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INTERNATIONAL ATOMIC ENERGY AGENCY
INTERNATIONAL CENTRE FOR THEORETICAL PHYSICS
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SMR.998d - 6

Research Workshop on Condensed Matter Physics
30 June - 22 August 1997
MINIWORKSHOP ON
QUANTUM WELLS, DOTS, WIRES
AND SELF-ORGANIZING NANOSTRUCTURES
11 - 22 AUGUST 1997

"Optical Spectroscopy of Semiconductor Nanostructures with high spatial resolution"

PART I

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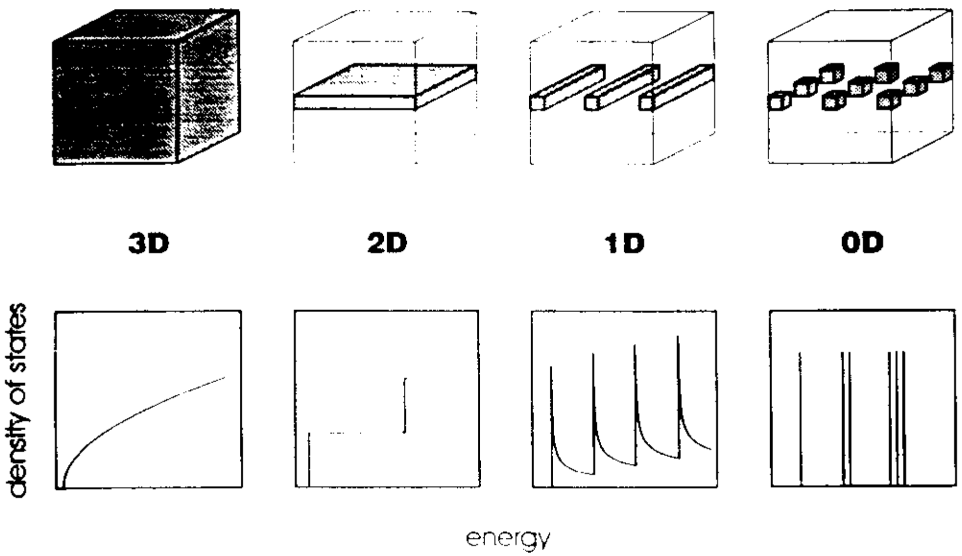
Germany

Optical spectroscopy of semiconductor nanostructures with high spatial resolution

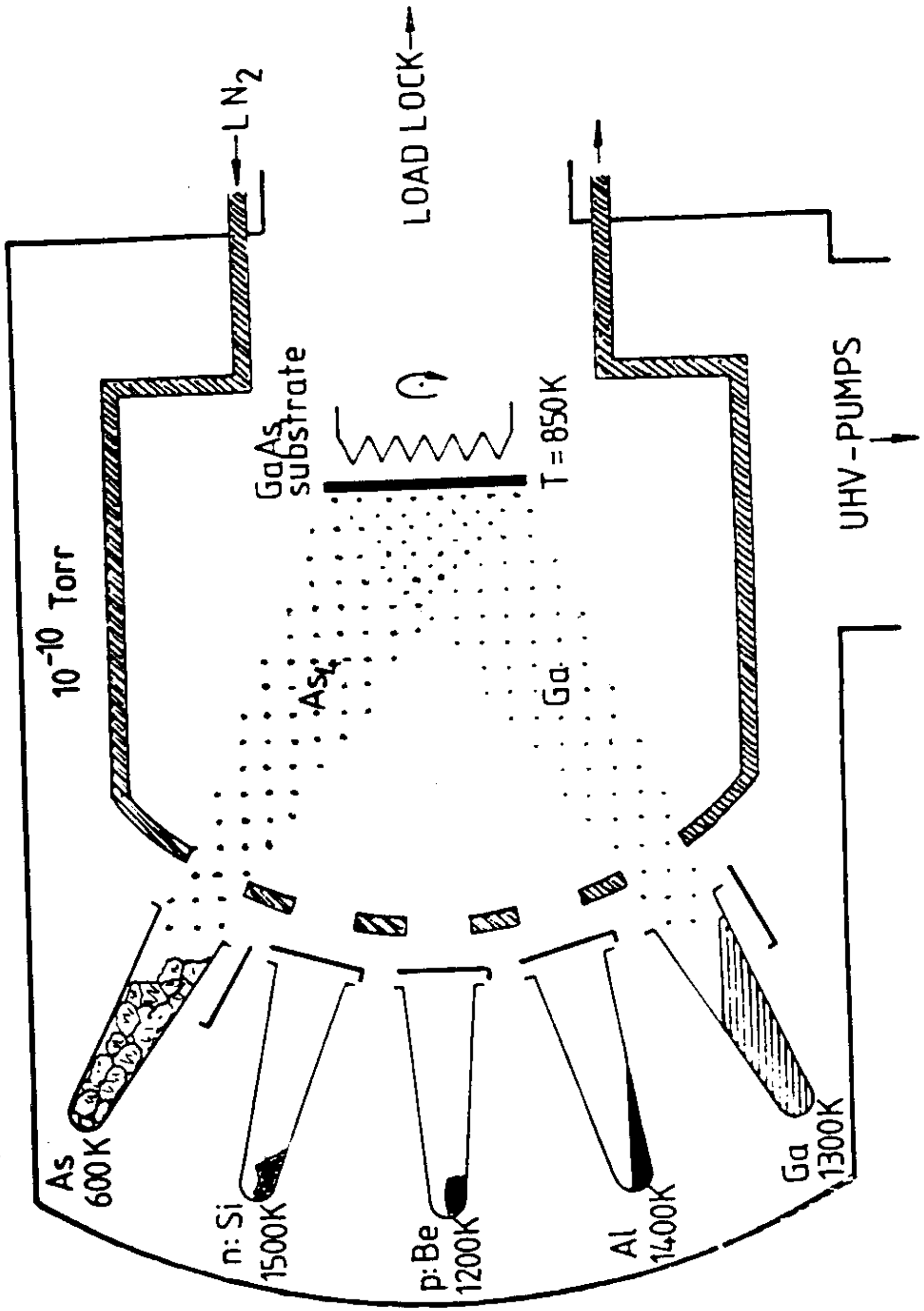
Gerhard Abstreiter

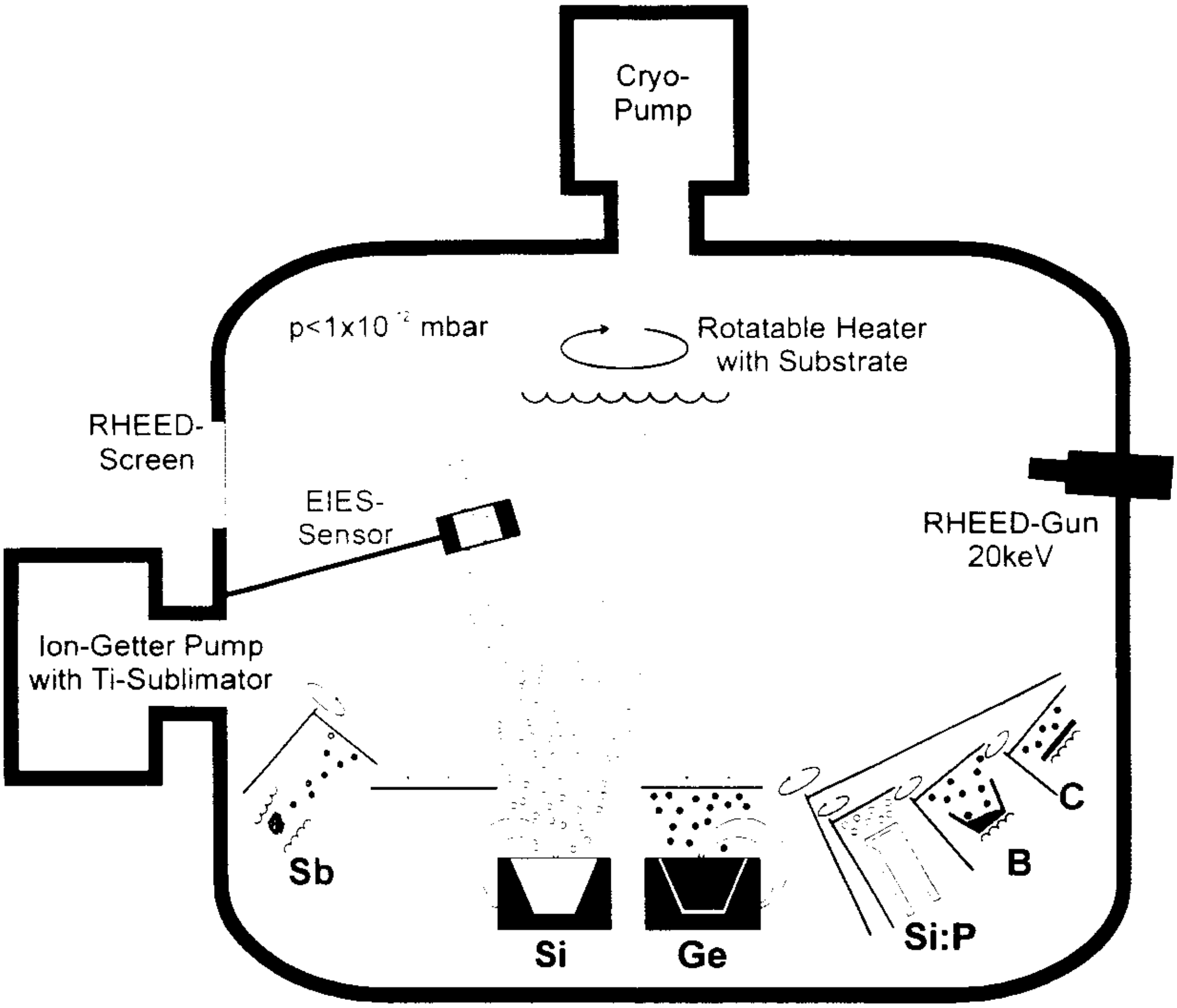
Walter Schottky Institut
Techn. Univ. München
D-85748 Garching

