Semiconductor Nanostructures

Fabrication and Properties of Self-Assembled Quantum Dots

Gerhard Abstreiter

Walter Schottky Institute, TUM, Garching

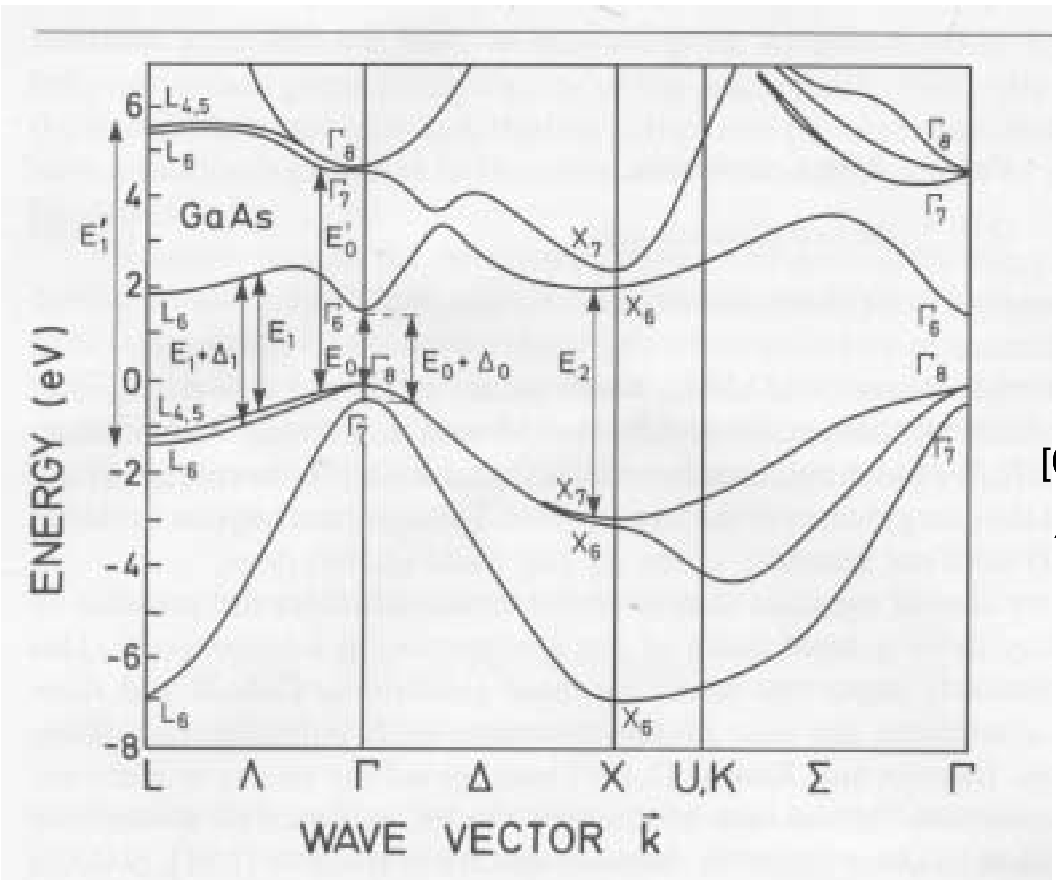
TECHNISCHE UNIVERSITÄT MÜNCHEN

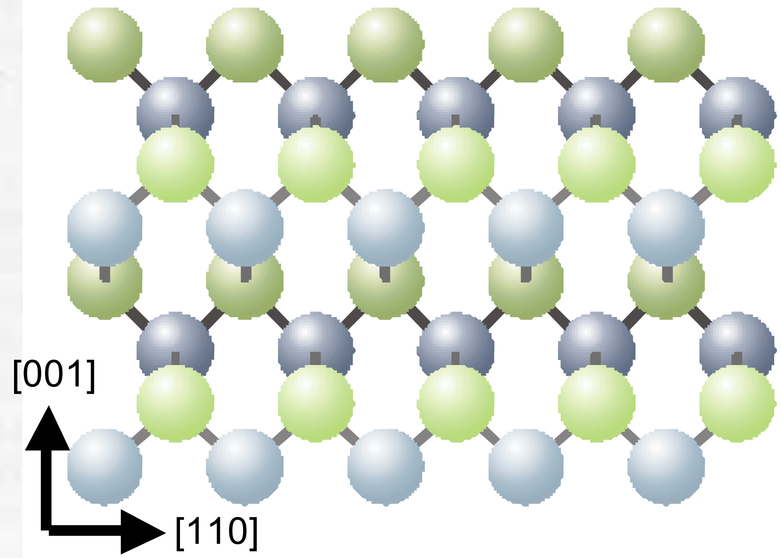
Outline:

- introduction to low-dimensional semiconductor structures
- fabrication of nanostructures with MBE
  - ➢ cleaved edge overgrowth (CEO)
  - ➢ self-assembled quantum dots (SAQD)
- structural properties of SAQDs
- electronic level structure of SAQDs
- control of charge in novel SAQD devices
- coherent control of a single dot photodiode
- charge and spin storage in SAQDs

crystal - and electronic structure

example: GaAs

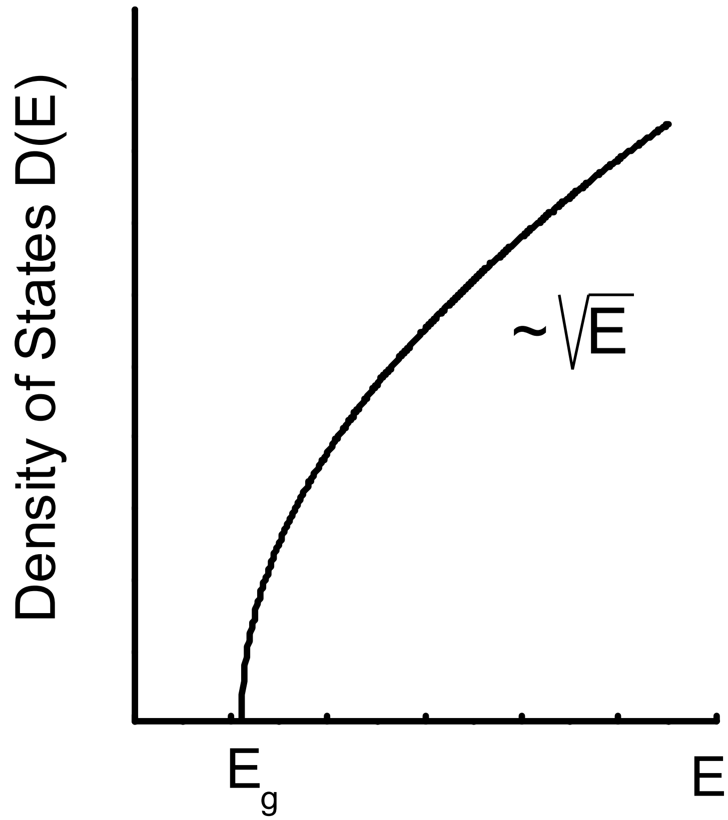




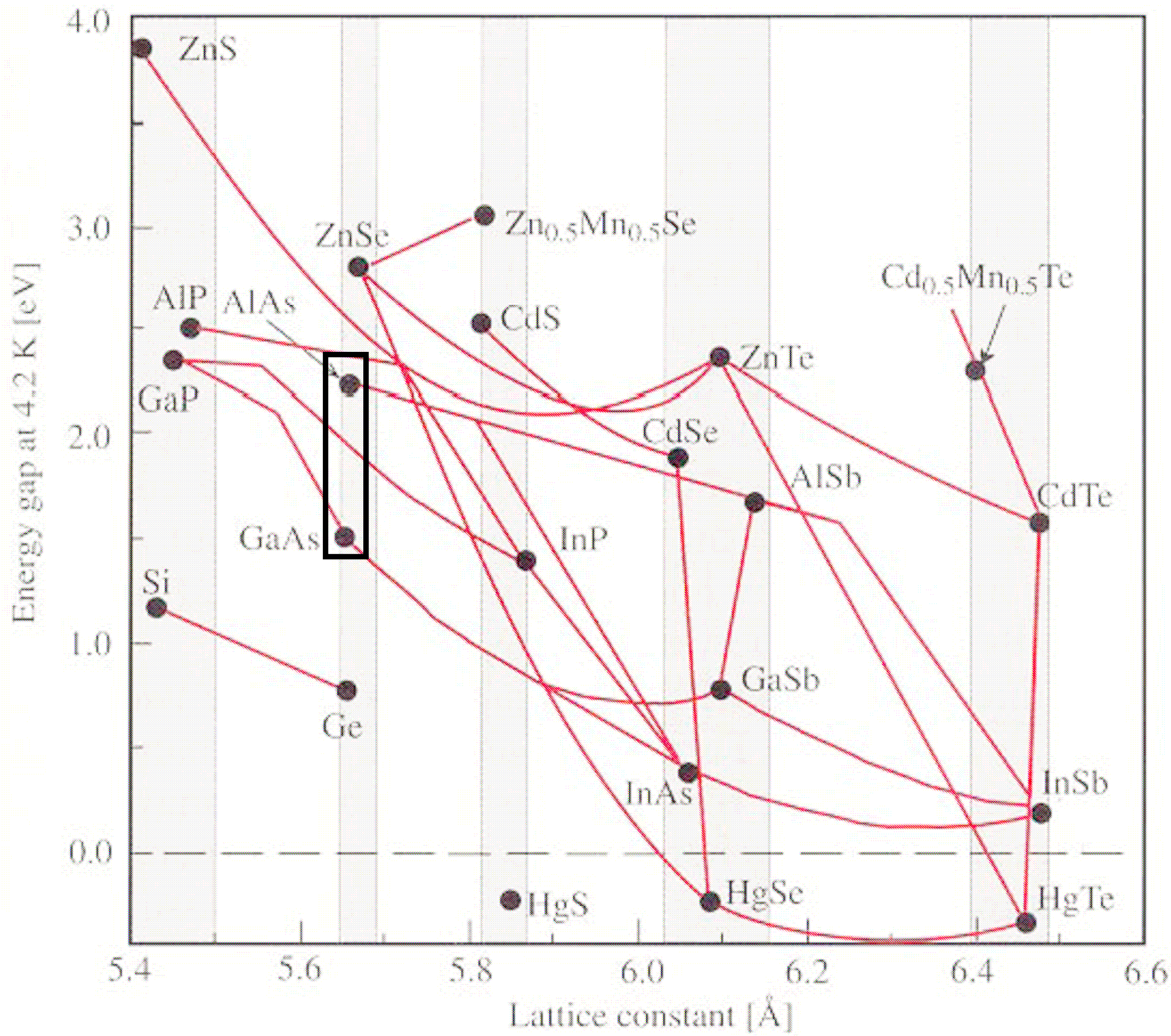
density of states for parabolic bands

3D

~1cm

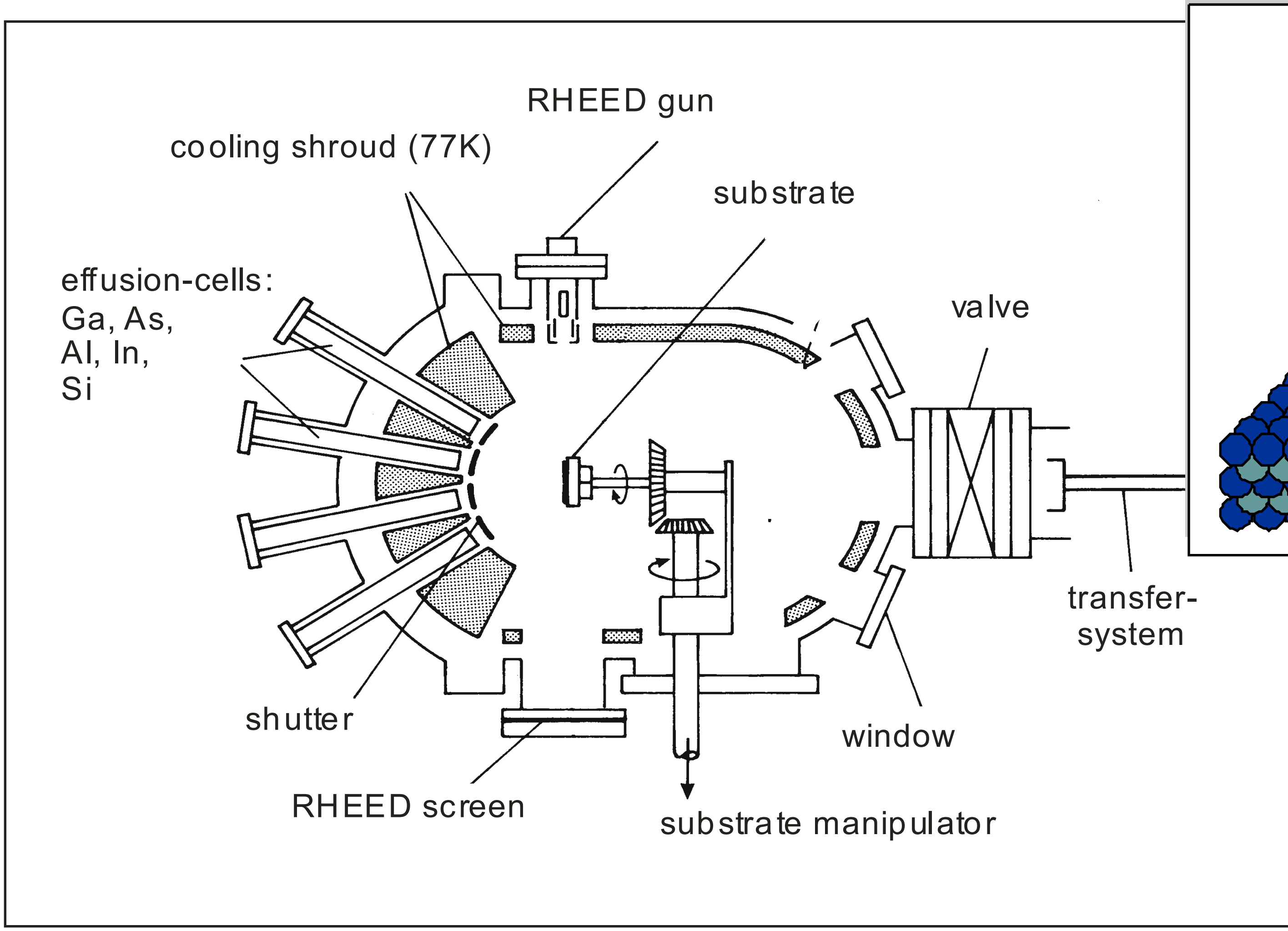


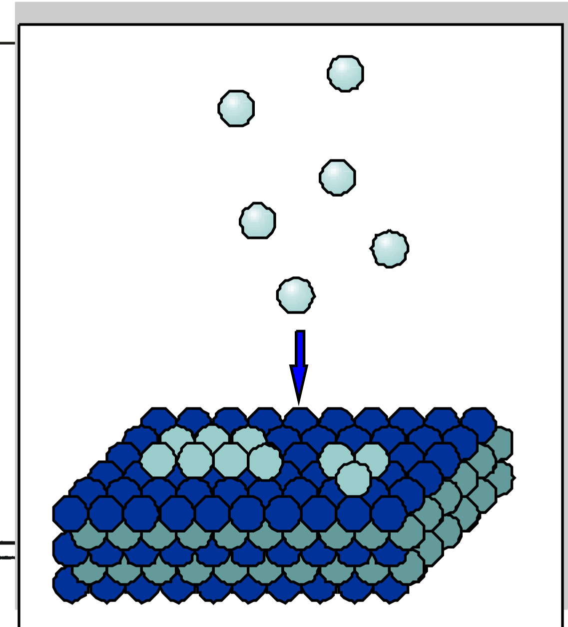
low-dimensional semiconductors: heterostructures and quantum wells



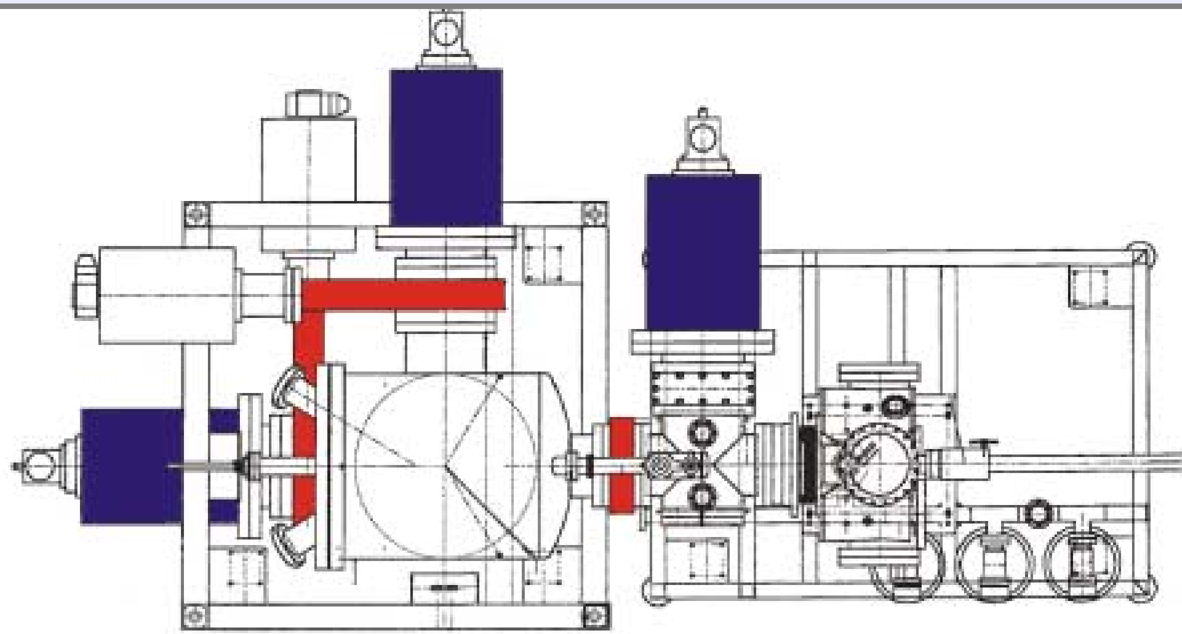
fabrication by molecular beam epitaxy

schematics of a Ga(Al,In)As system



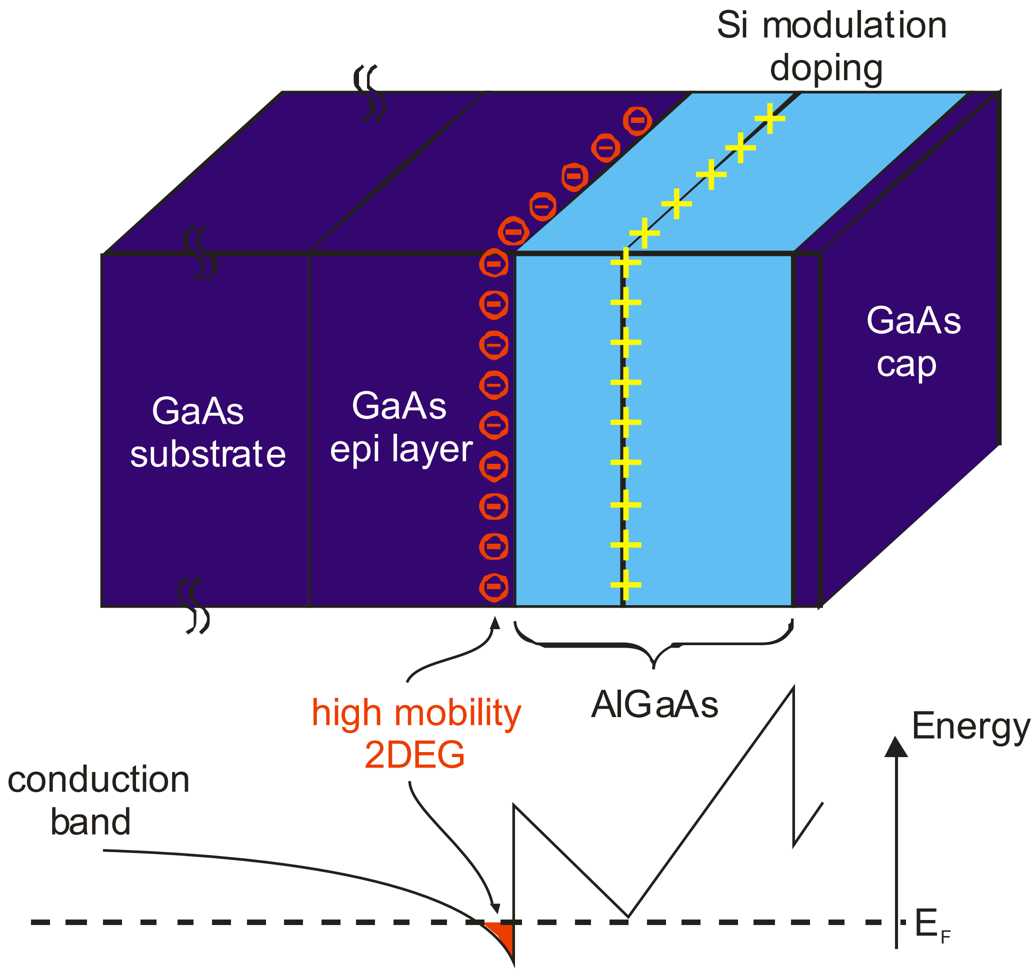


ultra clean MBE system at Walter Schottky Institut

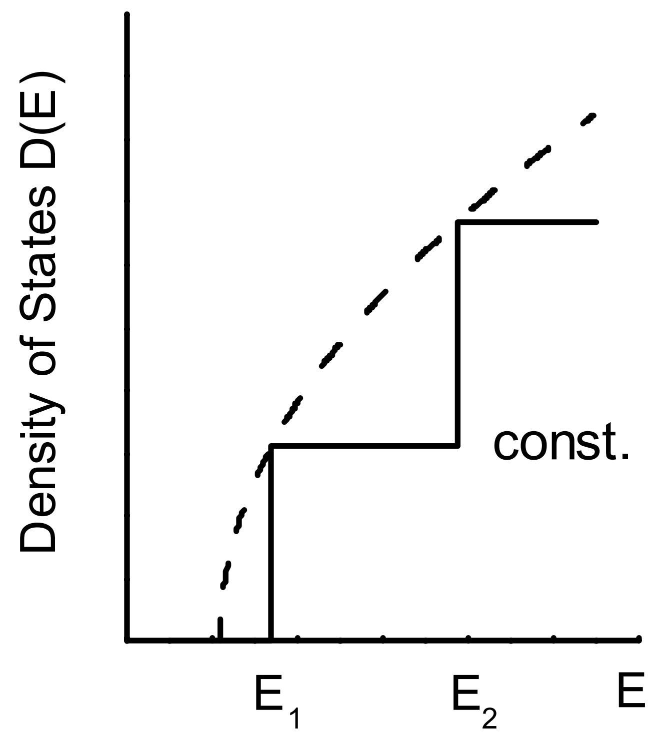


- excellent vacuum ($p \leq 5x10^{-12}$mbar)
- long-term closed growth chamber
- source materials: Ga, Al, In, As
- Valved cracker cell provides As_4 *or* As_2
- *only* Si as dopant

high mobility 2-d electron gas



electric subbands



Important achievements with heterostructures:

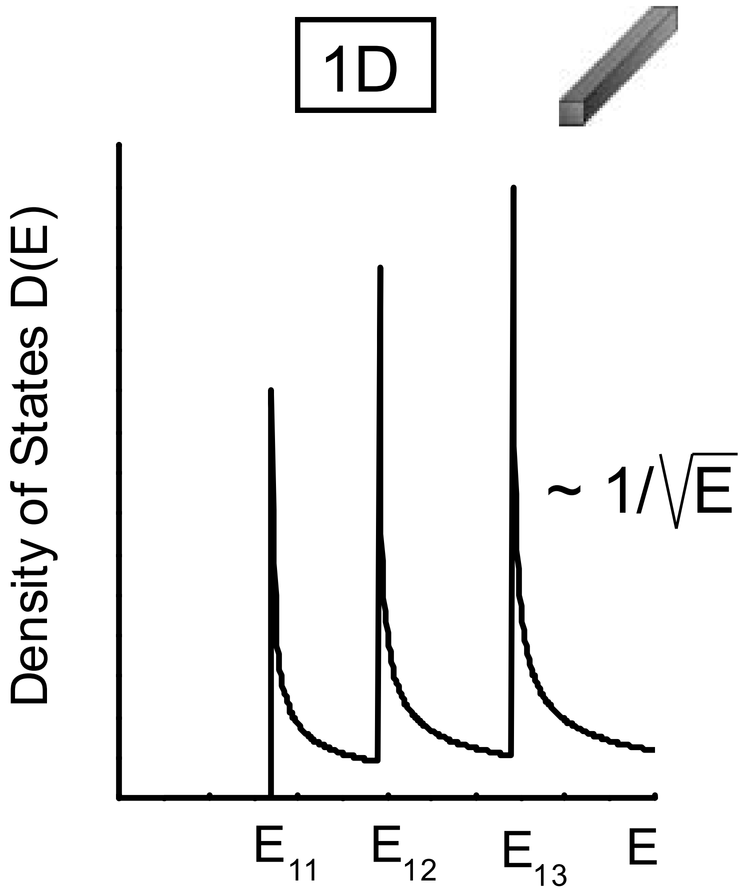
- basic physics:
  - magnetotransport, Shubnikov-de Haas Effect
  - Quantum Hall Effect, Fractional Quantum Hall Effect
  - interband and intersubband spectroscopy
  - superlattice and miniband physics

  …………
- devices:
  - high electron mobility transistors
  - quantum well lasers
  - quantum cascade lasers
  - quantum well intersubband detectors

  ……………

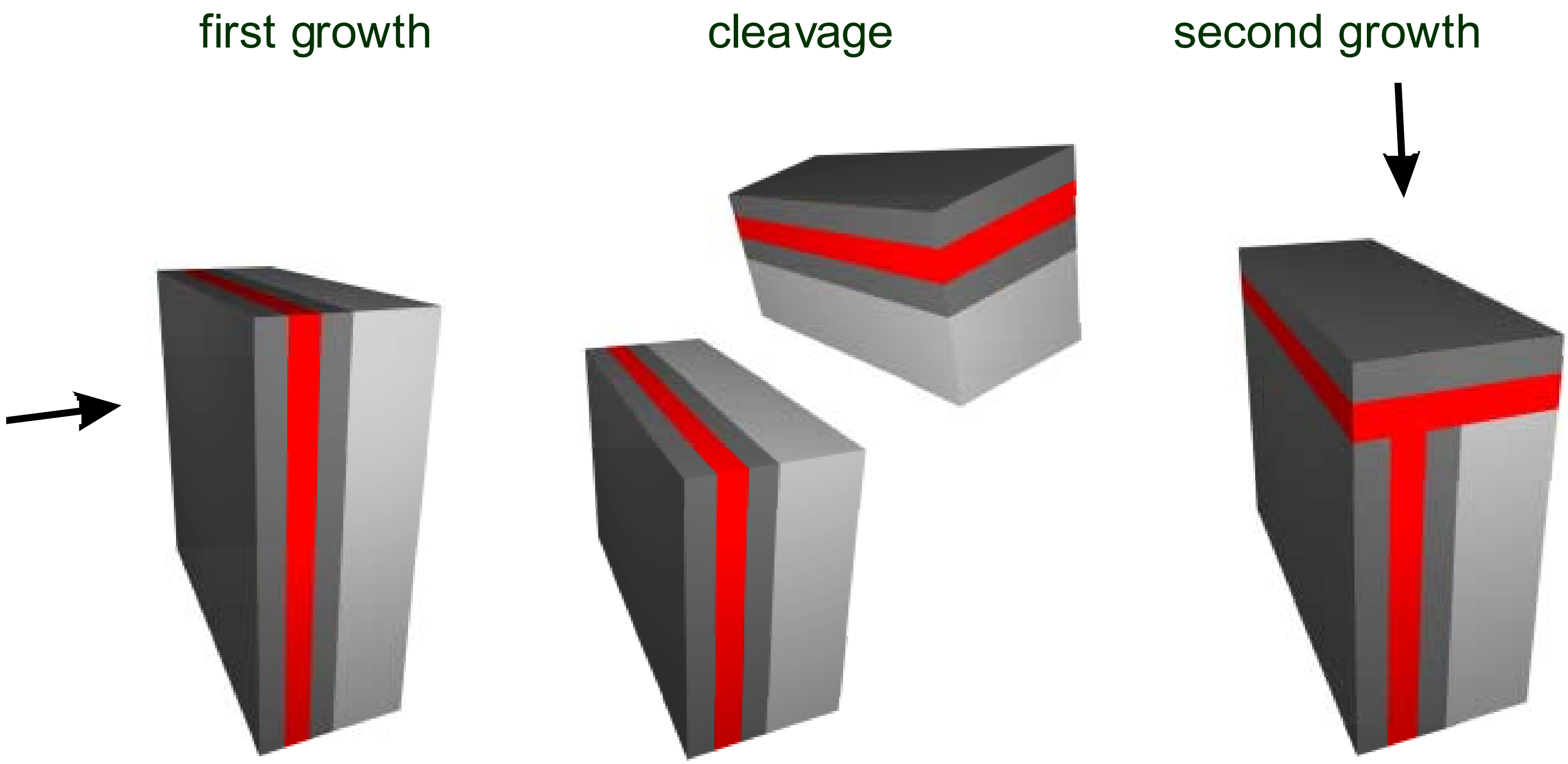
towards one and zero-dimensional systems

length scale: ~10 nm

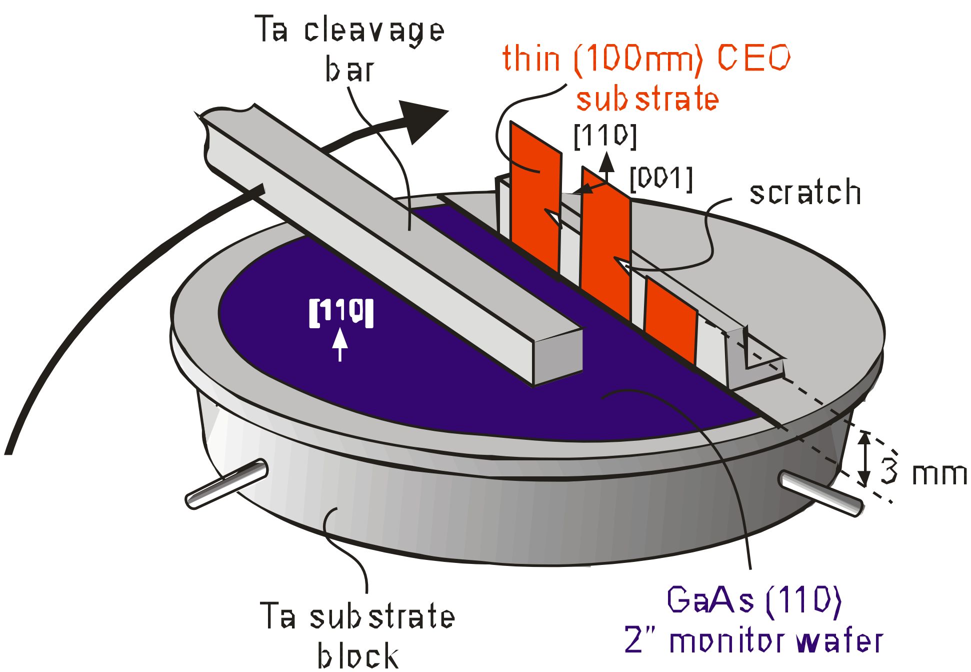


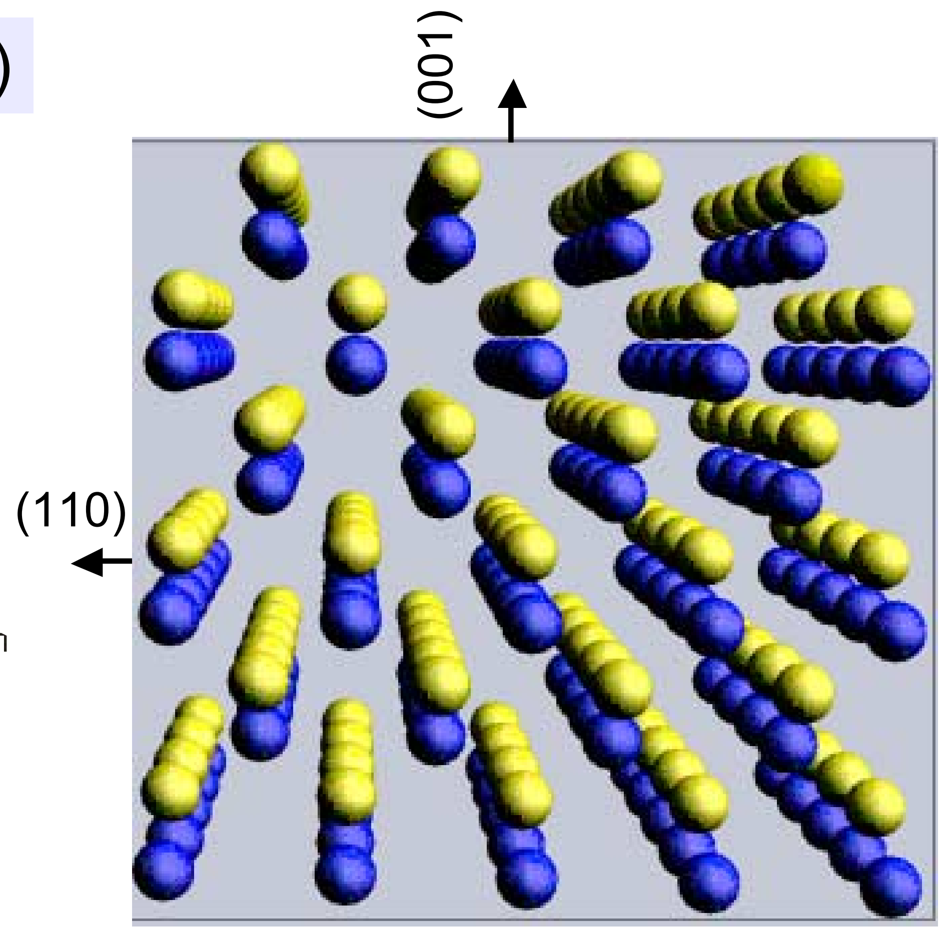
discrete:
- artificial atoms

wires and dots by cleaved edge overgrowth (CEO)

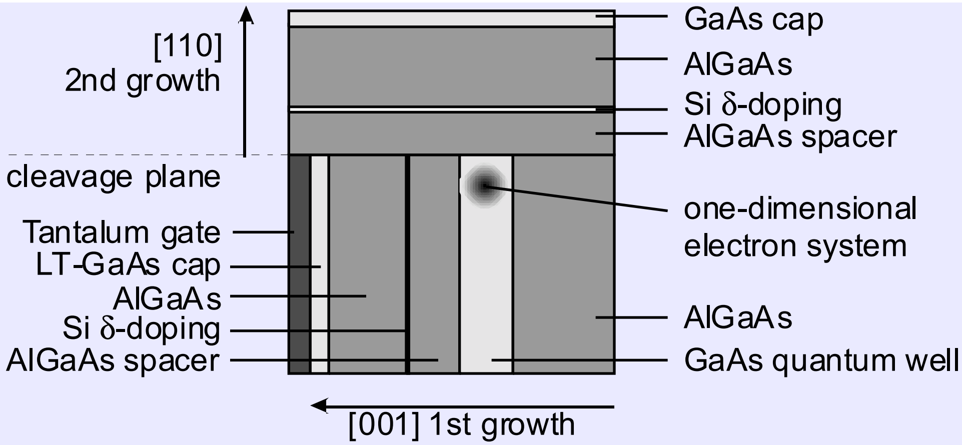


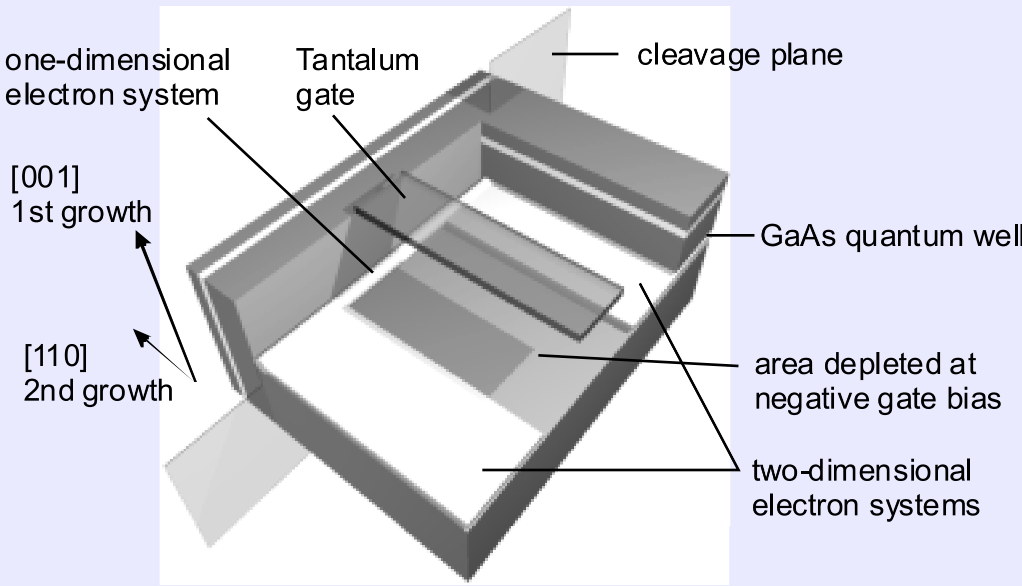
natural cleavage plane: (110)





Quantum wires: quantized conductance





$$I_+ = e\int D(E)v(E)f(E)dE,$$

$$D(E) = \frac{1}{\pi}\left(\frac{\partial E(k)}{\partial k}\right)^{-1}$$

$$v(E) = \frac{1}{\hbar}\frac{\partial E(k)}{\partial k}$$

$$I_+ = \frac{2e}{h}\mu_+,$$

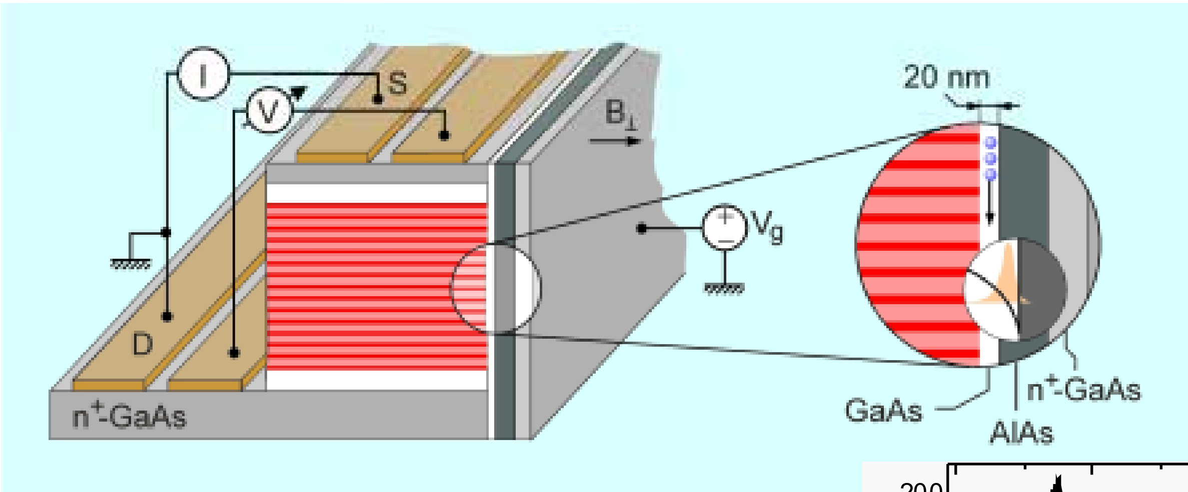
$$\mu_+ - \mu_- = eU,$$

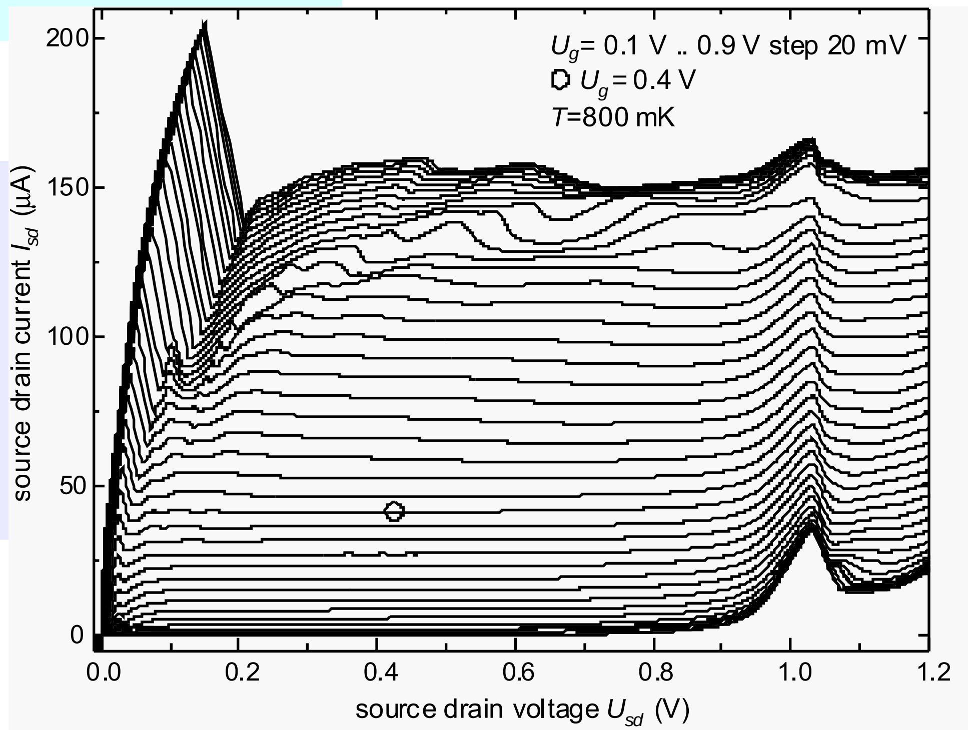
$$G = \frac{I_+ - I_-}{U} = \frac{2e^2}{h}.$$

Amir Yacoby et al. PRL 77, 4612 (1996)

Martin Rother, PhD thesis, TUM (2000)

superlattice field effect transitor, electrons in atomically precise potential landscapes

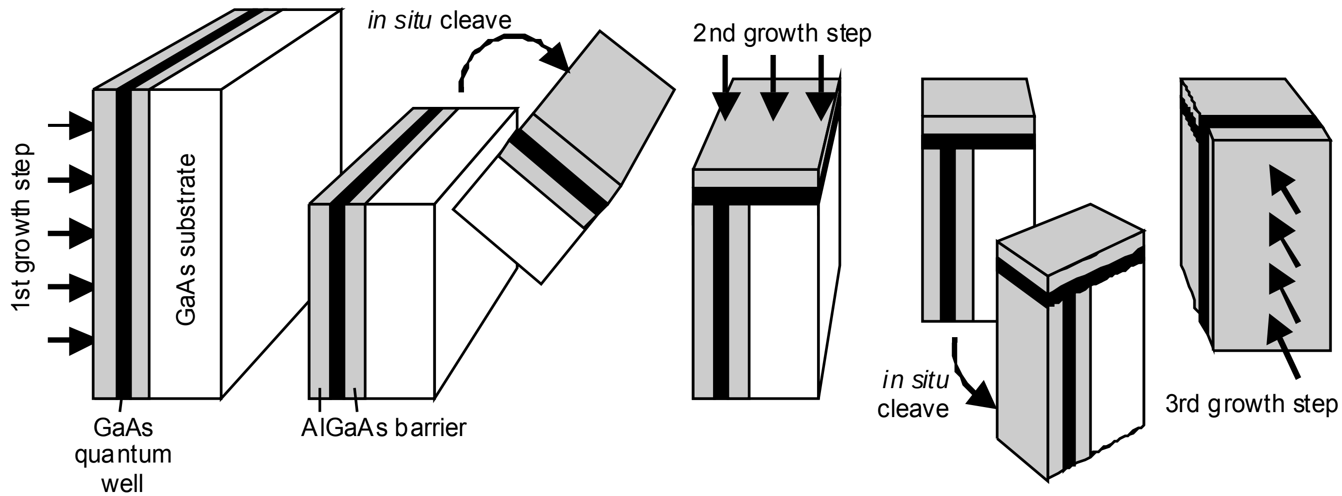




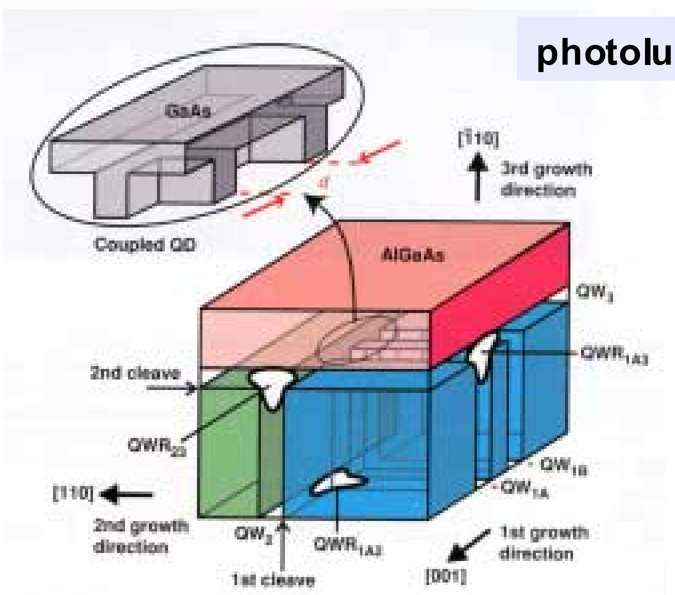
- miniband transport, quantum interference
- fractional QHE > 2d Ising ferromagnets
- gate voltage control of nuclear spin

