OPTICAL AND ELECTRICAL SPIN INJECTION IN SEMICONDUCTOR QUANTUM DOTS

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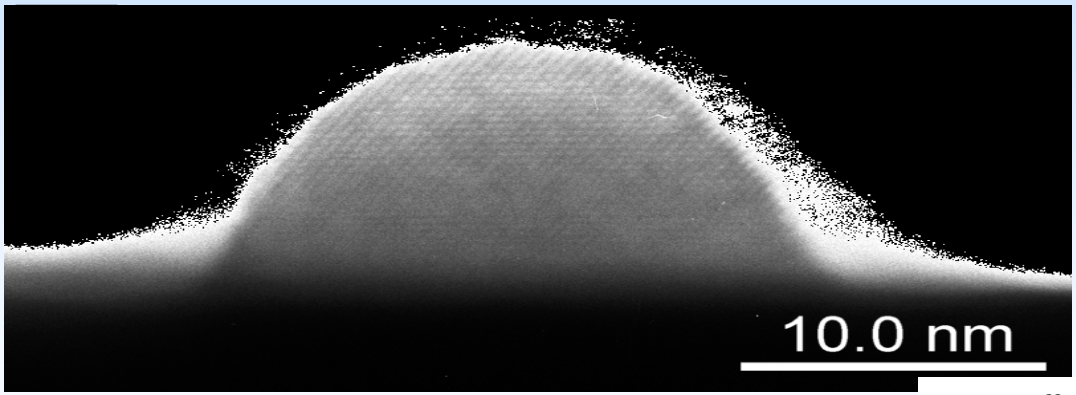
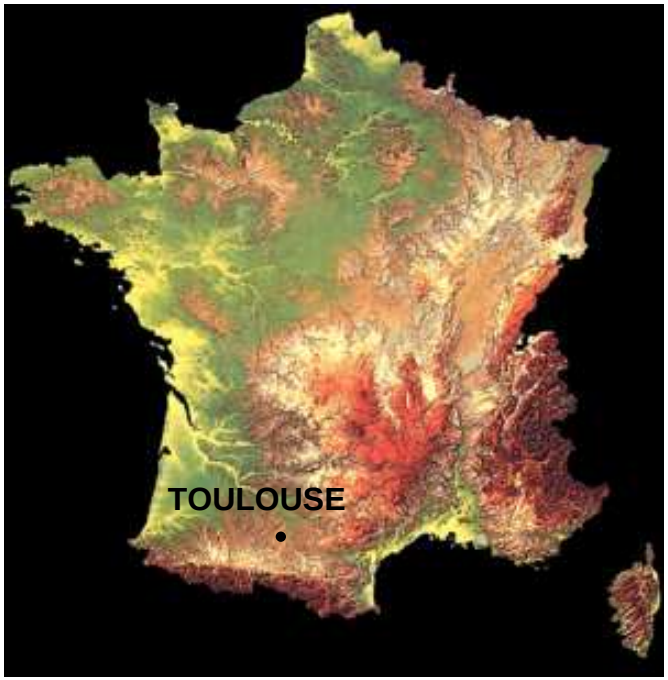
University of Toulouse, France



@ Mc Caffey

* *Institut Universitaire de France*

NanoSpain, March 2009



Toulouse city

Introduction...

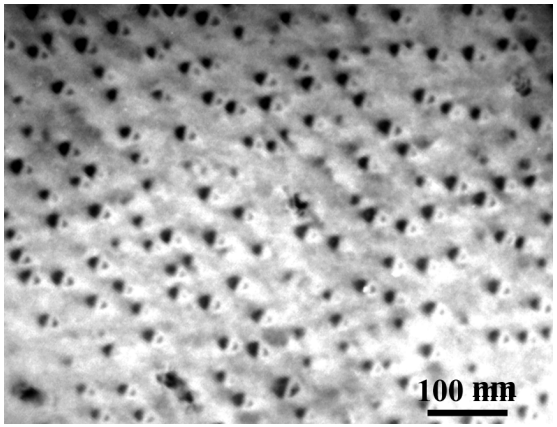
- **Growing interest in the manipulation of carrier spins in semiconductor**

Spin Transistor, Spin-LED, Spin-VCSEL ,

Single electron spin memories, Entangled photon pair sources

Spin-based quantum gates (C-NOT, Spin rotation)...

Control the spin coherence



Semiconductor Quantum Dots (QD) : good candidates ?

- **Spin dynamics in QDs :**

Spin relaxation mechanisms in zero-dimensional structures ?

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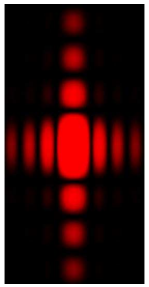
Introduction...



Optics ⟷ **Spin**

- **Efficient way to spin-polarize the carriers in semiconductors**
- **Efficient probe (luminescence, transmission…) of the spin properties**

❖ Optical injection of polarised electrons in semiconductors

❖ Electrical injection / Optical detection in Spin-LED, Spin-Laser

❖ Spin dynamics in individual nano-objects (quantum dots)…

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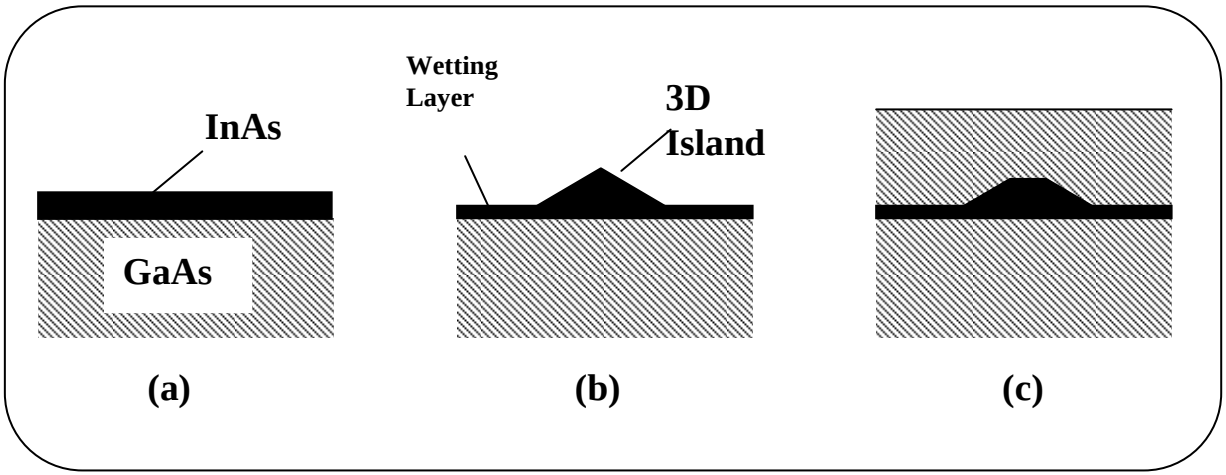
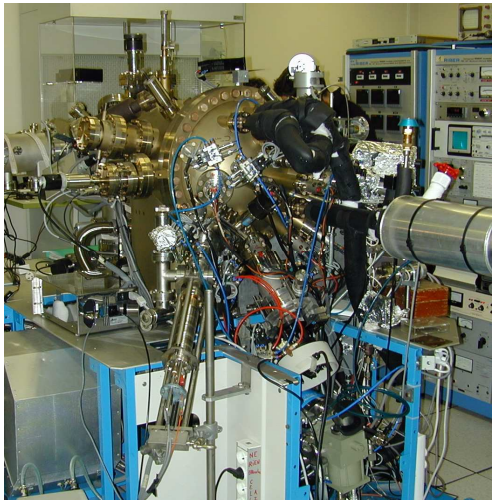
SELF-ORGANIZED InAs/GaAs QUANTUM DOTS

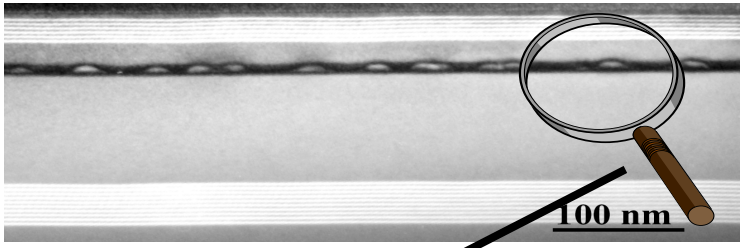
Stransky-Krastanov growth

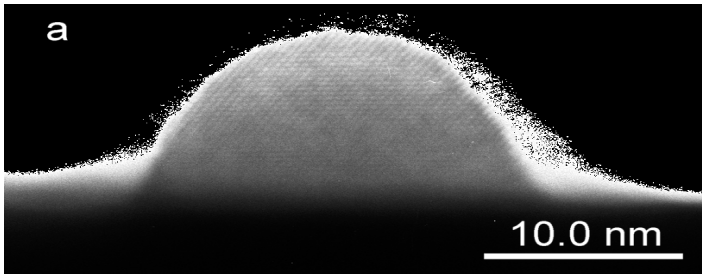
Lattice mismatch InAs/GaAs : ~7 %

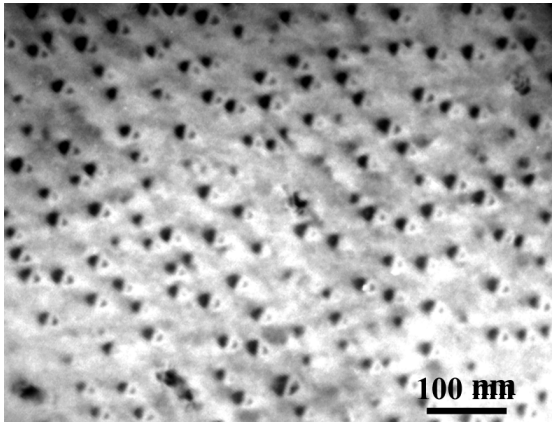




MBE







TEM Images (Y. Musikhin, IOFFE Institute)

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Outline…

- *Self-organized Quantum Dots (QDs)*

- ***Optical Spin Injection and Manipulation***
  - *Optical Orientation experiments*
  - *Spin Relaxation Dynamics in InAs/GaAs QDs*
  - *Spin Manipulation in GaN/AlN QDs*