Trieste, 12. August 1997

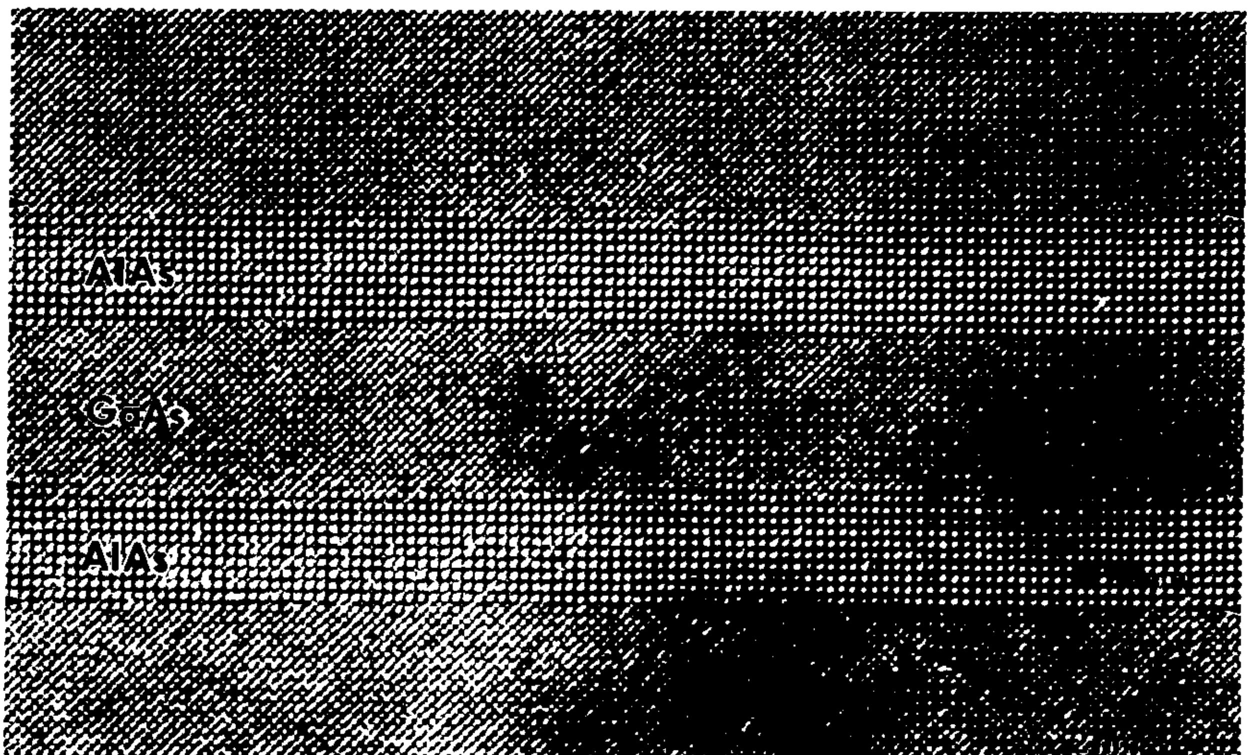


Molekularstrahlepitaxie



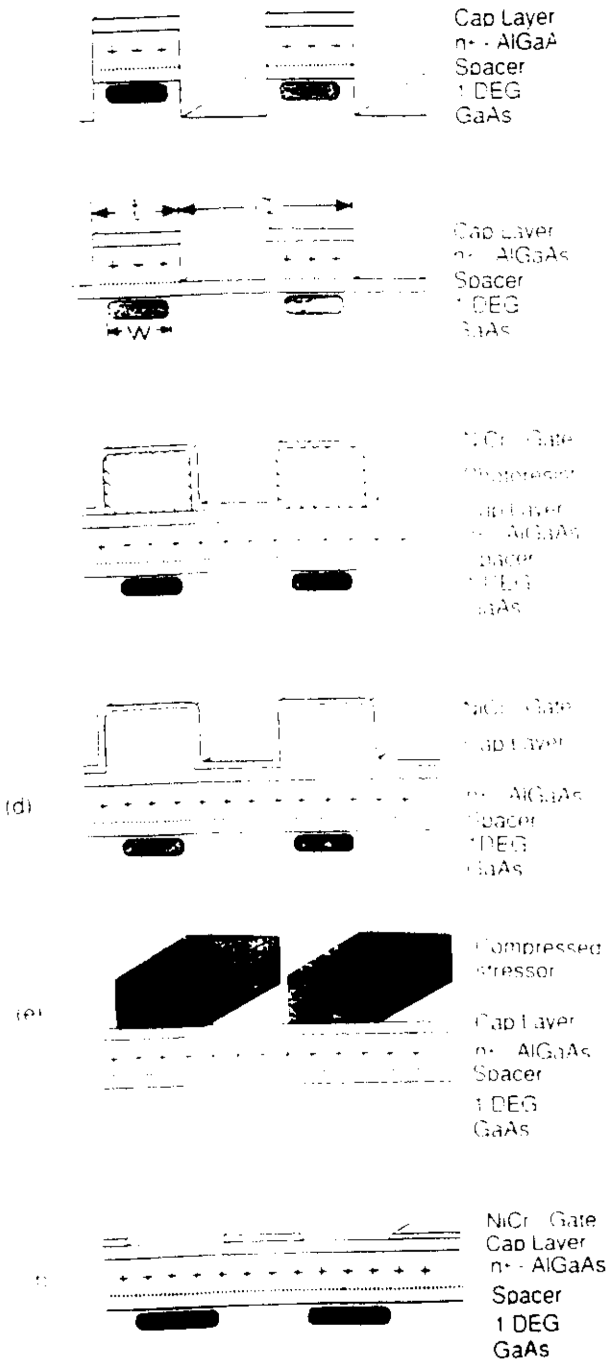


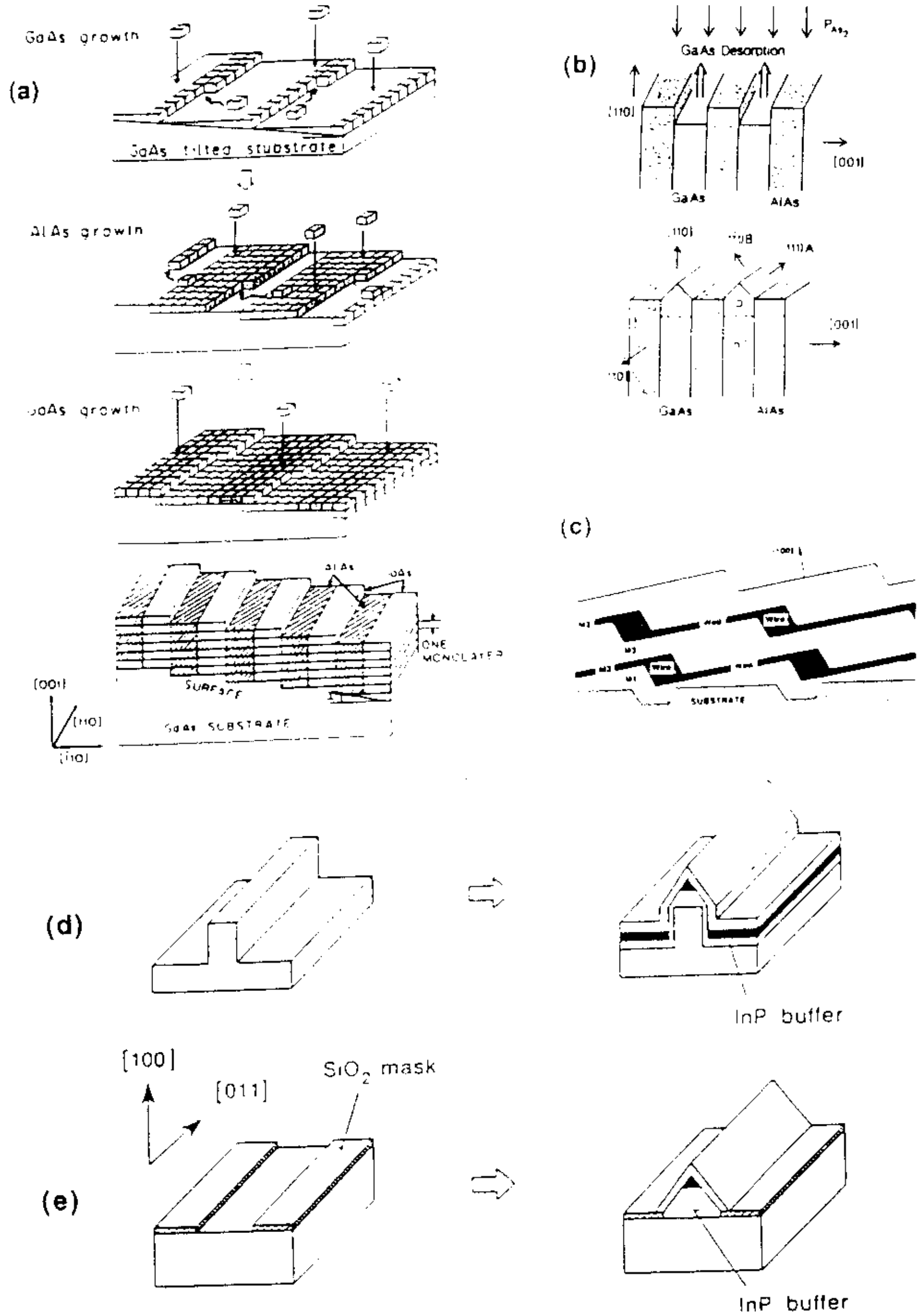
SIEMENS MR 91 1177

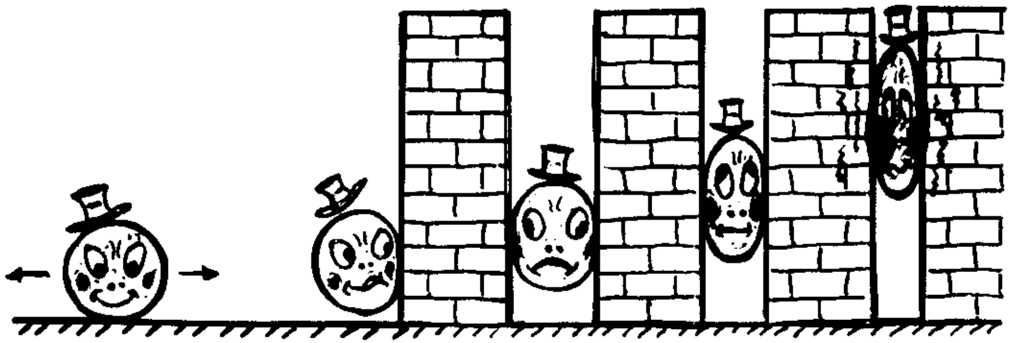


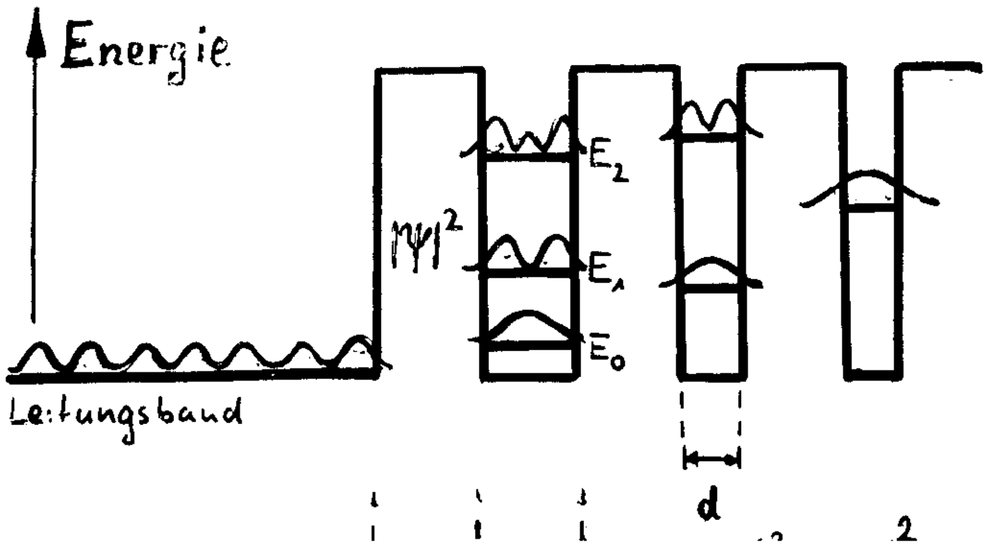
AlAs / GaAs double barrier structure

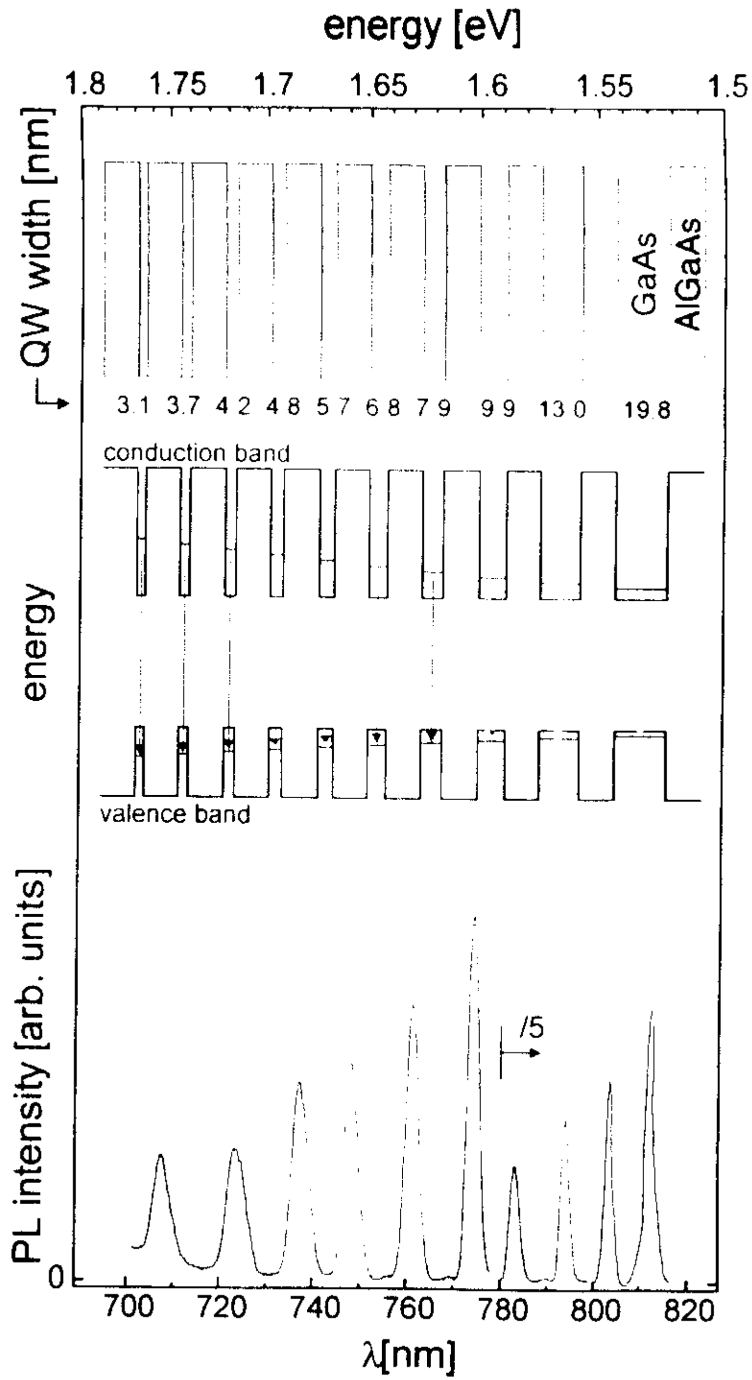
