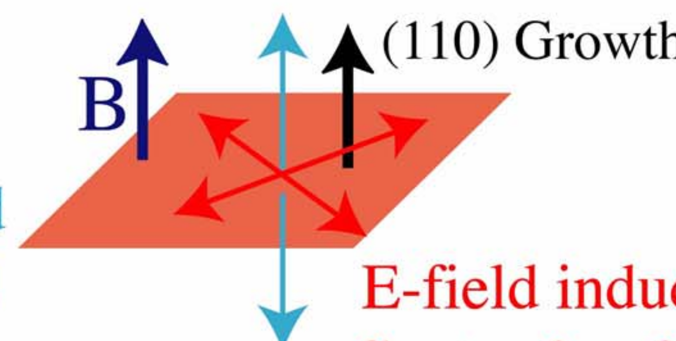


Tunability of T_1 and T_2





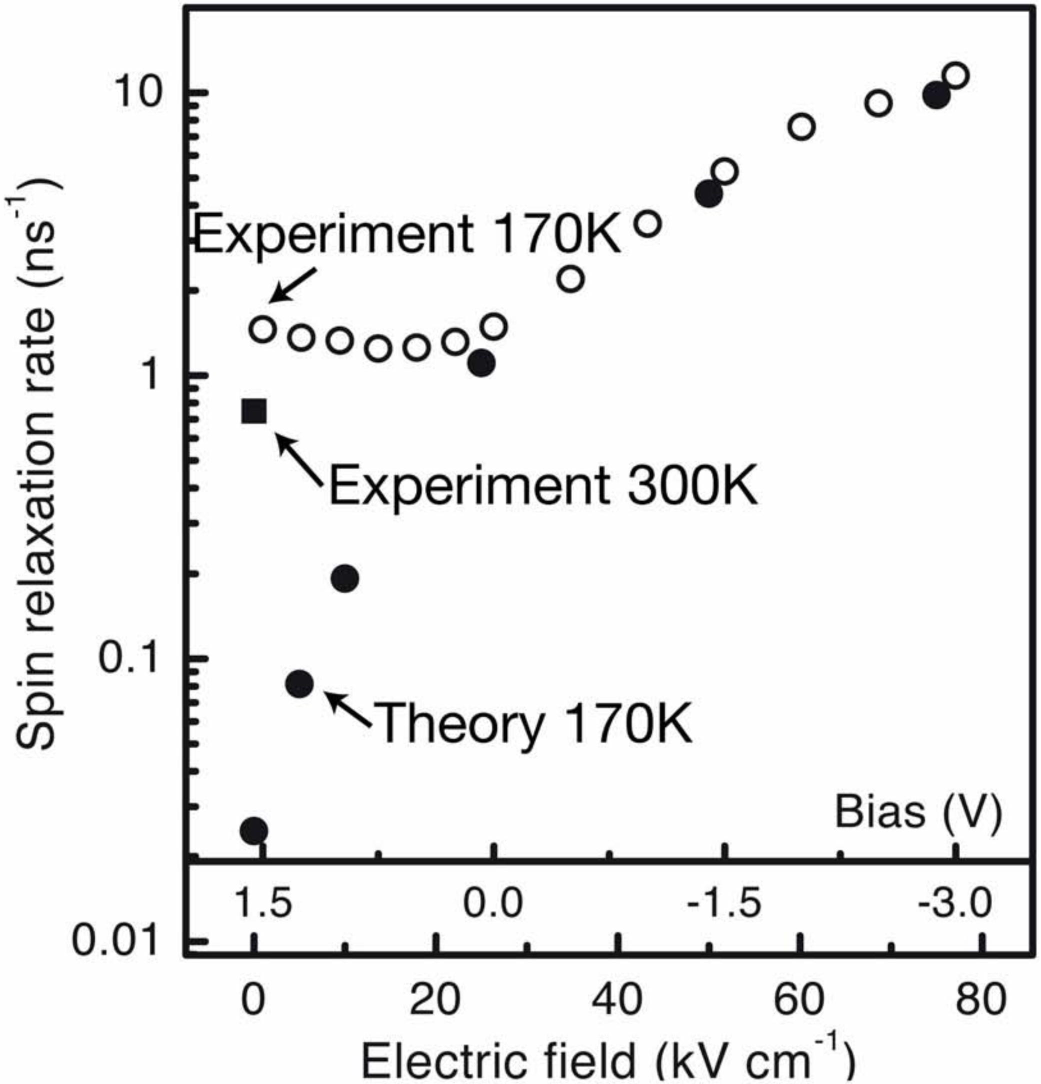




7.5 nm GaAs/AlGaAs QW

Suppression of T_1 by over a factor of 100! ***J. Appl. Phys. 91, 8682 (2002).***

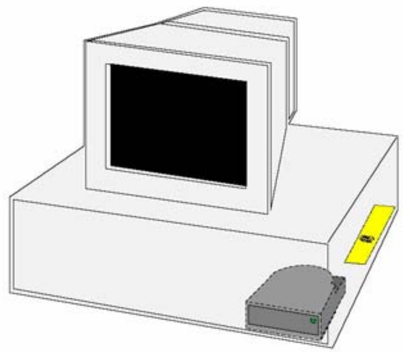
T_1 in 75 A (110) GaAs/AlGaAs QW



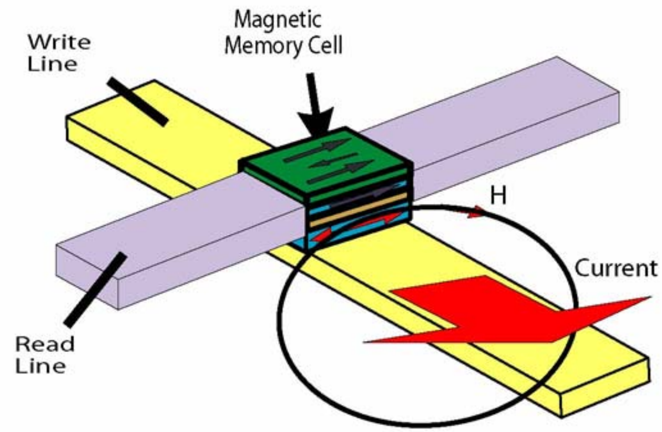
Factor of 10 tunability demonstrated

Karimov, et al., cond-mat/0305396

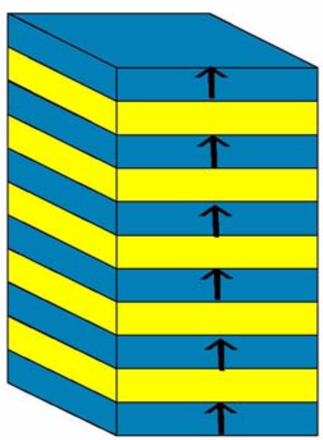
Use of Magnetic Multilayers in Technology

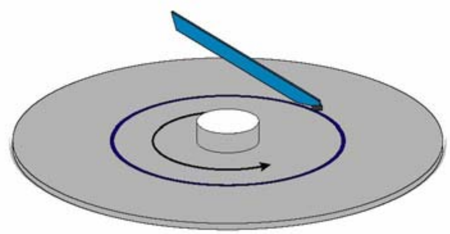


Magnetic Random Access Memory

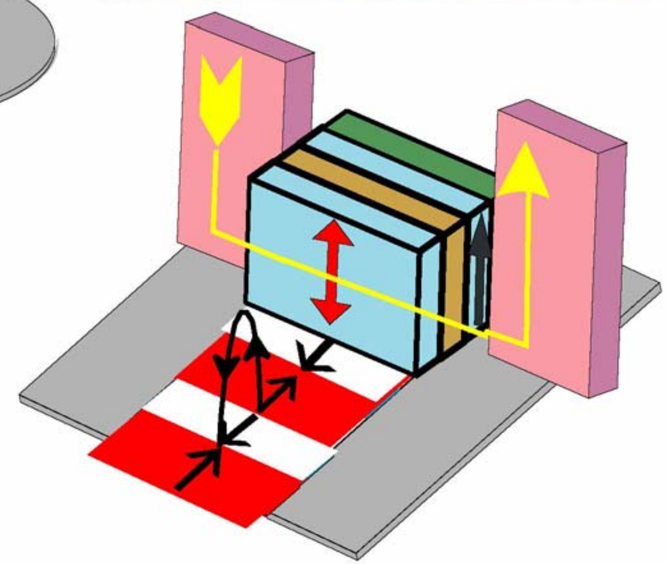


Magneto-optical Disk





Spin-Valve Read Head



(image courtesy J. Stöhr)

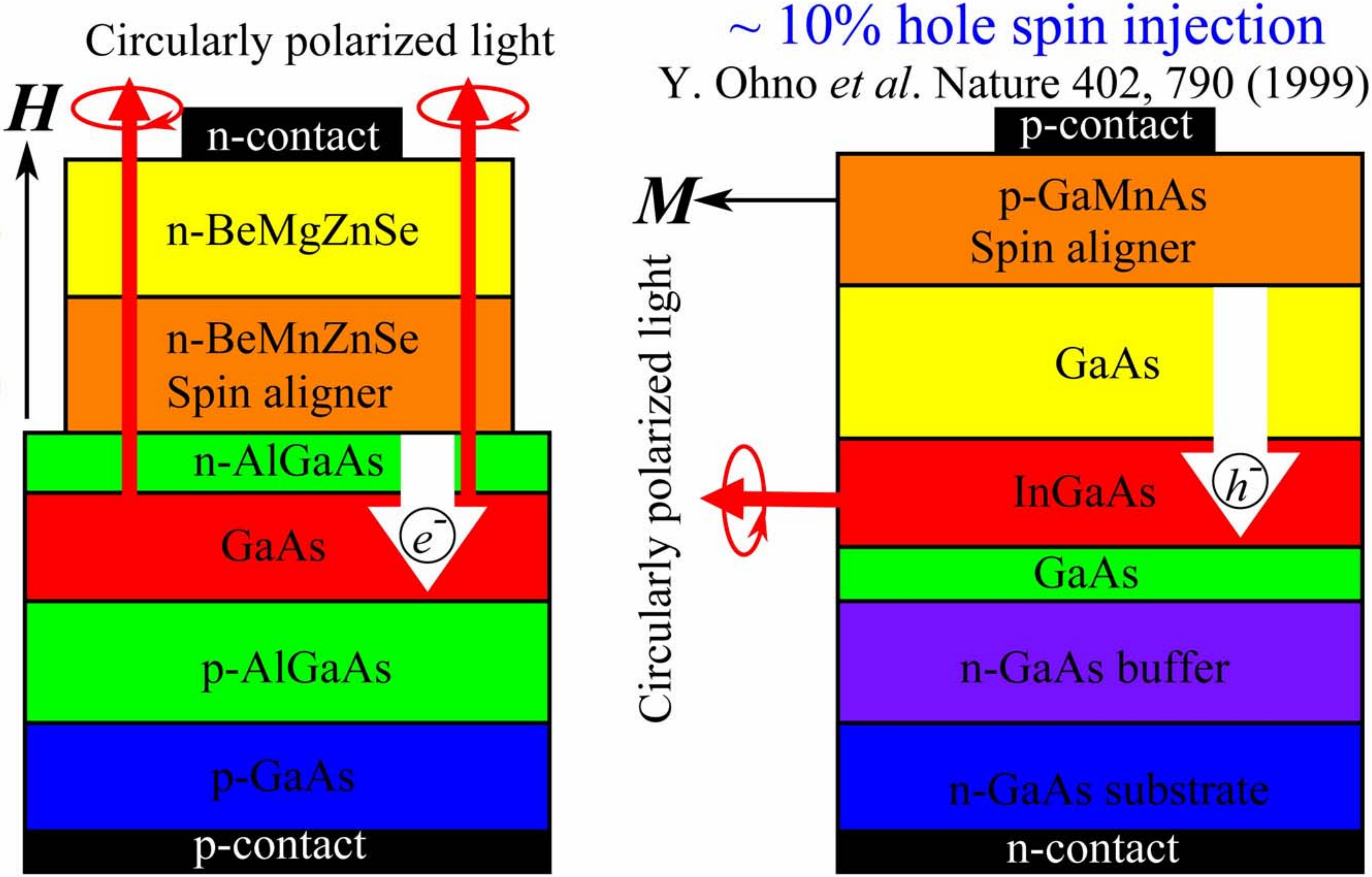
see Stöhr, Nakajima, IBM J. Res. Dev. 42 (1) (1998)

Spin-polarized light emitting diode (LED)