- ***Electrical Spin Injection***
  - *Spin-LED*
  - *Spin-Laser*

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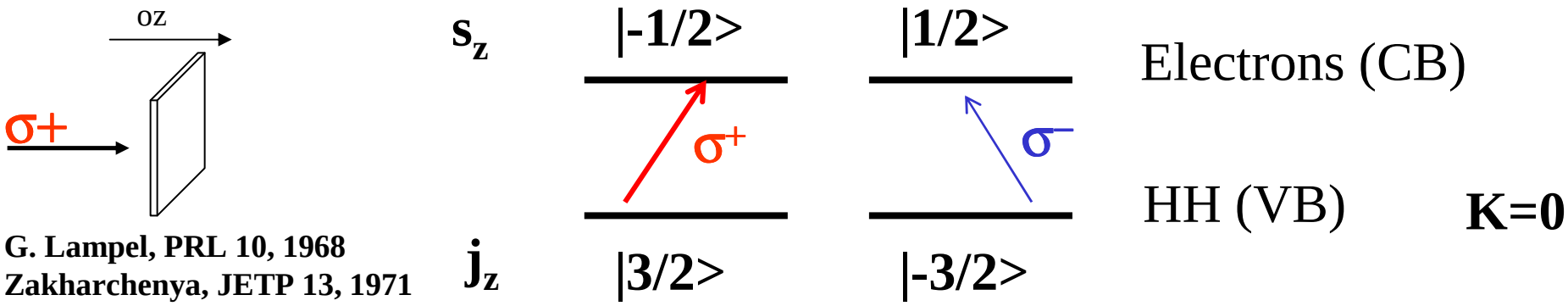
OPTICAL ORIENTATION



G. Lampel, PRL 10, 1968
Zakharchenya, JETP 13, 1971

For a review, see

- *Optical Orientation*, ed. Meier and Zakharchenya (1984)

- *Spin Physics in Semiconductors*, ed. D'Yakonov, Springer (2008)

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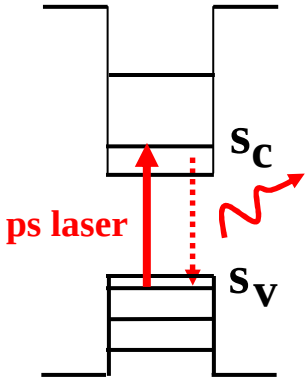
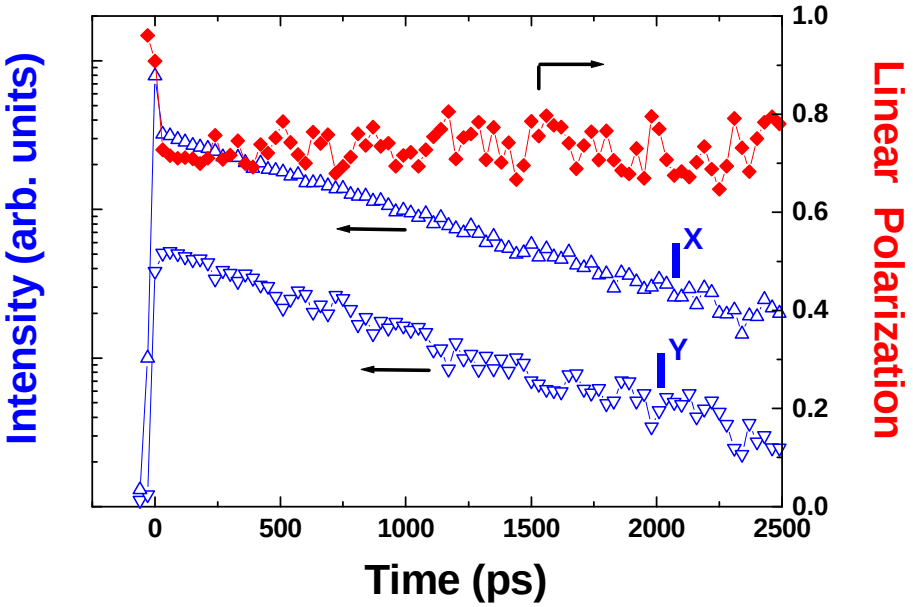
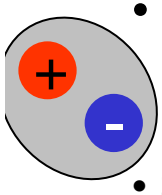
Resonant excitation of the neutral exciton X^0 (linearly-polarised excitation)



Excitation σ^X

T=10 K





- **Photogeneration of linear excitons :**

$$|X\rangle = \left(|3/2,\downarrow\rangle + |\overline{3}/2,\uparrow\rangle\right)/\sqrt{2}$$

- **Strong linear polarization**

$$P_L = \frac{I^X - I^Y}{I^X + I^Y} \cong 0.75$$

→ **No measurable decay ! : τ_s> 20 ns**
Neither the electron, nor the hole spin relax on the exciton time scale

Paillard *et al*,, **PRL 86, 1634 (2001) ;** Cortez *et al*, **PRL. 89, 207401(2002) ;** Laurent *et al*, **PRL 94, 147401 (2005);**
Braun *et al*, **PRL 94, 116601 (2005) ; Nature, Research Highlights, Vol. 434, 839 (2005)** **Toulouse-Paris**

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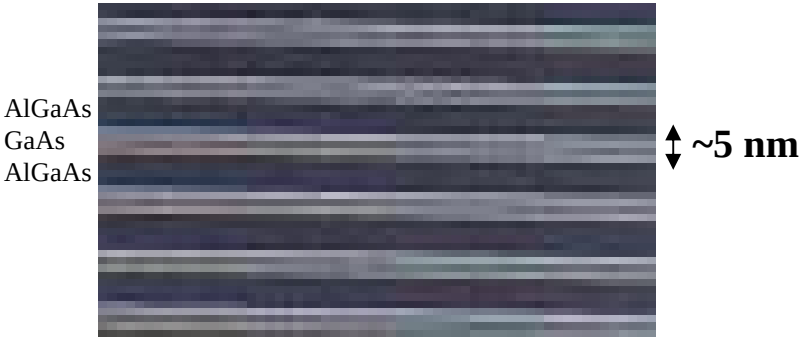
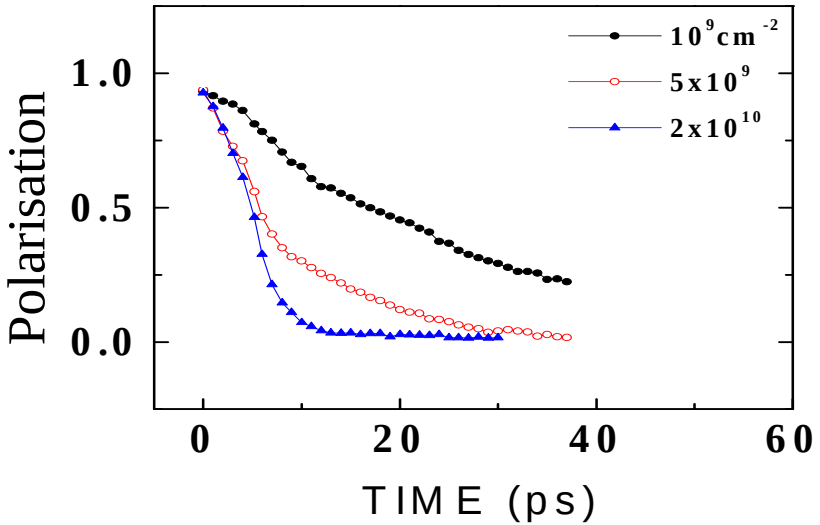
Exciton Spin Relaxation in Quantum Wells GaAs/AlGaAs



Resonant Excitation :



T_{s2}~ 20 -50 ps

- *Worsley et al., PRL 76 (1996)*
- *Marie et al., PRL 79 (1997) …*

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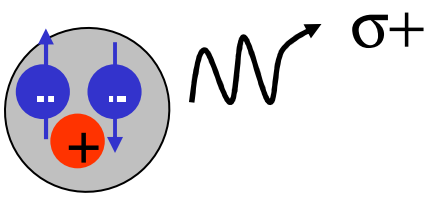
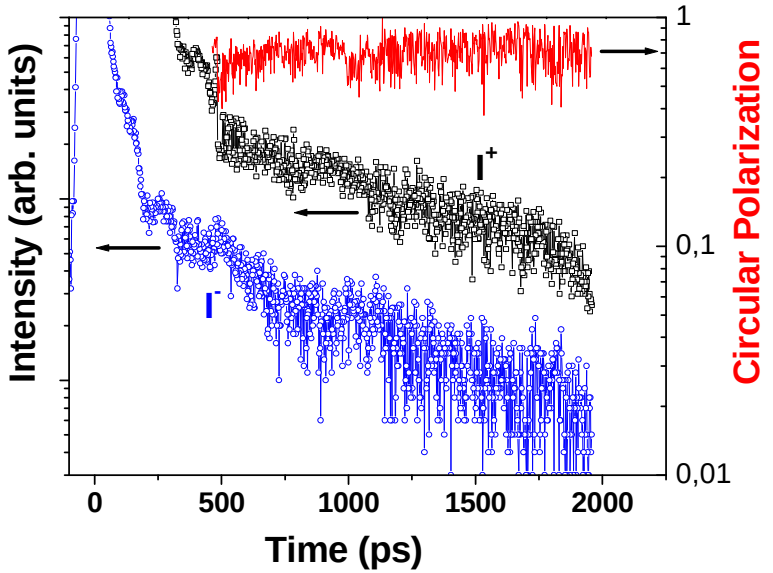
Resonant excitation of negatively charged exciton (X-)

~ 1 doping electron/QD



Negatively Charged exciton X^-



Hole spin stability : τ_s>~ 20 ns !

InAs/GaAs QDs : Toulouse - Paris

Ensemble : ICPS (2002) ; PRL **in press** (2009) : **~ *μs* !**

Single dot : PRL **94,** (2005)