MBE: H. Riechert
TEM: A. Mitwalsky

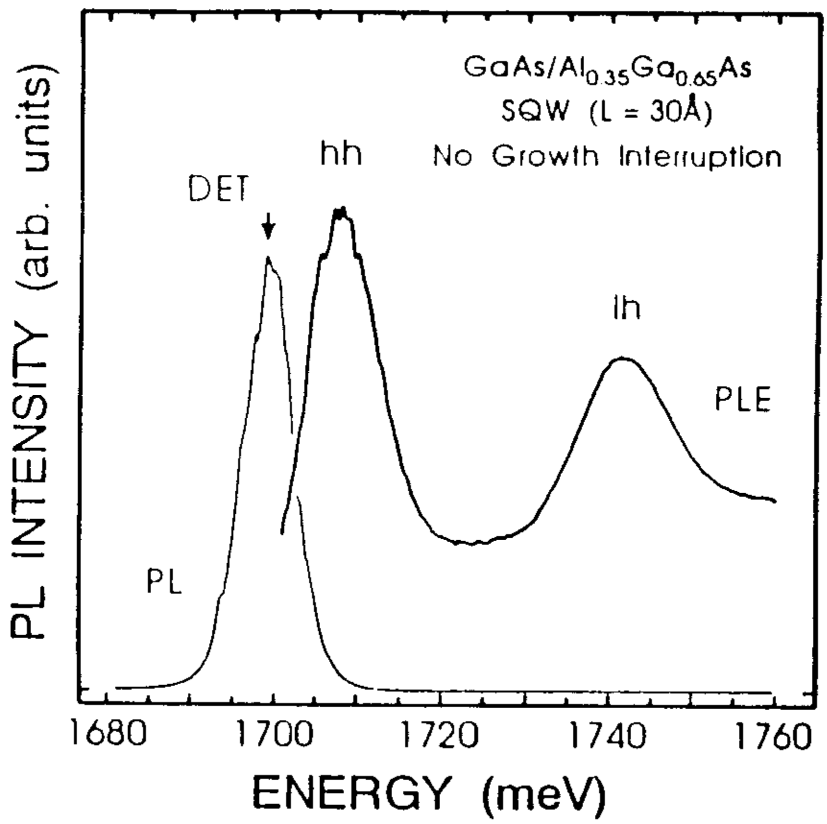

Cap Layer
n+ - AlGaA
Spacer
1 DEG
GaAs
(d)
Compressed
stressor
Cap Layer
n+ - AlGaAs
Spacer
1 DEG
GaAs
NiCr Gate
Cap Layer
n+ - AlGaAs
Spacer
1 DEG
GaAs

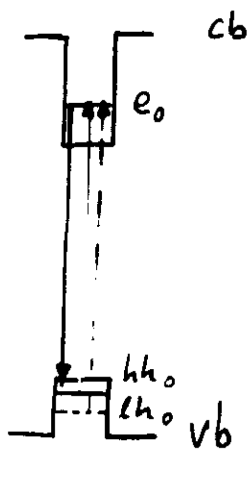

(a)
GaAs growth
AlAs growth
ONE MONOLAYER
SURFACE
GaAs SUBSTRATE
(b)
GaAs Desorption
[001]
GaAs
AlAs