R. Deutschmann et al. PRL 86, 1857 (2001)
J.H. Smet et al. PRL 86, 2412 (2001)
J.H. Smet, et al. Nature 415, 281 (2002)

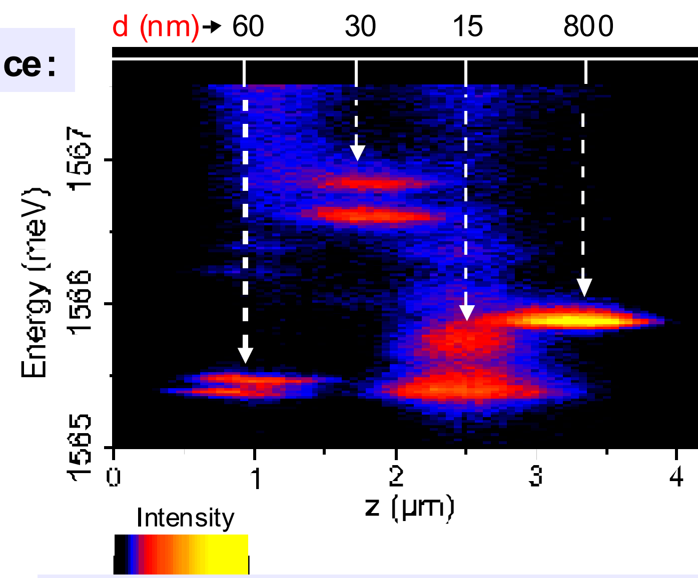
Quantum dots by double CEO



coupled dots with precision on an atomic scale:



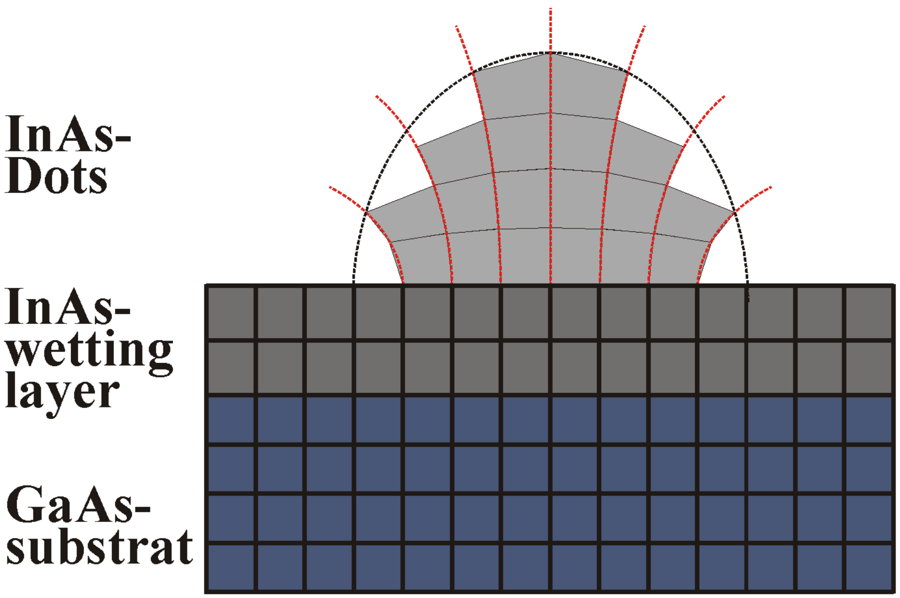
photoluminescence:



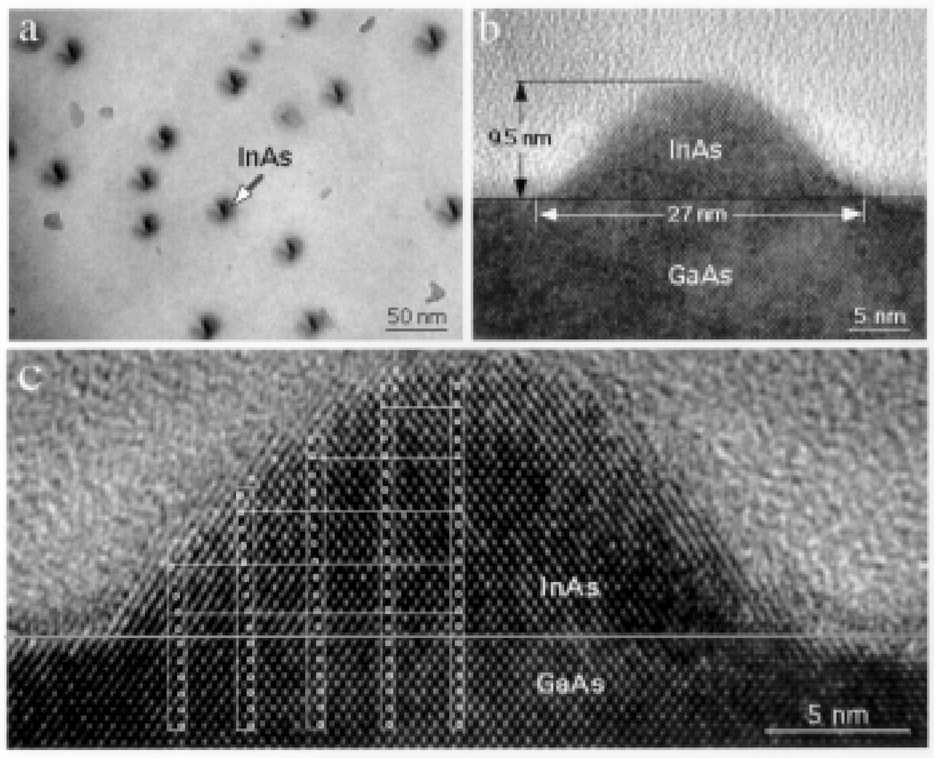
G. Schedelbeck et al., Science 278, 1677 (1997)

quantum dots by self-assembly

lattice mismatched systems like InAs/GaAs or Si/Ge:
➢ Stranski-Krastanov growth mode

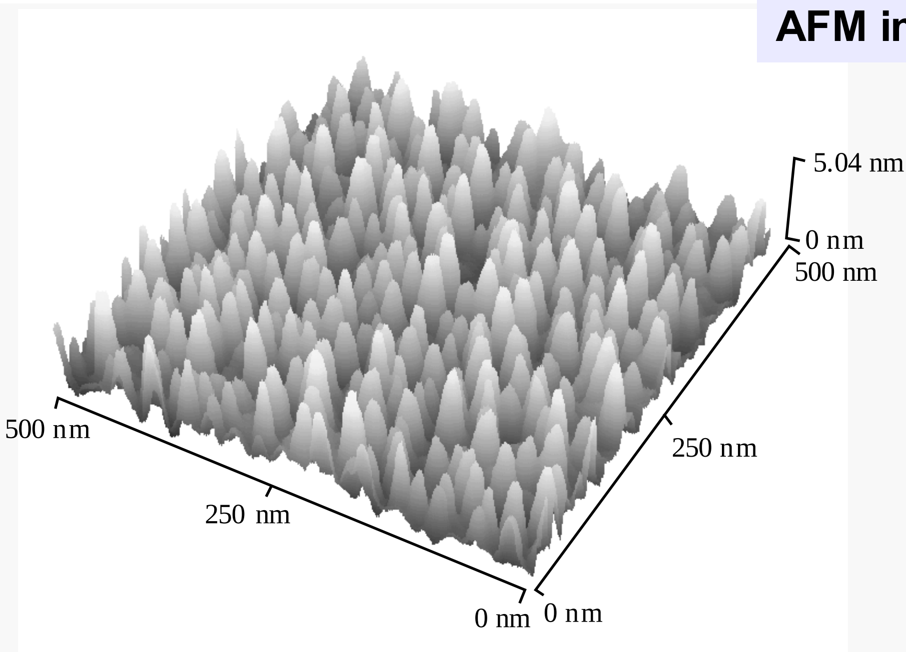


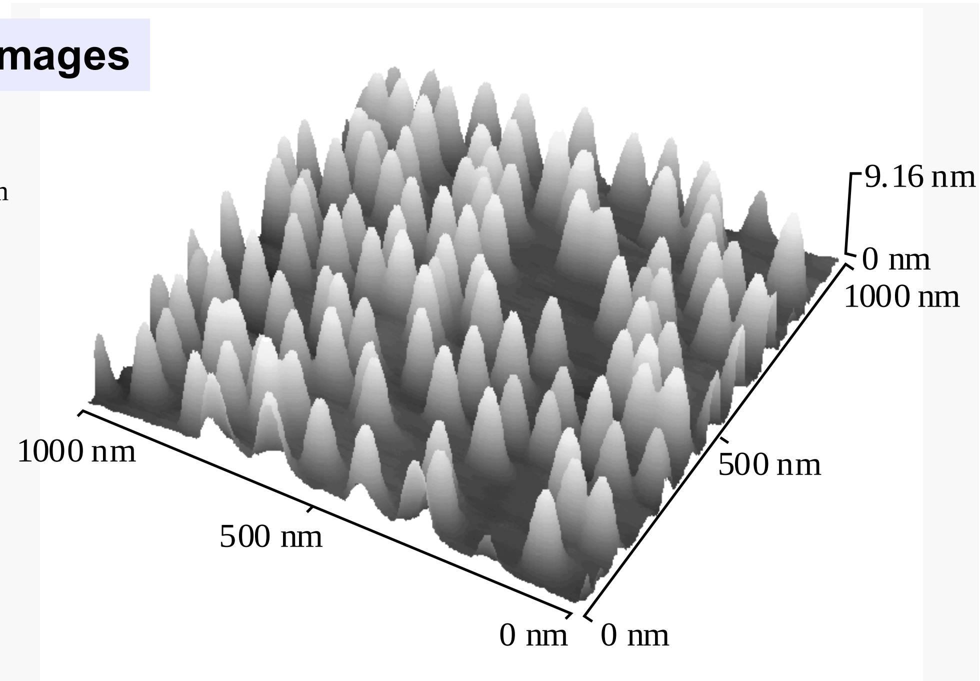
TEM micrographs



density, size, shape and composition depend on growth conditions

AFM images





T_g = 480°C
density:
$10^{11}cm^{-2}$

T_g = 530°C
density:
$1.2x10^{10}cm^{-2}$

Growth parameters:

- substrate temperature
- growth rate
- III to V ratio (beam equivalent pressure)
- growth interuption
- amount of deposited material
- nominal composition (InAs or InGaAs)
- capping material

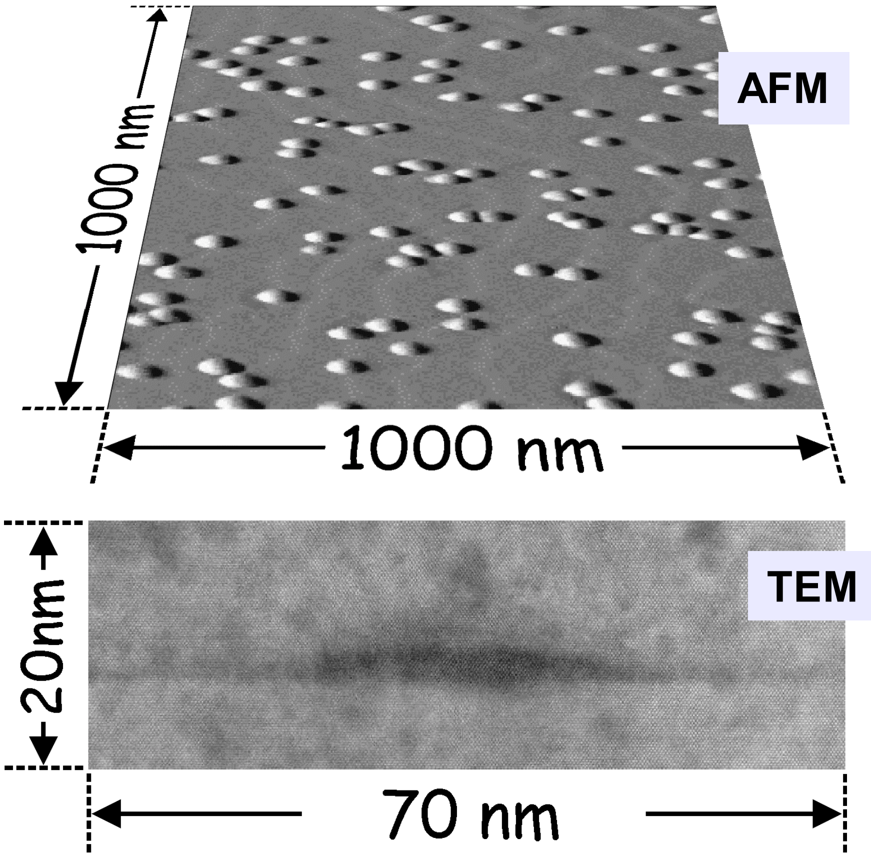
Structural characterisation:

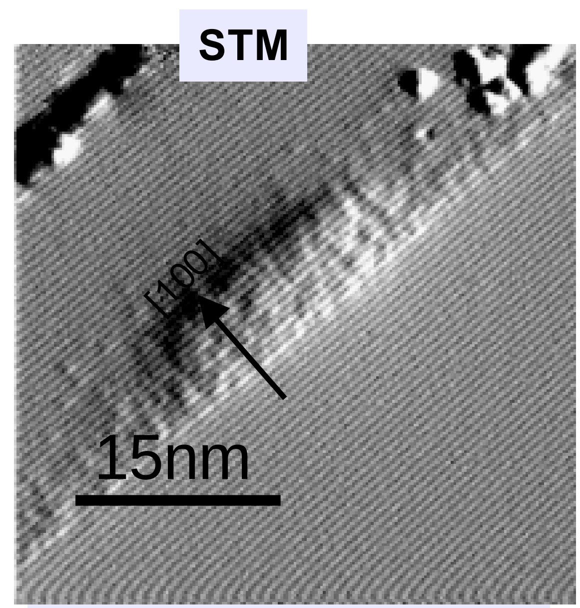
- STM and AFM
- electron microscopy
- X-ray analysis

Important:

shape, size and composition are changed during overgrowth due to interdiffusion and segregation

typical shapes: lenses, pyramids, trunkated pyramids



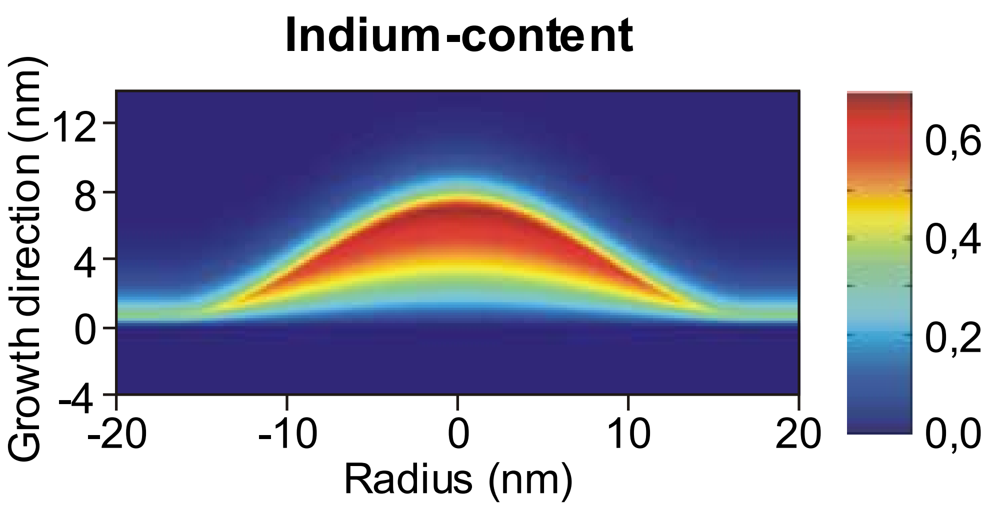


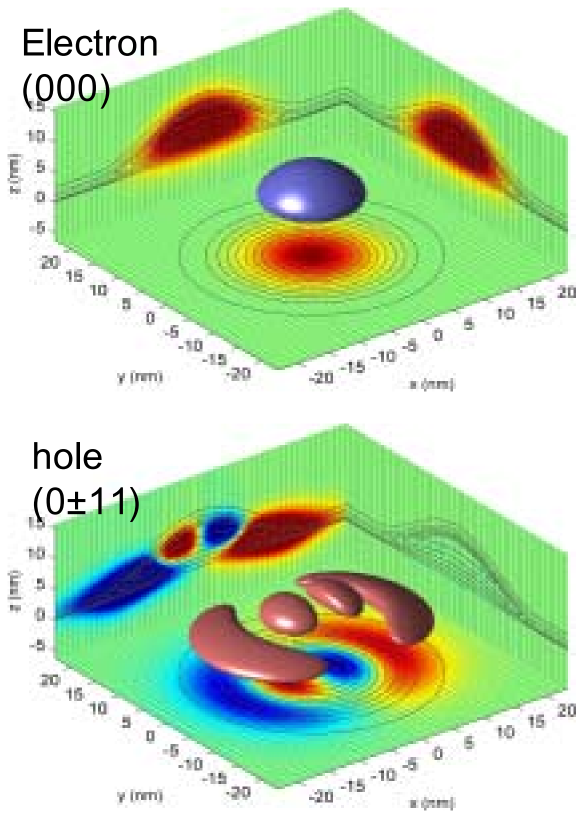
P.M.Koenraad, Eindhoven

A detailed analysis of the different characterisation methods leads to a consistent of size shape and composition

Example for:
T_S = 530°C, 2,8 ML InAs
as determined from X-ray and TEM

This information is basis for kp calculations resulting in a realistic electronic level structure



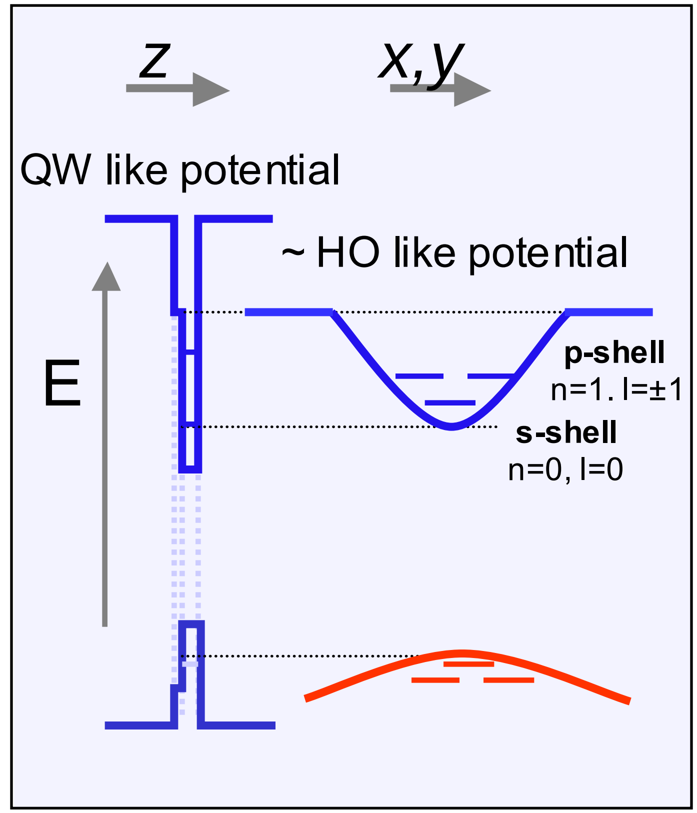


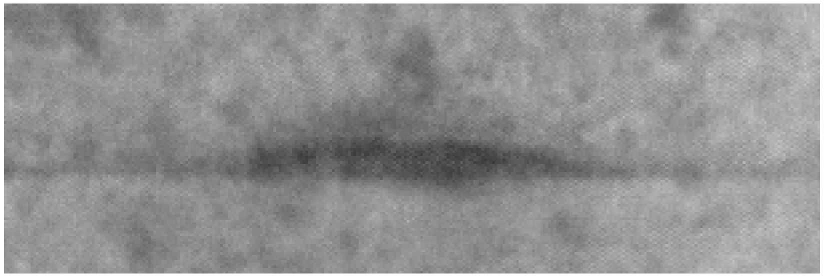
Simpler picture of the electronic level structure based on the fact that the diameter of the dots is typically much larger than the thickness:

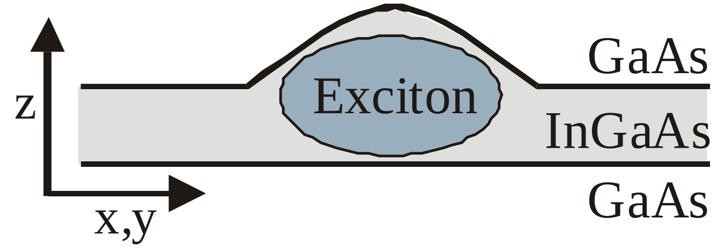
Narrow rectangular potential well in z-direction and parabolic well in x,y direction

Level structure analogue to shell structure of atoms > „artificial atoms“

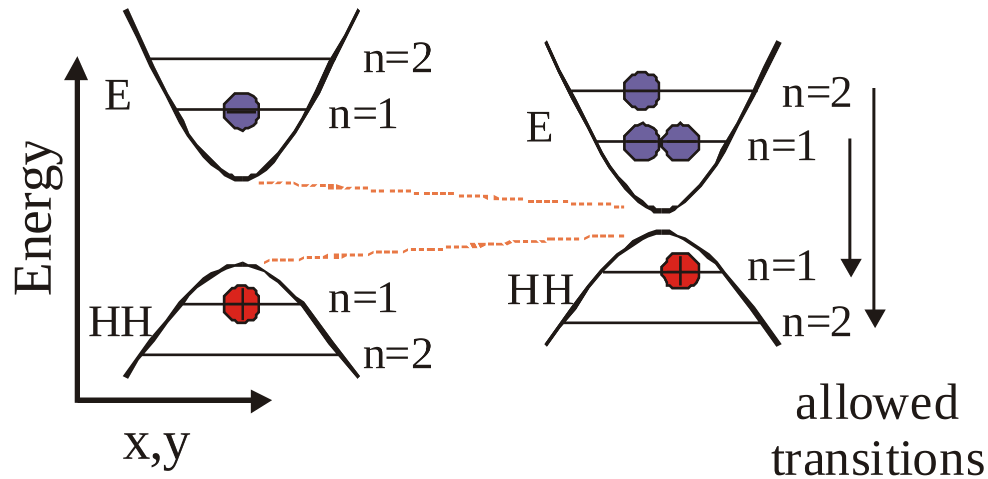
2 electrons in the s-shell, 4 in the p-shell,....