CdSe/ZnSe QDs : τ_s >18 ns
PRB **68** (2003), Berlin

Note : Hole spin relaxation in bulk : < 1 ps

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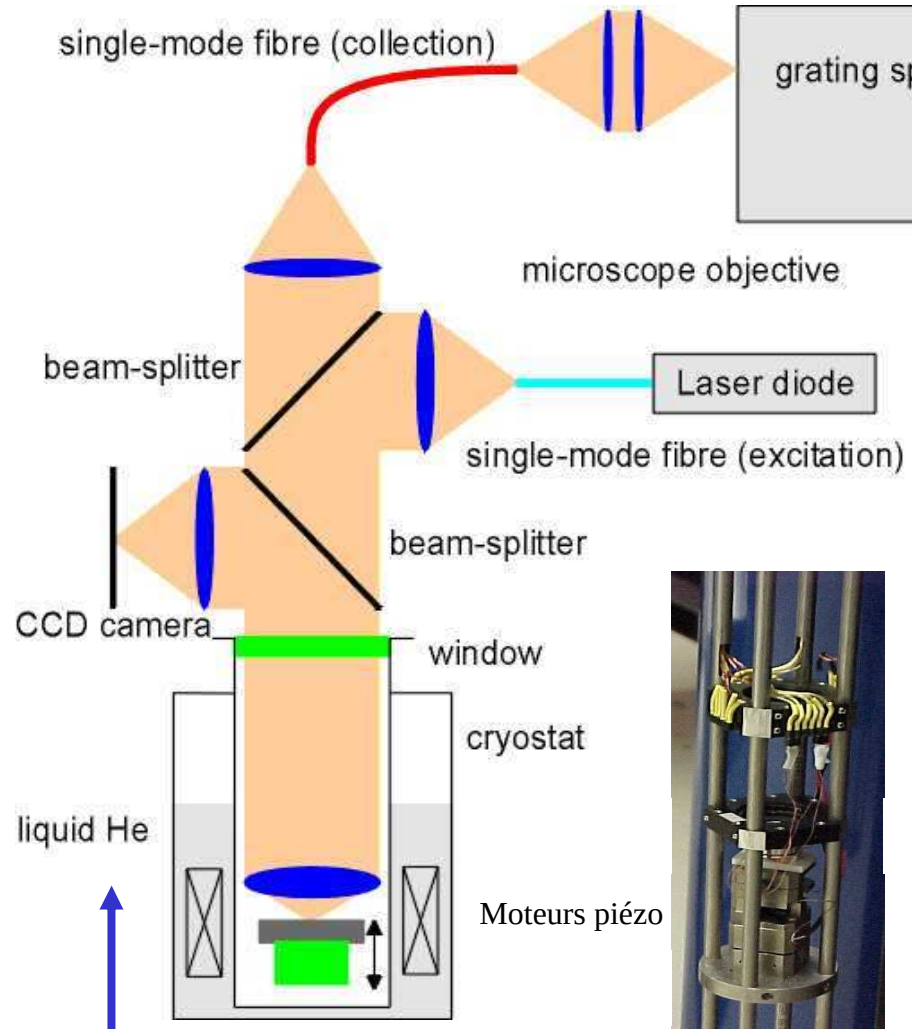
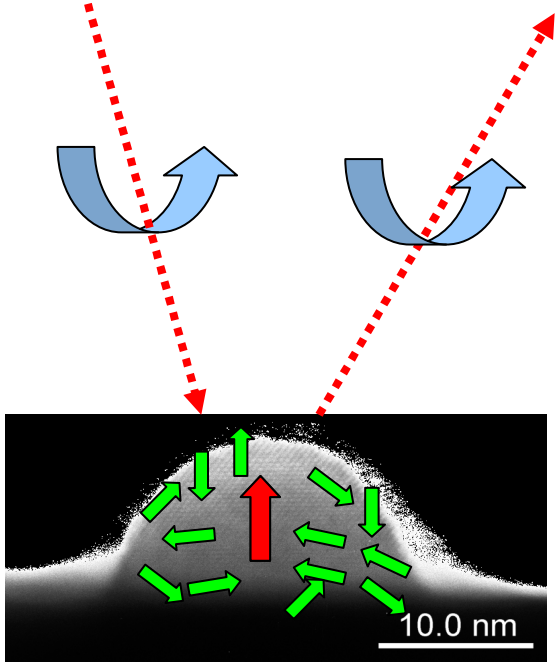
Single Dot Optical Spectroscopy

Confocal Microscope



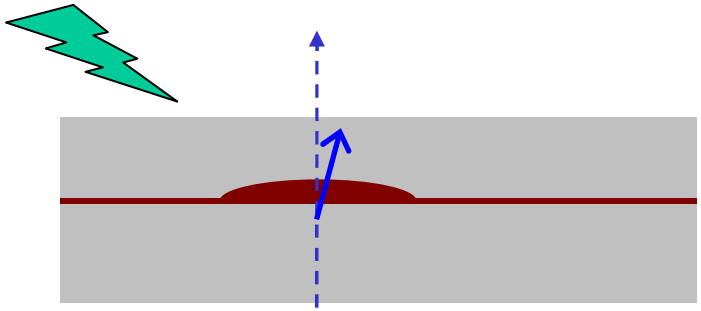
LASER

Detection:
- *photon energy*
- *polarization*



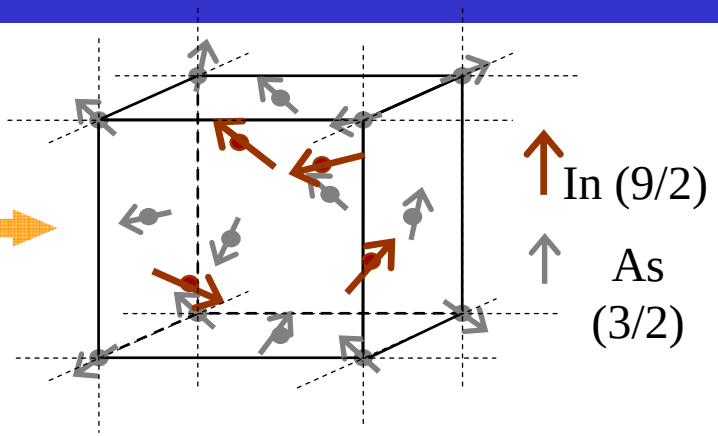
Bz

Optical pumping of nuclear spins…



1 conduction electron

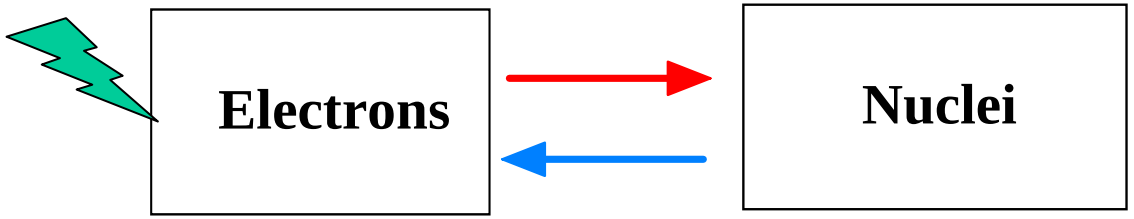
$\hat{H}_{hf}$



Sublattice of *N* nuclei with spin $\hat{I}^j$

$$\hat{H}_{hf} = \frac{\nu_0}{2} \sum_j A^j |\psi(\vec{r}_j)|^2 \left(2\hat{I}_z^j \hat{S}_z^e + [\hat{I}_+^j \hat{S}_-^e + \hat{I}_-^j \hat{S}_+^e] \right)$$

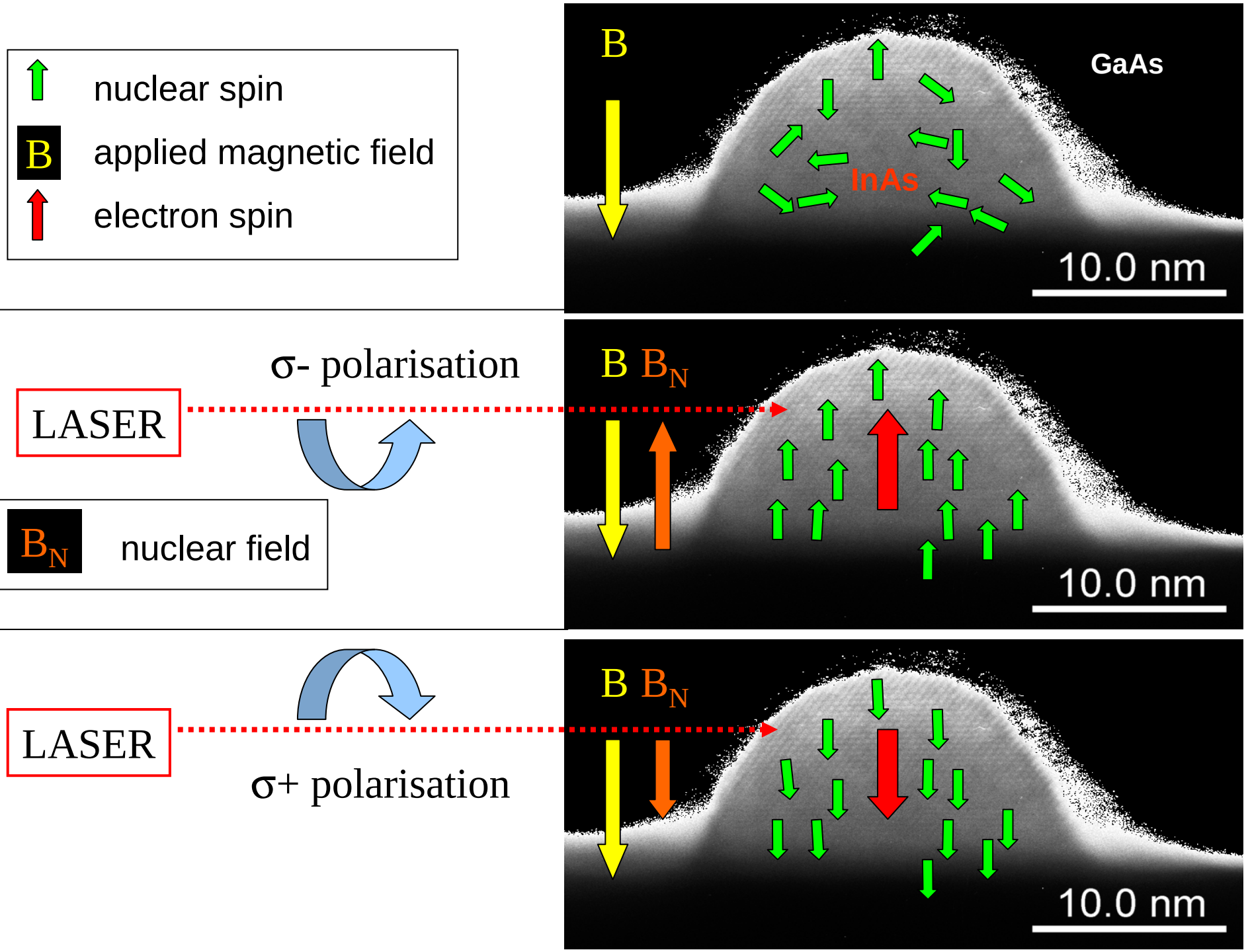
electron-nuclei "flip-flop"



$$|\uparrow^e\rangle \otimes |\, I_z\rangle \Leftrightarrow |\downarrow^e\rangle \otimes |\, I_z + 1\rangle$$

Transfer of angular momentum to the nuclear spins

For a review : Abragam, 1961 ; Dyakonov *et al.*, JETP **38,** 177 (1974) ; Paget *et al.*, PRB **15**, 5780 (1977); PRB**24**, 3776 (1981)