(c)
SUBSTRATE
(d)
InP buffer
(e)
[100]
[011]
SiO_2 mask
InP buffer



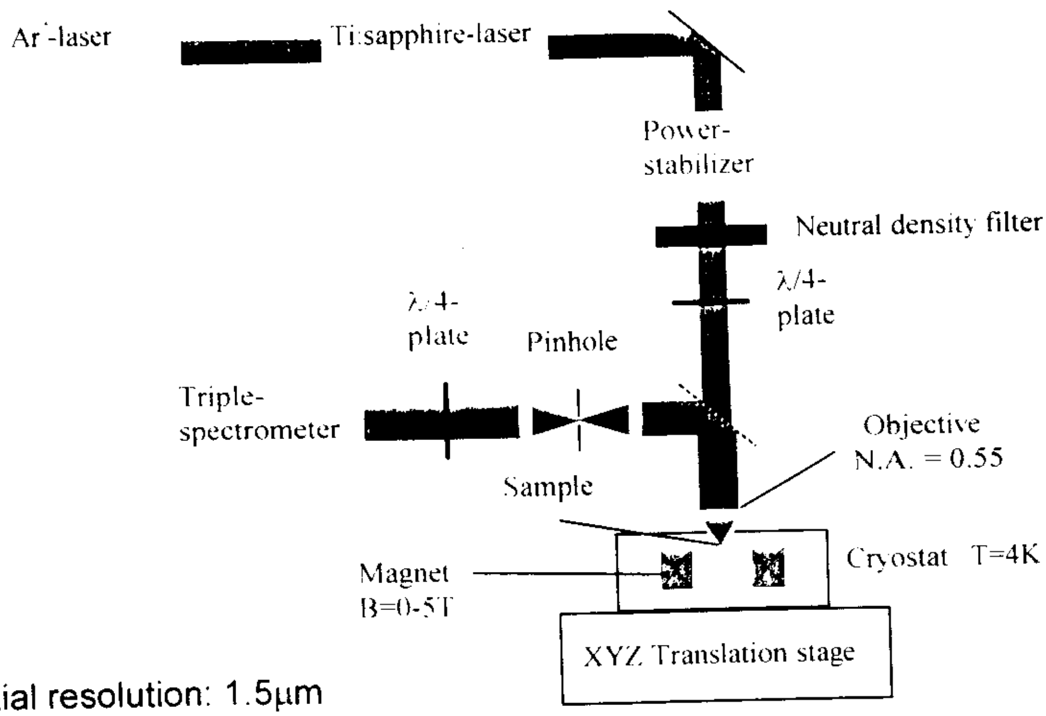

Energie
Leitungsband
|ψ|²
E2
E1
E0
d


energy [eV]
1.8
1.75
1.7
1.65
1.6
1.55
1.5
QW width [nm]
3.1 3.7 4.2 4.8 5.7 6.8 7.9 9.9 13.0 19.8
GaAs
AlGaAs
conduction band
energy
valence band
PL intensity [arb. units]
/5
0
700
720
740
760
780
800
820
λ[nm]