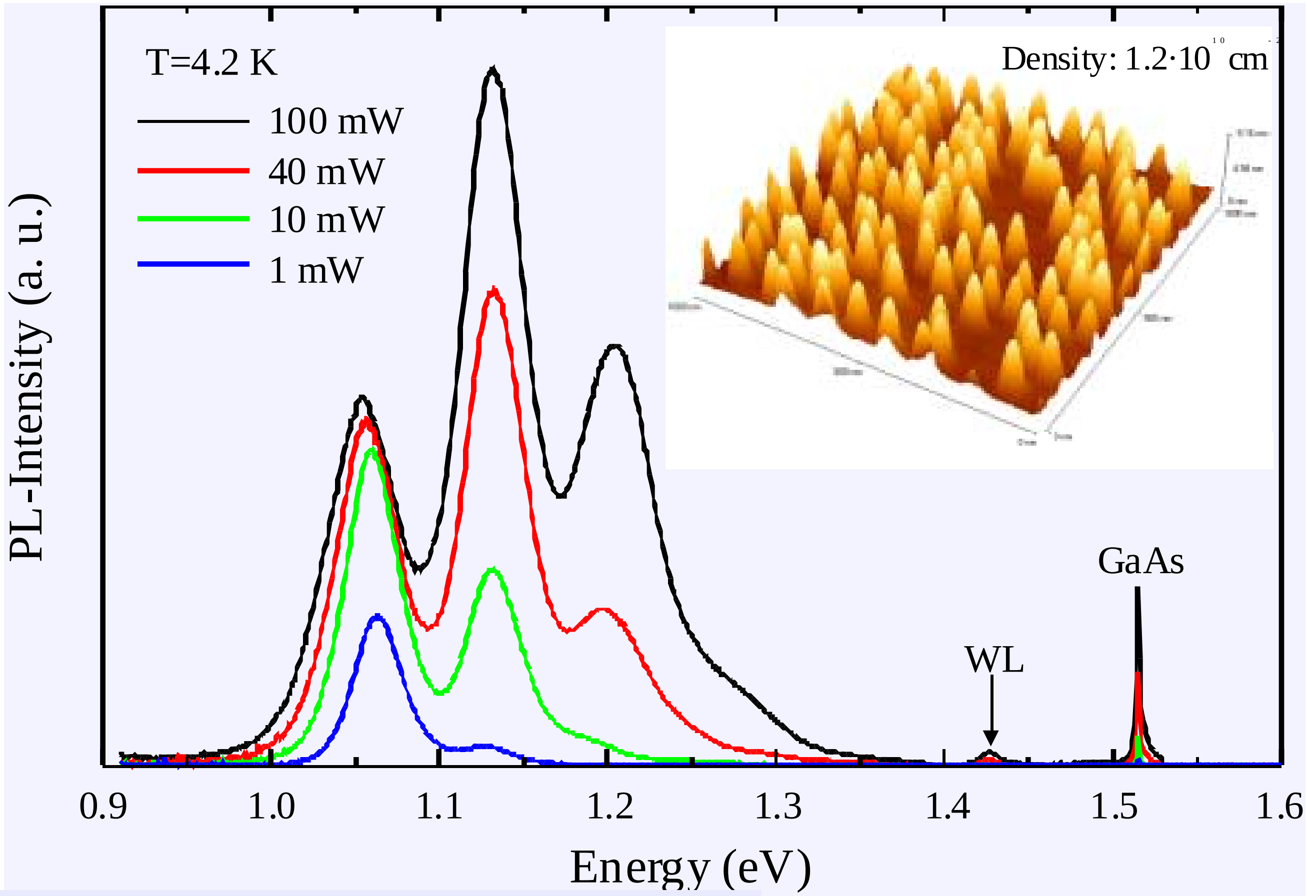


Single particle picture:



ocupation with few carriers: particle-particle interactions determine optical interband transition energies

Photoluminescence studies



- **Discrete recombination energies** ***(shell structure of electronic energy levels)***
- **Inhomogeneous broadening** ***(fluctuations in size, shape and composition)***

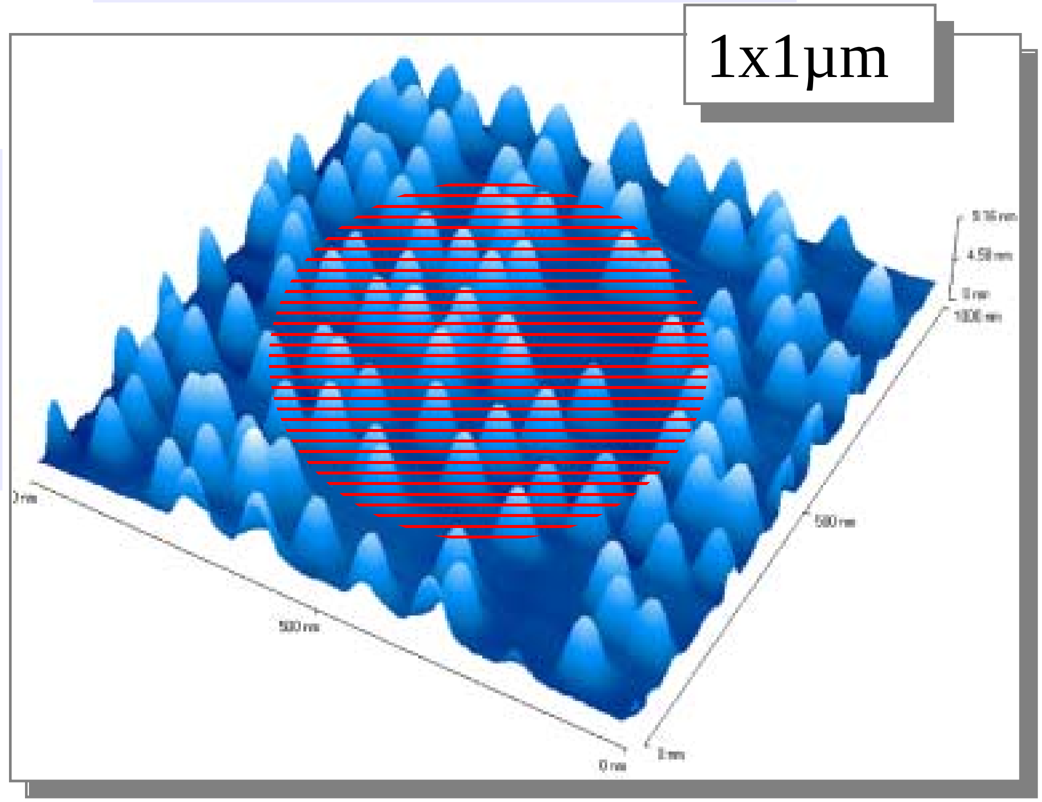
Chu et al., J. Appl. Phys. 75, 2355 (1999)

Towards single dot spectroscopy

Typical areal density 100µm^{-2}

Require low QD density material **and** spatially resovled spectroscopic techniques

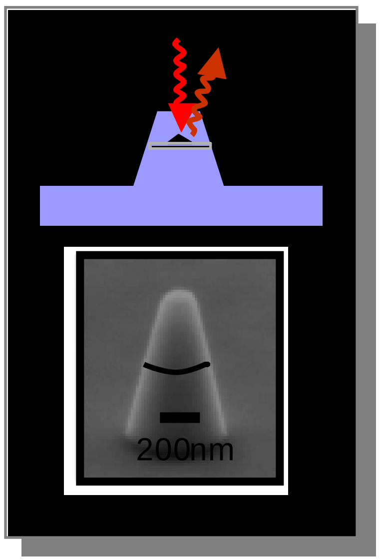
spatially resolved spectroscopy

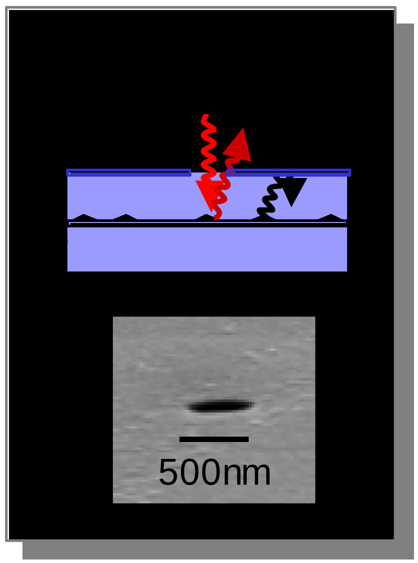


spectroscopy with high spatial reolution

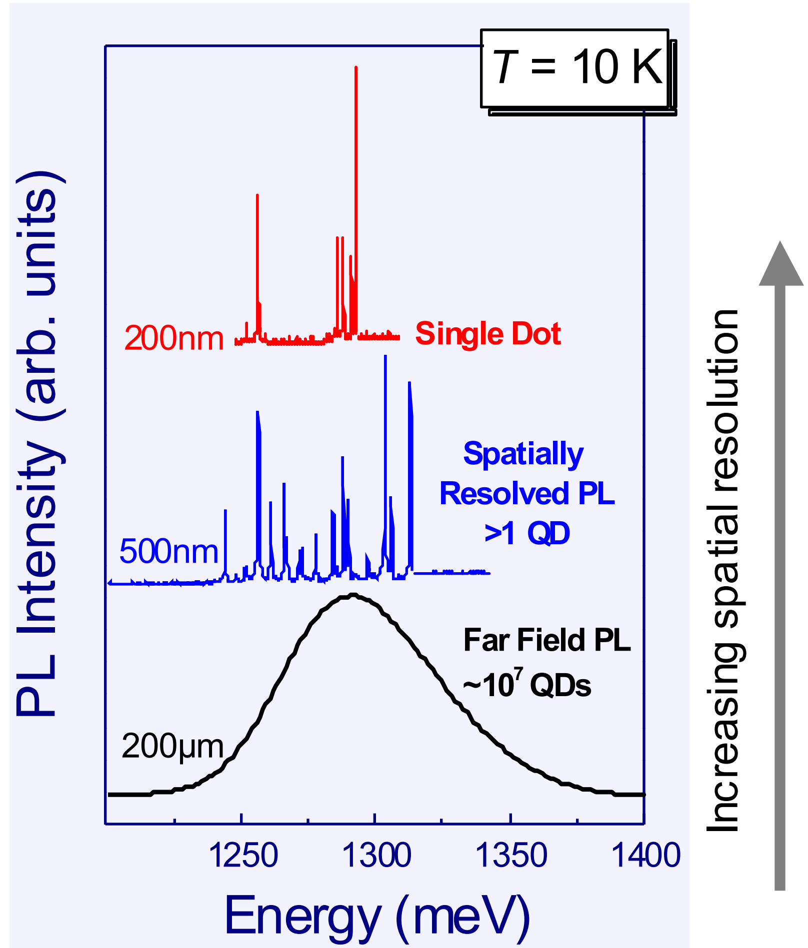
Sub Micron Mesas

Nano Apertures





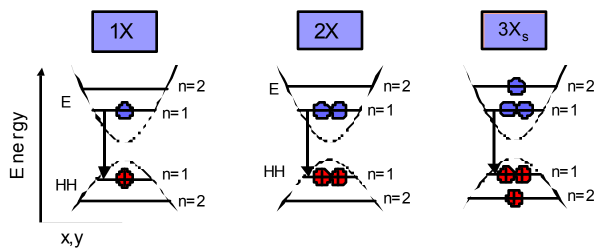
Structures defined by e-beam lithography



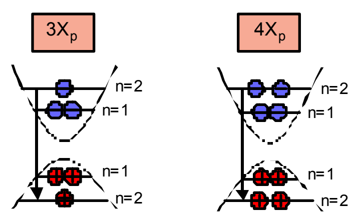
Photoluminescence in the few exciton limit

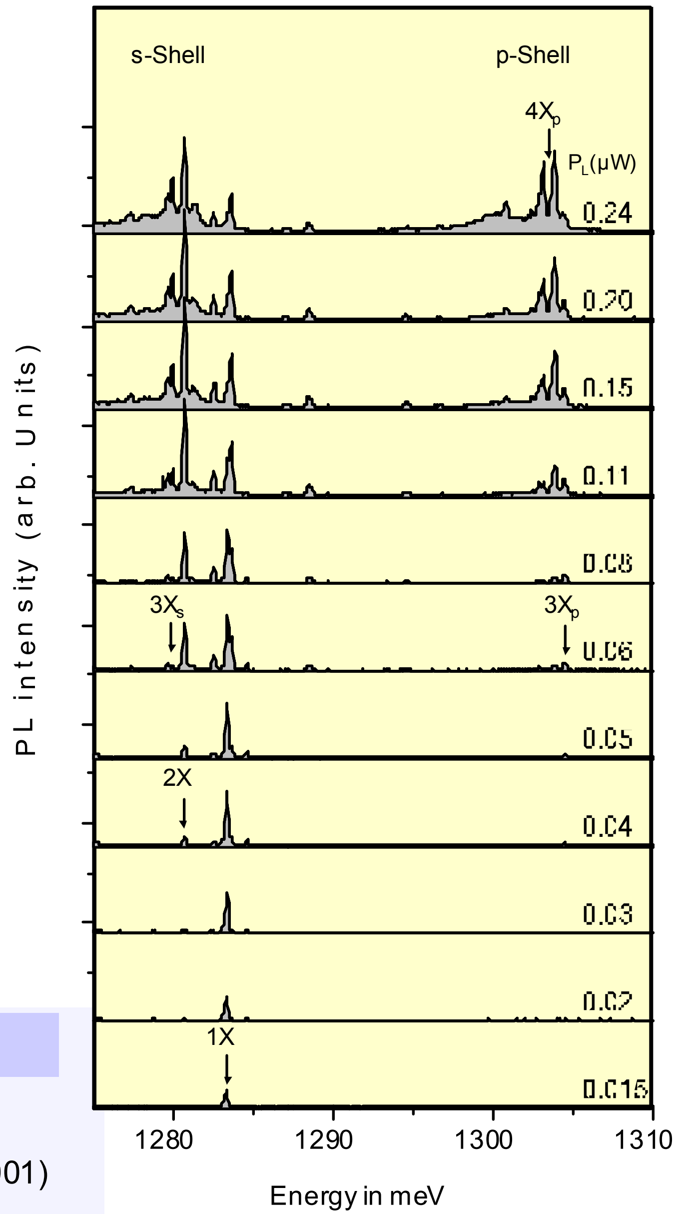
Multi-Exciton States:

s-shell:

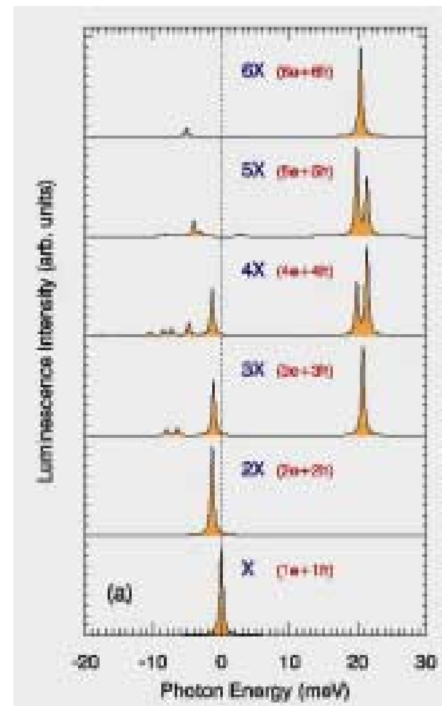


p-shell:





Theory:



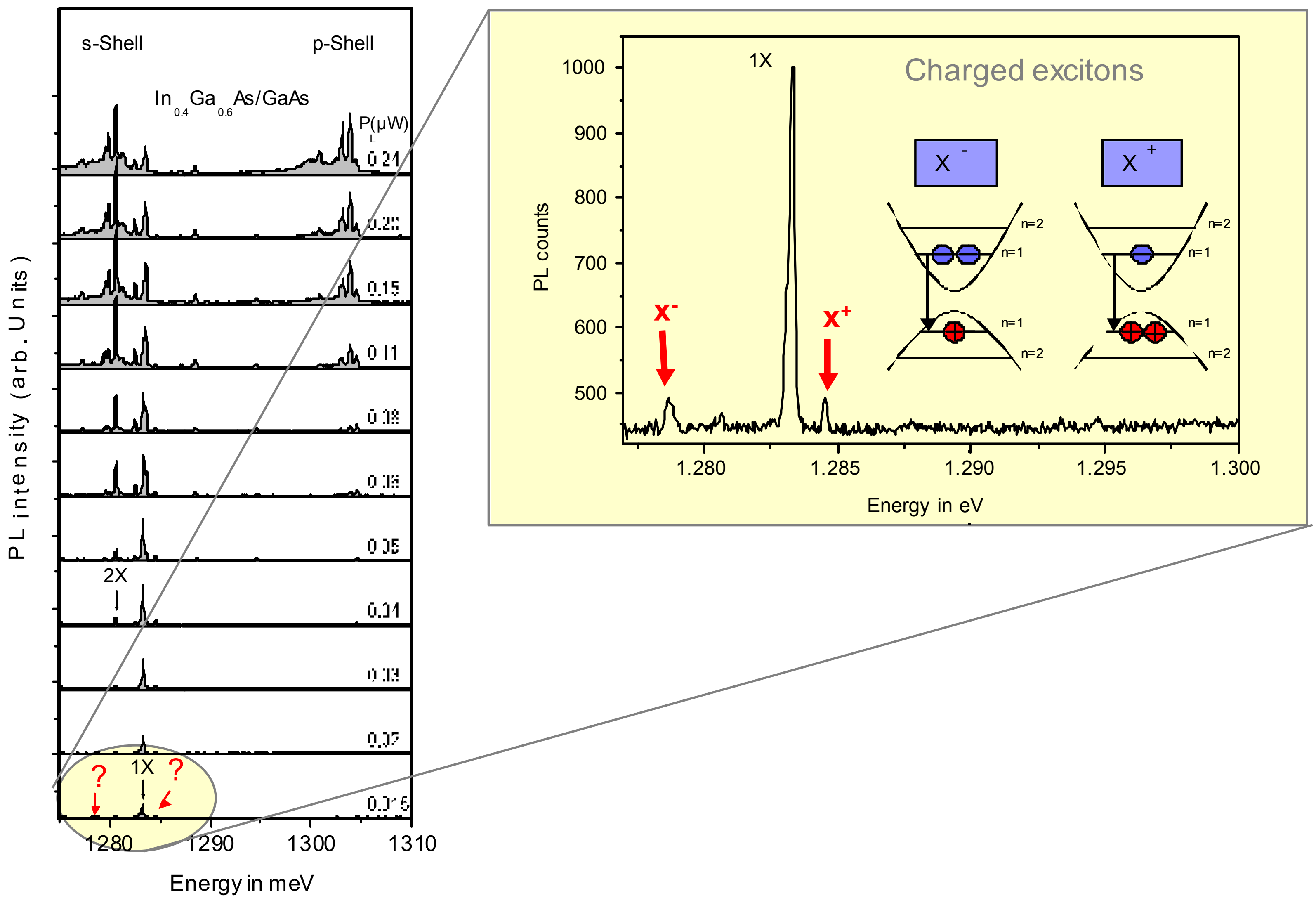
U. Hohenester and
E. Molinari

Findeis et al., SSC 114, 227 (2000)

See also: E. Dekel et al., PRL 80, 4991 (1998)

K. Hinzer, et al., PRB 63, 075314 (2001)

Charged excitons, trions



Pioneering work in single dot spectroscopy

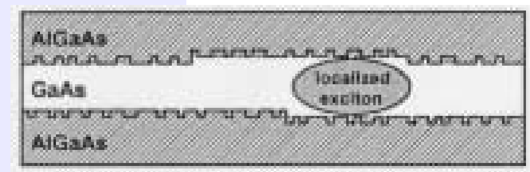
- **localized excitons in narrow quantum wells:**

  K.Brunner et al., PRL **69**, 3216 (1992), PRL **73**, 1138 (1994), APL **64**, 3320 (1994)

  A. Zrenner et al., PRL **72**, 3382 (1994)

  H. G. Hess et al., Science **264**, 1740 (1994)

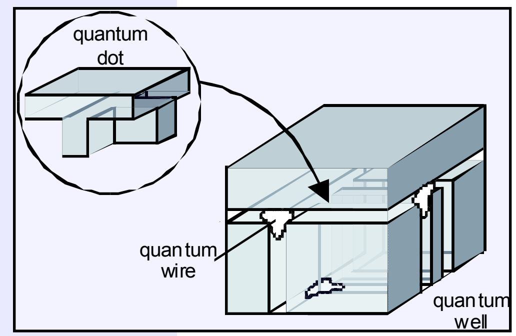
  D. Gammon et al., Science **273**, 87 (1996) and PRL 76, 3005 (1996)



- **cleaved edge overgrowth, coupled dots**

  W. Wegscheider et al., PRL **79**, 1917 (1997)

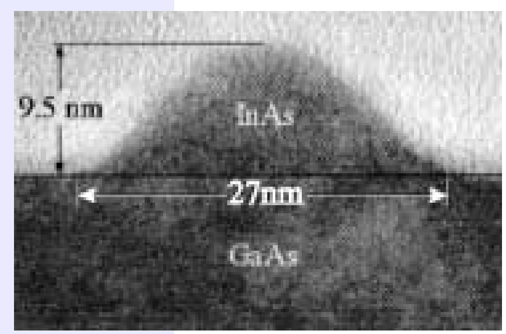
  G. Schedelbeck et al., Science **279**, 1792 (1997)



- **„self-assembled“ quantum dots**

  J.-Y. Marzin et al., PRL **73**, 716 (1994)