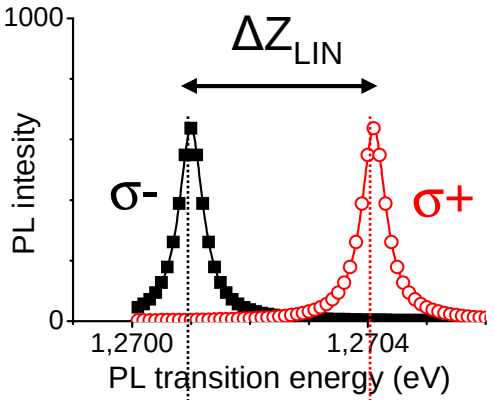

nuclear spin
B
applied magnetic field
electron spin
B
GaAs
InAs
10.0 nm
σ- polarisation
LASER
B B$_N$
10.0 nm
B$_N$
nuclear field
LASER
σ+ polarisation
B B$_N$
10.0 nm

Measuring the nuclear polarisation

Zeeman splitting ΔZ at B_{ext}=2T

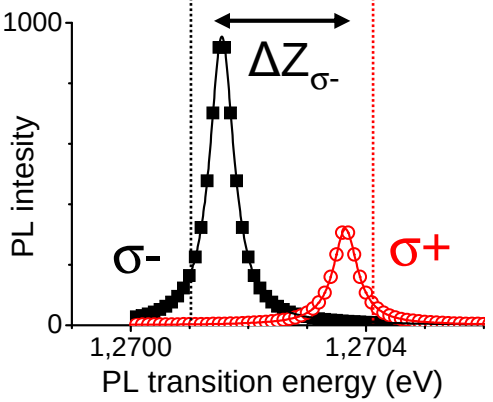
linearly polarized
Laser excitation

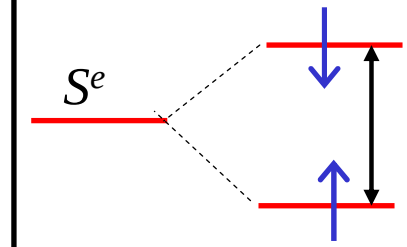
no nuclear polarization



σ- polarized
Laser excitation

strong nuclear polarization up to 50%

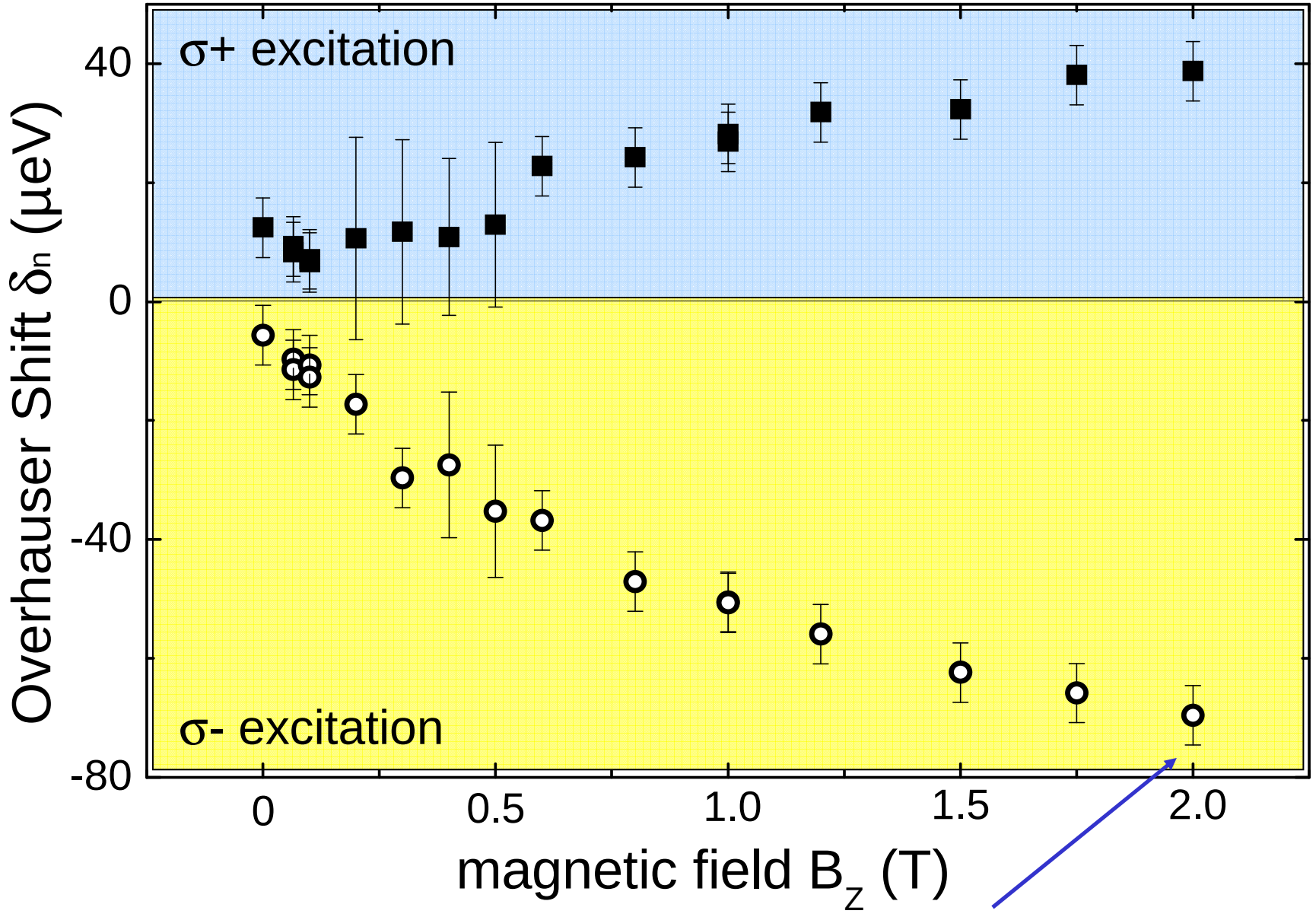




Overhauser shift : $\delta_n = \Delta Z_{\sigma-} - \Delta Z_{LIN}$

→ The Overhauser shift is related to the average nuclear spin : $\delta_n = 2\tilde{A}\langle \hat{I}_z \rangle$

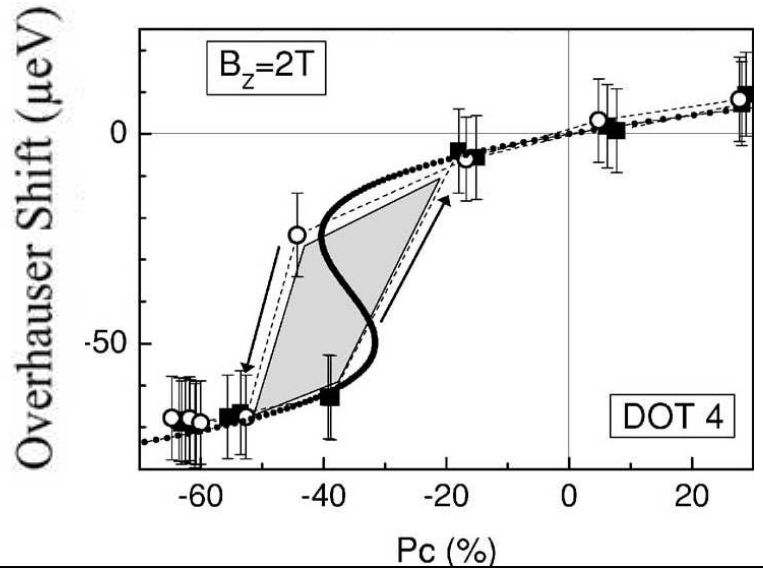
Magnetic field dependence I



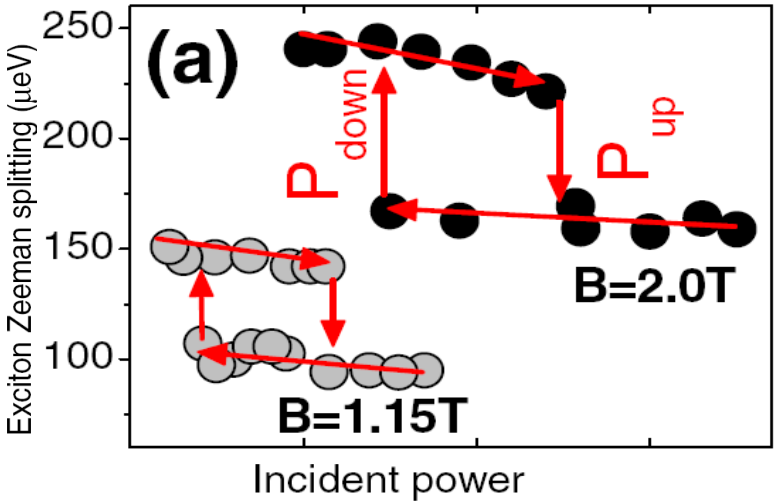
~50% nuclear polarisation

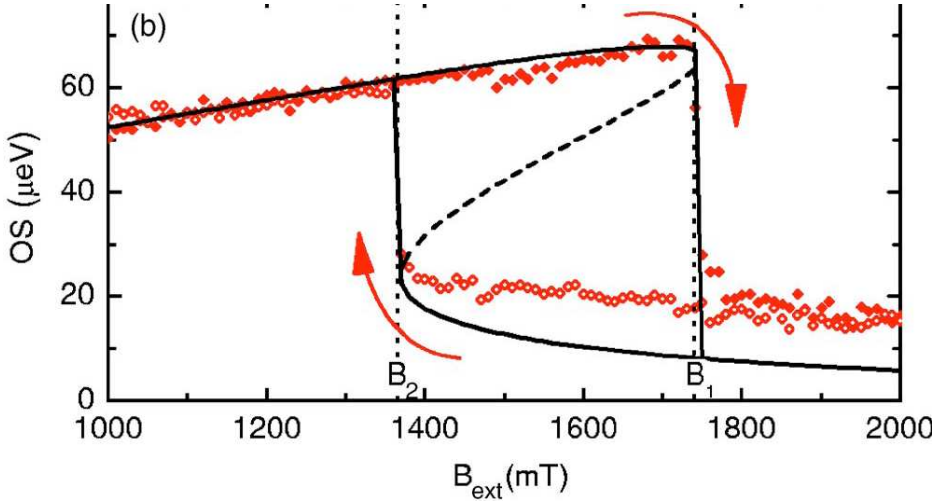
Bistability of the nuclear polarisation in a single InAs quantum dot

Toulouse-Marcoussis: PRB 74, 245306 (2006)
PRB 76 (R), 201301(2007)