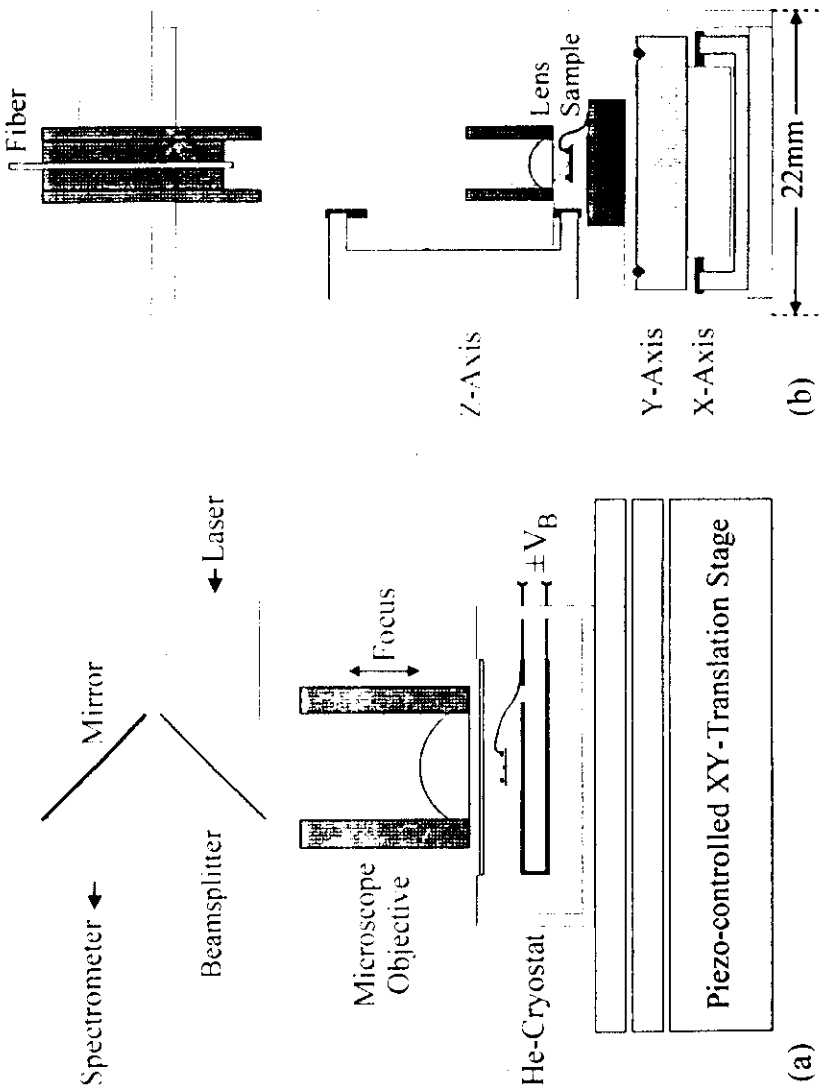


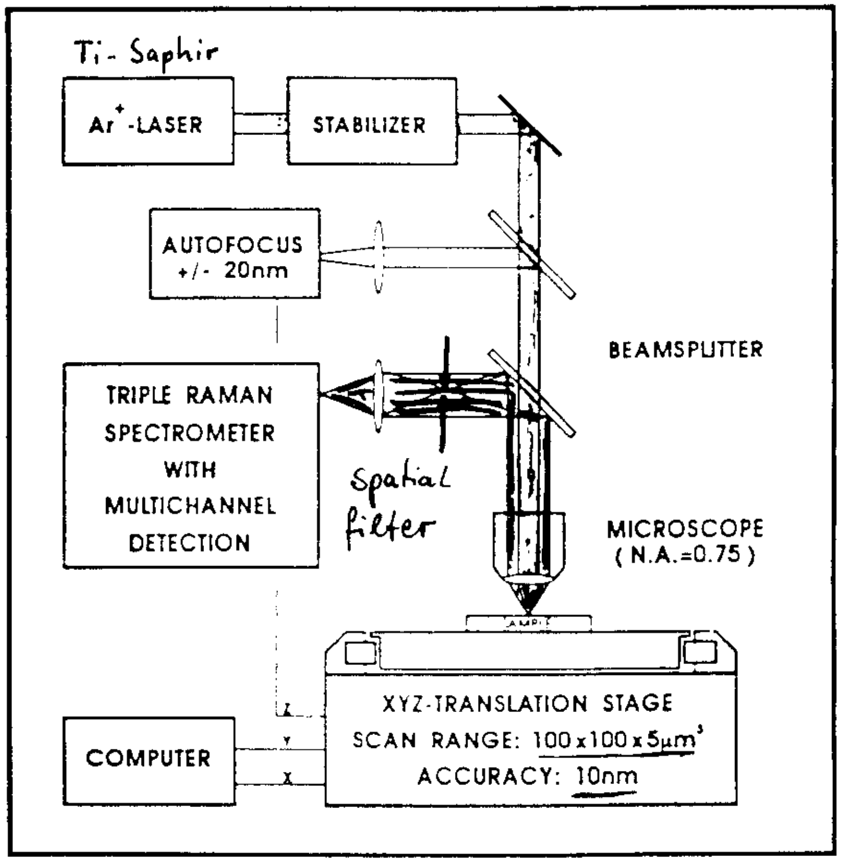
EXPERIMENTAL SETUP



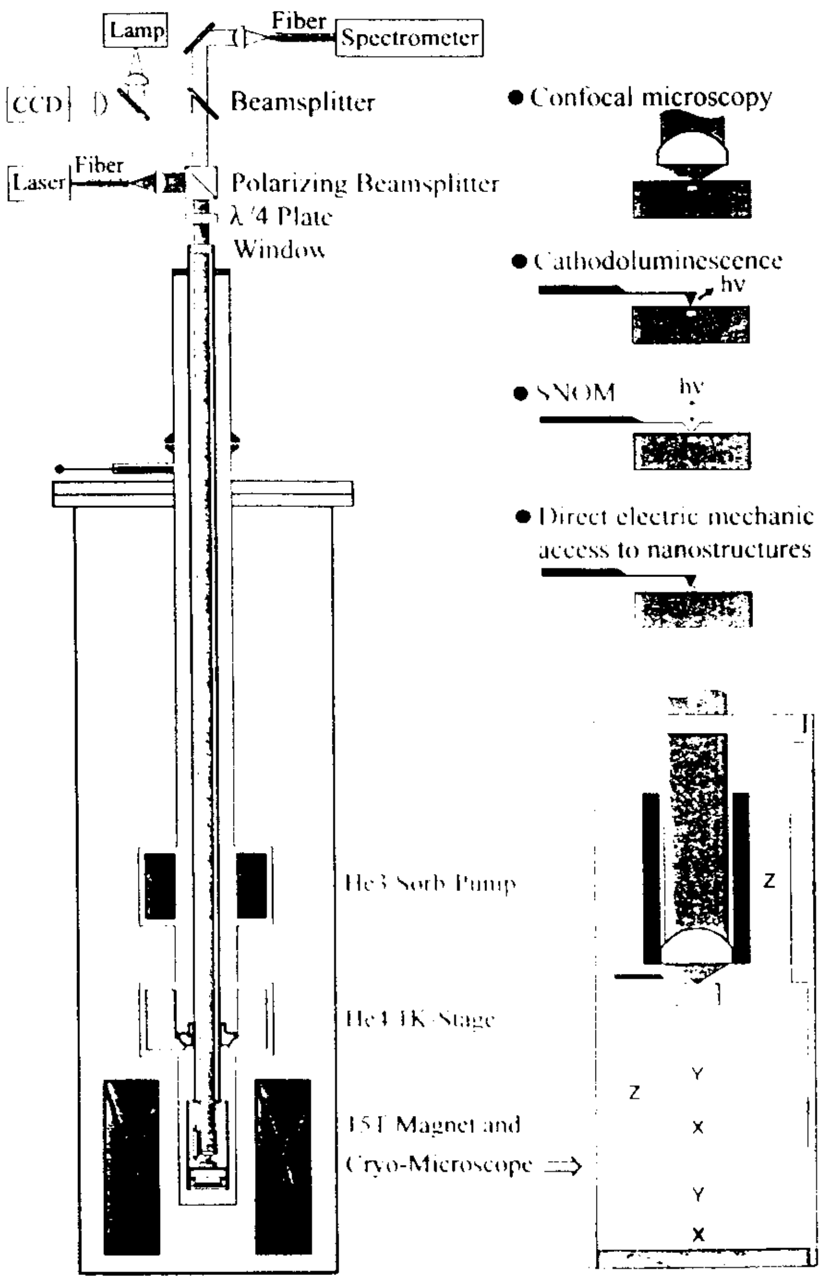
Spatial resolution: 1.5μm
Spectral resolution: 70μeV

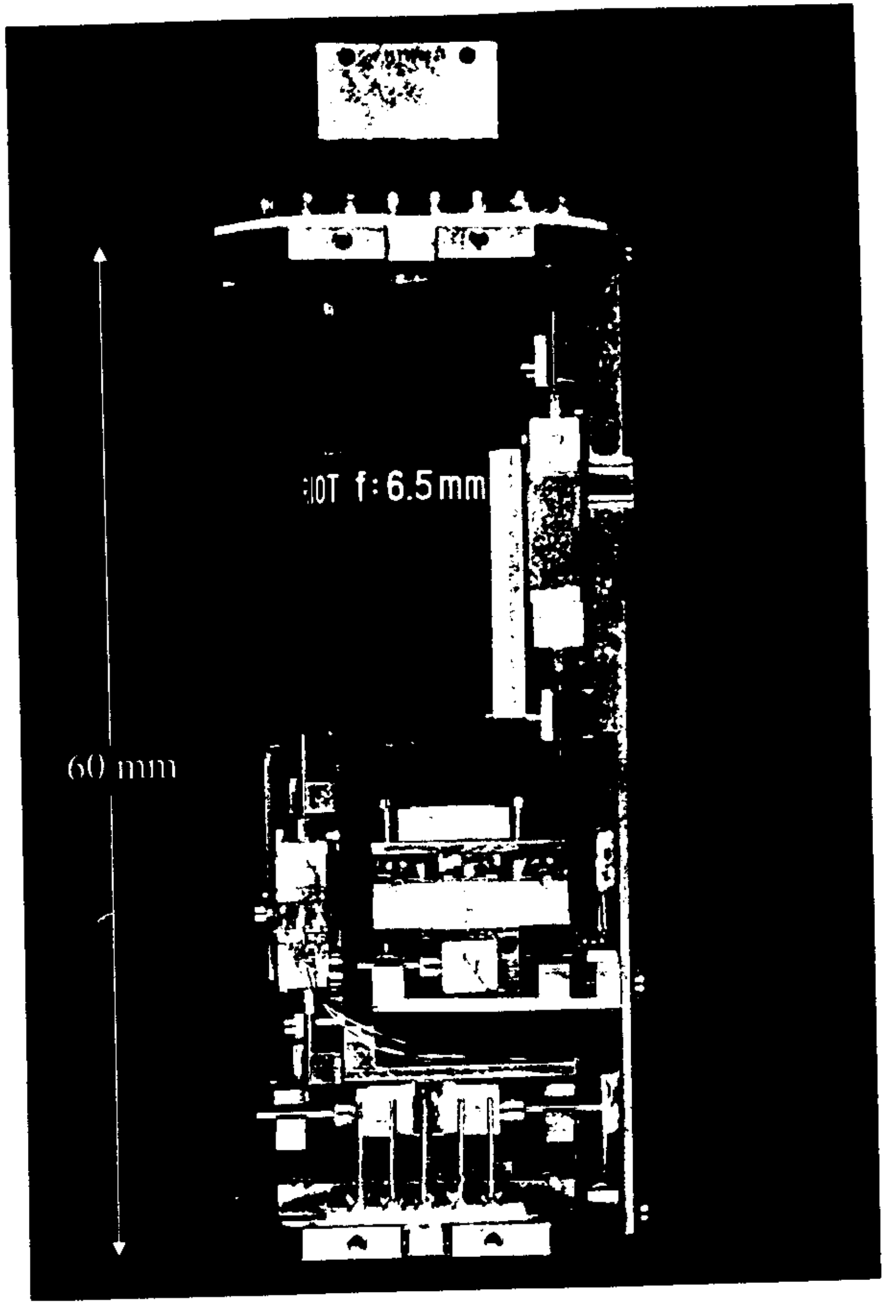
Spatially Resolved PL: Experimental Setups