~ 10% hole spin injection

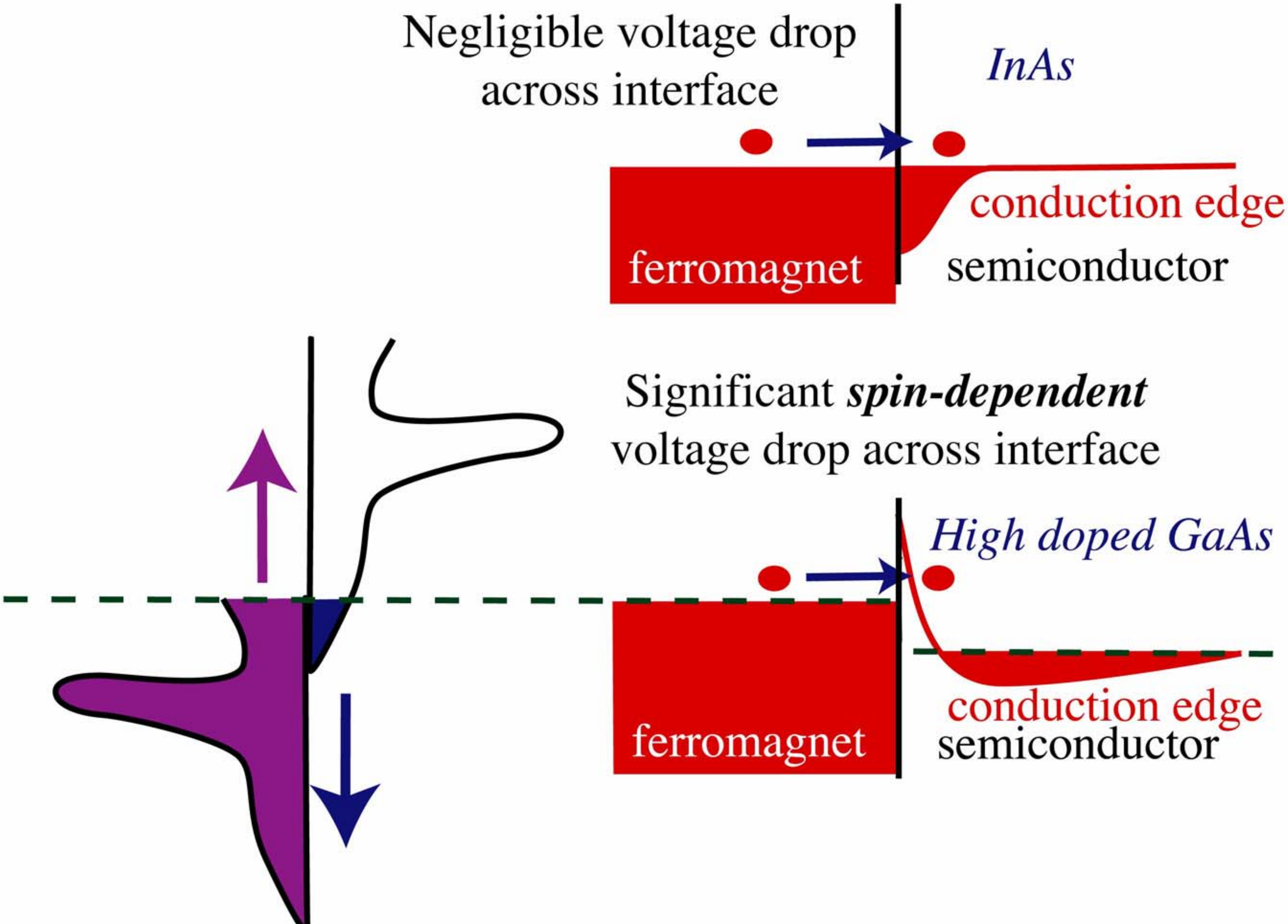
Y. Ohno *et al*. Nature 402, 790 (1999)

~ 90% electron spin injection

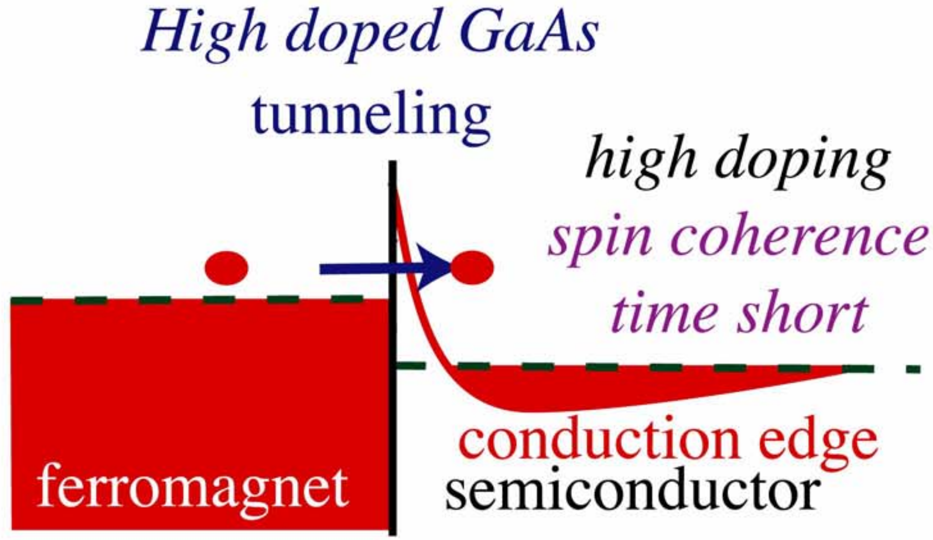


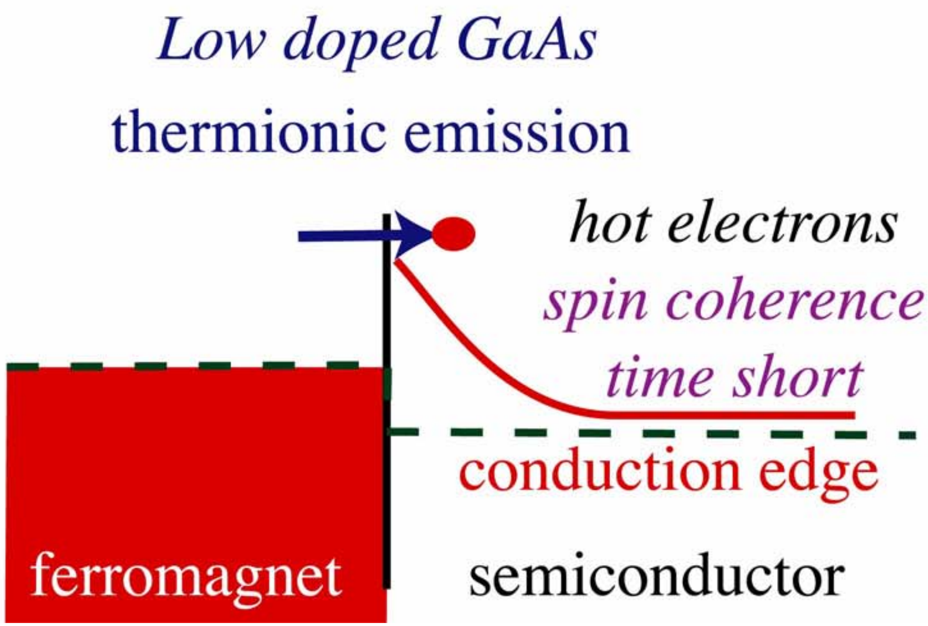
R. Fiederling *et al*. Nature 402, 787 (1999)

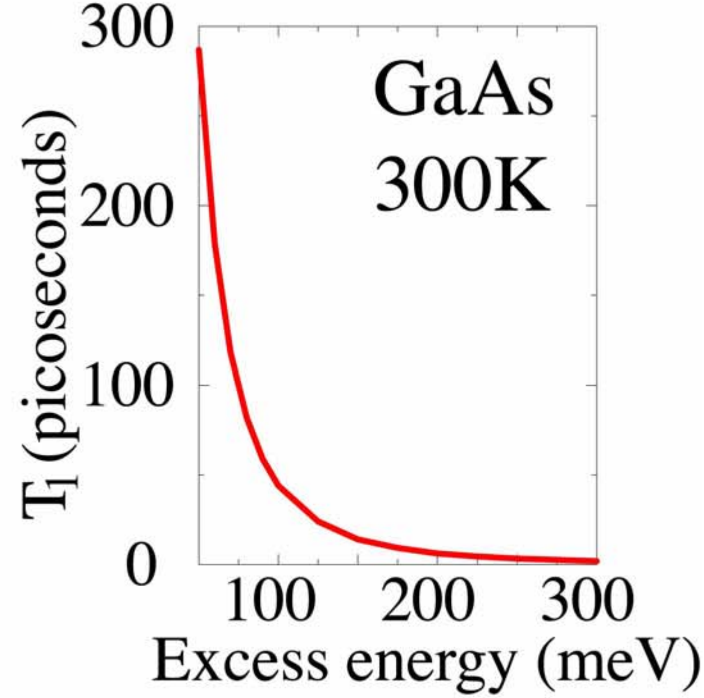
Metal-semiconductor contacts



Metal-semiconductor contacts

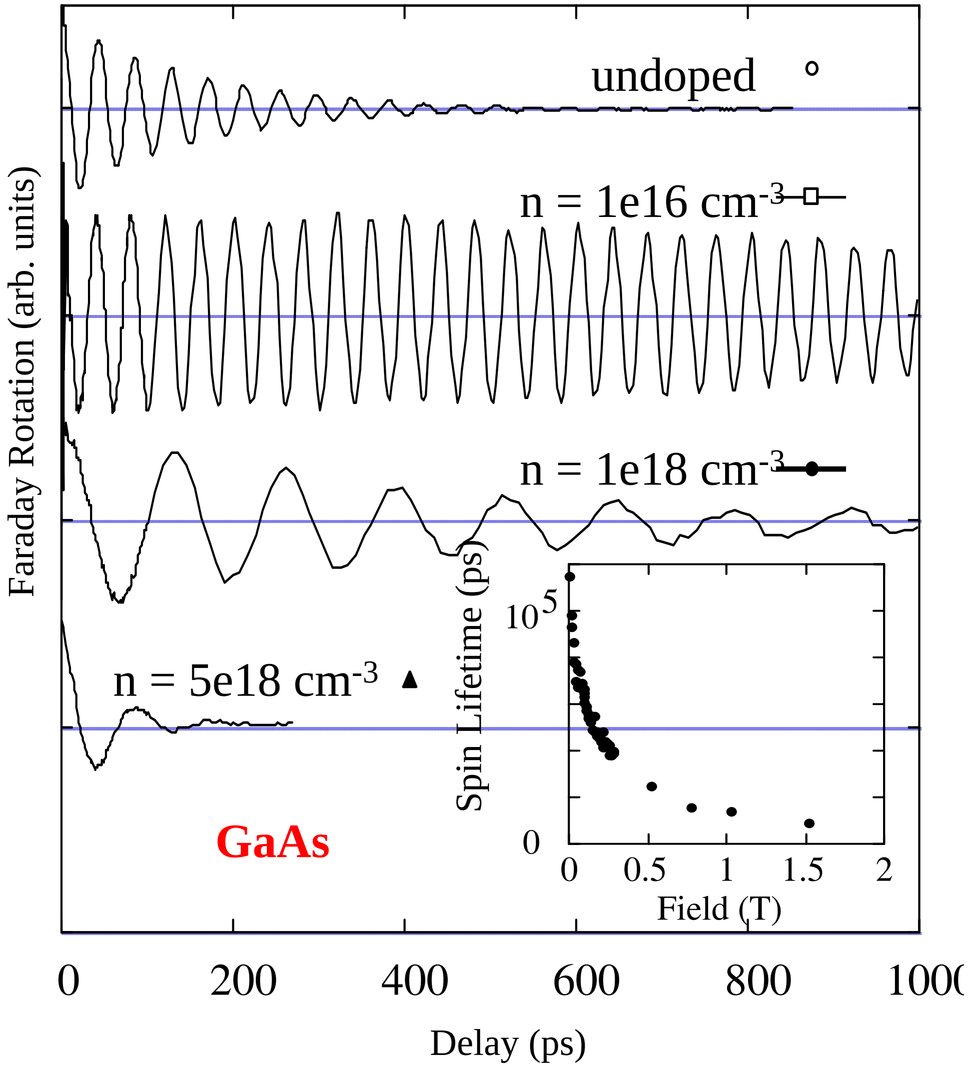






Bulk GaAs

Kikkawa and Awschalom, PRL 80, 4313 (1998).