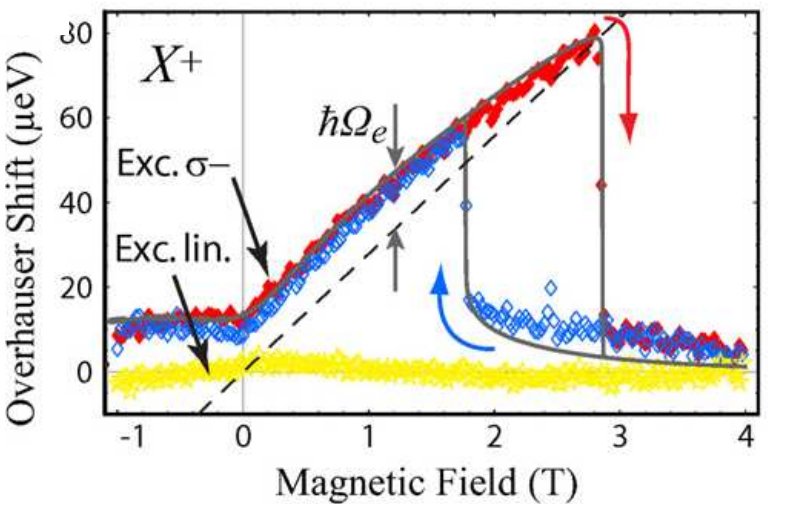


Sheffield : PRL 98, 26806 (2007)

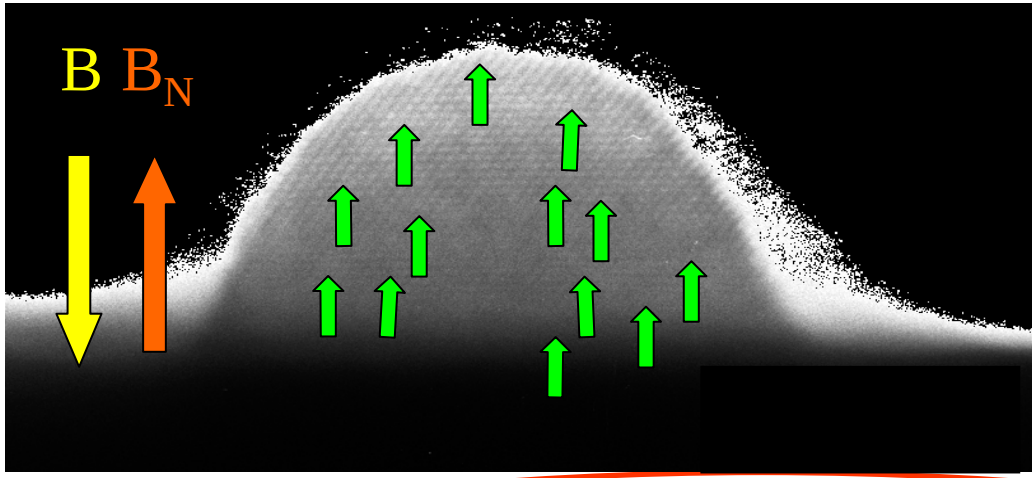




ETH Zurich : PRB 75, 035409 (2007)



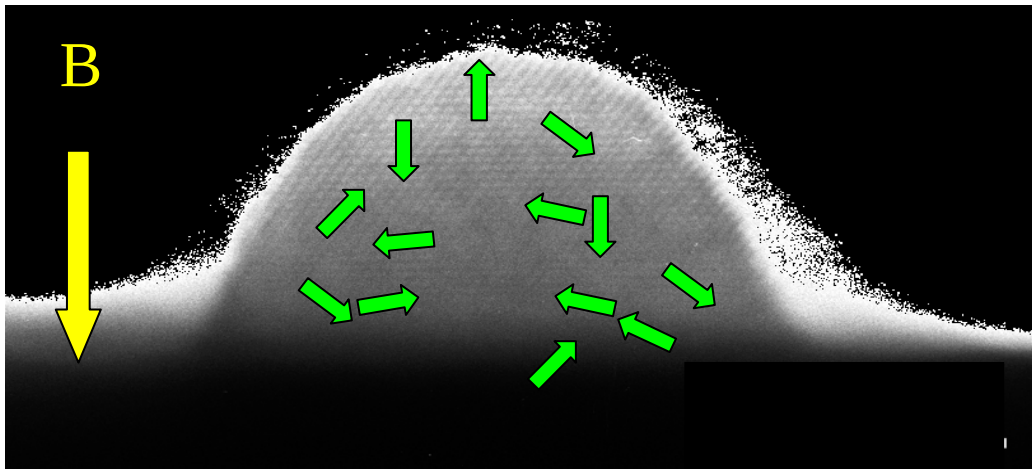
Marcoussis-Toulouse : C.R. Physique 9, (2008)



Bistability:

switching the nuclear polarisation of a single quantum dot ON and OFF

through a slight variation of an external parameter



Outline…

- *Self-organized Quantum Dots*

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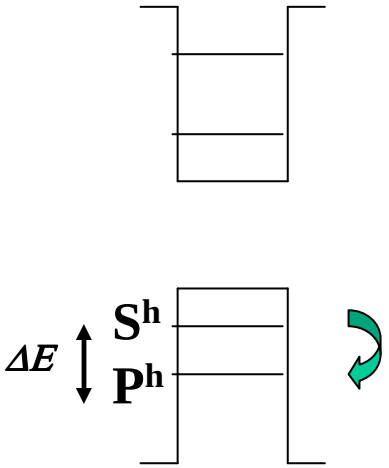
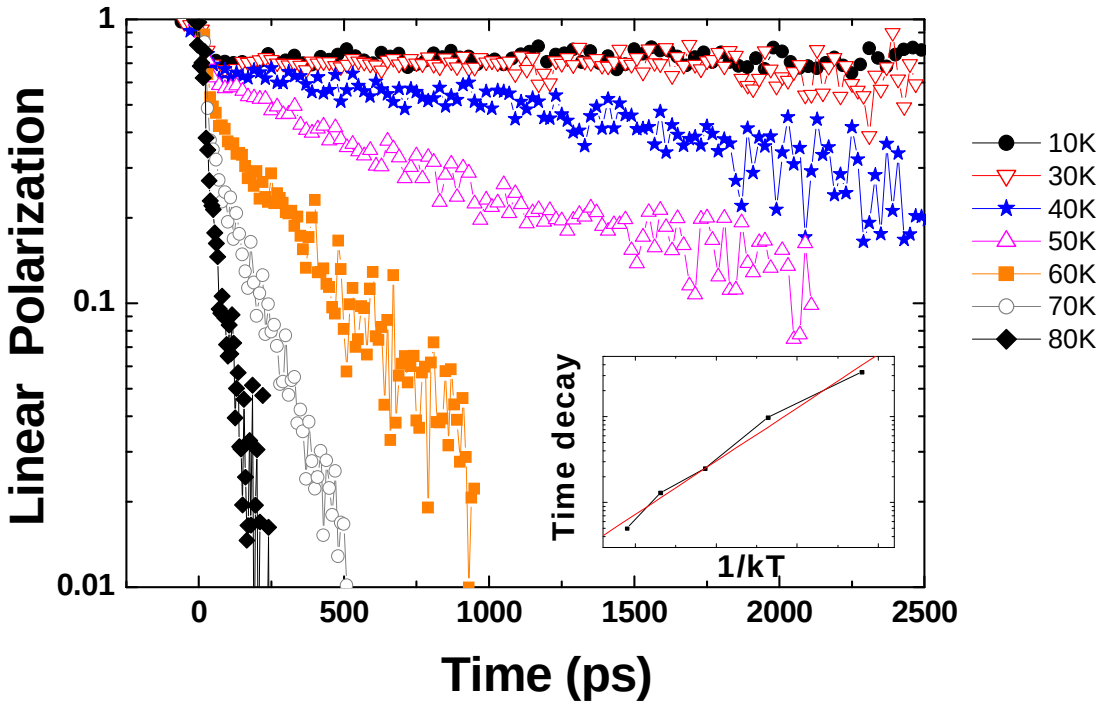
Temperature problems with InAs/GaAs quantum dots





Solutions : GaN , ZnO Quantum Dots ?

- (In)GaN/AlN , collaboration LSP/CEA Grenoble and Sharp (Oxford)
- ZnO* , collaboration IOP (Beijing)

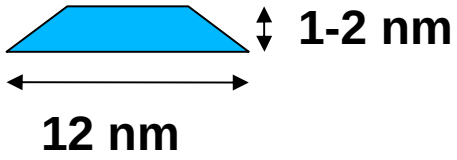
* Liu et al, PRL **98**, 186804 (2007) ; Seatle

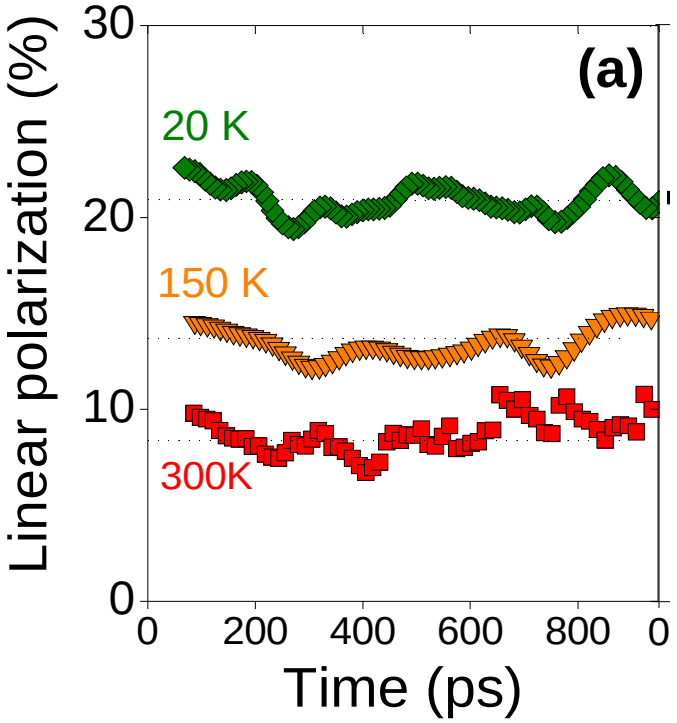
Spin Dynamics in GaN/AlN Quantum Dots (cubic)

Collaboration : H. Mariette, S. Founta (Grenoble)

Martinez-Guerrero, APL **77**, 809 (2000)