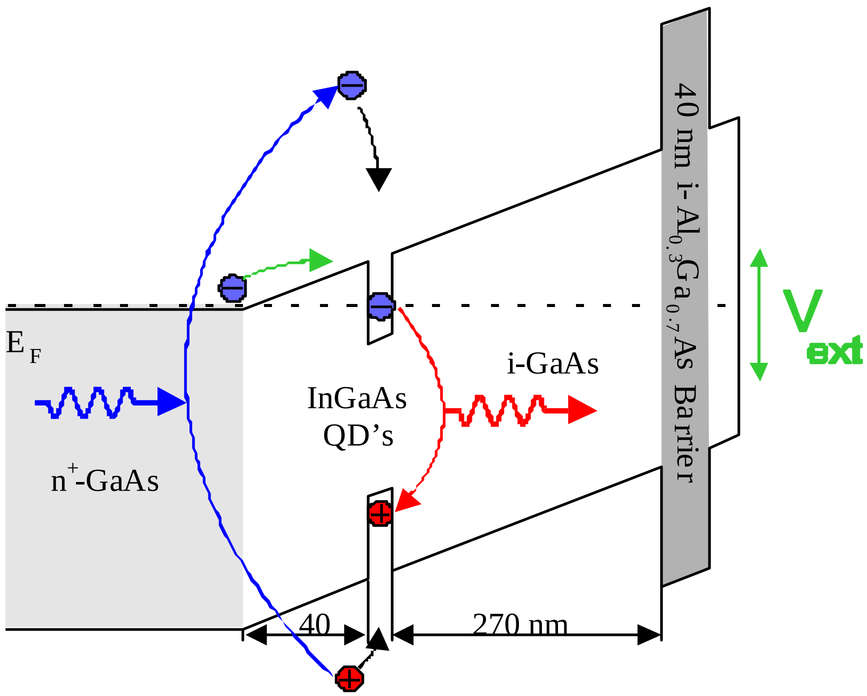
  M. Grundmann et al., PRL 74, 4043 (1995)

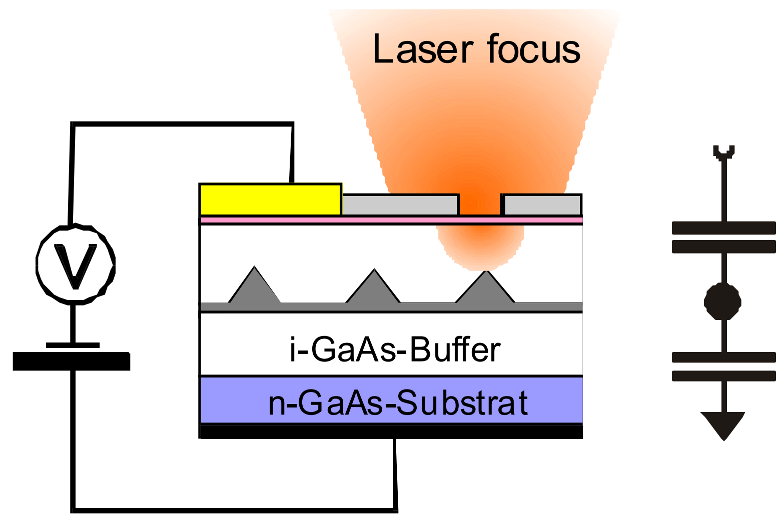


more than 400 publications over the past 6 years:

for an overview see: Proceedings of Int. Conf. On Semiconductor Quantum Dots 2000 and 2002, published in Pysica Status Solidi

Single dot photodiode: control of charges



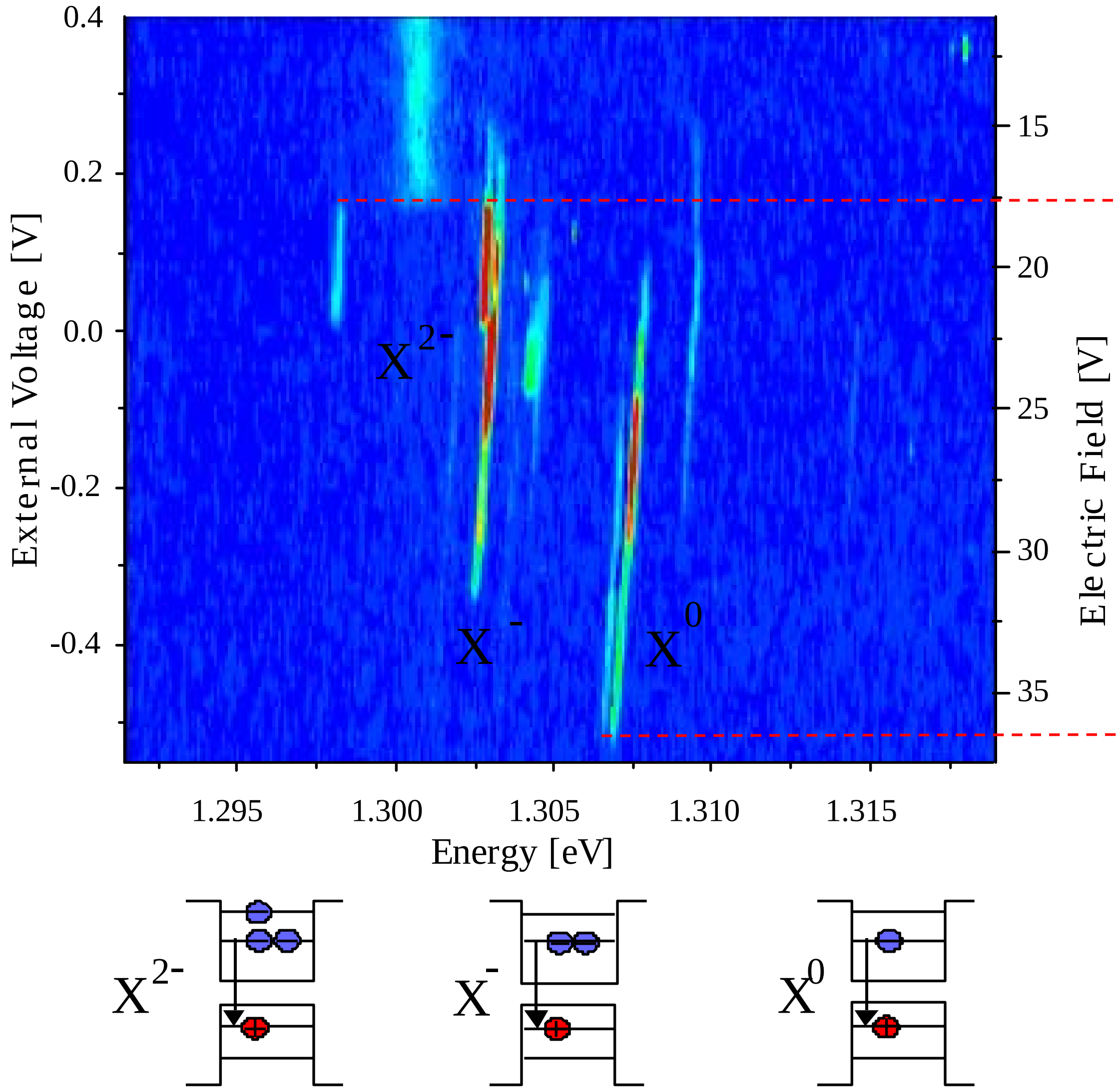


- Single electron charging from the n^+-GaAs back-contact

Coulomb-charging energy:

$C_{QD} \sim 5 \times 10^{-18}$ F $\rightarrow$ $E_c \sim 20$ meV

see e.g. Drechsler et al. PRL 94



WL filled with electrons

- Single electron charging: neutral, single and double charged single exciton states

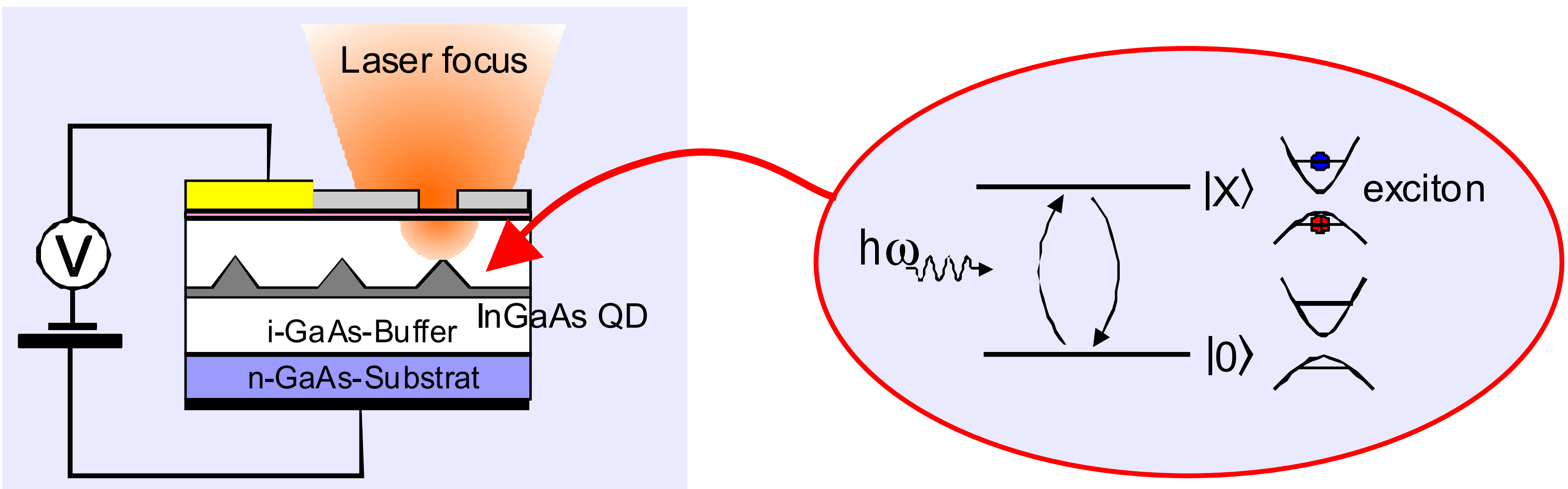
- Tunnel escape of the carriers before recombination
  => Photocurrent regime

Findeis et al, PRB 63, R121309, (2001)

Similar work: Warburton et al., Nature 2000, Finley et al. PRB 2001, Hartmann et al. PRL 2000, ………

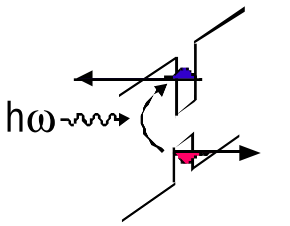
Resonant excitation

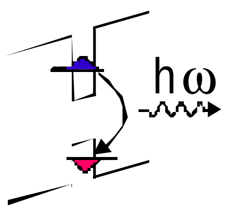
Single QD photodiode ≙ Electrically contacted two-level system

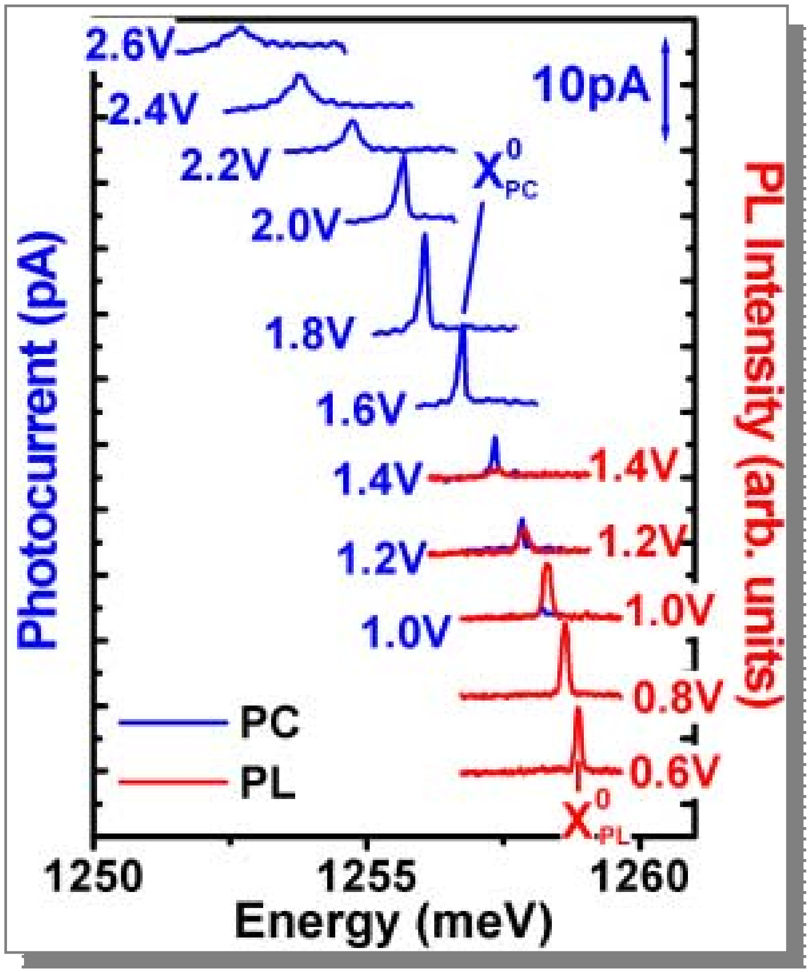


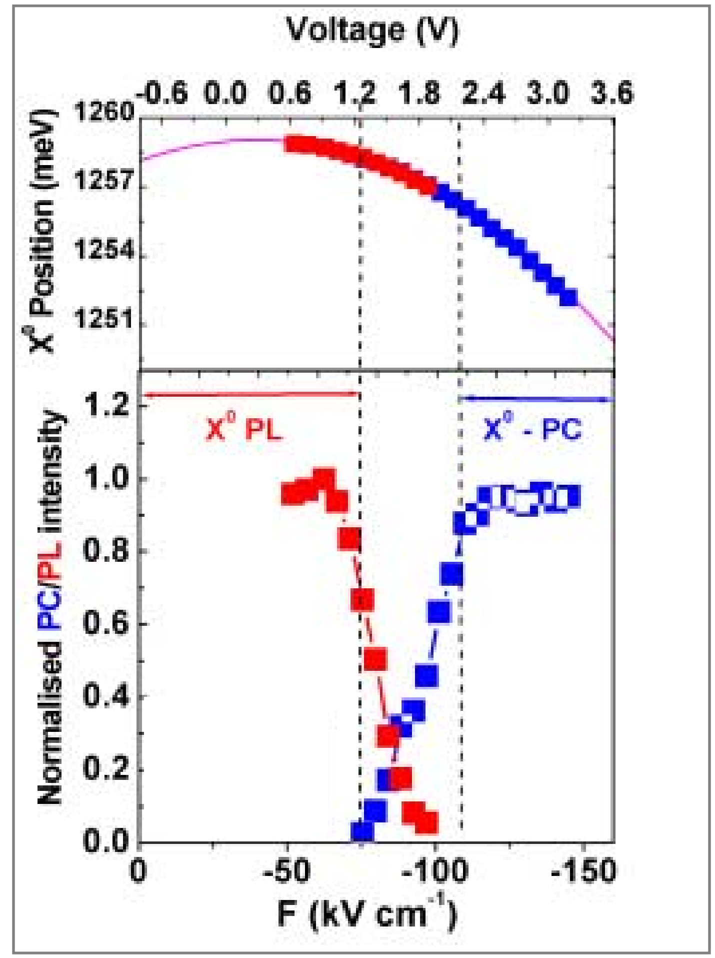
- Optical excitation of a single QD exciton
- Carrier-tunneling and photocurrent detection

PL versus photocurrent







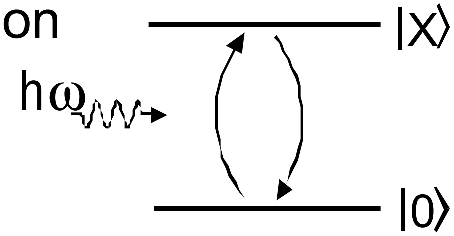


Oulton et al., PRB 66, 45313 (2002)

driving a two-level system

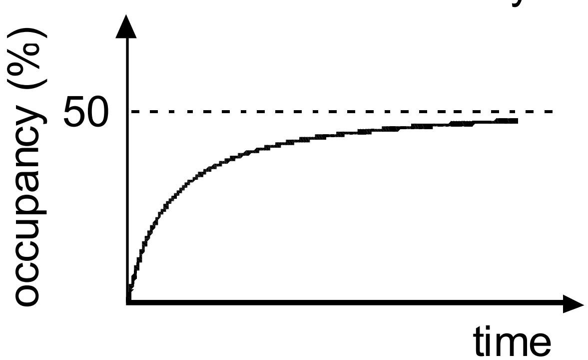
Incoherent regime

cw excitation



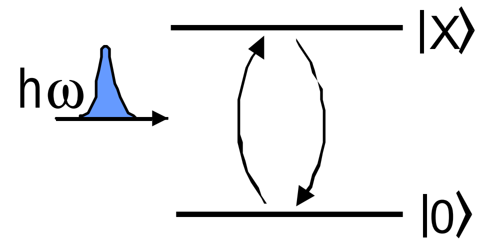
experimental timescales > dephasing time

50% maximum inversion of the two-level system

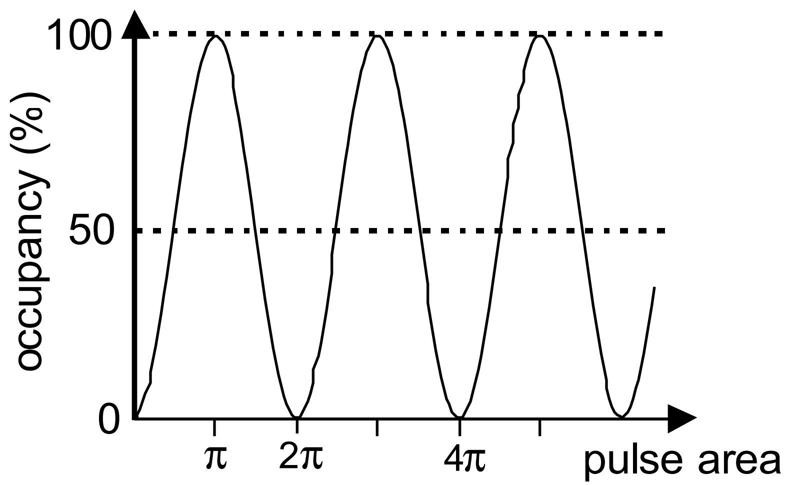


Coherent regime

excitation with ps-pulses



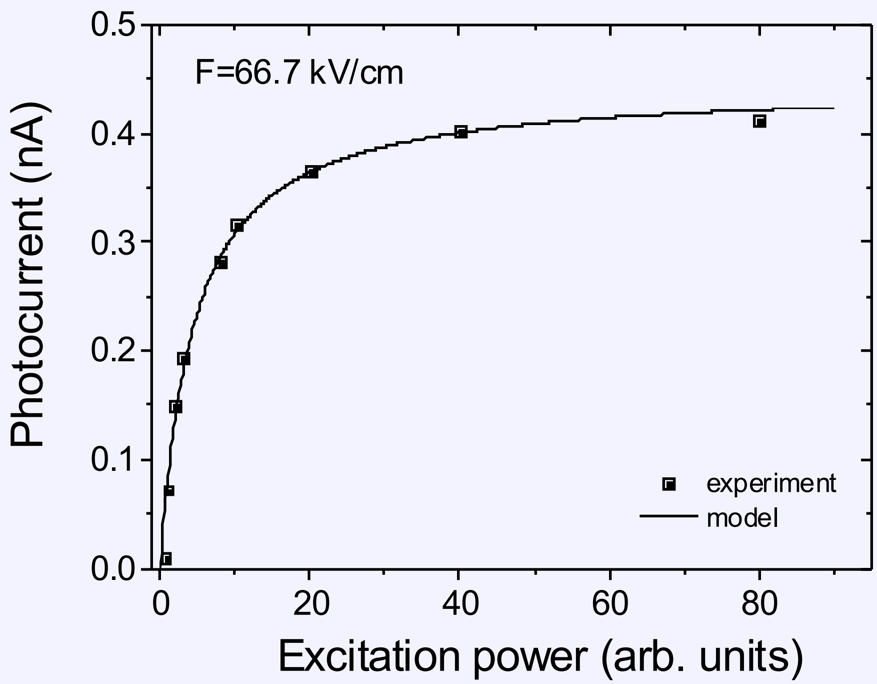
Pulse length < dephasing time



Incoherent regime:

→ **Two-level system driven into saturation**

→ **Tunable escape time of the carriers**

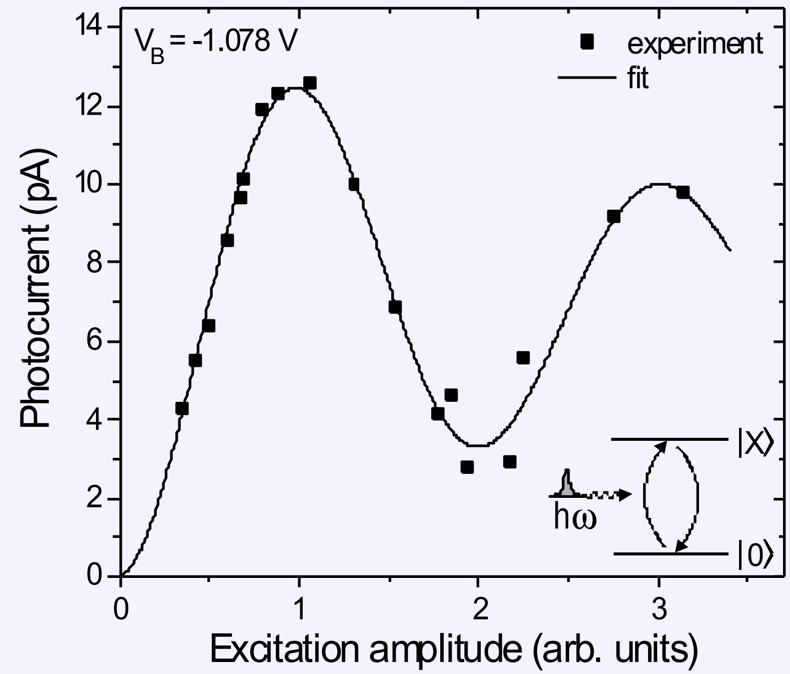


E. Beham et al, Appl. Phys. Lett. 79, 2808 (2001)

Coherent regime:

→ **Rabi-oscillations of the QD PC**

→ **deterministic current source**



A. Zrenner et al., Nature 418, 612 (2002)

"all optical" work in QDs:

T. H. Stievater et al., Phys. Rev. Lett. 87, 133603 (2001).
H. Kamada et al., Phys. Rev. Lett. 87, 247401 (2001).
H. Htoon et al., Phys. Rev. Lett. 88, 087401 (2002).
P. Borri et al., PRB 66, 081306 (2002)