Spin Transport in p-n diode

Persistent sourcing of coherent spins for multifunctional semiconductor spintronics

I. Malajovich*, J. J. Berry , N. Samarth & D. D. Awschalom*

NATURE | VOL 411 | 14 JUNE 2001 | www.nature.com

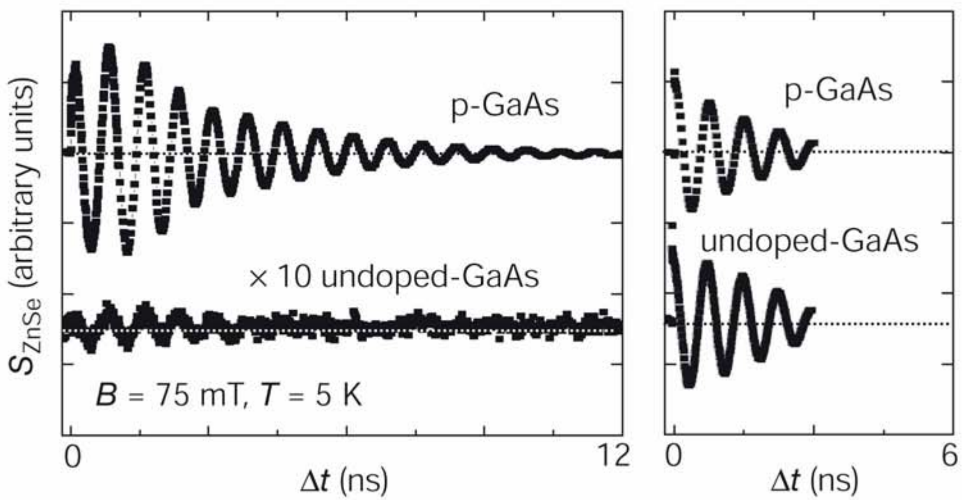
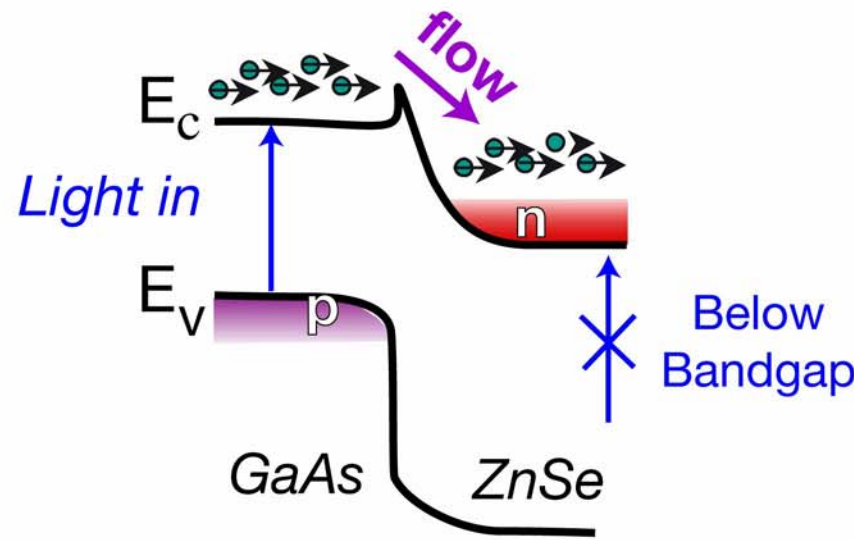


Figure 4 Time evolution of the spin polarization transfer across a p-GaAs/n-ZnSe heterojunction. Zn p-type doping concentration, 10^{19} cm^{-3}. Transfer across an undoped-GaAs/n-ZnSe is shown for comparison. Dotted lines show the zeros, and an offset was added for clarity. a, Spins transported across the interface (two-colour pump probe). b, Spins excited and measured in the ZnSe epilayer (degenerate pump probe).



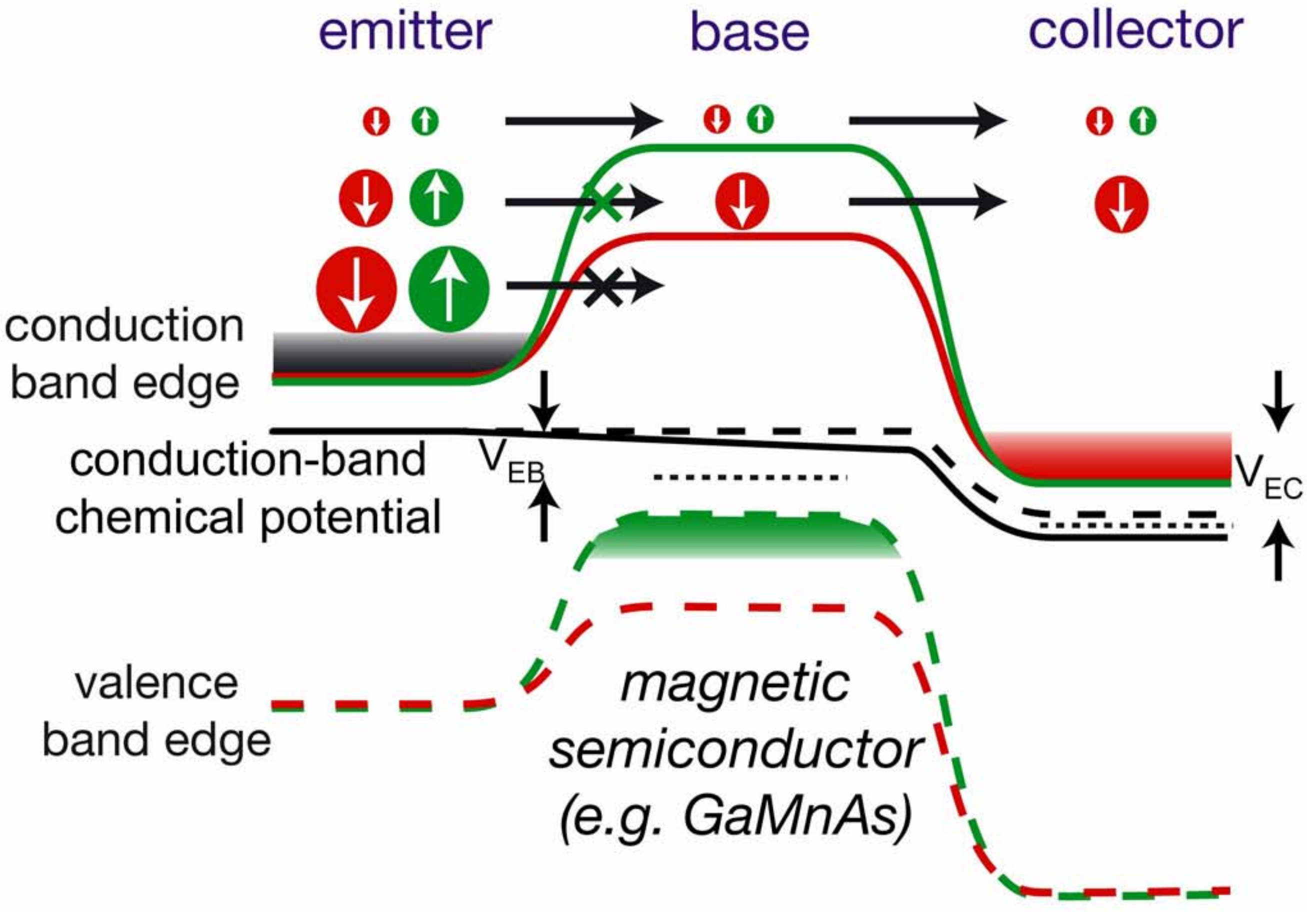
The time-reverse of this is minority carrier injection

minority carrier spin electronics should be possible

npn magnetic bipolar transistor (MBT)

Appl. Phys. Lett. 82, 4740 (2003)

active configuration



permits ~100% spin-polarized current even though spin density polarization of base << 100%

ultrafast switching or long-lived gating

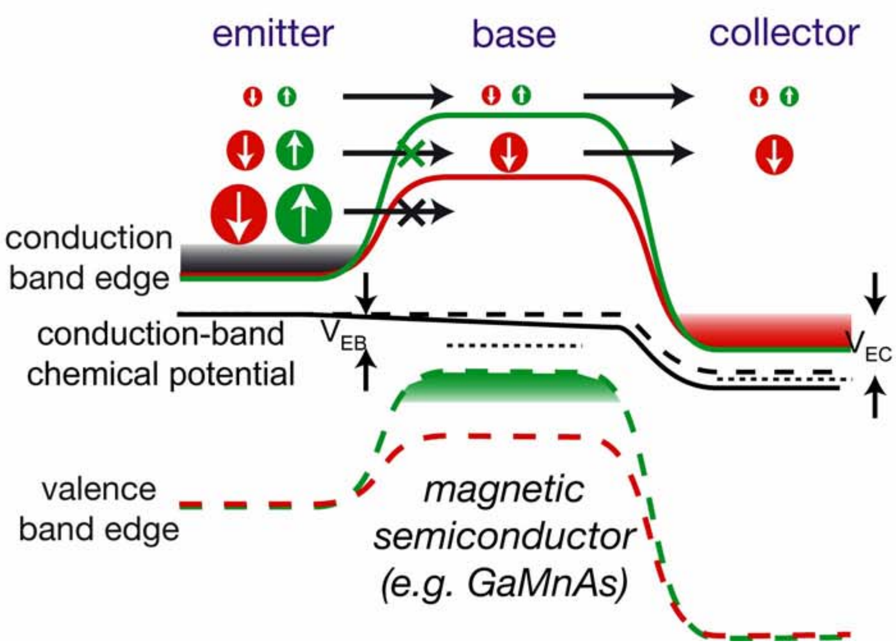
patent pending

MBT spin polarization

Appl. Phys. Lett. 82, 4740 (2003)

Conduction band spin splitting S_c

$$\frac{n_{B\downarrow o} - n_{B\uparrow o}}{n_{B\downarrow o} + n_{B\uparrow o}} = \tanh(S_c/2k_BT)$$



Spin-filter

Shockley approximations:

$$\frac{n_{B\downarrow}}{n_{B\uparrow}} = \frac{n_{B\downarrow o}}{n_{B\uparrow o}}$$

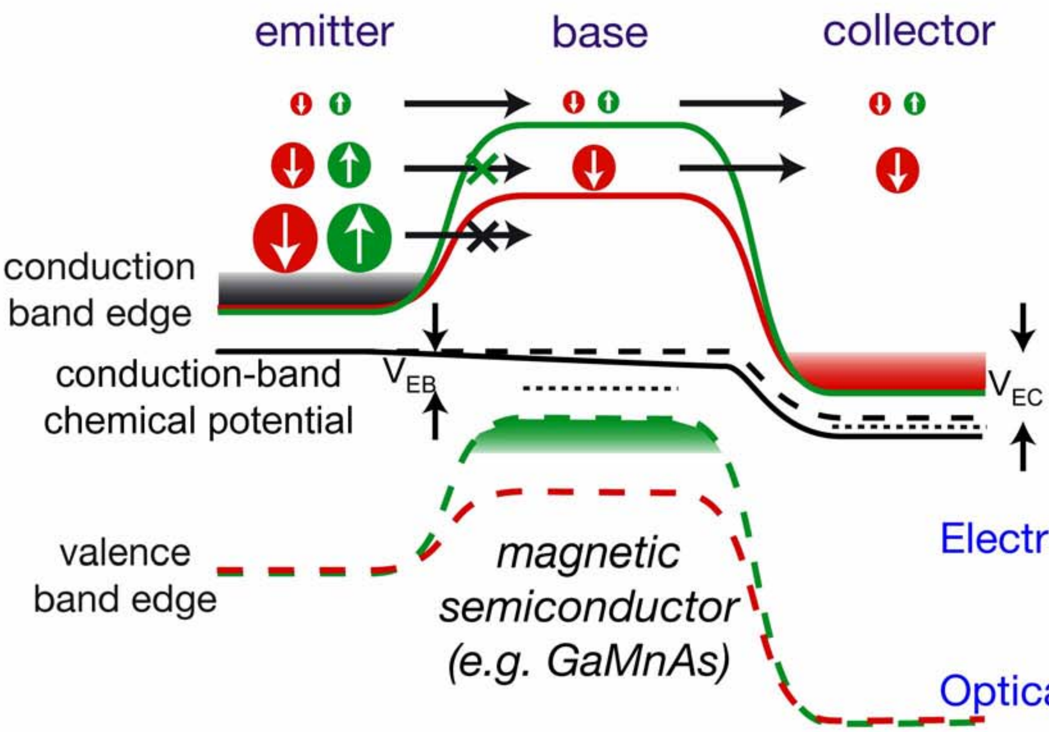
Hence even when $n_{B\downarrow} >> n_{B\downarrow o}$