- Dot size



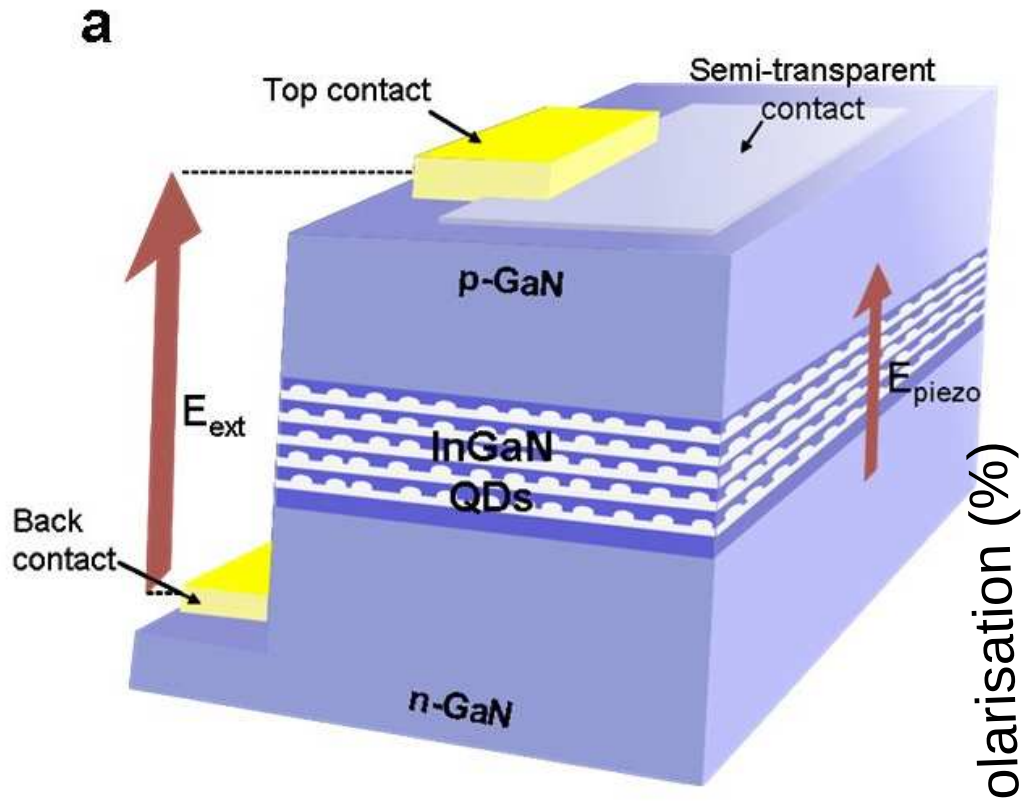


Polarisation decay time > 10 ns, even at 300 K !

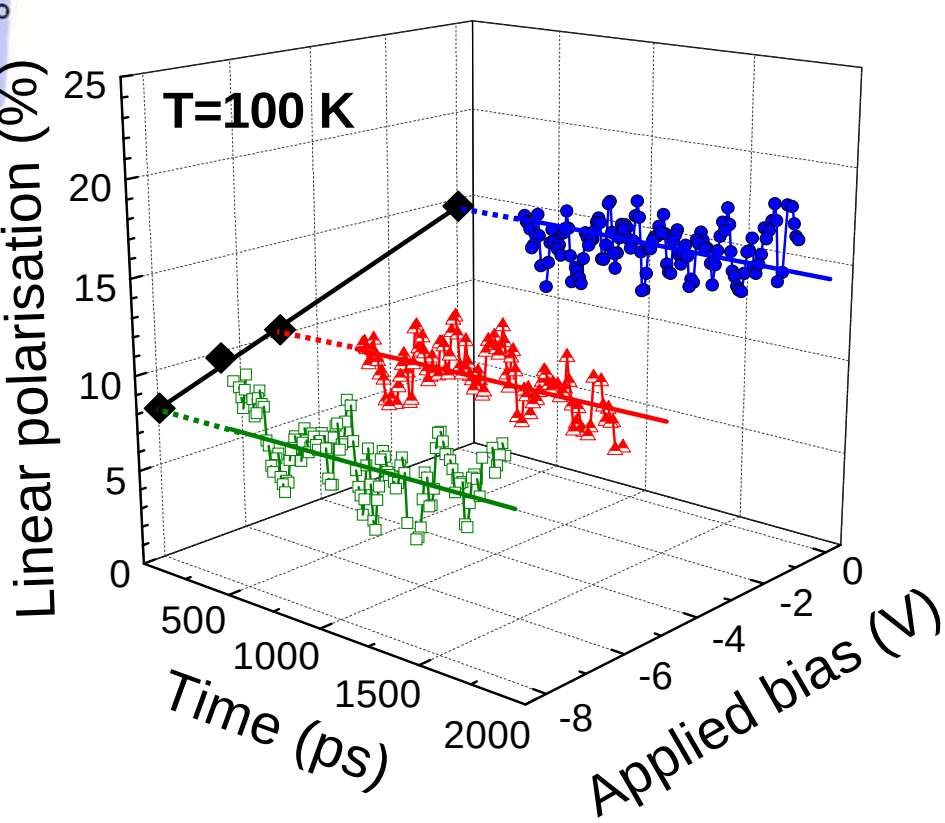
Lagarde et al., PRB **77**, R (2008) ; Toulouse-Grenoble

GaN bulk Wurzite, **t ~1 ps**, Brimont *et al*, PRB **77**, (2008)

Electrical Control of the Exciton Spin in InGaN Quantum Dots



Collaboration : Sharp , Oxford



Senes, Lagarde *et al*, submitted (2009)

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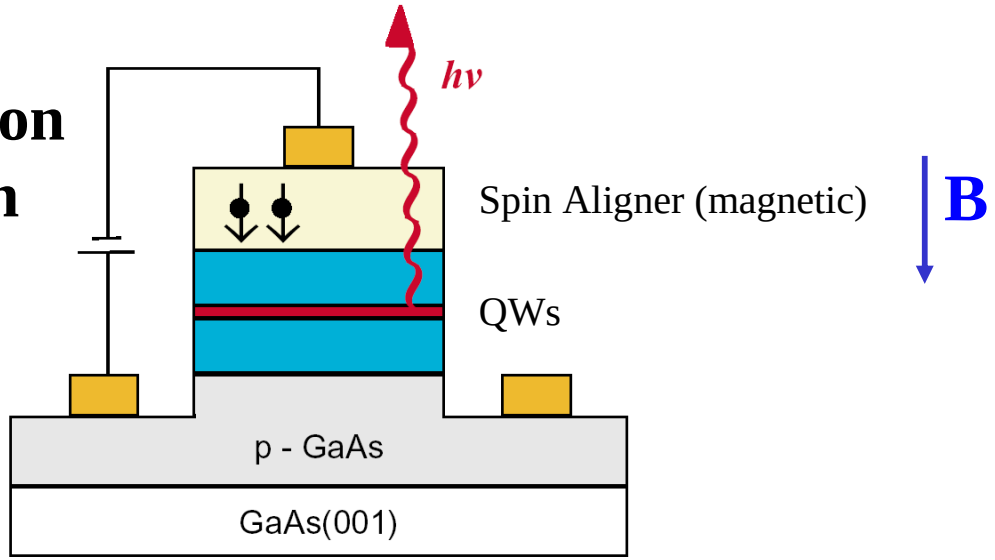
Electrical Spin Injection

Magnetic Material/ Semiconductor Material

- **Electrical Injection**
- **Optical Detection**



Spin-LED

Two kinds of Spin aligner :

- **Diluted Magnetic Semiconductor (ZnMnSe, GaMnAs…)**
- **Ferro-magnetic Metal (Fe, Co,…)**

University of Würzburg : Fiederling *et al*., Nature **402** (1999)
Naval Research Laboratory : Hanbicki *et al*., APL **80** (2002)

Toulouse Spin-LED (schottky) : Liu *et al*., Physica E **17**, 358 (2003) ; PSS (c) **1**, 475 (2004)

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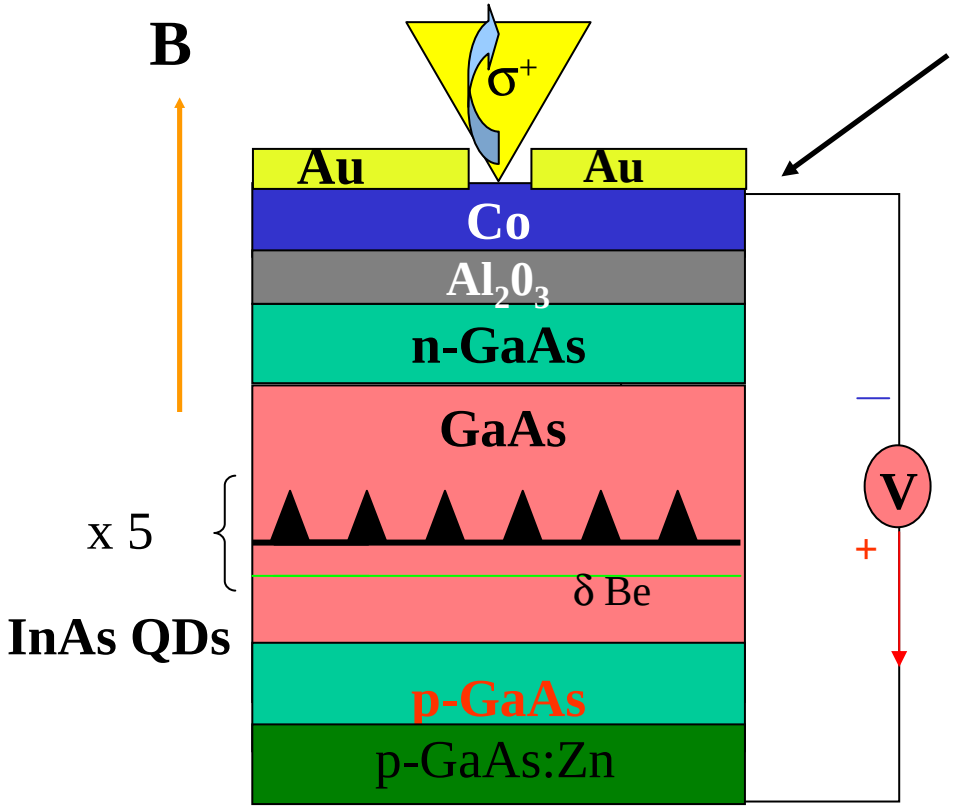
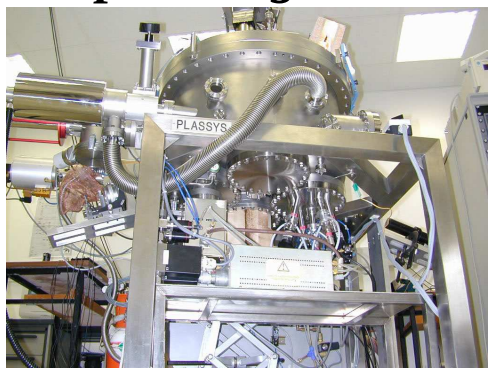
SPIN-LED with InAs/GaAs Quantum Dots