Single dot photodiode: a two-level system with contacts

Photocurrent $I = L(A_{exc}) \cdot e \cdot f$

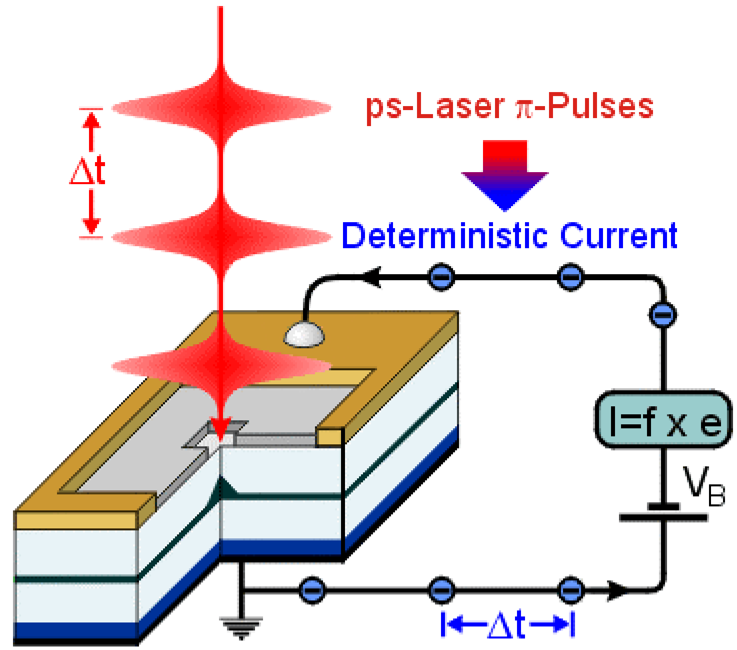
- Theoretical limitation for maximum photocurrent:

excitation with π-pulse: $L(A_{exc})=1$ ⇒ Inversion of the two-level system ⇒ one e-h-pair per pulse ⇒ $I_{max} = e \cdot f = 13.1$ pA

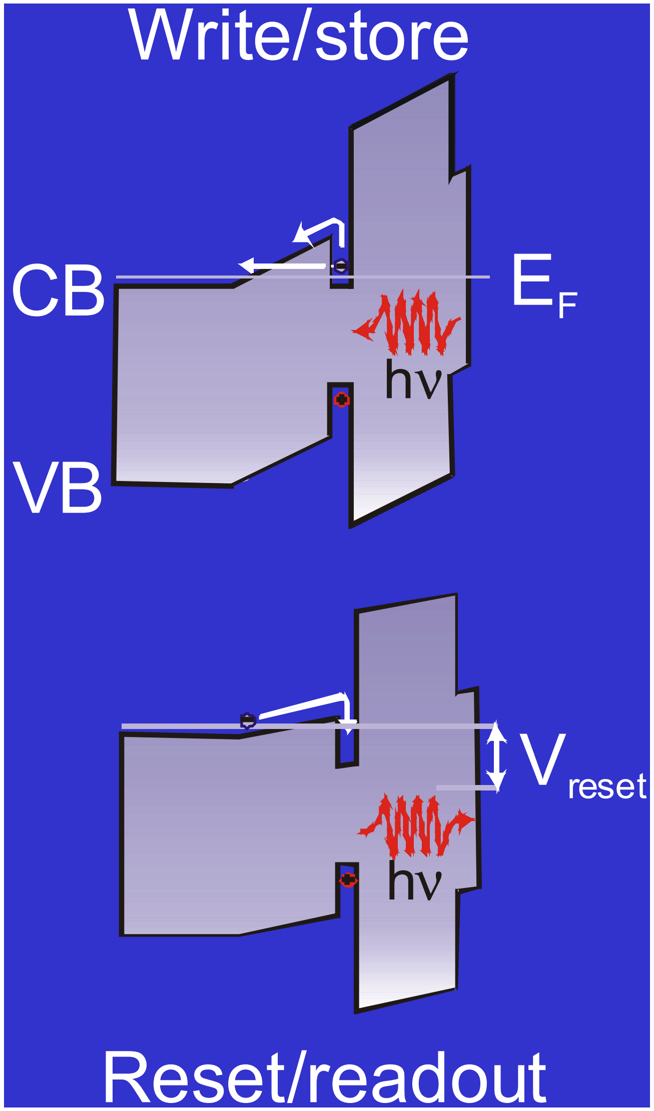
f=82 MHz (laser repetition rate)

- Experimentally: **(12.3 ± 0.5) pA**

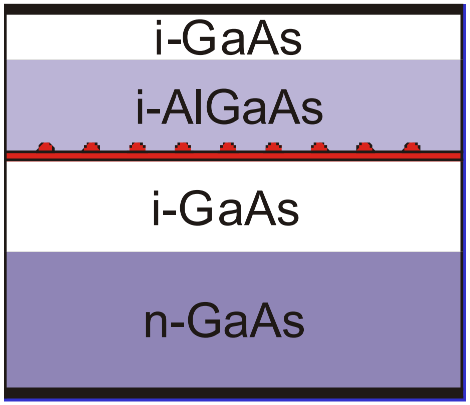
⇒
- Quantitative proof for Rabi-flopping
- QD acts as deterministic current source
- Optically triggered single electron turnstile effect



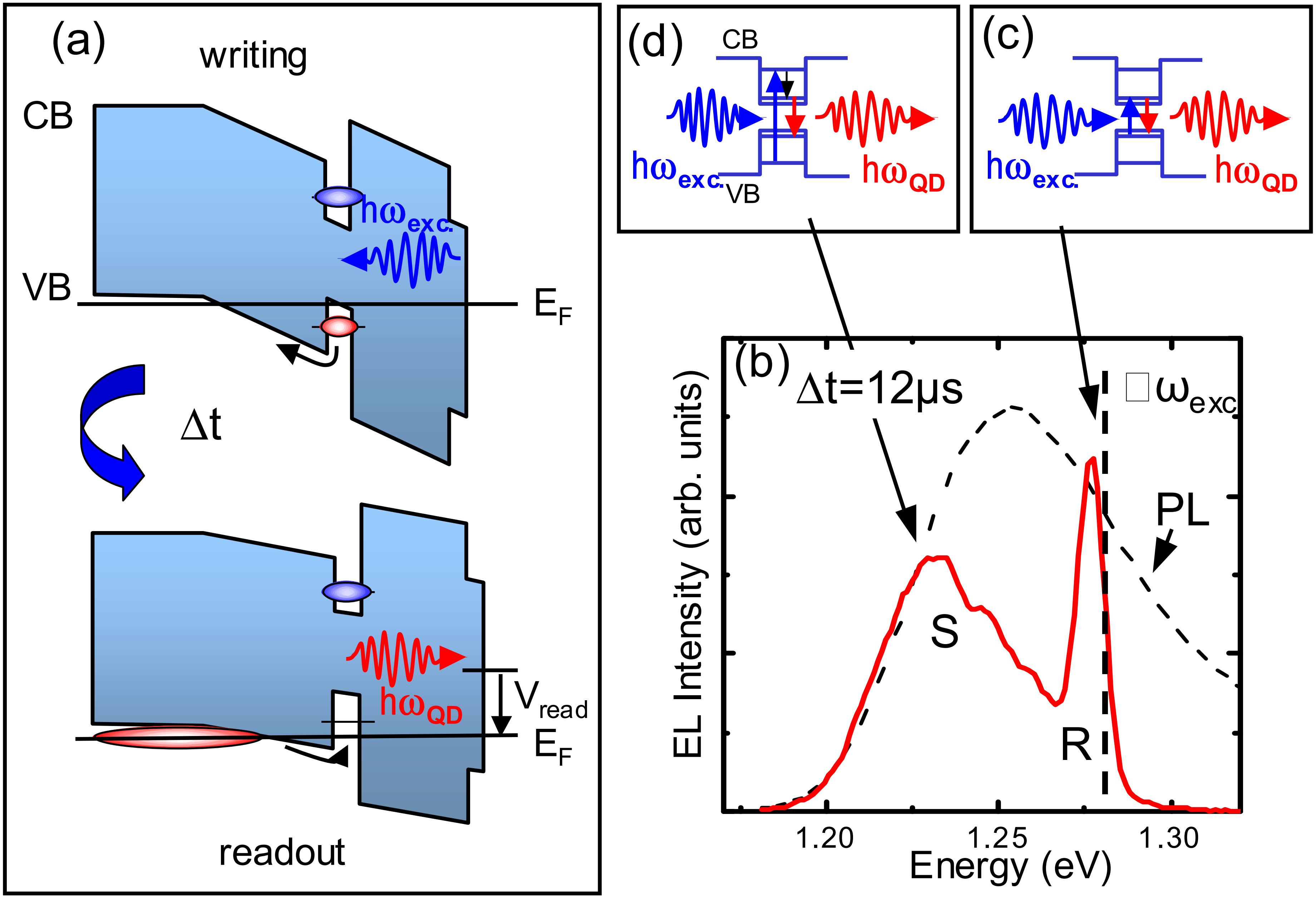
Charge storage in self-assembled dots

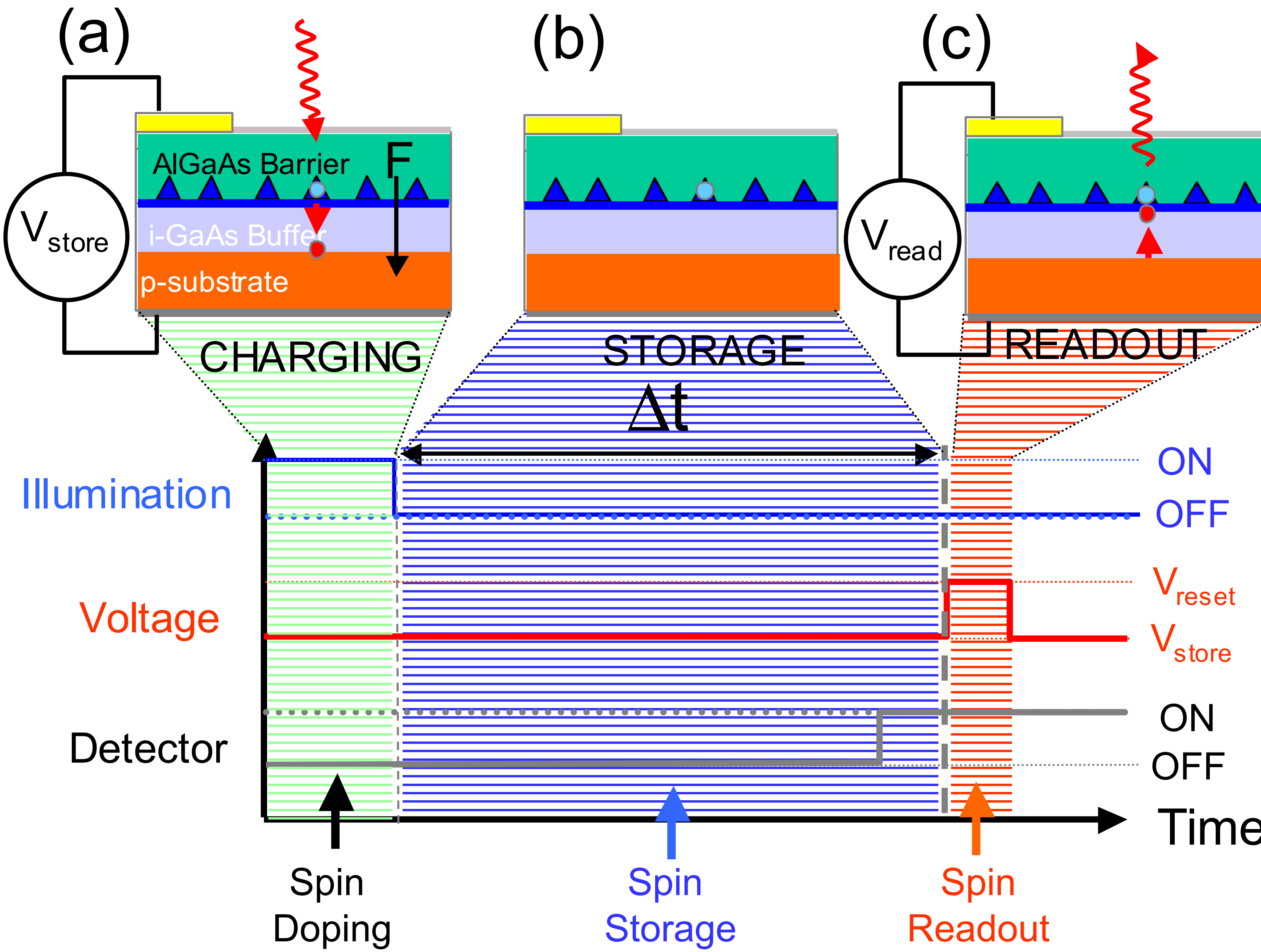


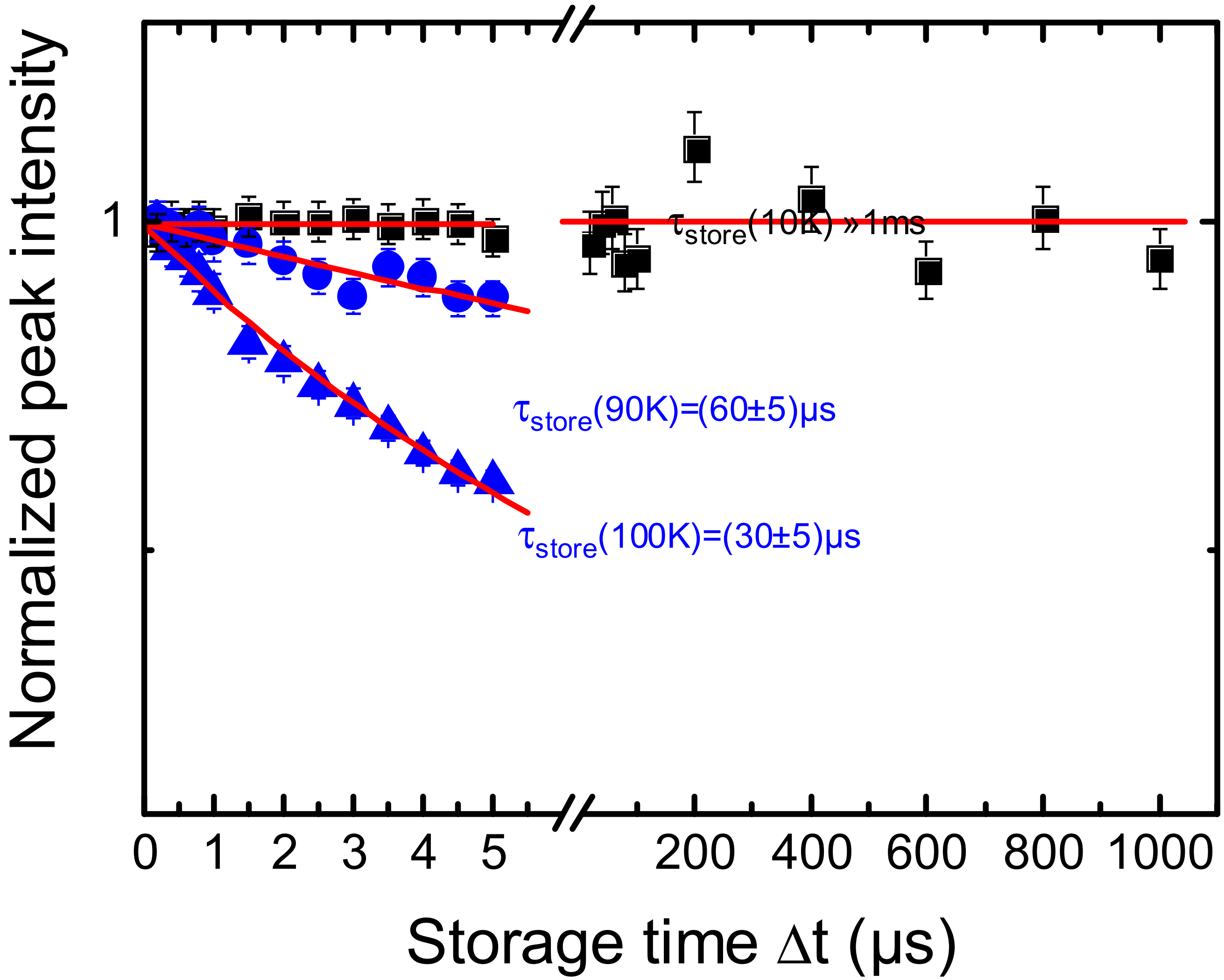
n-i-hetero-Schottkydiode for hole storage



p-i-hetero-Schottkydiode for electron storage


(a)
writing
CB
hω exc.
VB
E F
Δt
hω QD
V read
E F
readout
(d)
CB
hω exc.
VB
hω QD
(c)
hω exc.
hω QD
(b)
Δt=12μs
ω exc
PL
S
R
EL Intensity (arb. units)
1.20
1.25
1.30
Energy (eV)

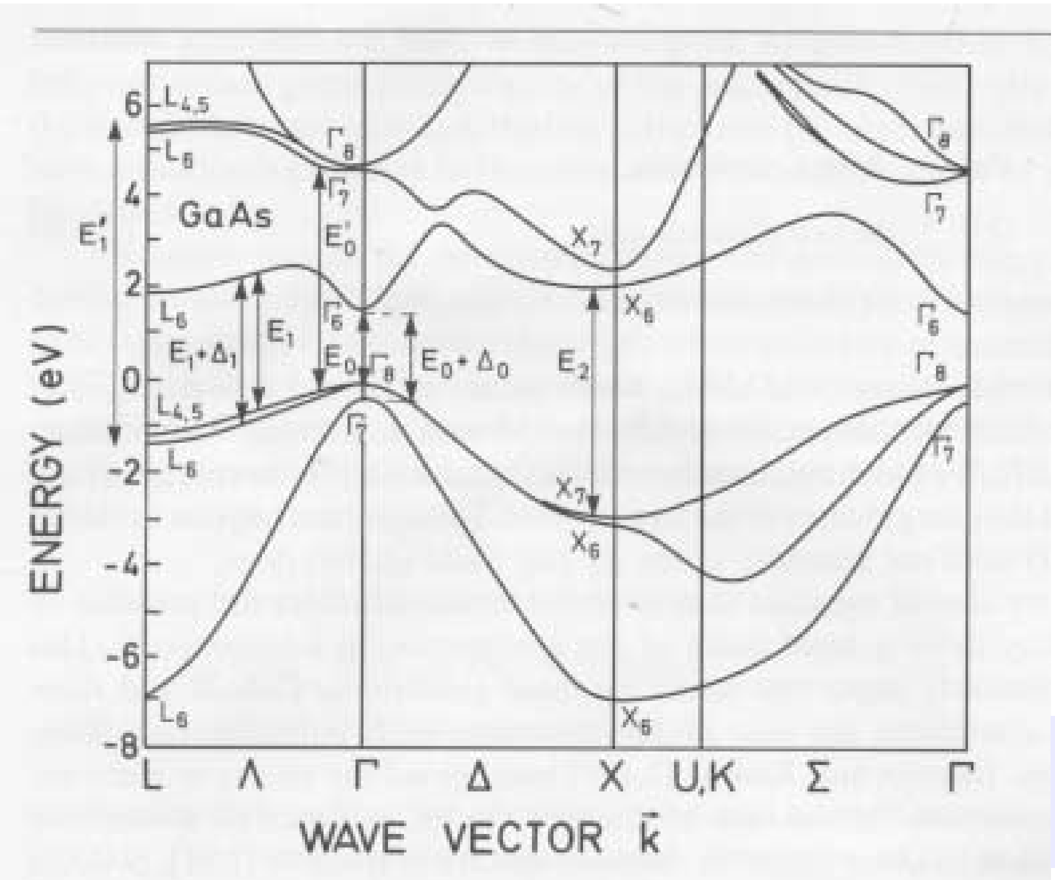

(a)
(b)
(c)
AlGaAs Barrier
F
V store
i-GaAs Buffer
p-substrate
V read
CHARGING
STORAGE
Δt
READOUT
Illumination
ON
OFF
Voltage
V reset
V store
Detector
ON
OFF
Time
Spin Doping
Spin Storage
Spin Readout

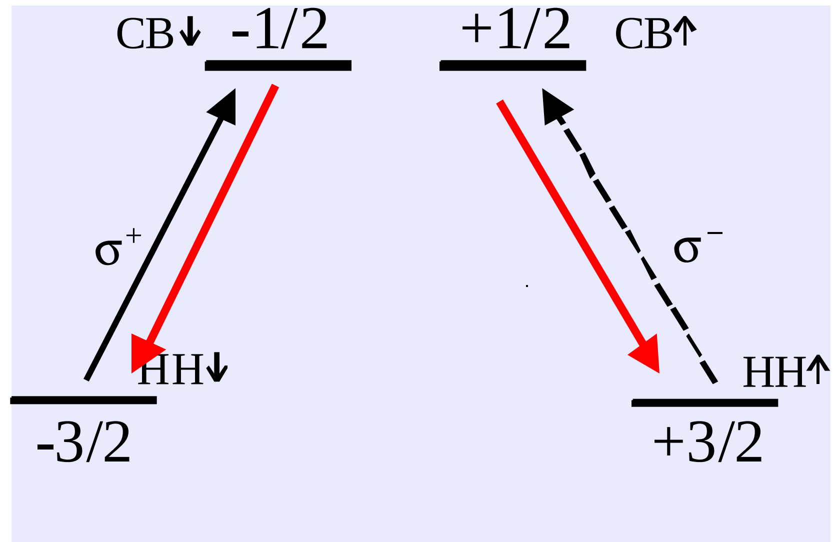

Normalized peak intensity
1
τstore(10K) »1ms
τstore(90K)=(60±5)μs
τstore(100K)=(30±5)μs
0 1 2 3 4 5 200 400 600 800 1000
Storage time Δt (μs)