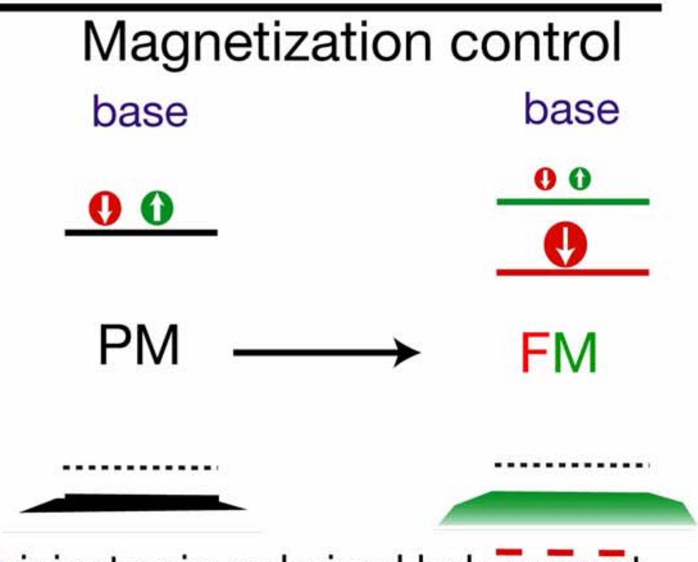
$$\frac{n_{B\downarrow} - n_{B\uparrow}}{n_{B\downarrow} + n_{B\uparrow}} = \tanh(S_c/2k_BT)$$

Spin-relax

$$\frac{n_{B\downarrow} - n_{B\uparrow}}{n_{B\downarrow} + n_{B\uparrow}} = \frac{\tau_{\downarrow\uparrow} - \tau_{\uparrow\downarrow}}{\tau_{\downarrow\uparrow} + \tau_{\uparrow\downarrow}}.$$

Switching npn magnetic bipolar transistor





Electrical: inject spin-polarized hole current
change base hole density or use
current-induced spin torque

Optical: (1) spin-polarized electron-hole injection.
Electrons swept out to emitter or
collector
(2) ultrafast (resonant) splitting of
conduction spin bands

Through independent control of base magnetization and base voltage,

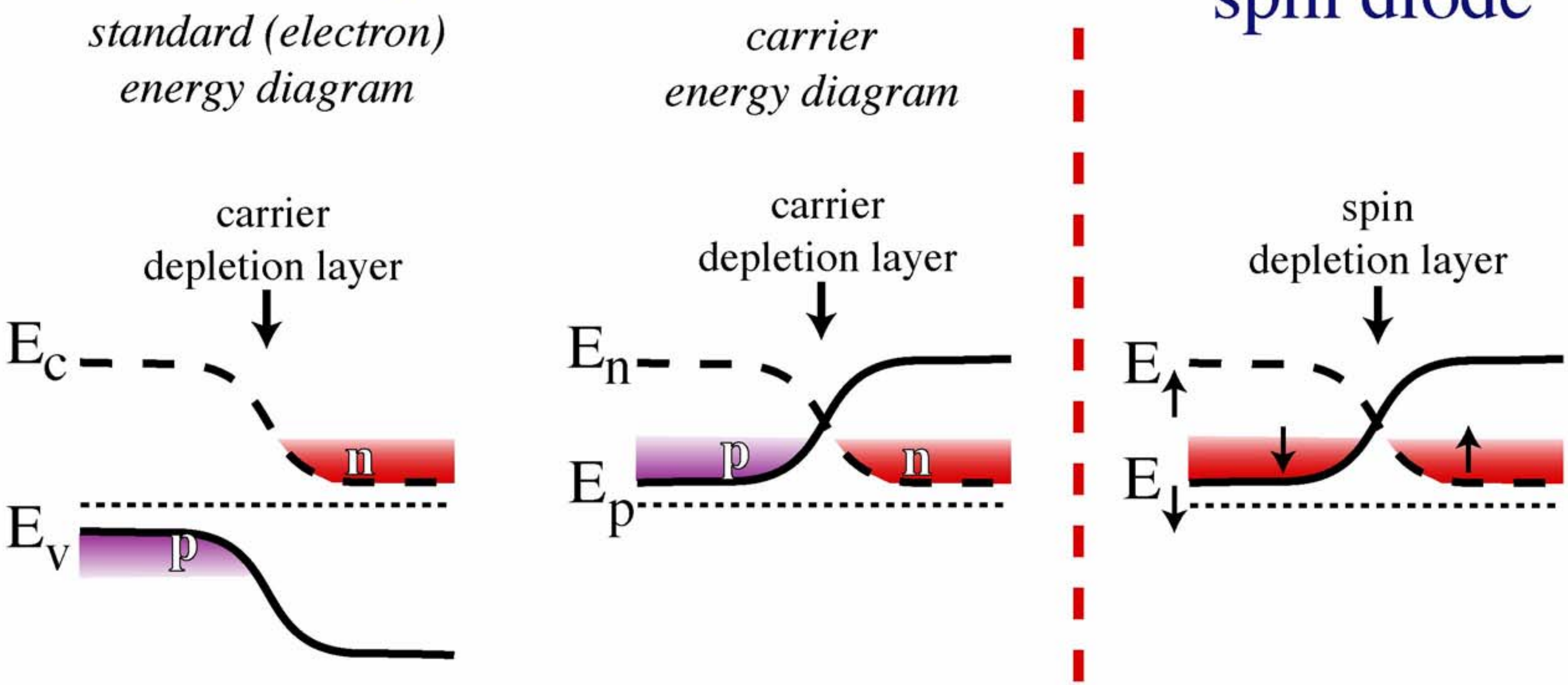
independent amplification of spin-up current and spin-down current are possible.

Both spin current gain and charge current gain

Unipolar spin diode (equilibrium)

p-n diode

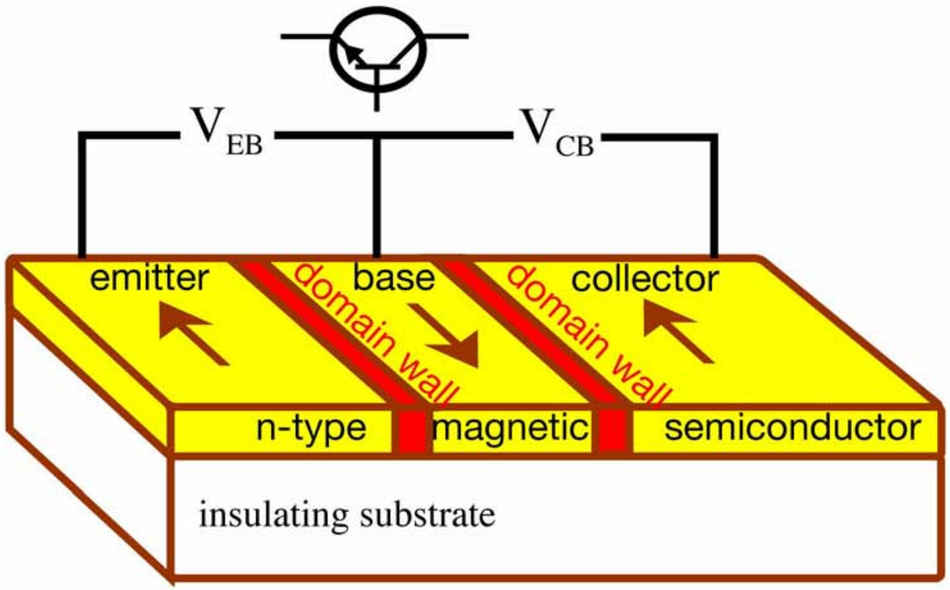
unipolar spin diode



APL 78, 1273 (2001).

Unipolar Spin Transistor

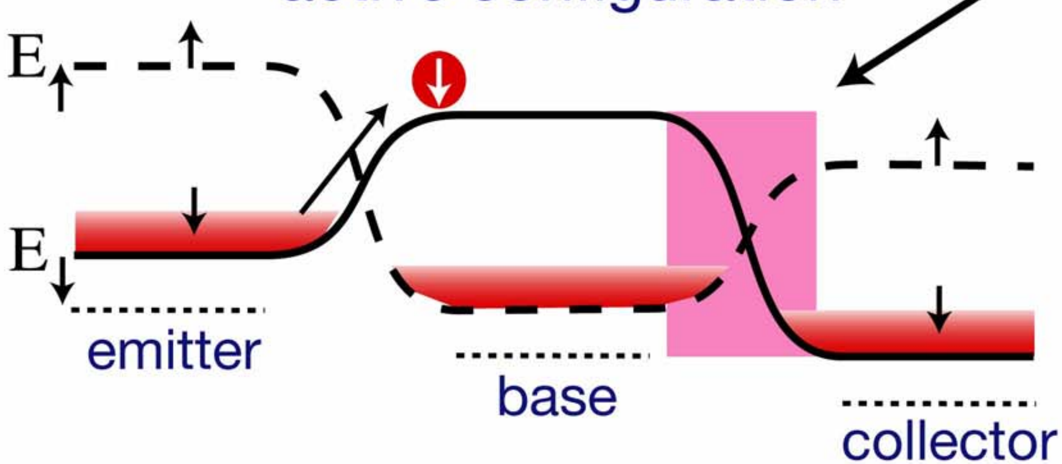
APL 78, 1273 (2001)



possible applications to
reprogrammable logic
non-volatile memory
magnetic sensing

Transport across domain wall (noncollinear spin)

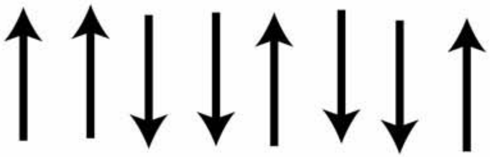
active configuration



Optical orientation of nuclear spin

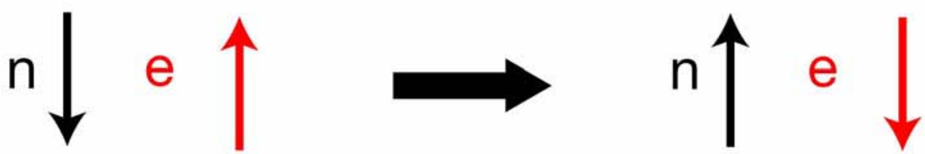
"*Overhauser effect*"

begin with unpolarized nuclear spins



optical generation of polarized electrons

kinetic process



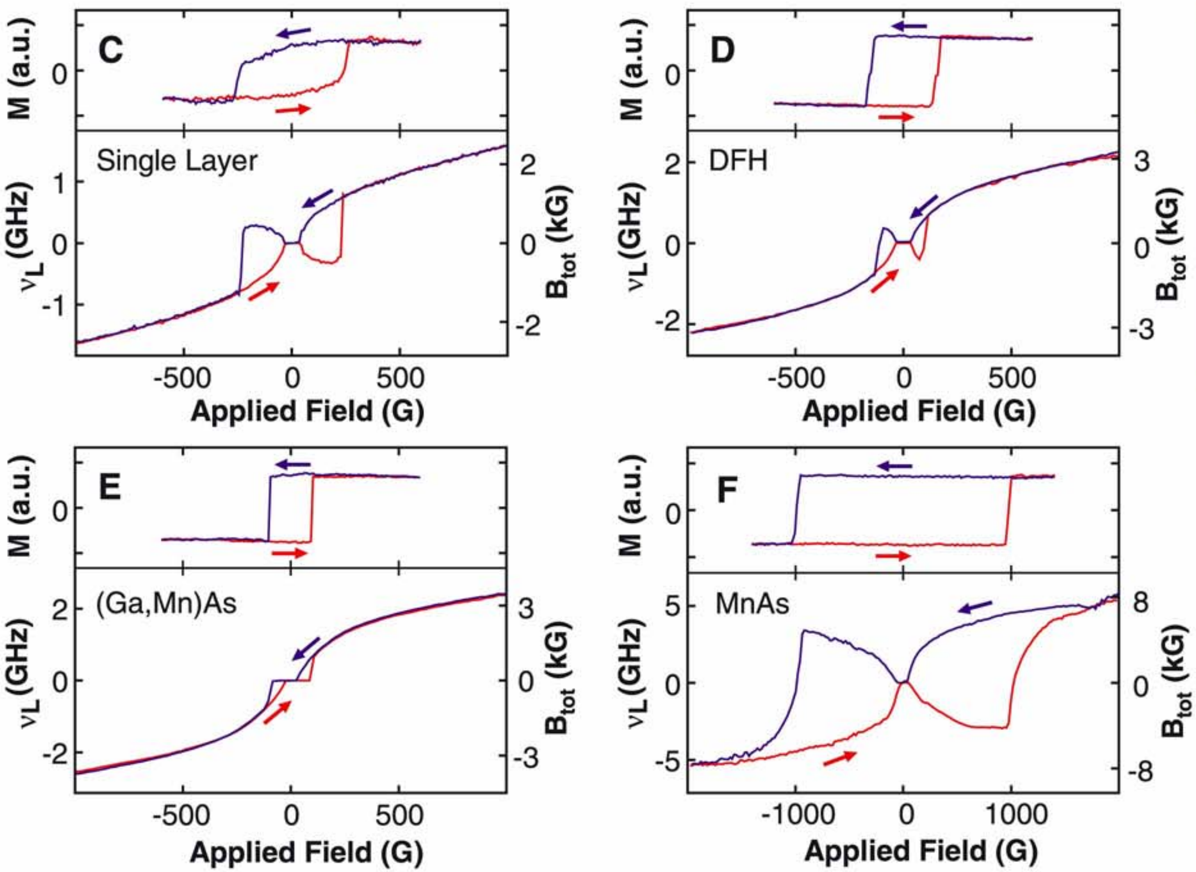
result - highly polarized nuclear spins (out of thermal equilibrium)