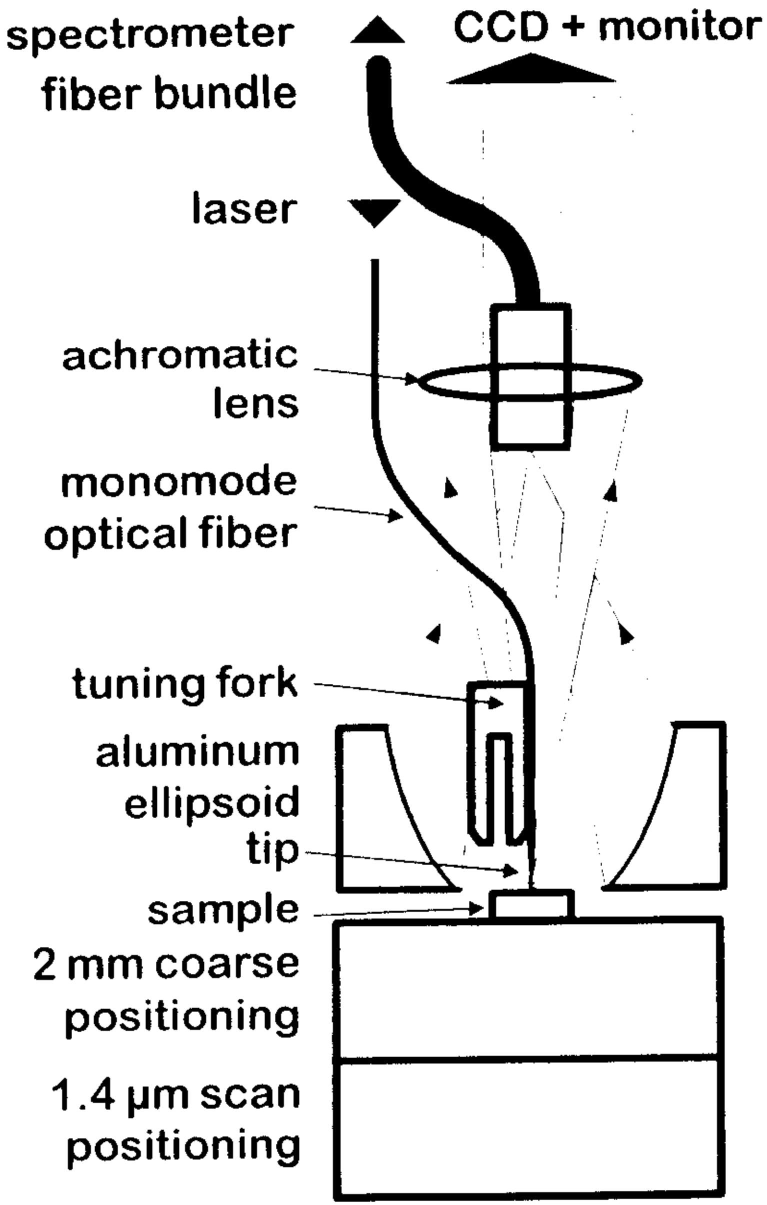




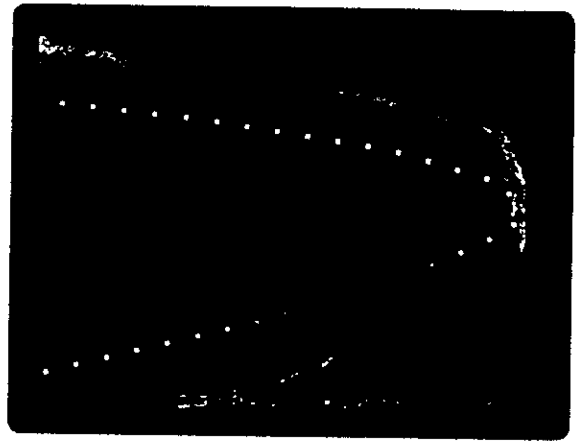
Spatially resolved low-temperature microscopy



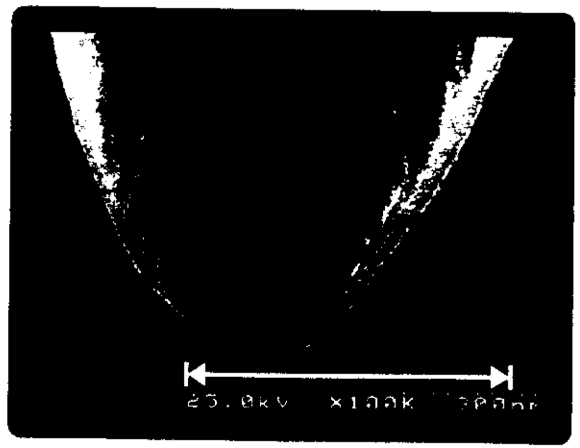




80 nm tip
with 20 nm
gold coating



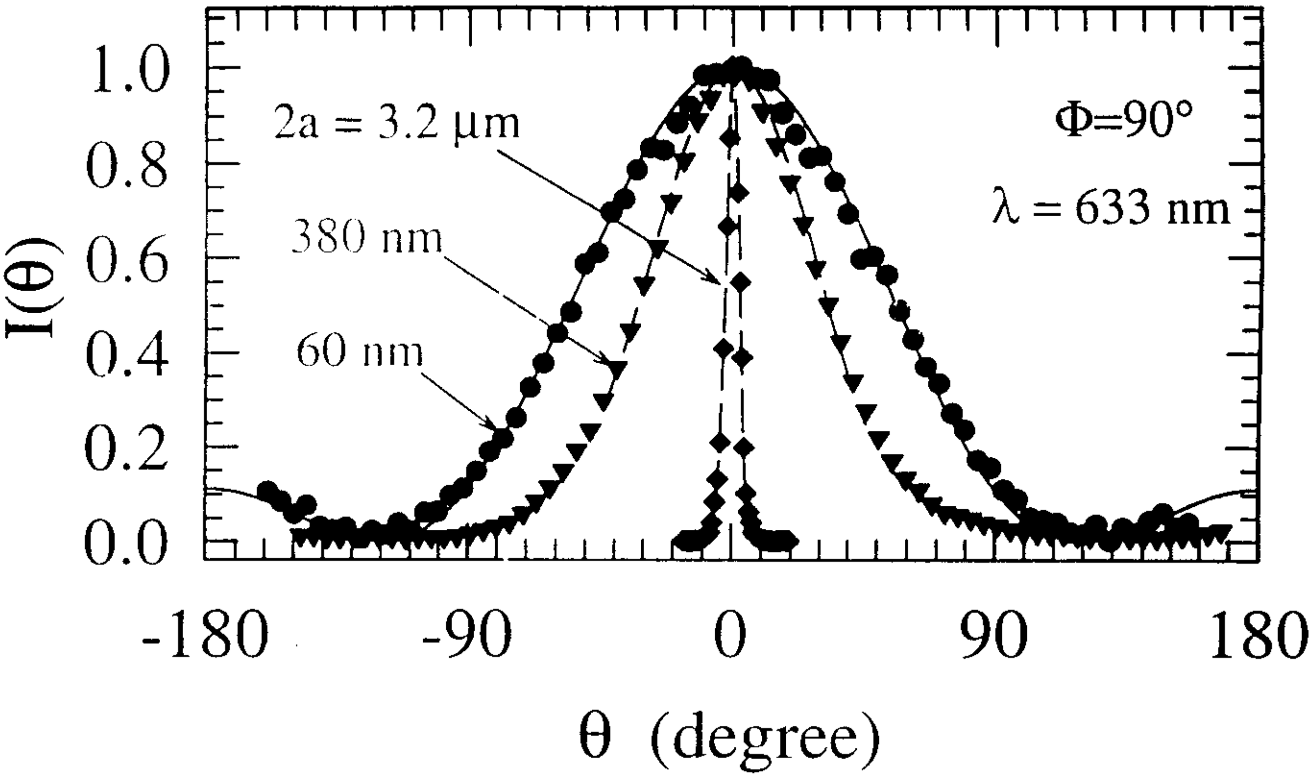
similar tip
with 120 nm
aluminium
coating