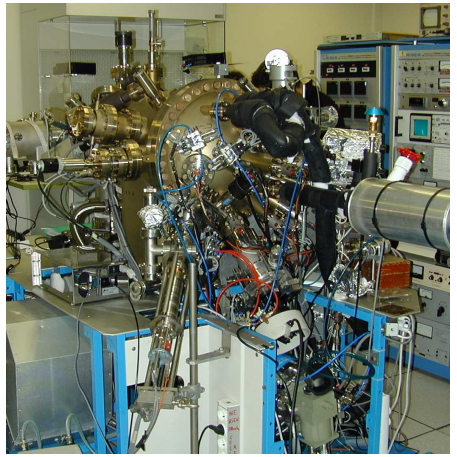


Sputtering

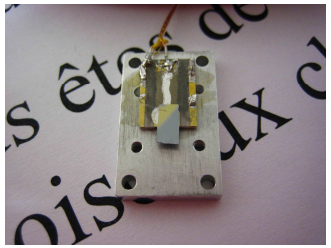


Co layer : 4 nm
Al_2O_3 : 1.5 nm

MBE



5 layers of InAs/GaAs QD with Be δ-doping layer



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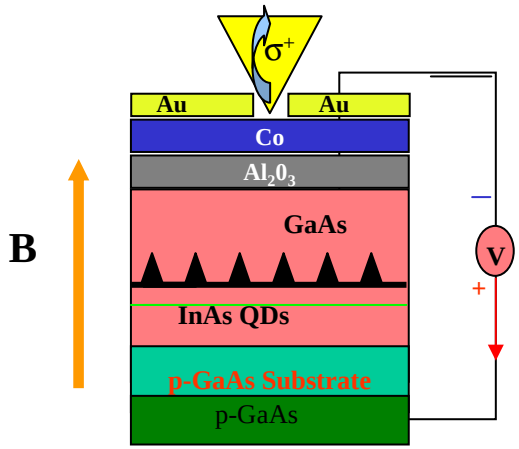
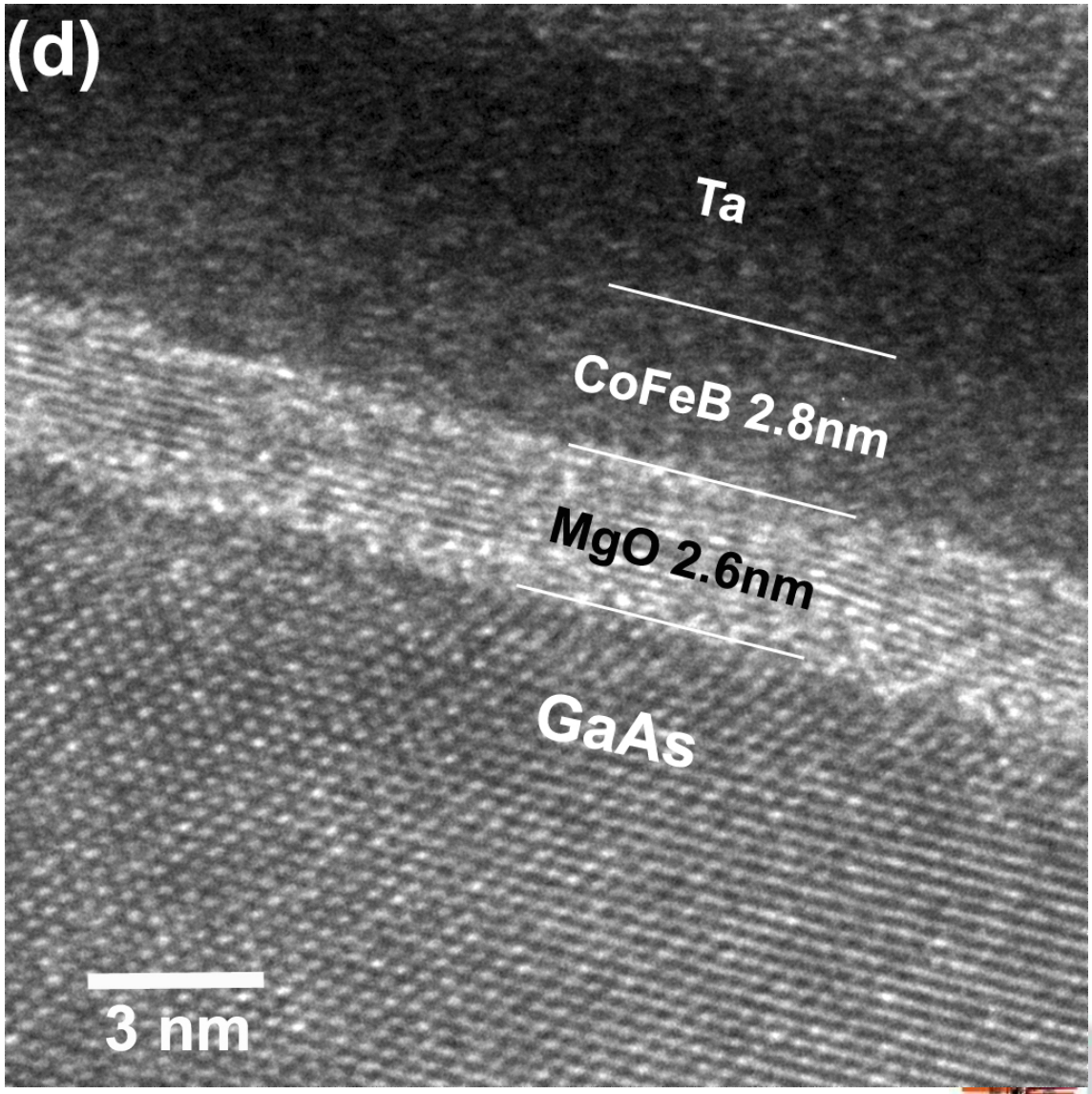
Spin-LED with InAs Quantum Dots (FM/insulator/Sc)

Collaboration :
CNRS-Thales (Palaiseau)



Lombez *et al*, APL **90**, 81111(2007)



Spin-LED with MgO tunnel barrier : P~50% !

APL **93**, 152102 (2008) ; APL in press (2009)

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Outline…

- *Self-organized Quantum Dots*

- ***Optical Spin Injection and Manipulation***
  - *Optical Orientation experiments*
  - *Spin Relaxation Dynamics in InAs/GaAs QDs*
  - *Spin Manipulation in GaN/AlN QDs*

- ***Electrical Spin Injection***
  - *Spin-LED*
  - *Spin-Laser*

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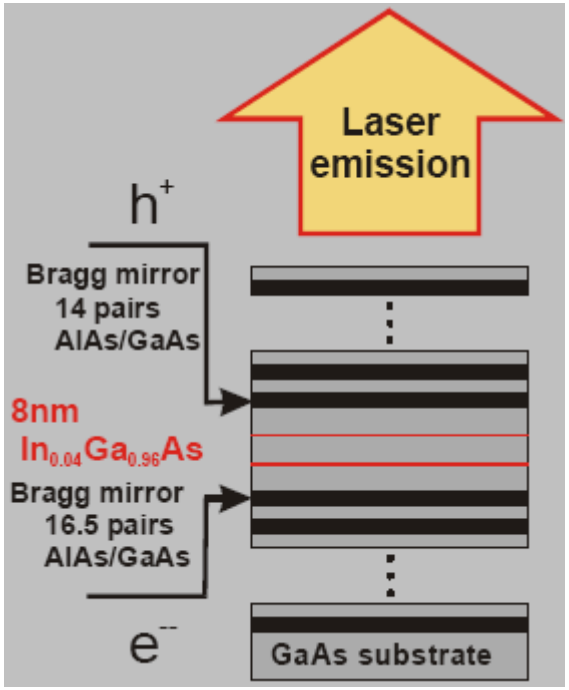
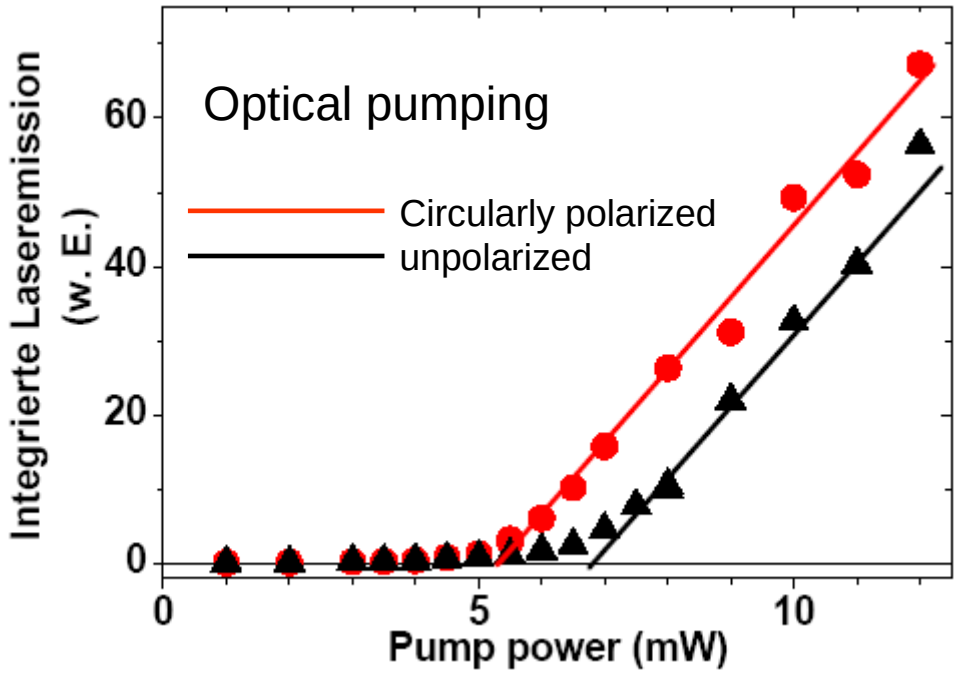
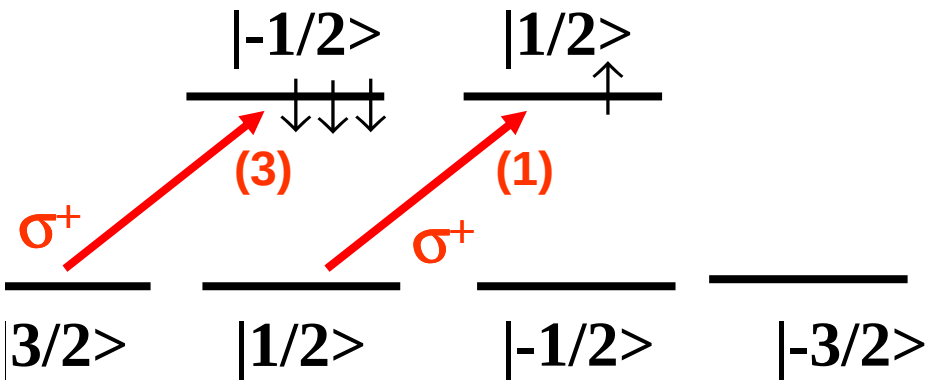
VCSEL :Vertical Cavity Surface Emitting Laser