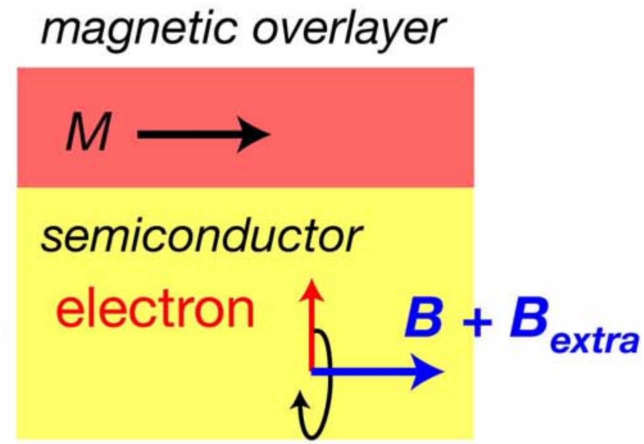
in quantum wells:

Barrett, et al., PRL 72, 1368 (1994)
Marohn, et al., PRL 75, 1364 (1995)
Malinowski and Harley, Solid State Comm. 114, 419 (2000)
Salis, et al., PRL 86, 2677 (2001)
Poggio, et al., (cond-mat/03xxxxx)

Ferromagnetic imprinting of nuclear polarization

Kawakami, et al., Science 294, 131 (2001)

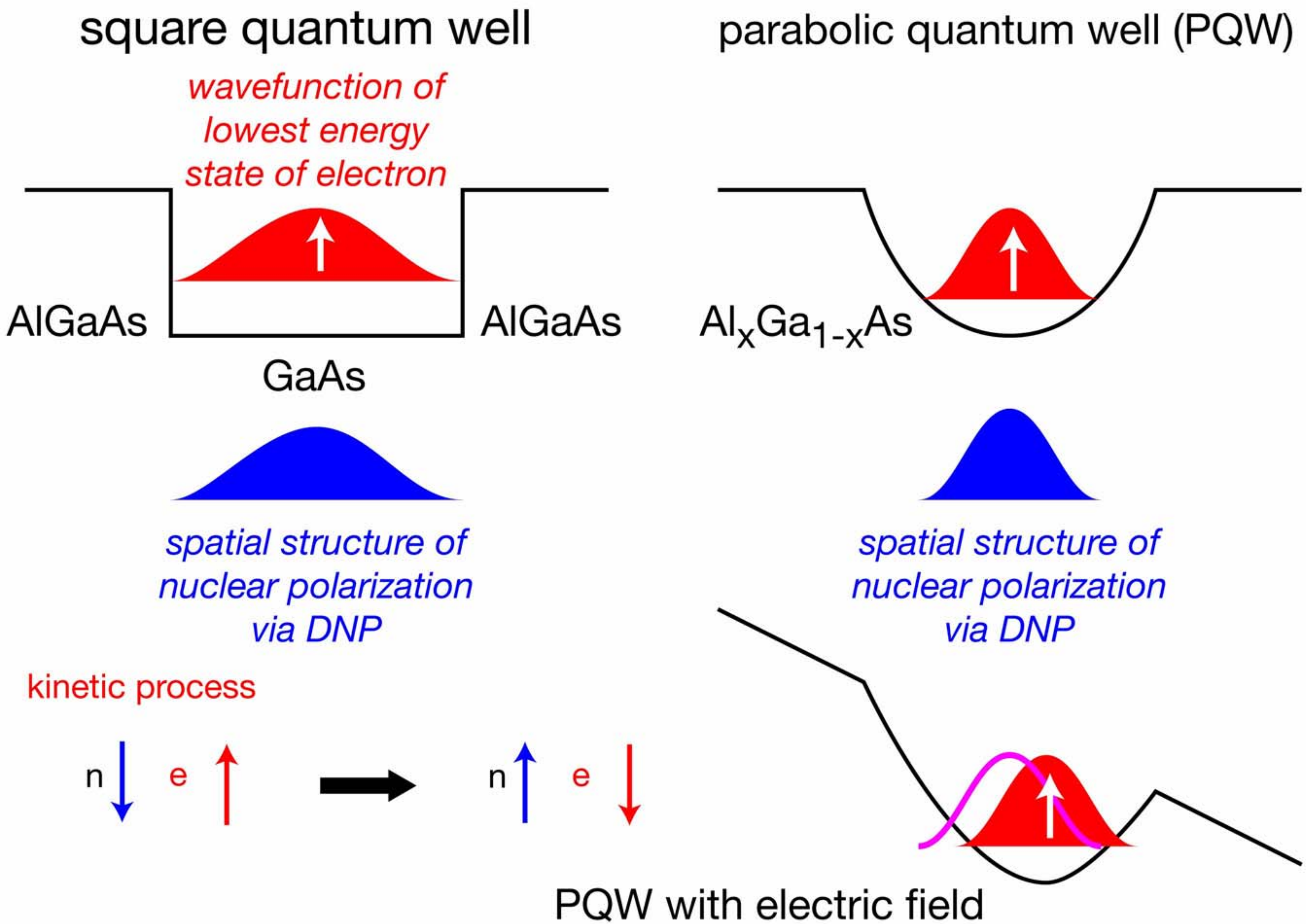




where is the extra magnetic field coming from?

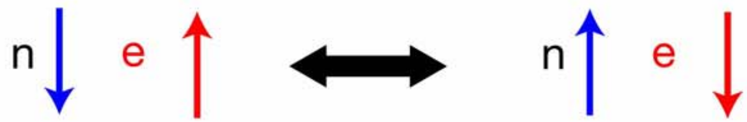
long-lived patterned polarization

Spatial structure of dynamic nuclear polarization



Spatial structure of nuclear spin relaxation

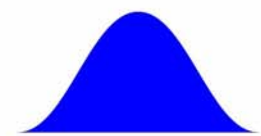
relaxation



polarize nuclei via DNP

$Al_xGa_{1-x}As$

$$T_{1n}^{-1}(\mathbf{r}_n) = \frac{512\pi^3\ \beta_e^2\ \beta_n^2\ k_B T\ \int d\varepsilon\ A^2(\mathbf{r}_n,\varepsilon)\ f'_{FD}(\varepsilon)}{3\hbar\ I(I+1)(2I+1)}$$

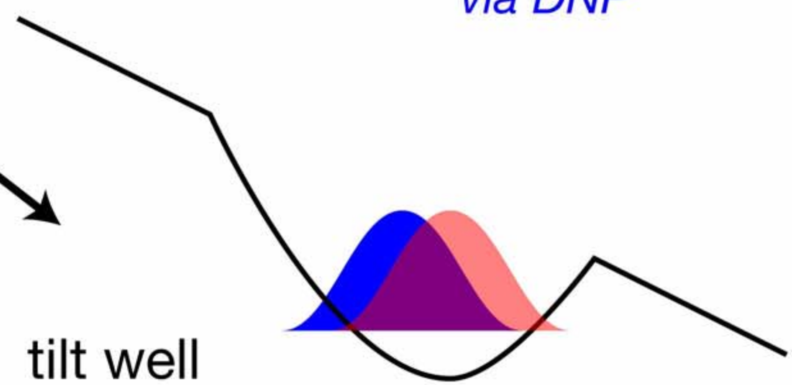


depends on the square of the
electronic local density of states

spatial structure of nuclear polarization via DNP

change electron density

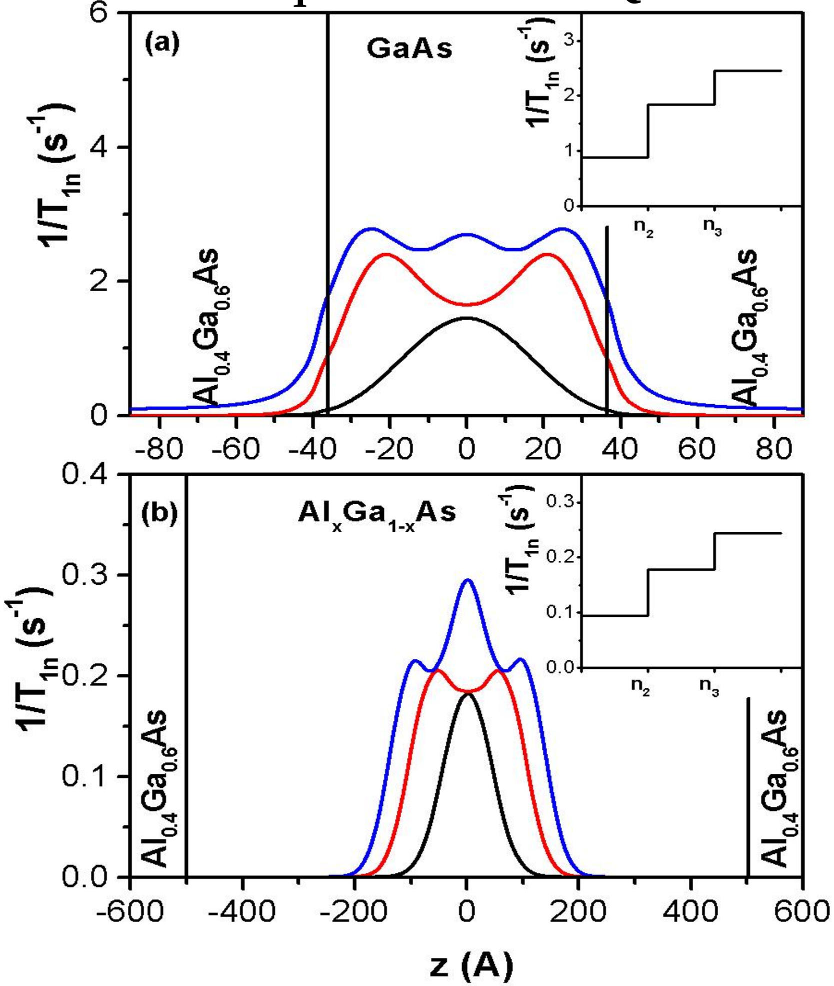
tilt well



Tuning nuclear spin dynamics with an electric field

I. Tifrea, MEF, PRL 90, 237601 (2003)

Square GaAs QW



Parabolic GaAs QW

The nuclear spin relaxation rate as function of the position in the QW for different conduction subband occupancy at T=30K