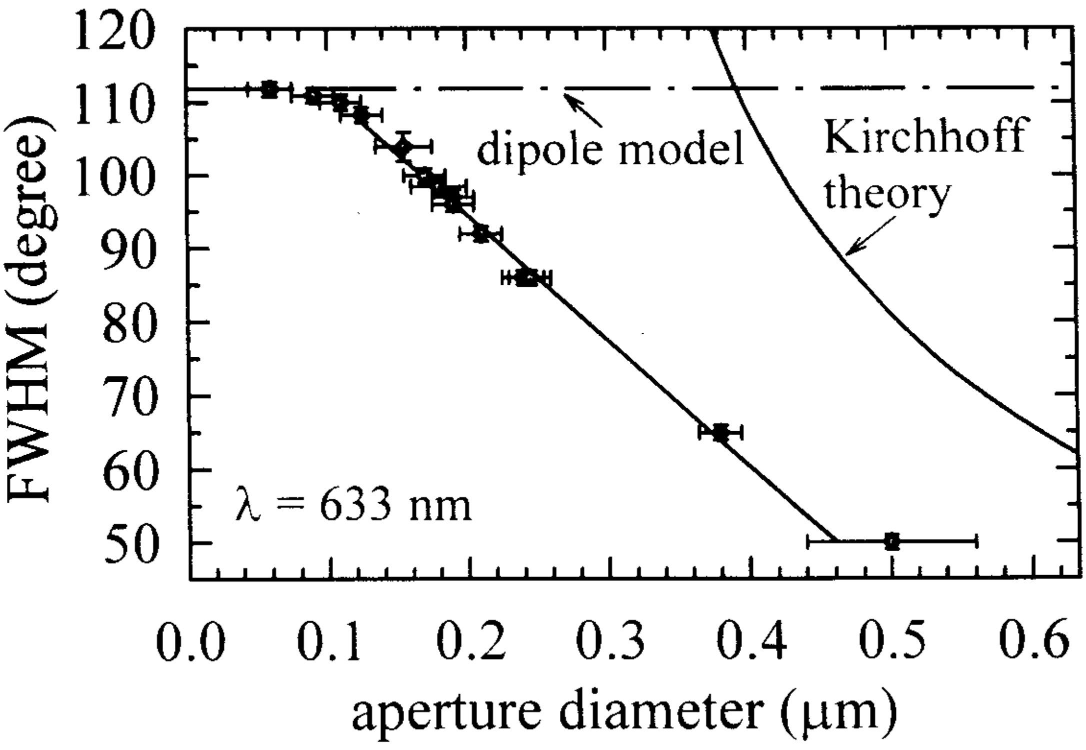
same tip

front view

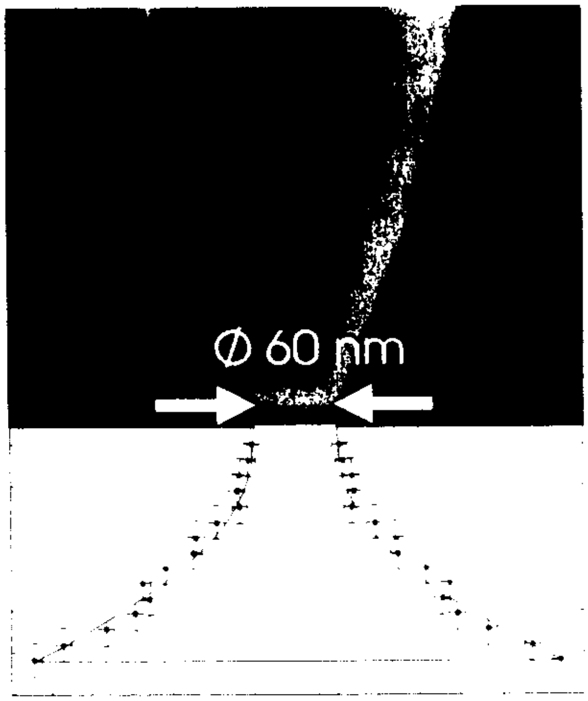
λ= 633 nm



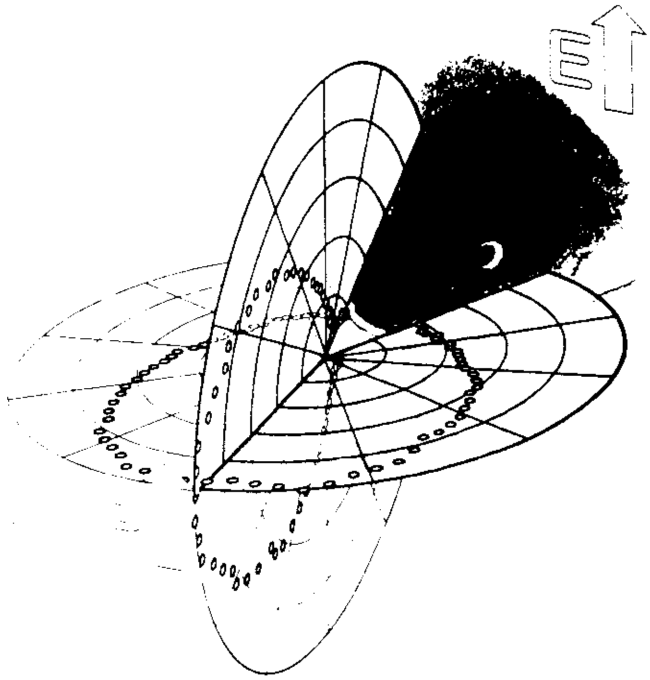
I(θ)
1.0
0.8
0.6
0.4
0.2
0.0
2a = 3.2 μm
380 nm
60 nm
Φ=90°
λ = 633 nm
-180
-90
0
90
180
θ (degree)



FWHM (degree)
120
110
100
90
80
70
60
50
dipole model
Kirchhoff
theory
λ = 633 nm
0.0
0.1
0.2
0.3
0.4
0.5
0.6
aperture diameter (μm)