Spin storage based on optical selection rules

GaAs bandstructure

energy levels in QDs

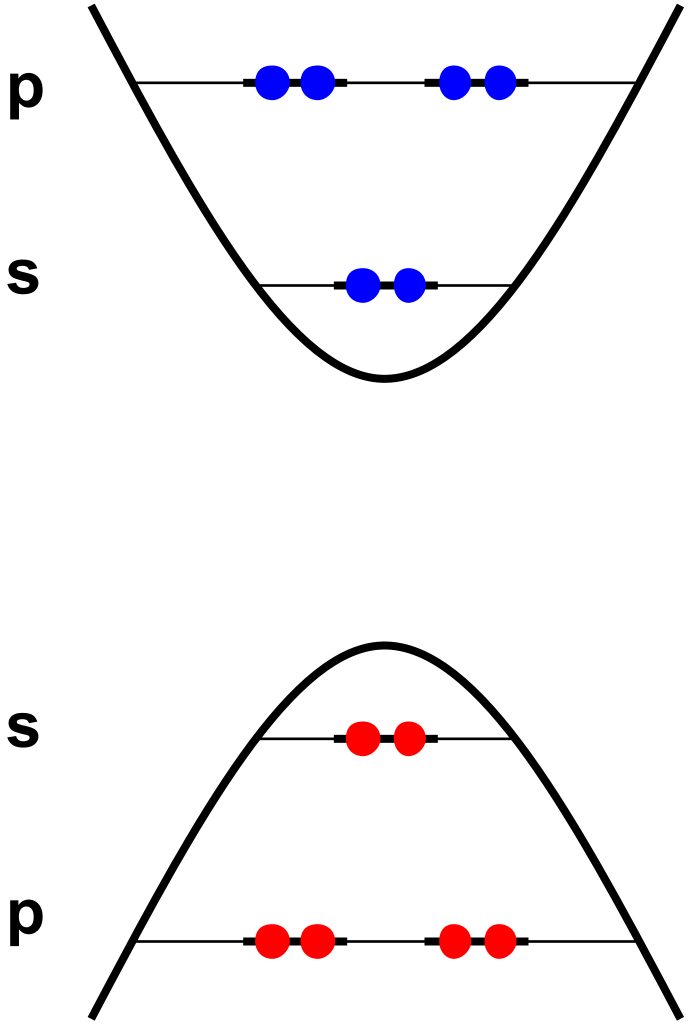


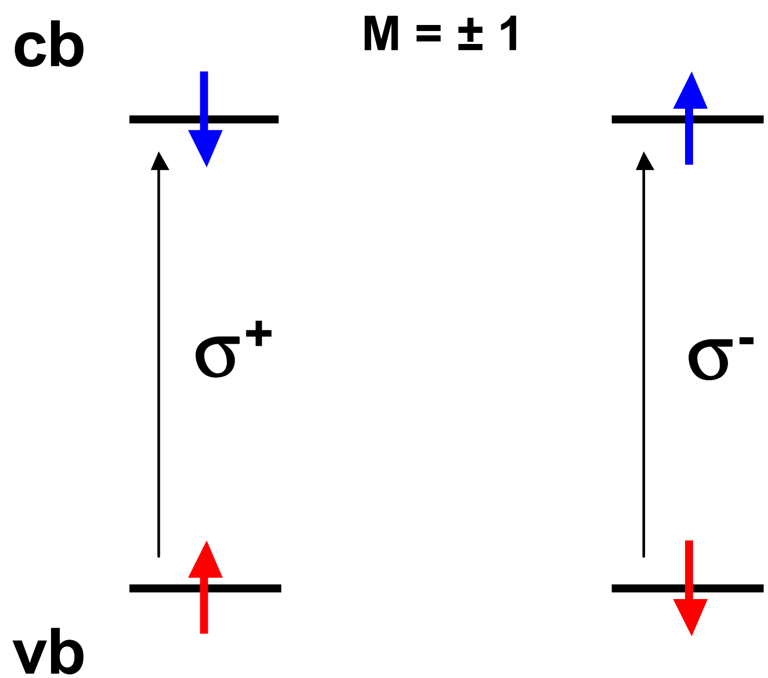


heavy hole – light hole splitting in quantum dots

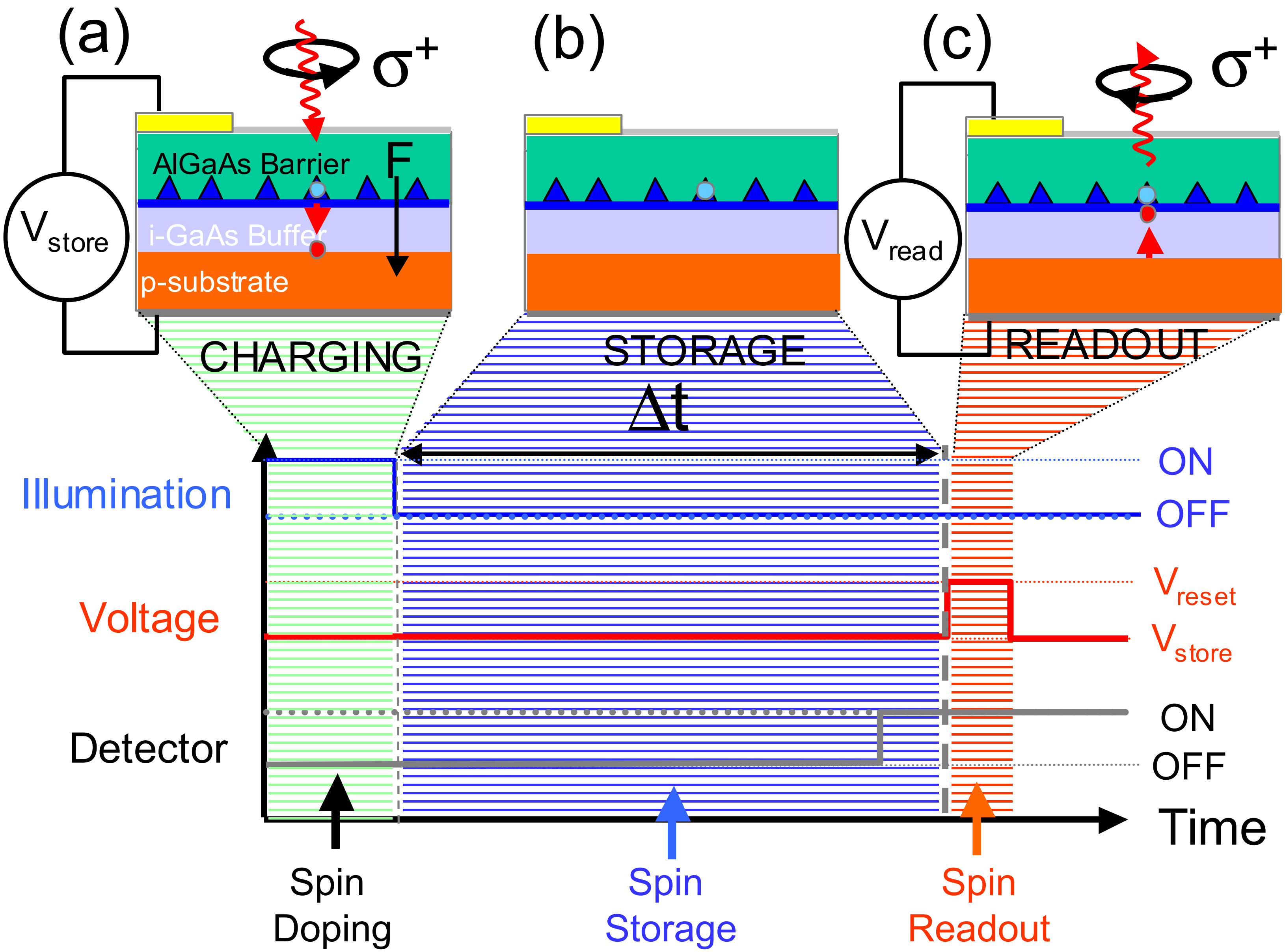
Electrons: $J_{e,z} = \pm 1/2$

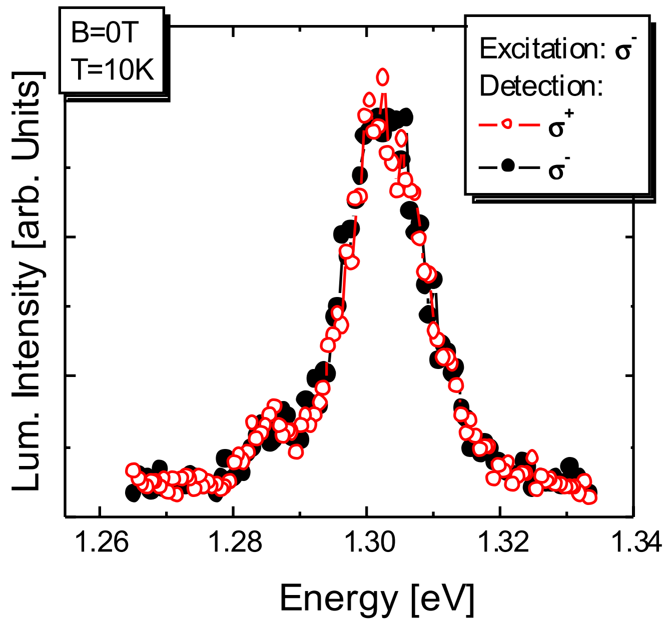
Heavy holes: $J_{h,z} = \pm 3/2$



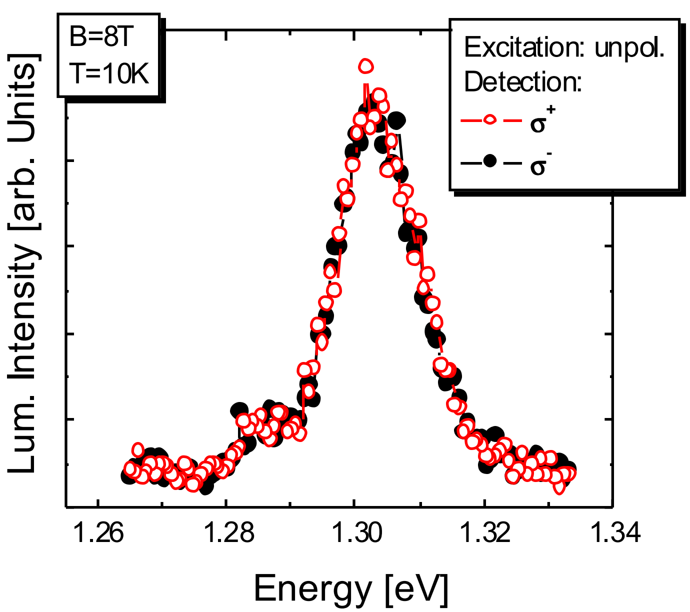


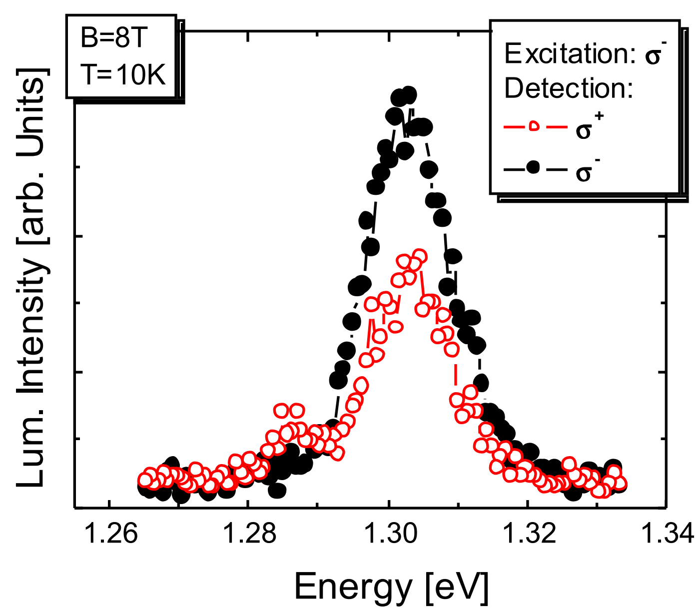
Operation principle



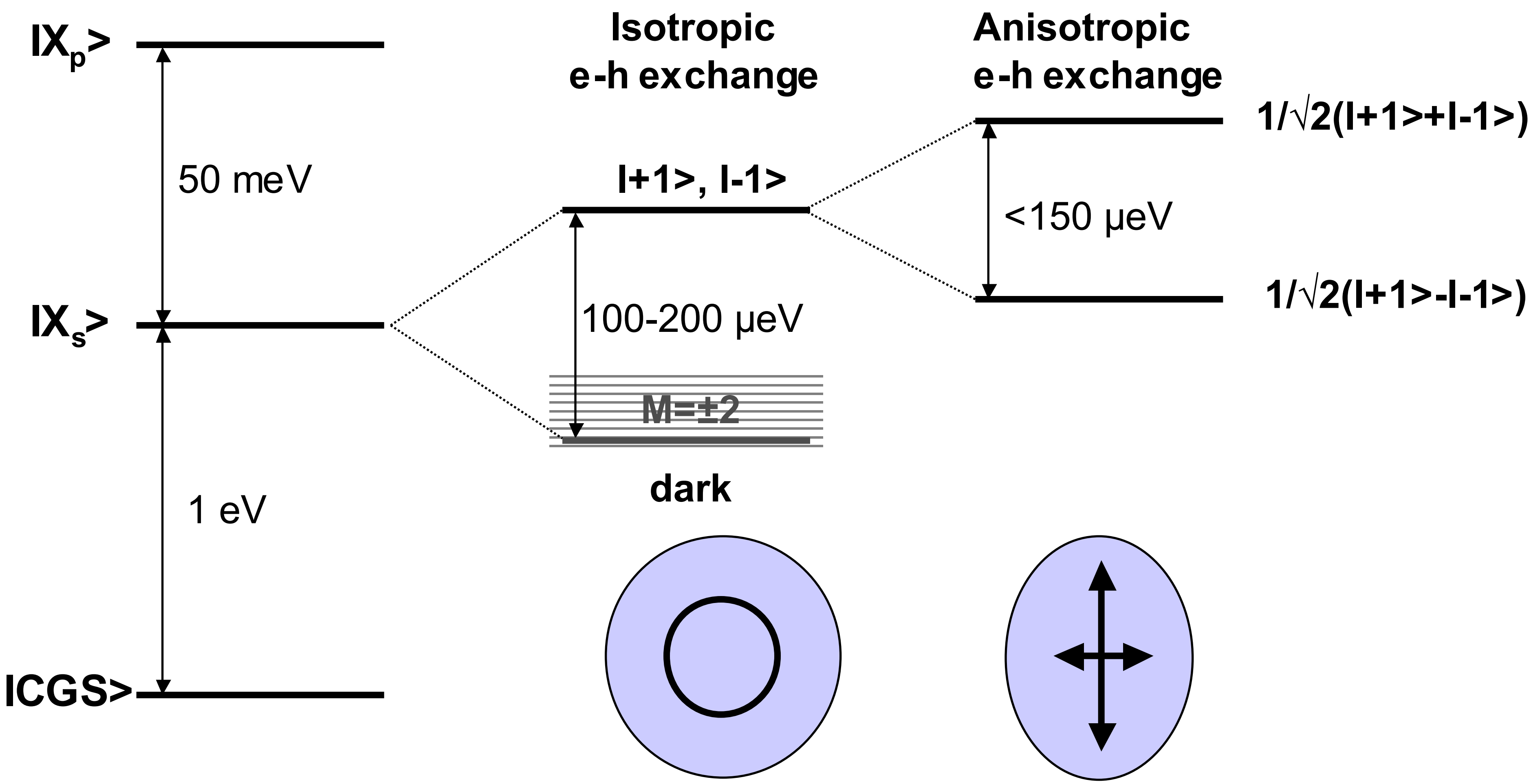

B=0T
T=10K
Excitation: σ-
Detection:
σ+
σ-
Lum. Intensity [arb. Units]
1.26
1.28
1.30
1.32
1.34
Energy [eV]

$\Delta t = 1\mu s$

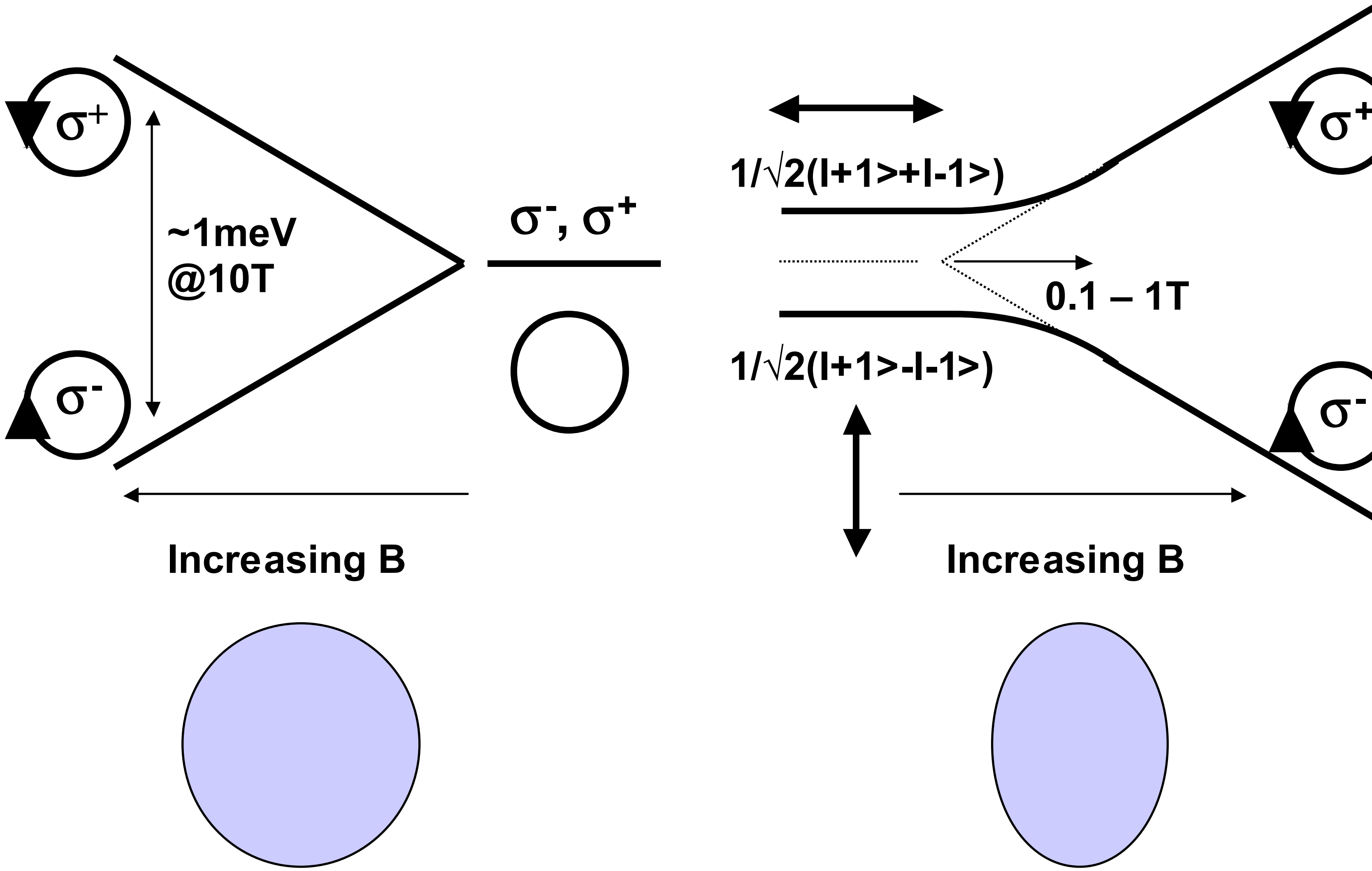

B=8T
T=10K
Excitation: unpol.
Detection:
σ+
σ-
Lum. Intensity [arb. Units]
1.26
1.28
1.30
1.32
1.34
Energy [eV]

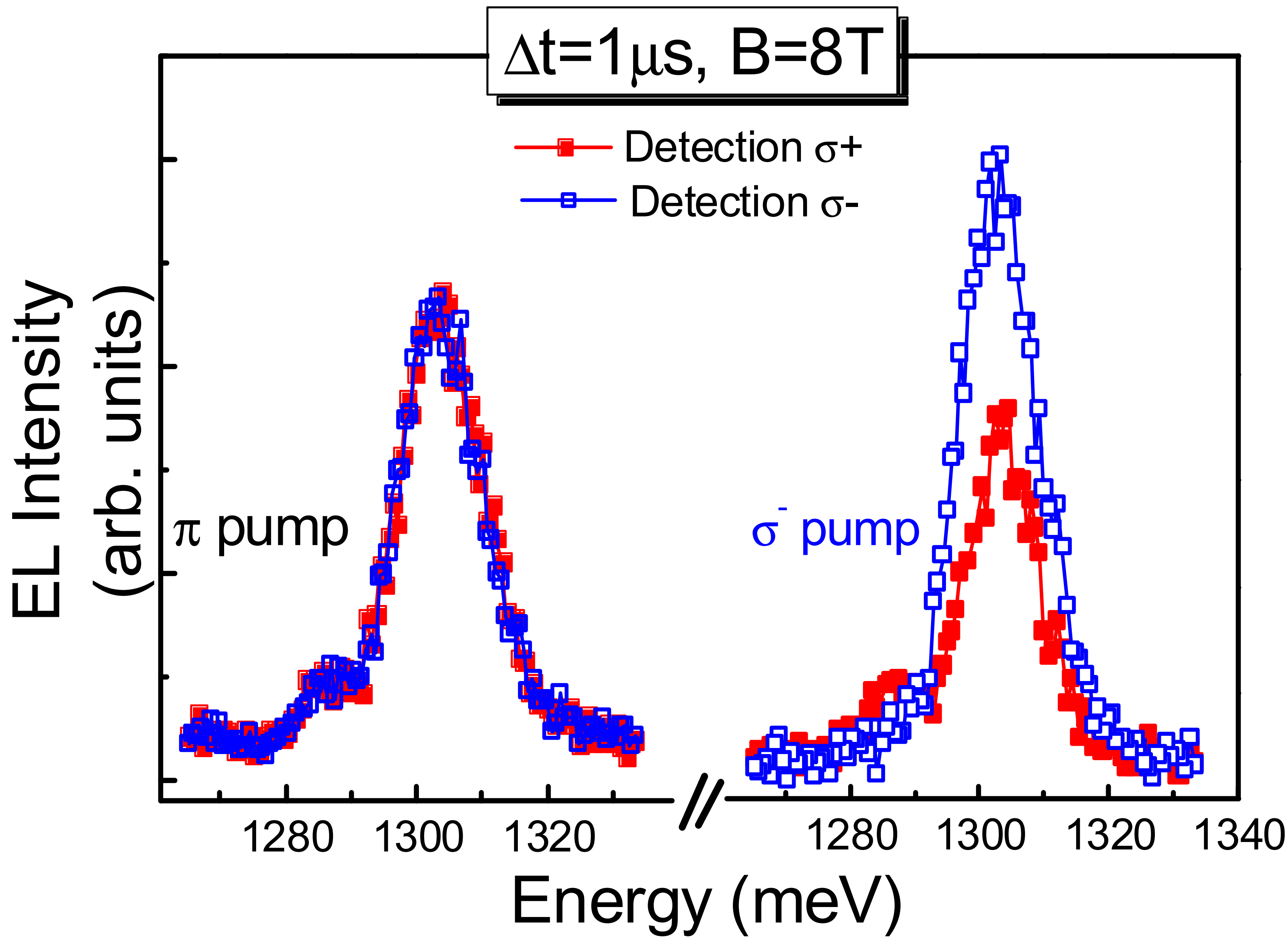

B=8T
T=10K
Excitation: σ-
Detection:
σ+
σ-
Lum. Intensity [arb. Units]
1.26
1.28
1.30
1.32
1.34
Energy [eV]