black line - single subband occupancy

red line - double subband occupancy

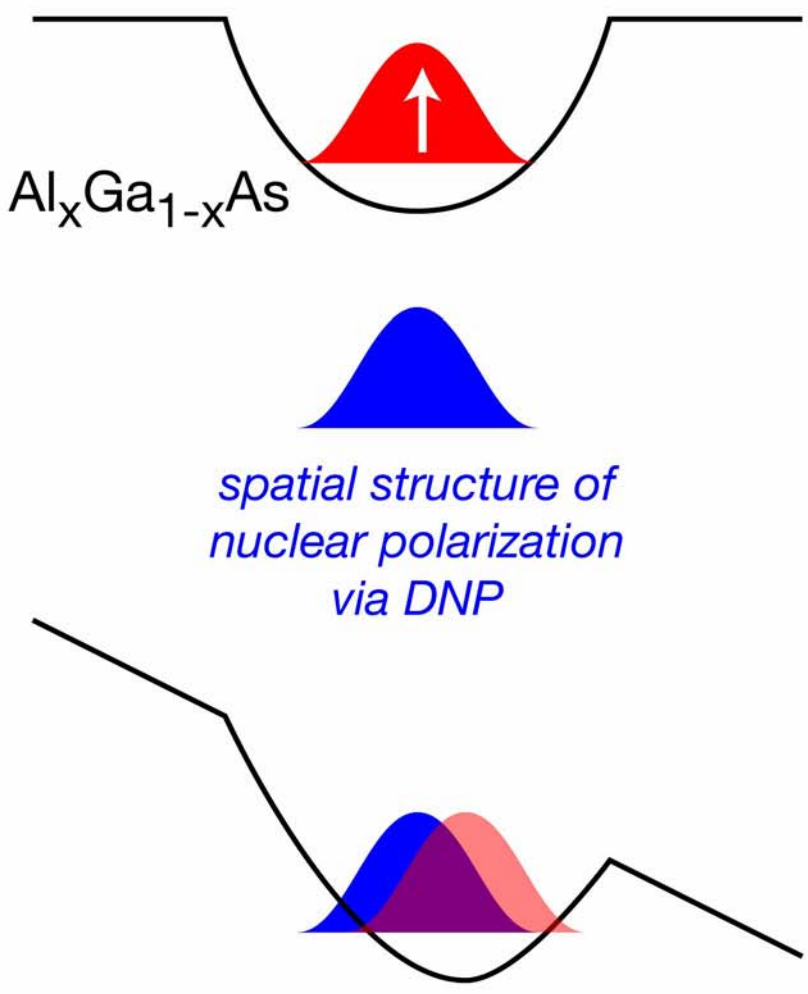
blue line-triple subband occupancy

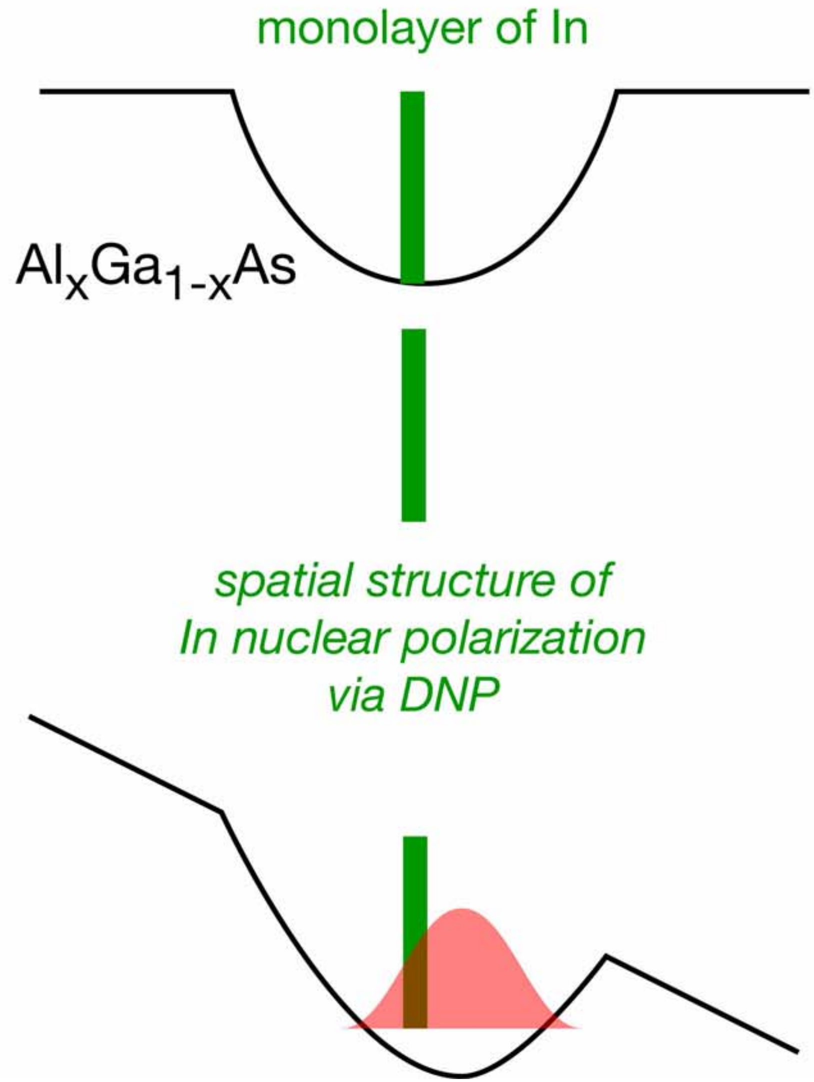
Inset: initial nuclear spin relaxation rate for different band occupancy; n_2 (n_3) represents the minimum doping level required for the occupancy of the second (third) conduction subband.

Amplifying the effect of a tilt (δ-doping)

use nucleus with different resonant frequency - like indium

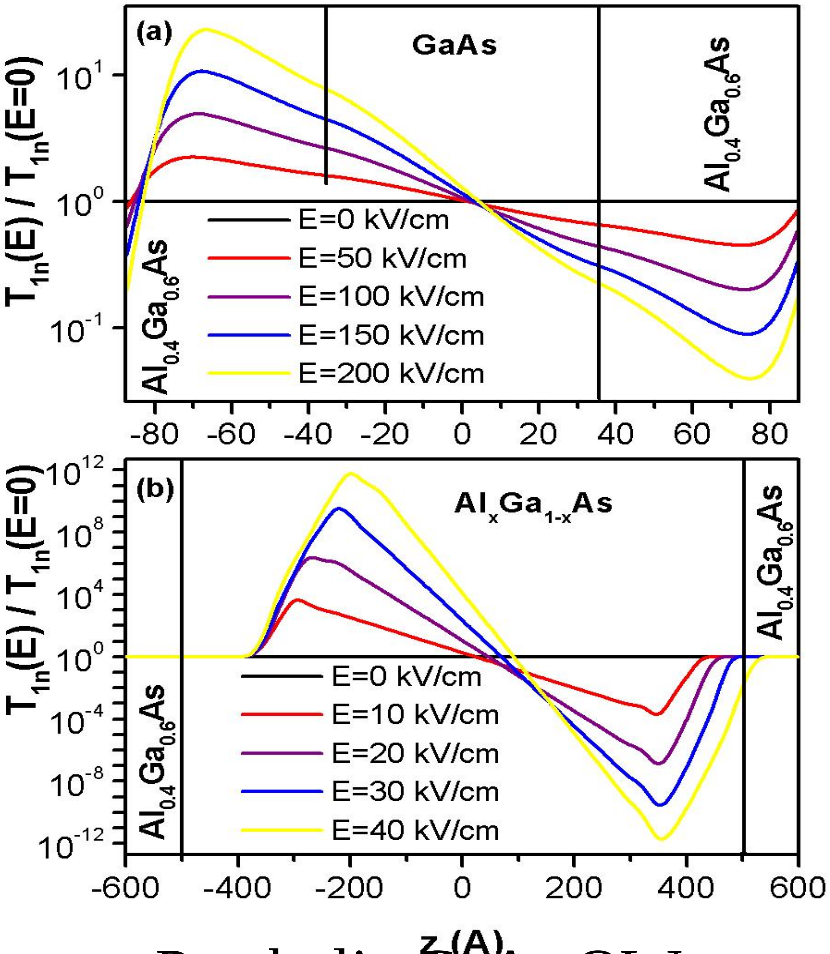
polarize nuclei via DNP





Manipulating a delta-doped layer of nuclei

Square GaAs QW

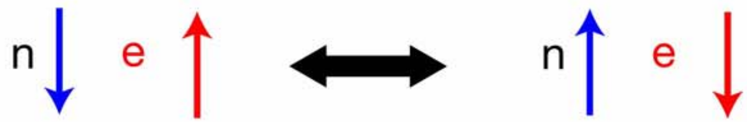


Parabolic GaAs QW

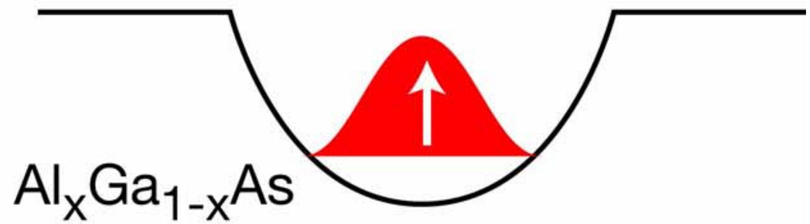
The ratio of the relaxation times in the presence and absence of the electric field as function of the position in the QW at T=30 K

Spatial structure of nuclear spin relaxation

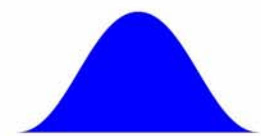
relaxation



polarize nuclei via DNP



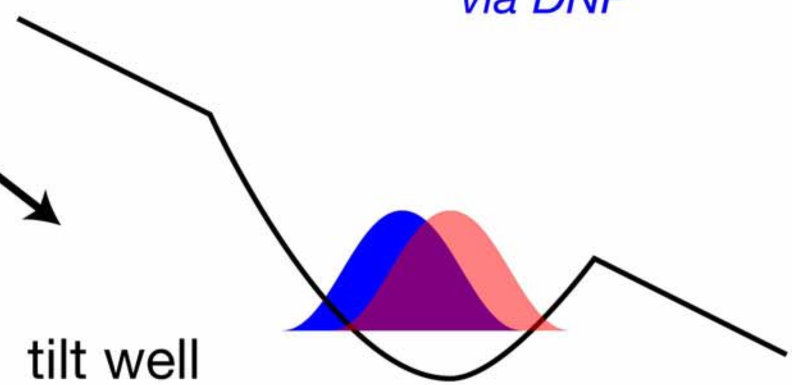
$$T_{1n}^{-1}(\mathbf{r}_n) = \frac{512\pi^3\ \beta_e^2\ \beta_n^2\ k_B T\ \int d\varepsilon\ A^2(\mathbf{r}_n,\varepsilon)\ f'_{FD}(\varepsilon)}{3\hbar\ I(I+1)(2I+1)}$$