M. Oestreich, University of Hannover





Reduced laser threshold
APL **82**, 4516 (2003)



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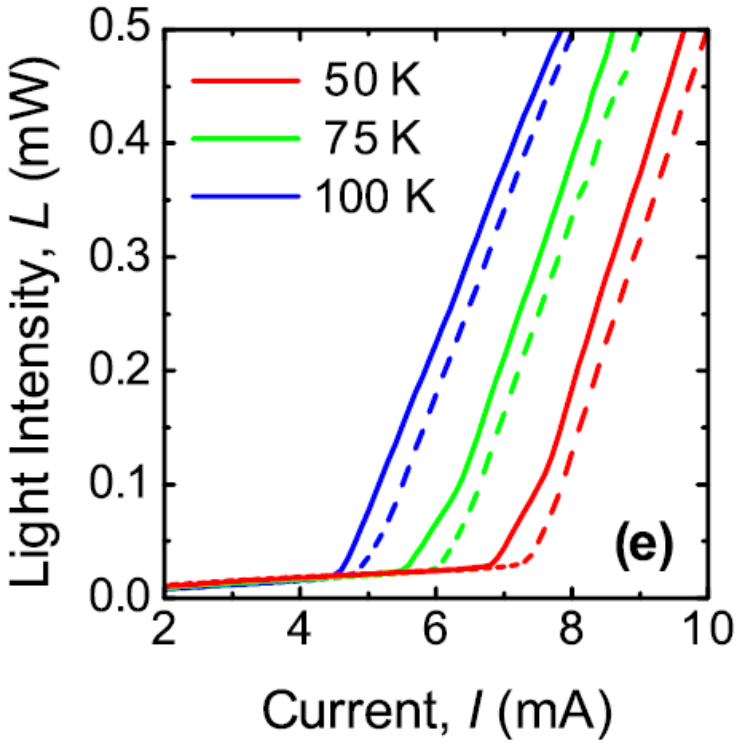
PRL **98,** 146603 (2007) PHYSICAL REVIEW LETTERS week ending 6 APRIL 2007

Electrical Spin Injection and Threshold Reduction in a Semiconductor Laser

M. Holub, J. Shin, D. Saha, and P. Bhattacharya

Solid-State Electronics Laboratory, Department of Electrical Engineering and Computer Science, University of Michigan, Ann Arbor, Michigan 48109-2122, USA



Electrically injected InAs Quantum Dot Spin Laser at T=200 K

*Basu et al, APL **92**, 91119(2008), Michigan*

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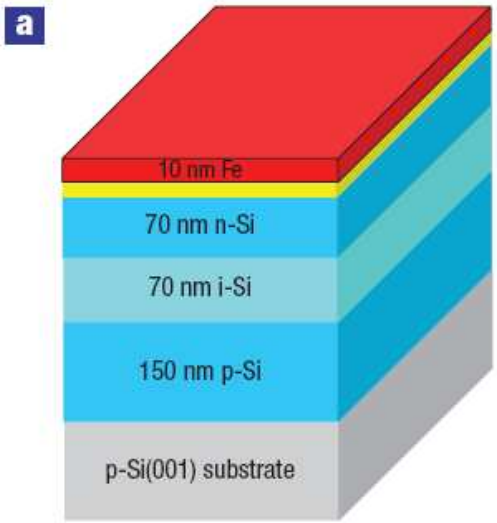
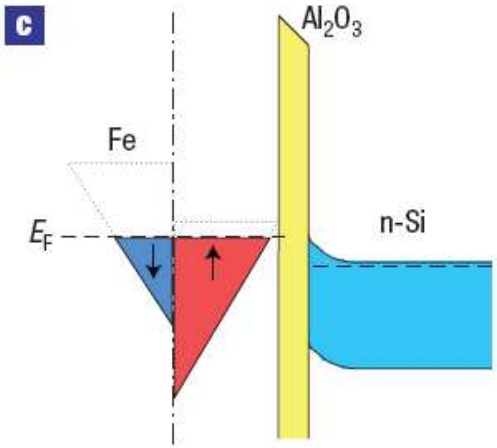
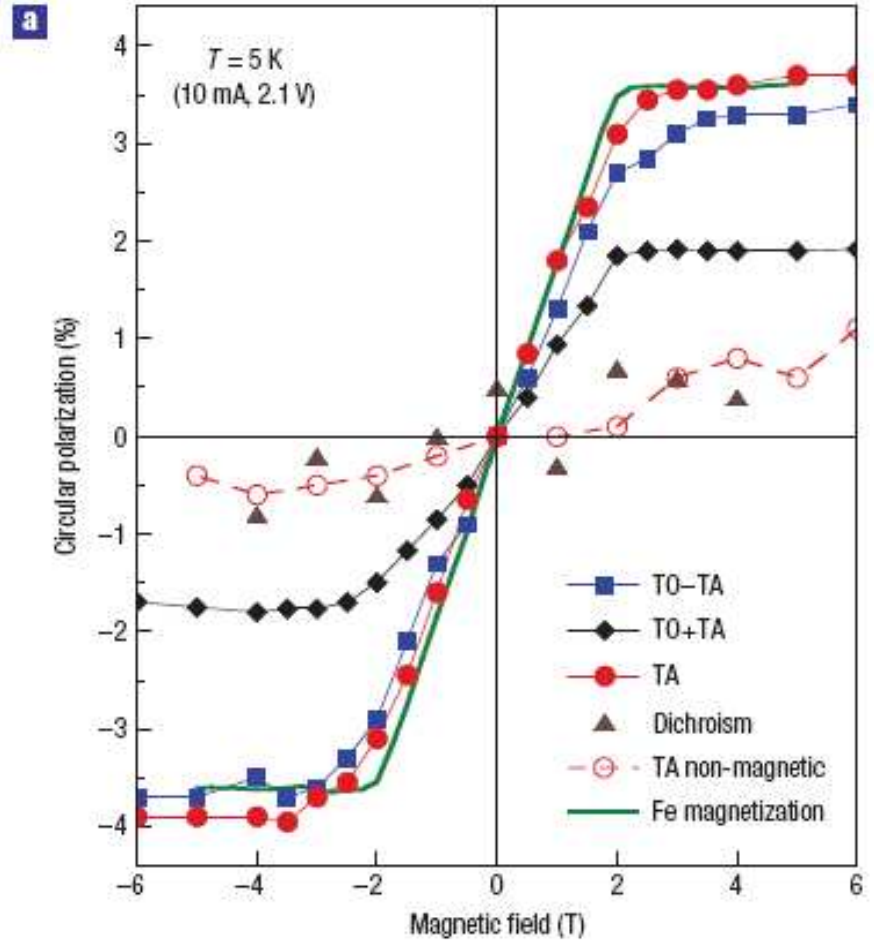
Outlooks : Electrical Spin Injection in Silicon

Jonker et al, Nature Physics 3, 2007 , Washington







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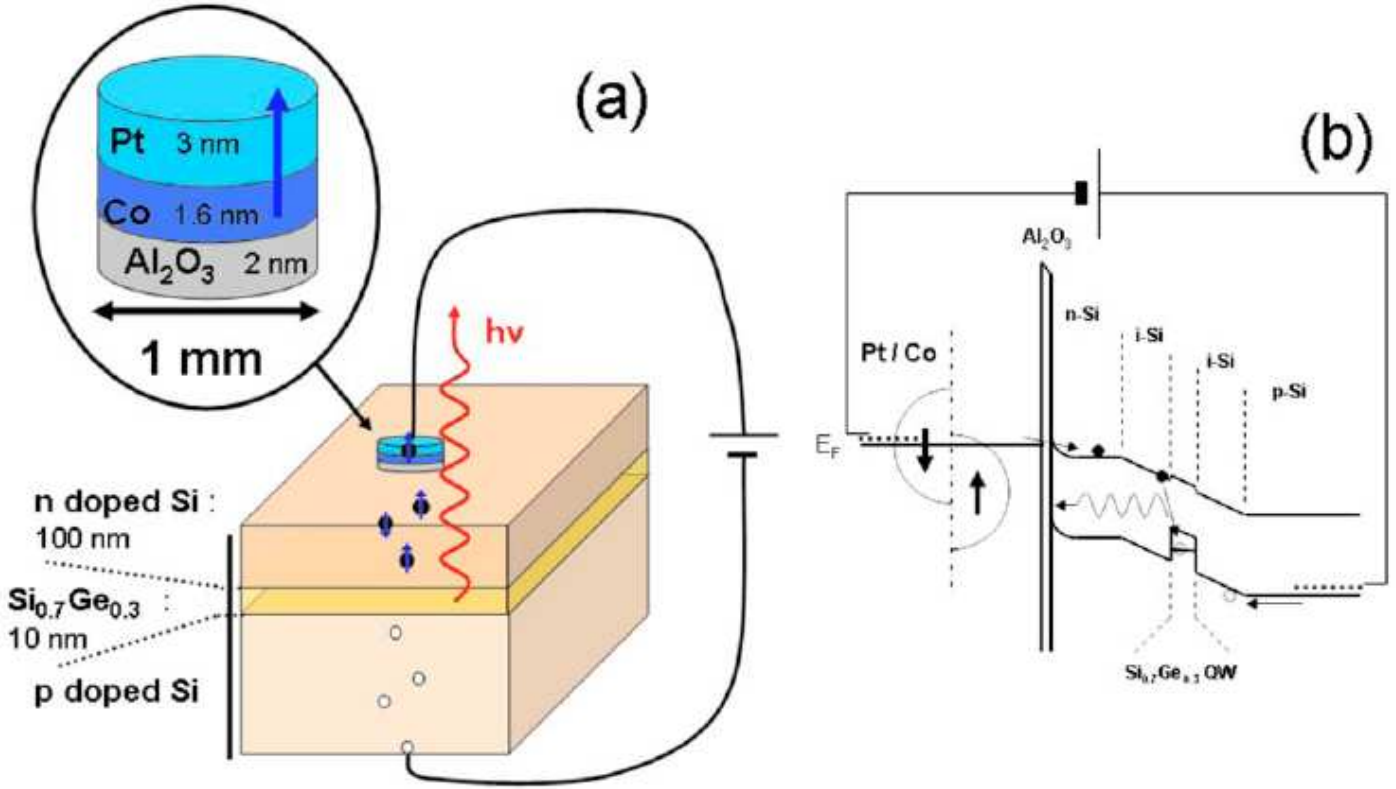
Outlooks : Electrical Spin Injection in Silicon at B=0

Grenet et al, APL **94**, 32502 (2009), Grenoble



External Magnetic field B=0

Spin Filtering in a non-magnetic Semiconductor Material
Wang *et al*, Nature Materials **8,** 198 (March 2009) Toulouse-Linköping

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