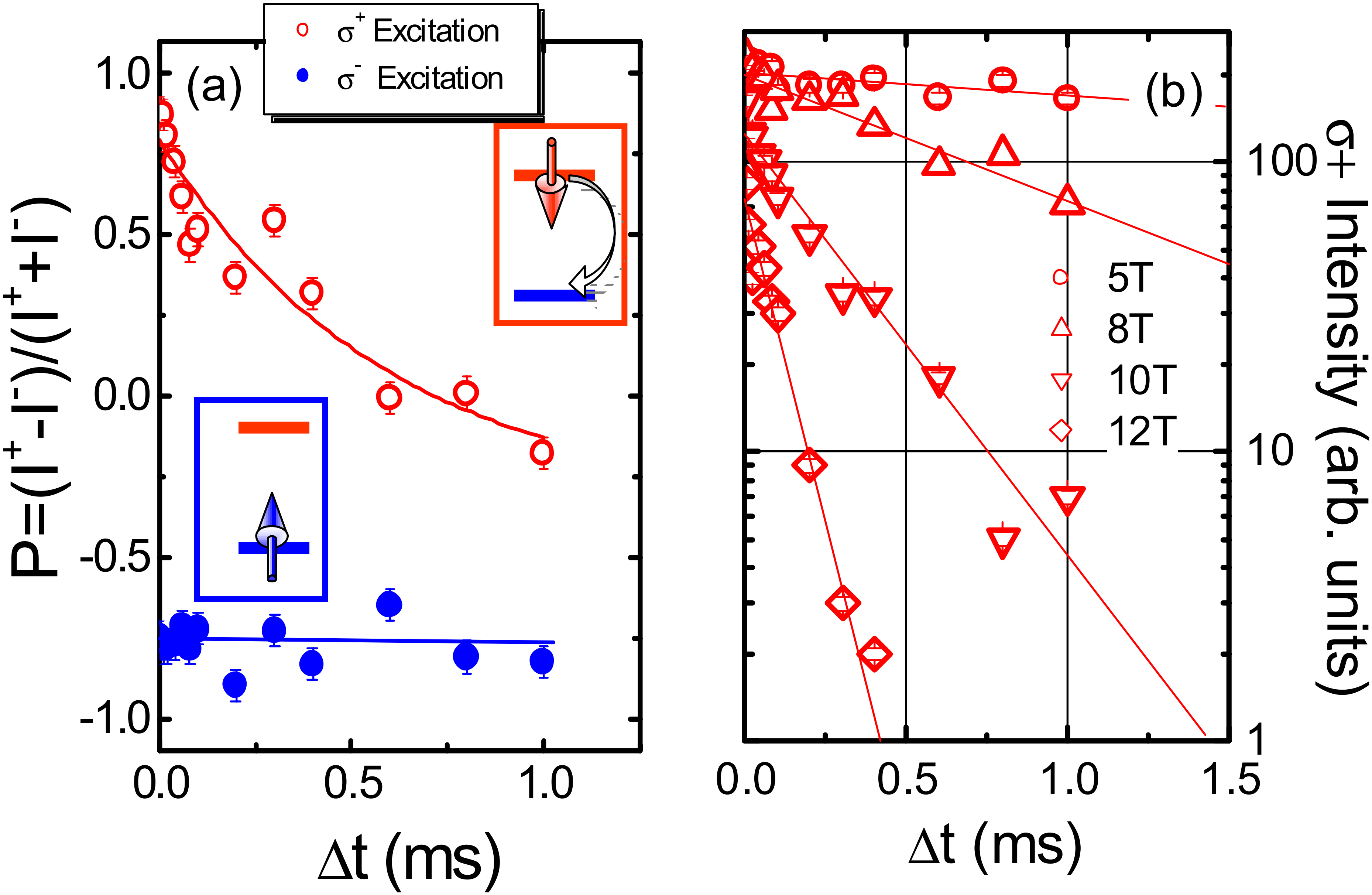
Exchange splitting



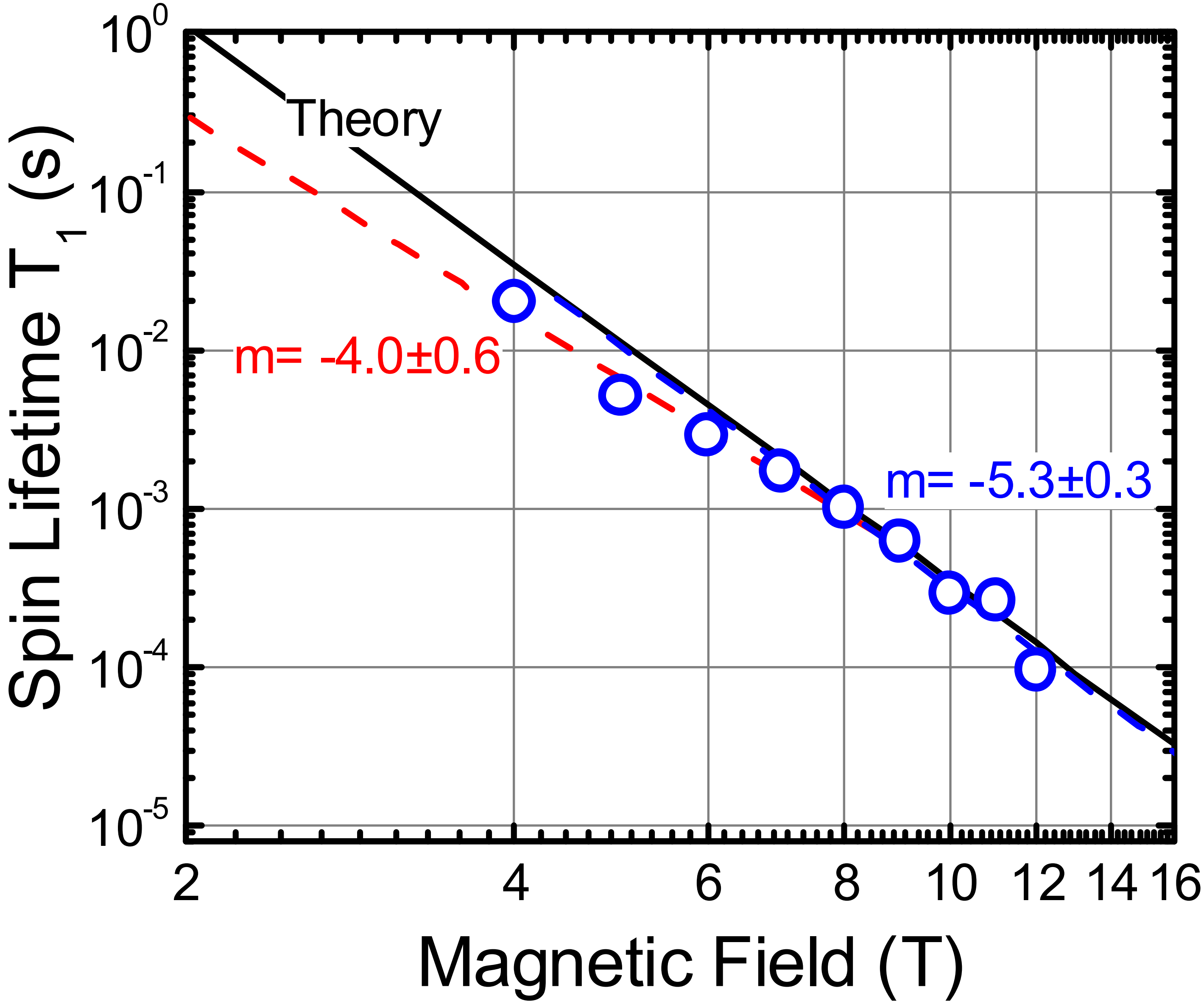
Zeemann splitting




Δt=1μs, B=8T
Detection σ+
Detection σ-
EL Intensity
(arb. units)
π pump
σ- pump
1280
1300
1320
1280
1300
1320
1340
Energy (meV)

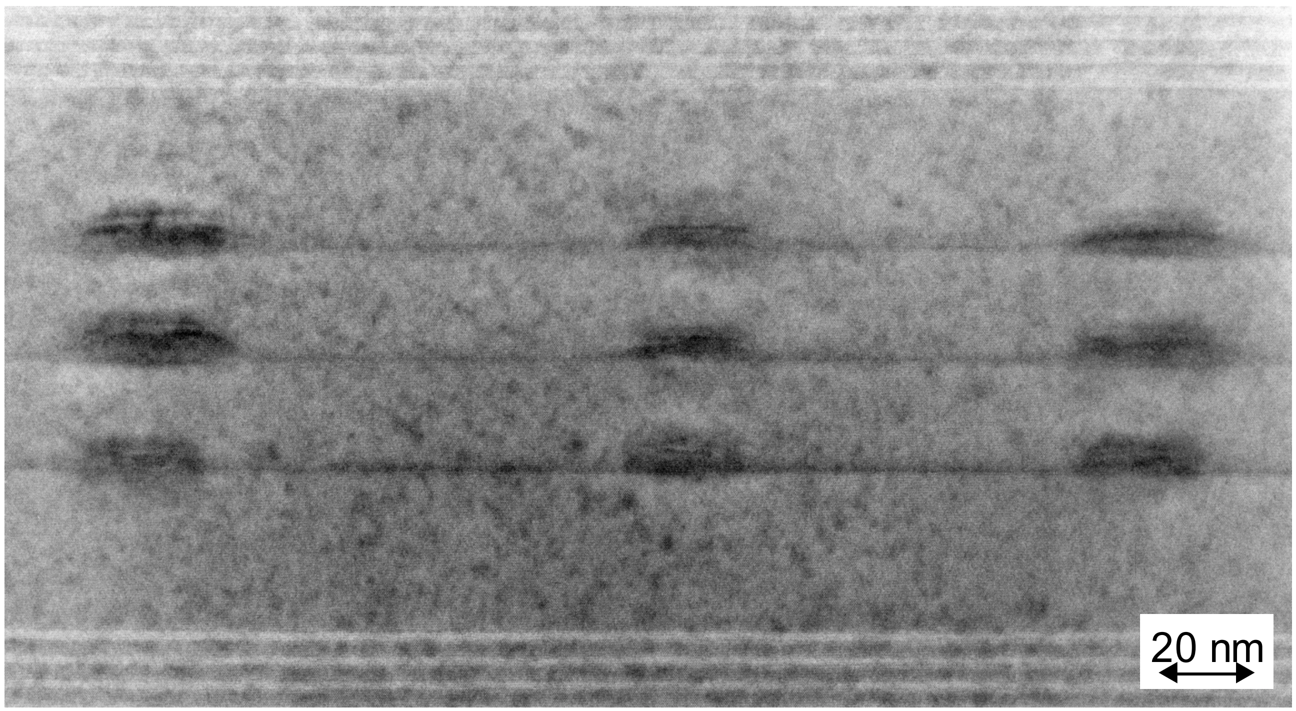


σ+ Excitation
σ- Excitation
(a)
1.0
0.5
0.0
-0.5
-1.0
P=(I+-I-)/(I++I-)
0.0
0.5
1.0
Δt (ms)
(b)
5T
8T
10T
12T
100
10
1
σ+ Intensity (arb. units)
0.0
0.5
1.0
1.5
Δt (ms)


Theory
m= -4.0±0.6
m= -5.3±0.3
Spin Lifetime T1 (s)
10^0
10^-1
10^-2
10^-3
10^-4
10^-5
2
4
6
8
10
12
14
16
Magnetic Field (T)

Towards ordering of dots

Vertical stacking is achieved nearly perfectly if the thickness of intermediate layers is smaller than 50 nm

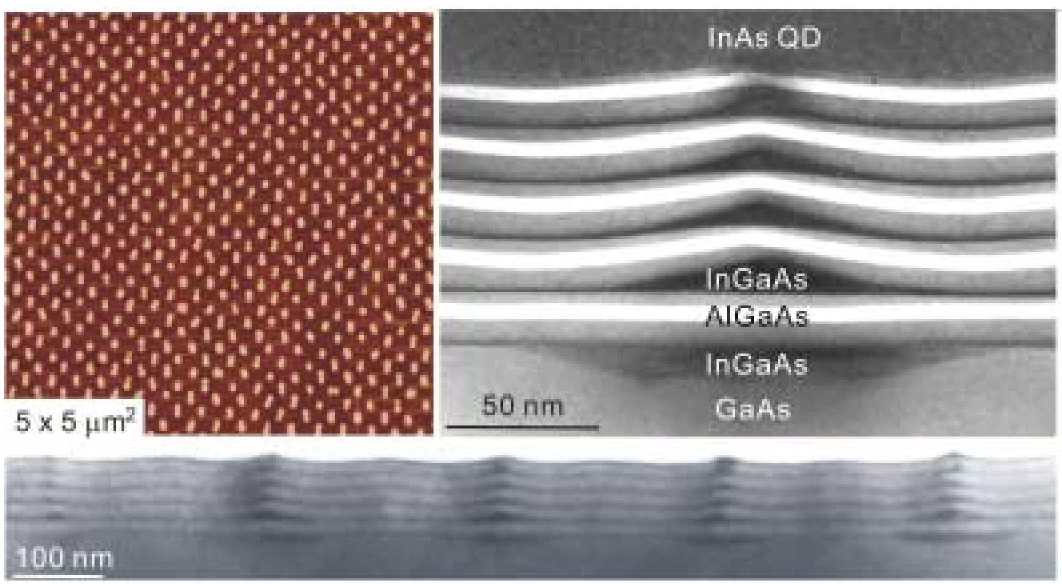


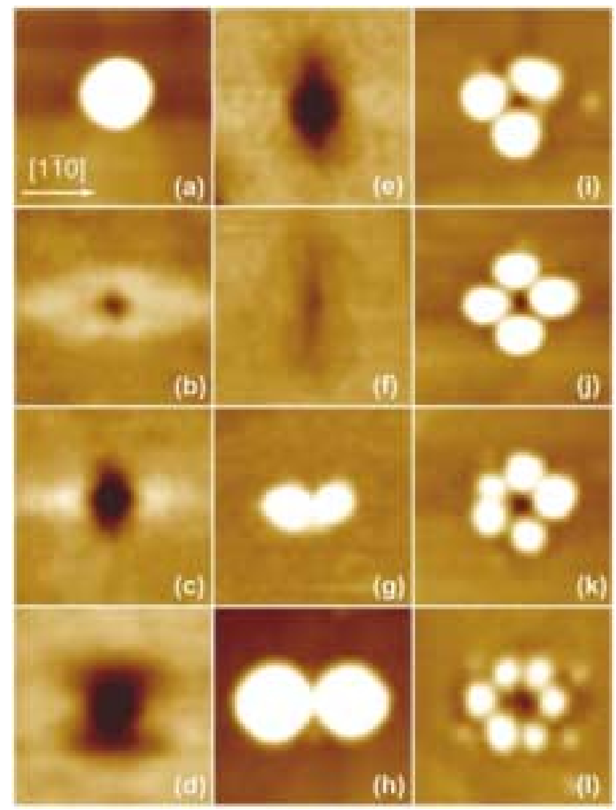
Lateral ordering:

Growth on patterned substrates (requires lithography)

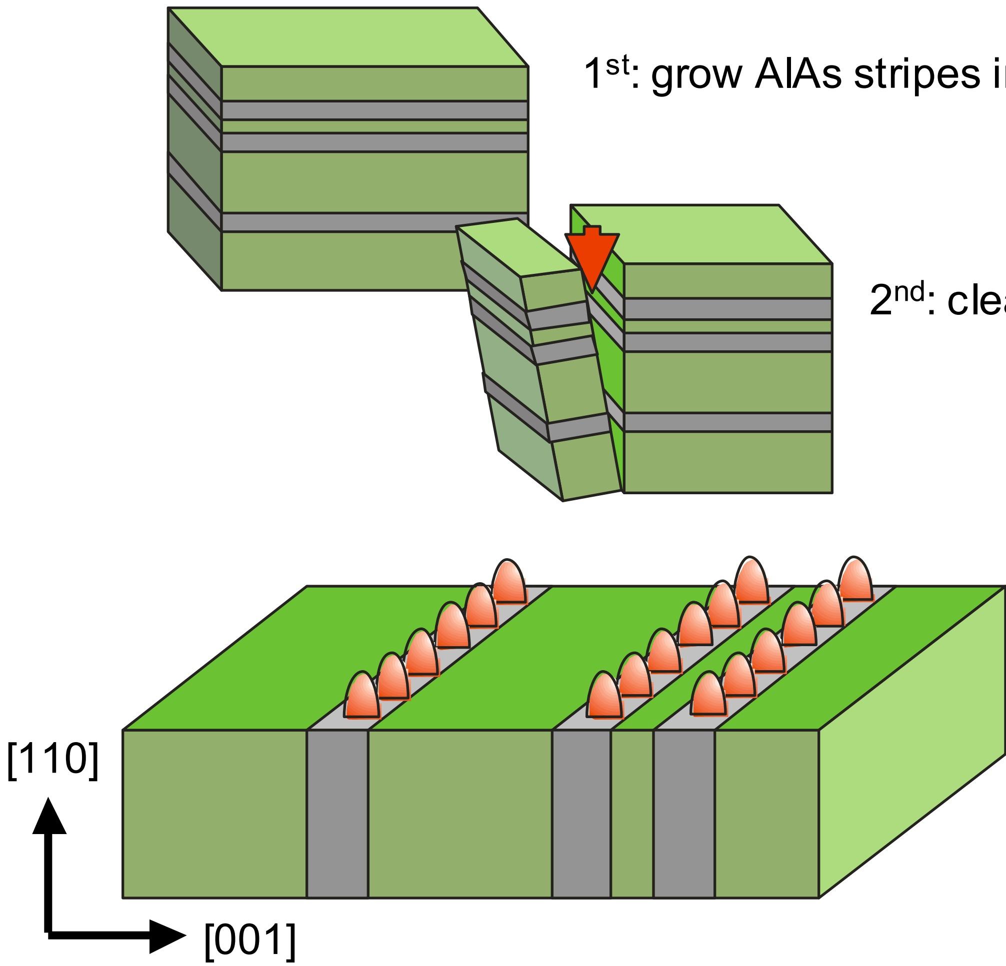
Growth on vicinal or high index surfaces

Examples form the work of O. Schmidt et al. MPI FKF, Stuttgart





Combination of CEO and self assembly

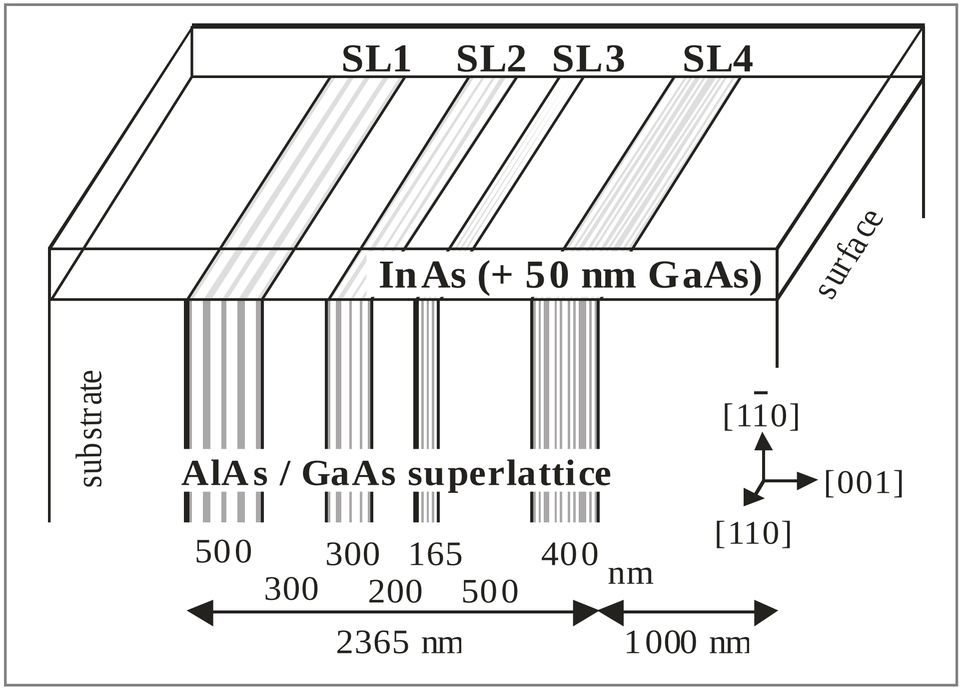


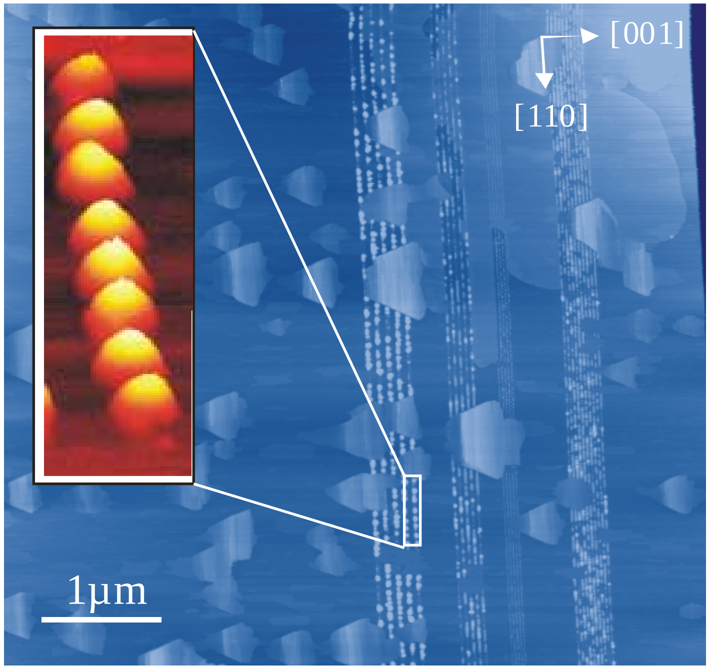
1st: grow AlAs stripes in GaAs matrix

2nd: cleave in MBE machine

3rd: grow InAs Dots on MBE patterned (110) surface

first results InAs on superlattices





SL1:
5x 32nm AlAs / 68nm GaAs

SL2:
5x 20nm AlAs / 40nm GaAs

SL3:
5x 11nm AlAs / 22nm GaAs

SL4:
10x 20nm AlAs / 20nm GaAs

Model:
nucleation and collection of InAs on AlAs due to less desorption and lower surface mobility