depends on the square of the
electronic local density of states

spatial structure of nuclear polarization via DNP

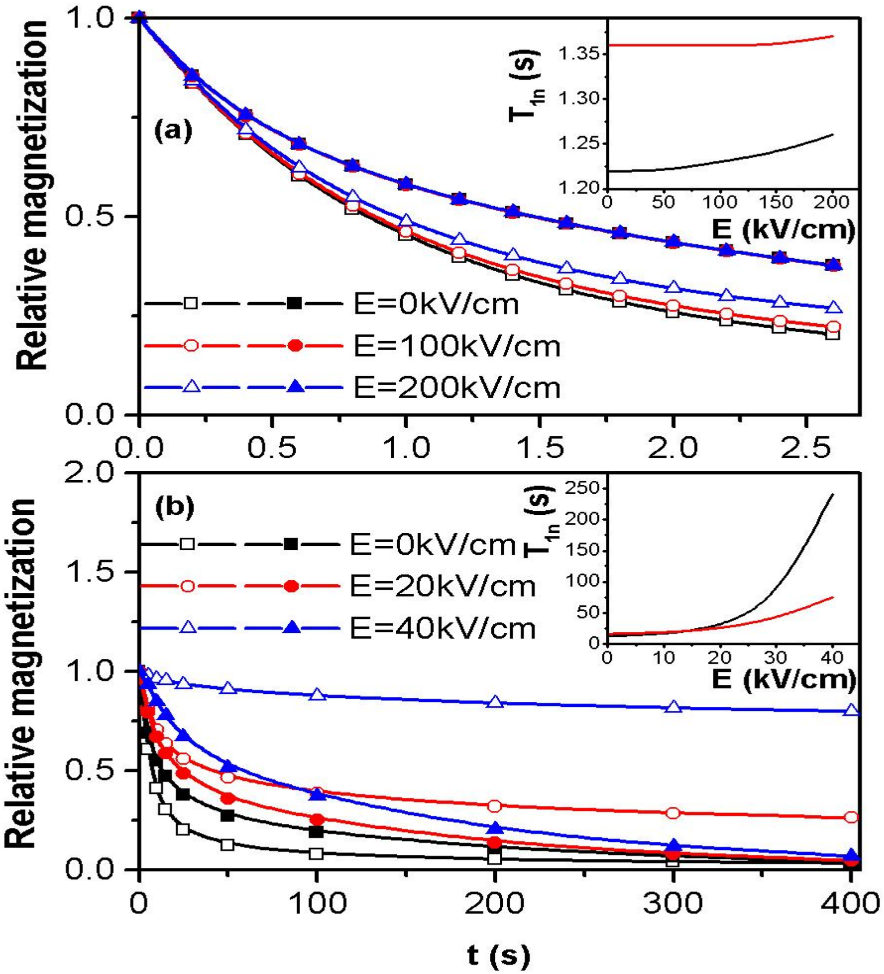
change electron density



tilt well

Manipulating uniformly distributed nuclei

Square GaAs QW



Parabolic GaAs QW

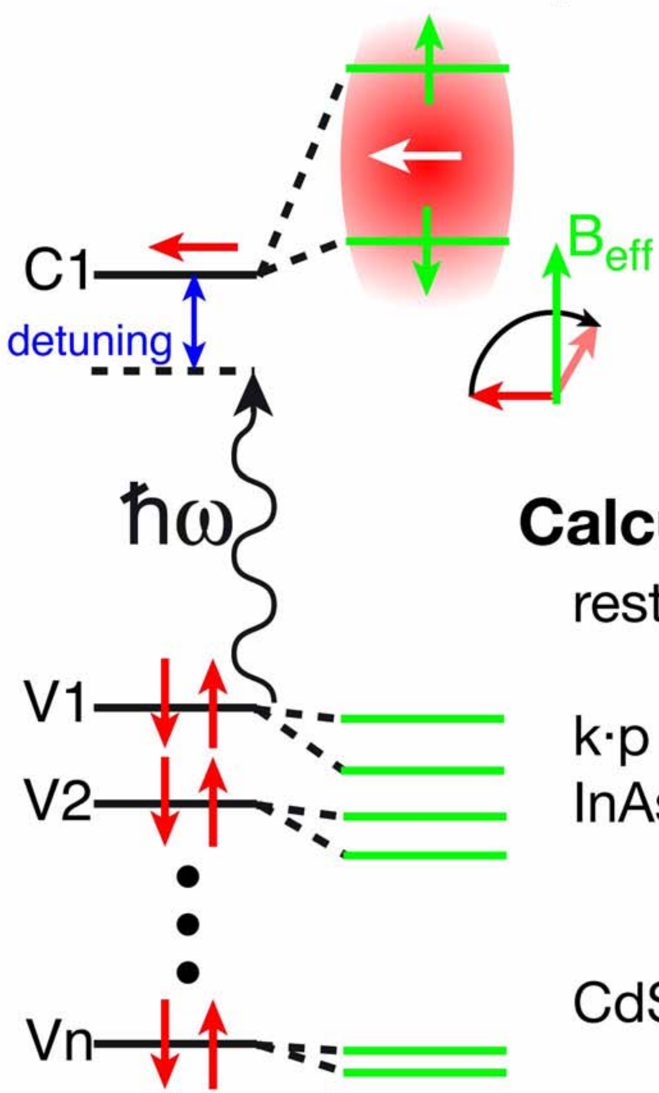
The total relative nuclear magnetization as function of time for different values of the applied electric field at T=30 K in the presence (full symbols) and absence (open symbols) of diffusion.

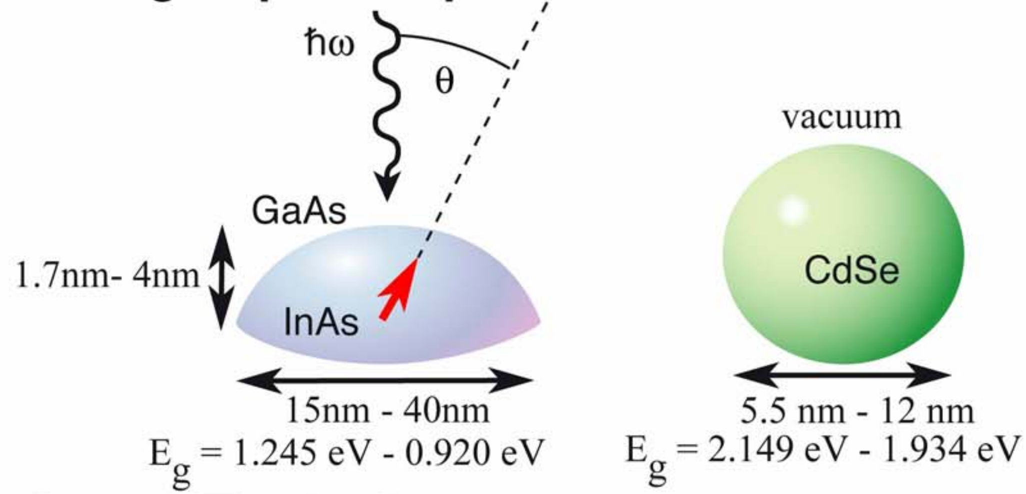
Inset: total nuclear spin relaxation time as function of the electric field

Spin Optical Stark Effect in Quantum Dots

Presence of virtual excitons creates a spin splitting which behaves as an effective magnetic field

ultrafast manipulation of single spins in quantum dots





Calculational Technique

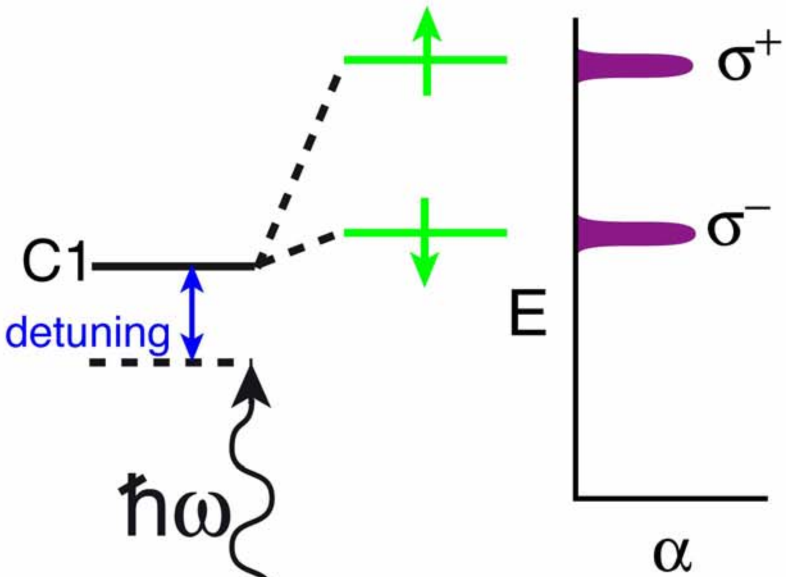
restricted basis of dot states solved non-perturbatively in strong light field

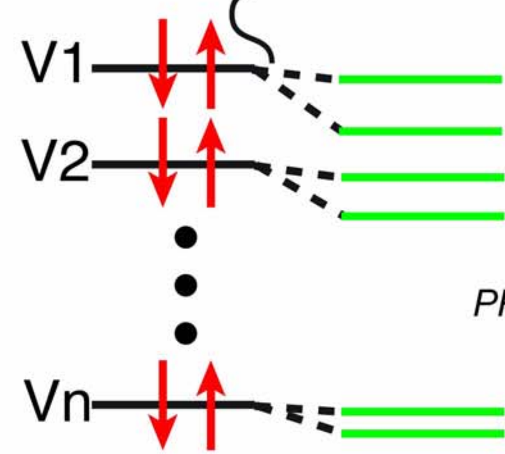
k·p Hamiltonian, envelope functions

InAs SAQD: minimize strain energy (continuum elasticity) 8-band model

CdSe CQD: (one-band) conduction and (four-band) valence models unstrained

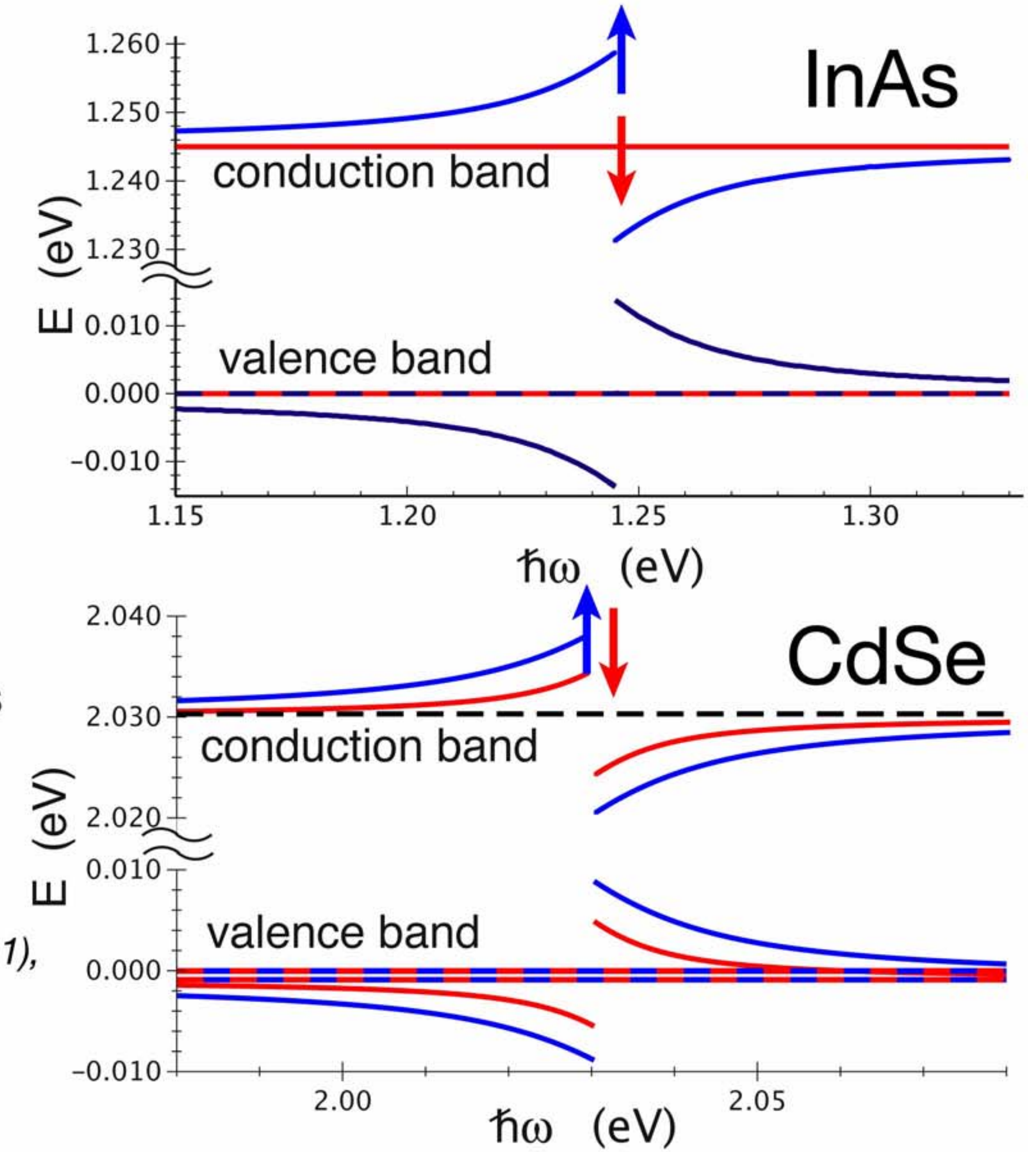
Detuning Dependence of Stark Shift



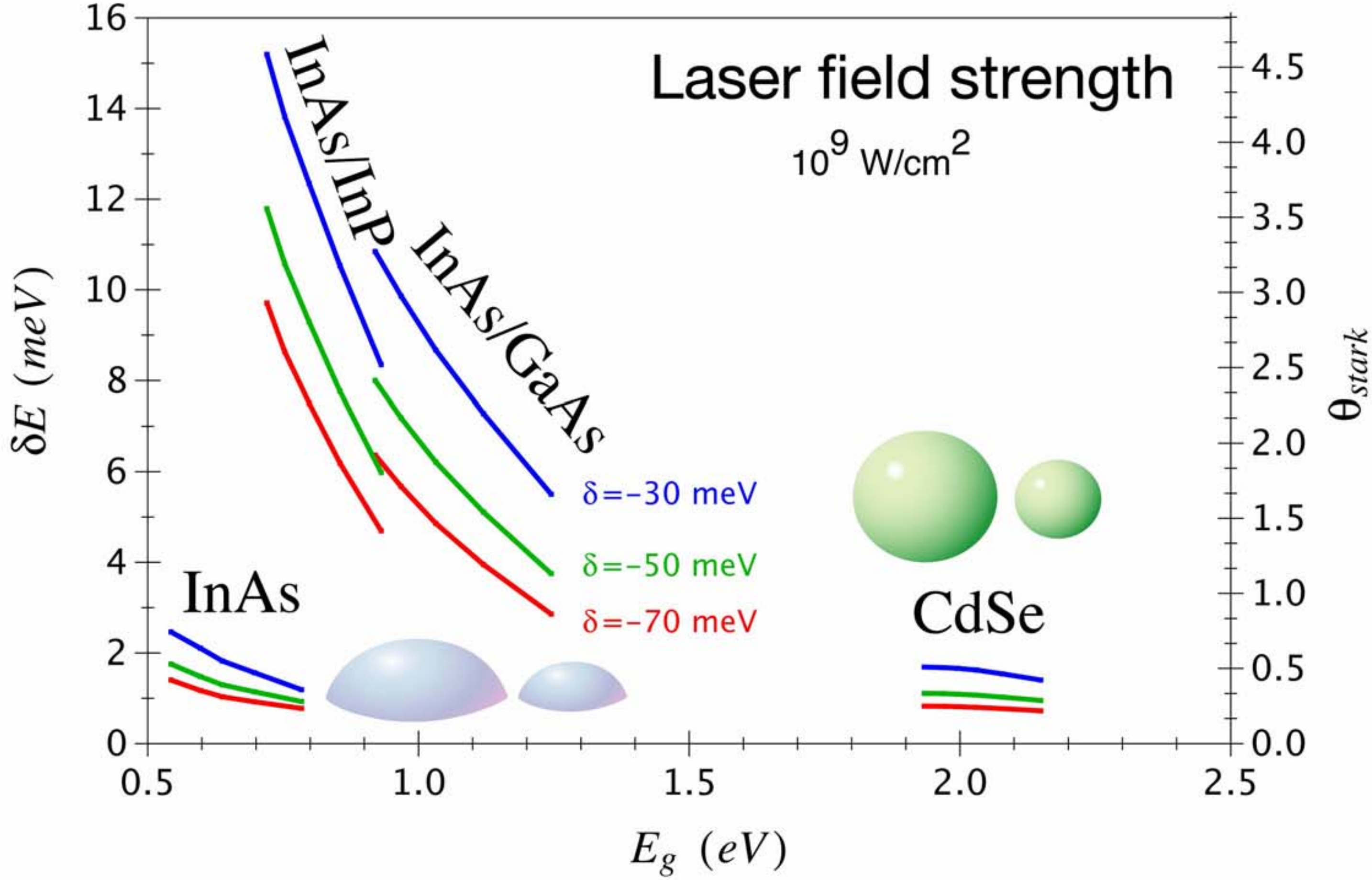


Splitting shows in optical absorption

J. A. Gupta and D. D. Awschalom, PRB 63, 085303 (2001), dot-doped glass

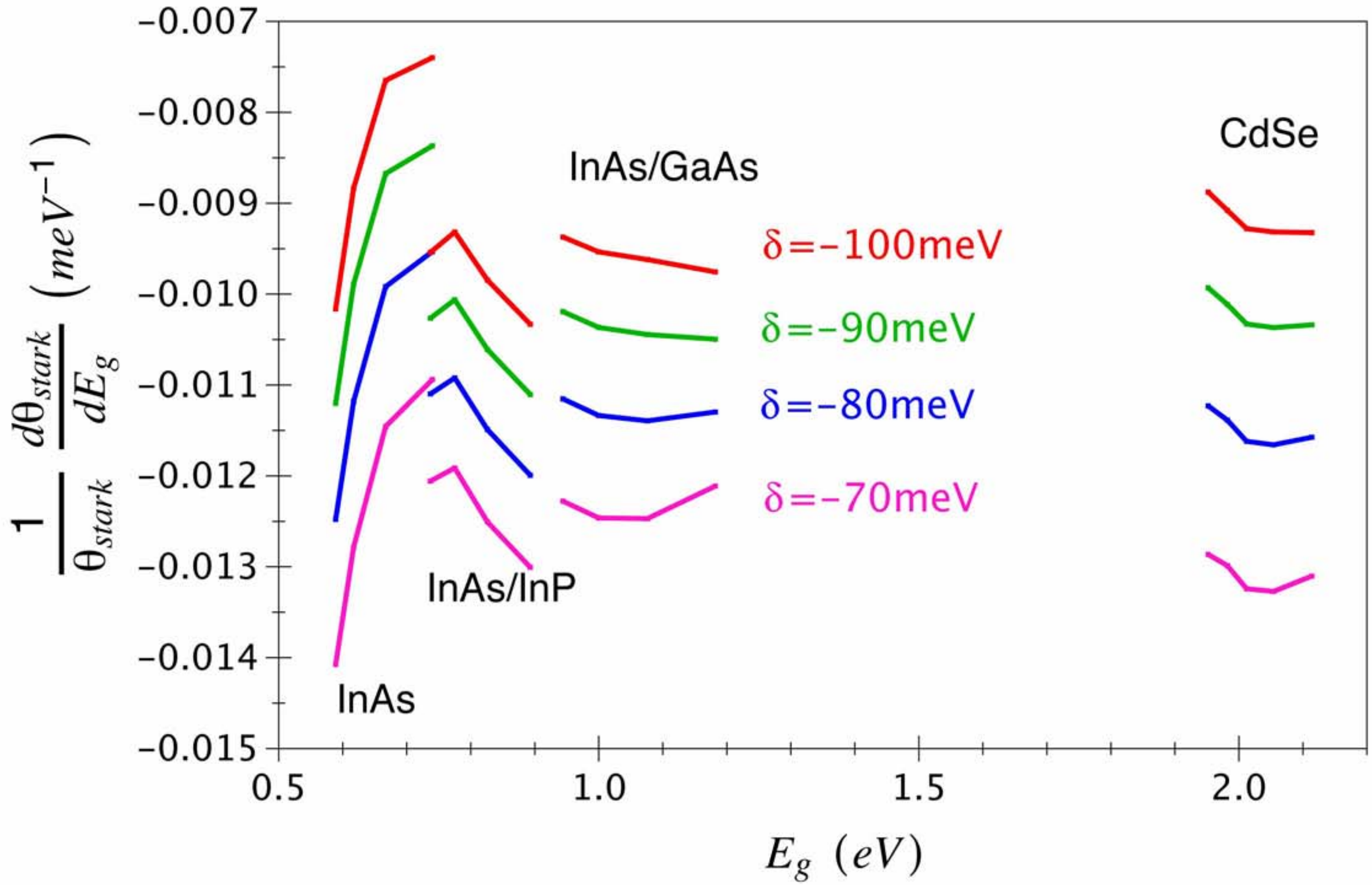


Optically-Induced Spin Splitting in Quantum Dots



Complete spin flip possible in 200 femtoseconds

Errors in single qubit operations using dots



Error for single qubit operation in InAs/InP dot with 0.1meV linewidth is 10^{-6}

Spin Fidelity from a Quantum Dot

cond-mat/0305304

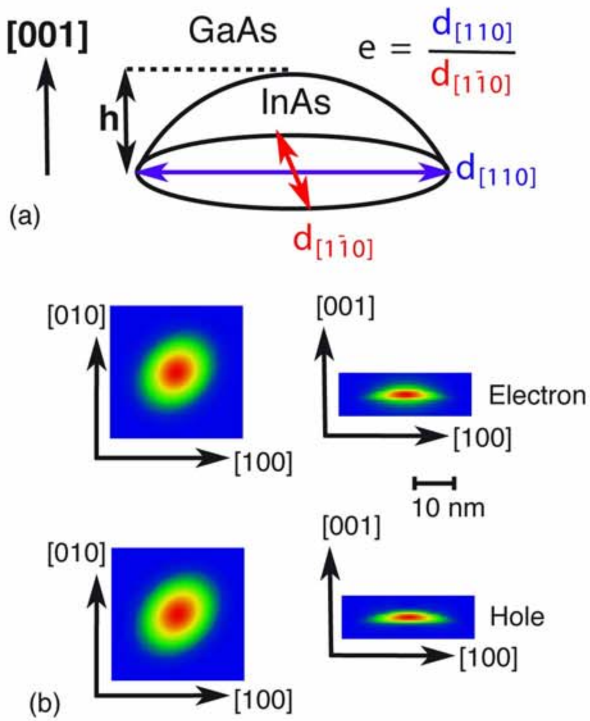


FIG. 1: (a)The quantum dot geometry. (b) Electron and hole wave functions for a dot with $e = 1.4$ and $h = 2.8\,\mathrm{nm}$

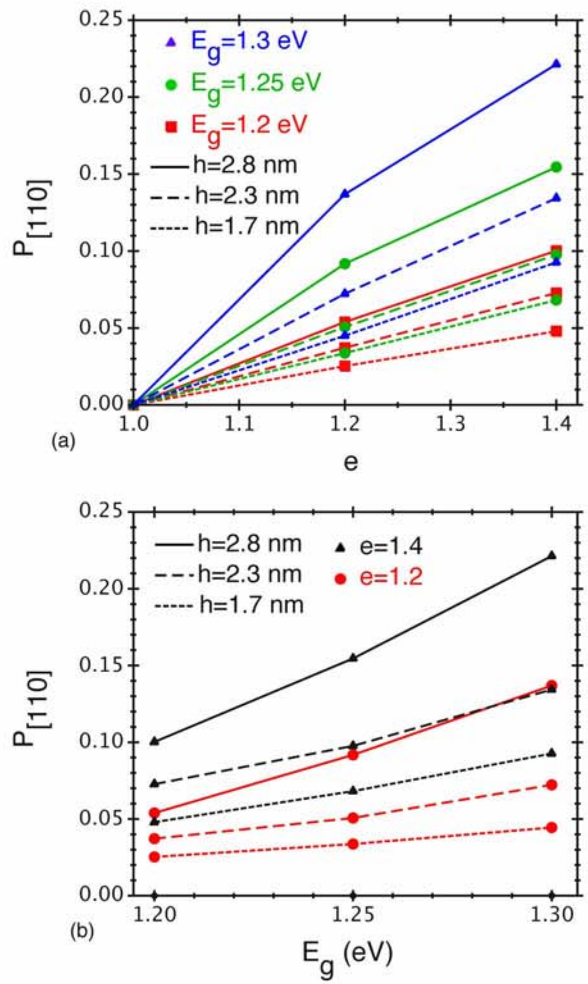
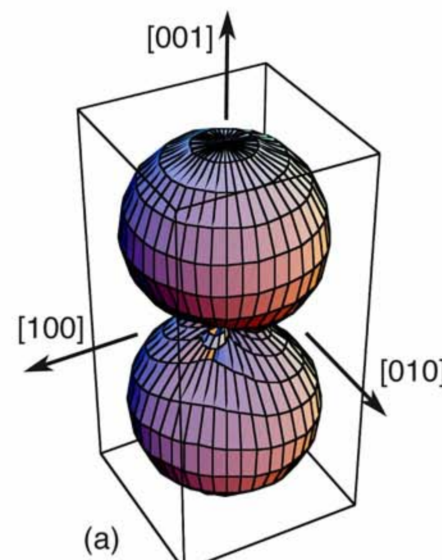


FIG. 2: (a) Polarization along [110], as a function of elongation. (b) Polarization along [110], as a function of bandgap.



Materials Issues are Essential for QI

Spin coherence times

influenced by inversion asymmetry of the material

(110) growth has promise:

control of spin coherence times with gates

Integration of magnetic and semiconducting materials

coherent transport between magnetic and nonmagnetic materials

- new spin detection and amplification methods

Control of nuclear properties in semiconductor structures

spatially-selective nuclear magnetic resonance

manipulation of nuclear pseudomagnetic fields

Spin manipulation and detection in quantum dots

importance of dot shape for selection rules for AC Stark effect and photoluminescence

IOWA

Spin coherence times in nanoscale geometries

Ferromagnetic Semiconductors

Inhomogeneous Spin transport

Optical manipulation Of nuclear spin

Spin manipulation In quantum dots

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