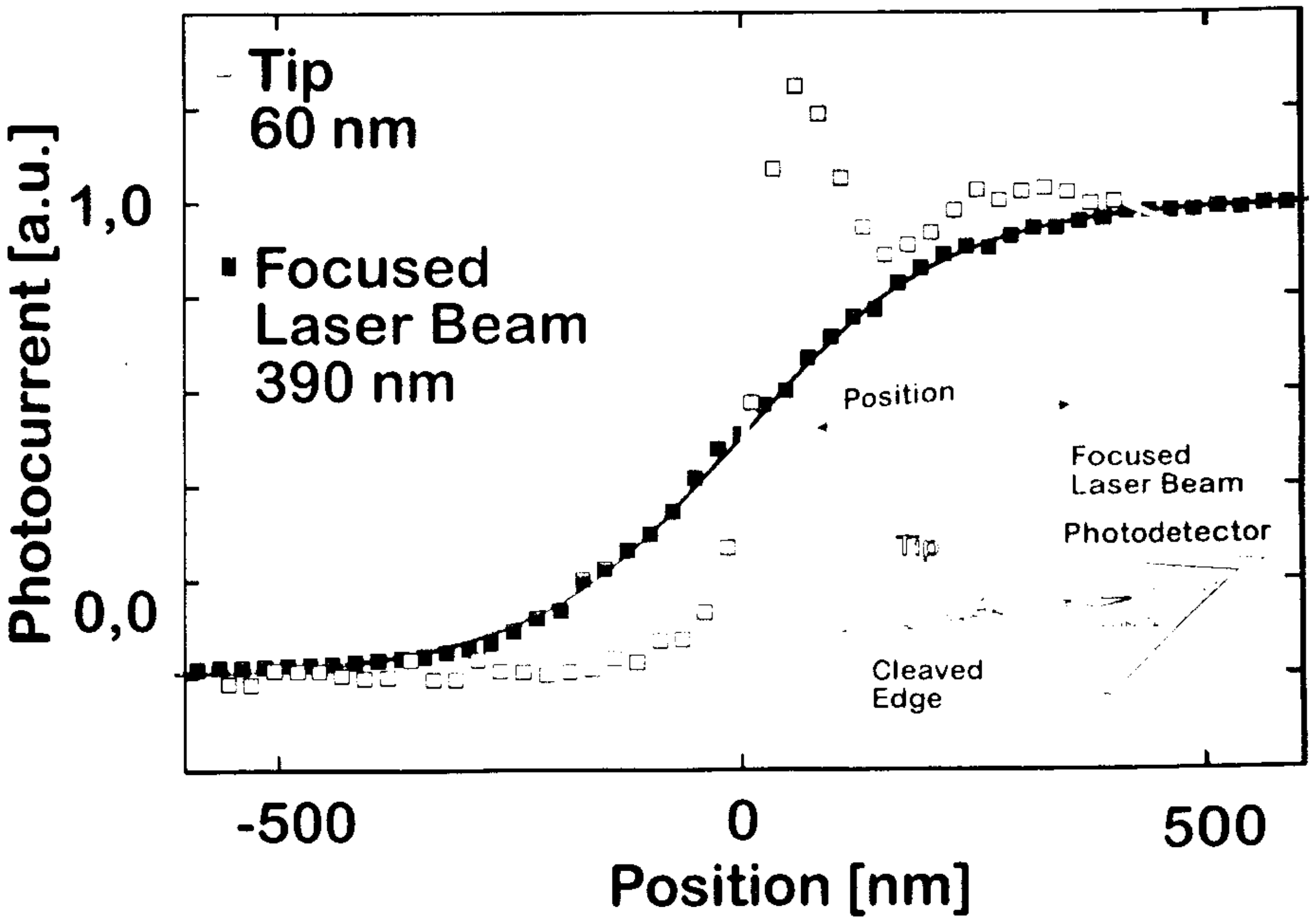


Measured beam profile as a function of the distance to the aperture

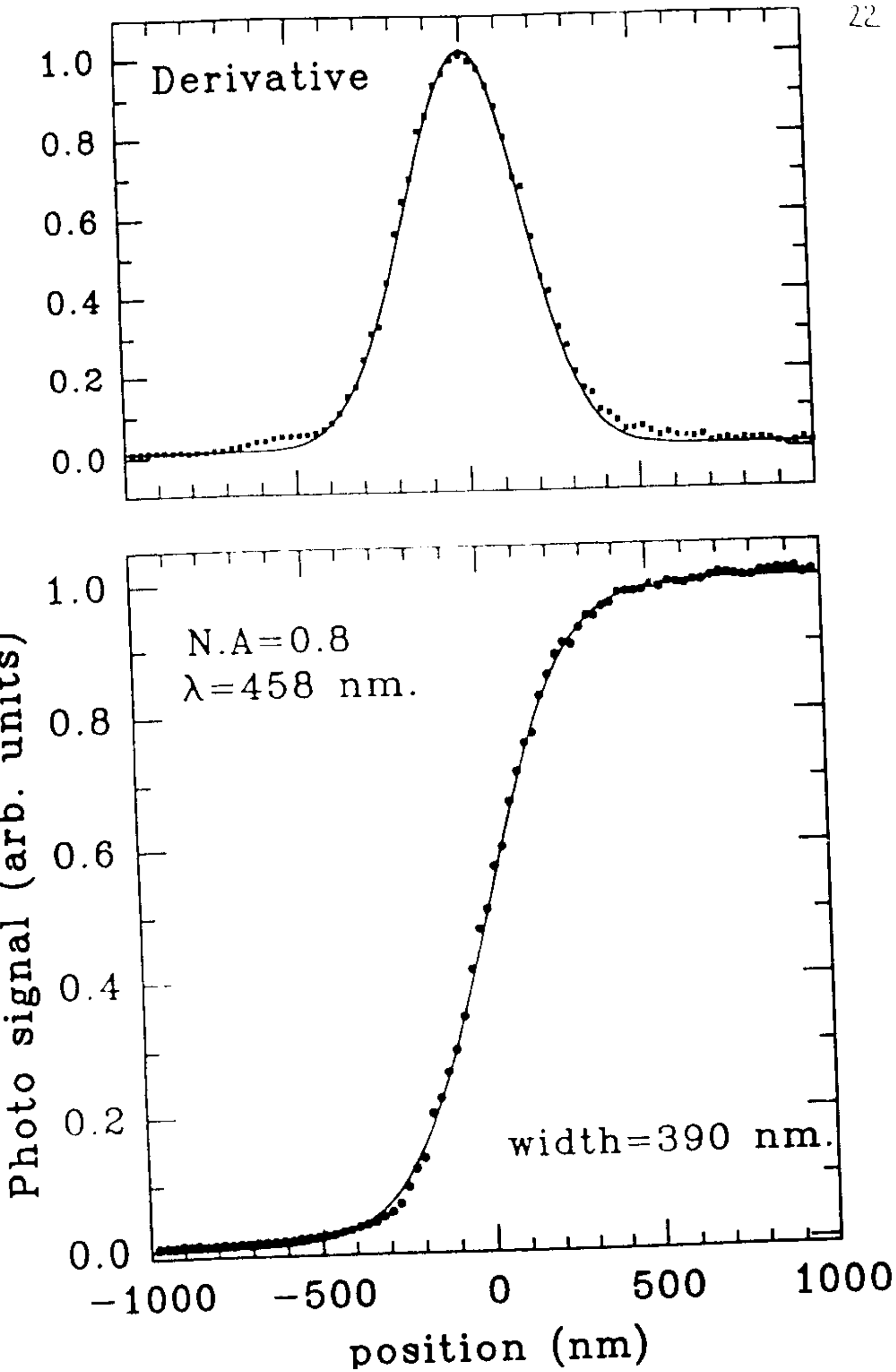


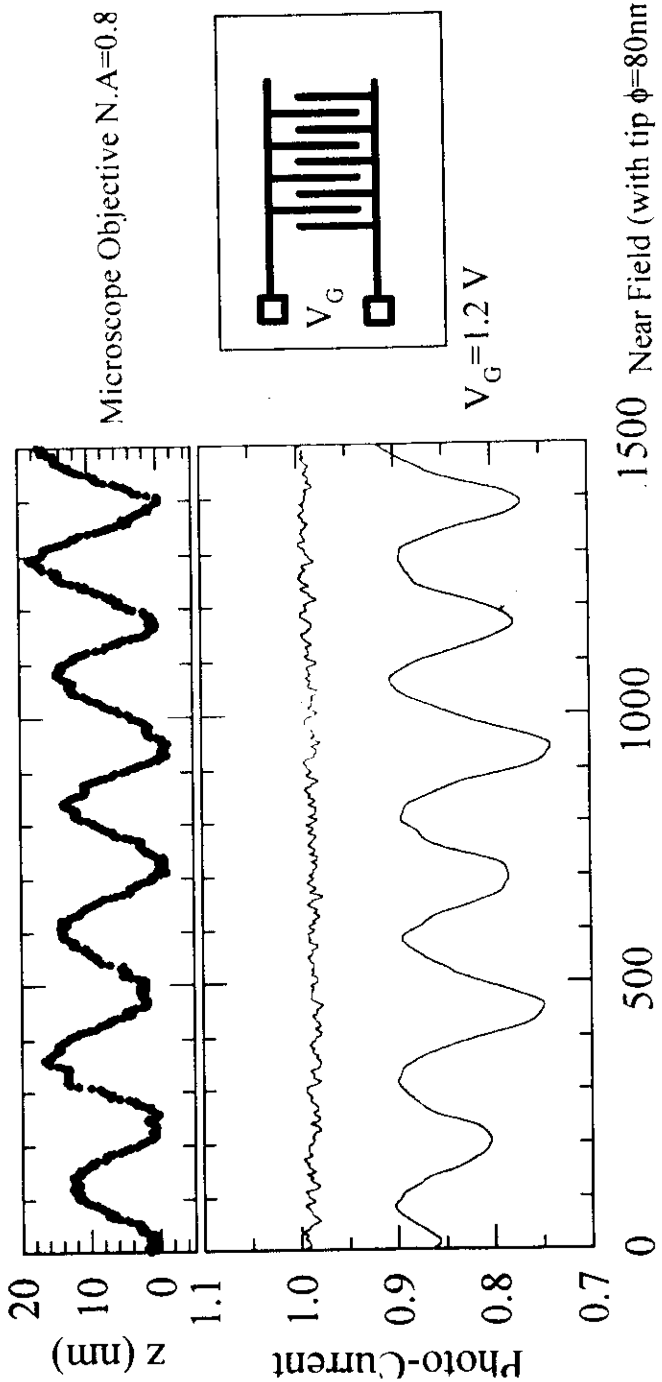
Far field intensity of the transmitted radiation in dependennce of polarisation and angle

20

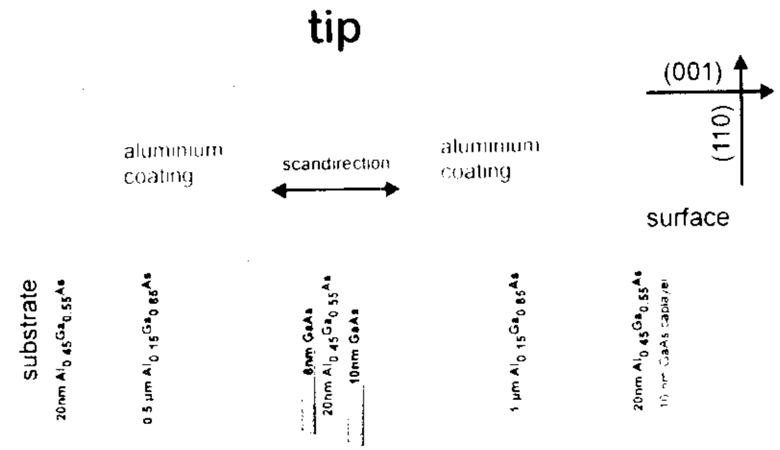


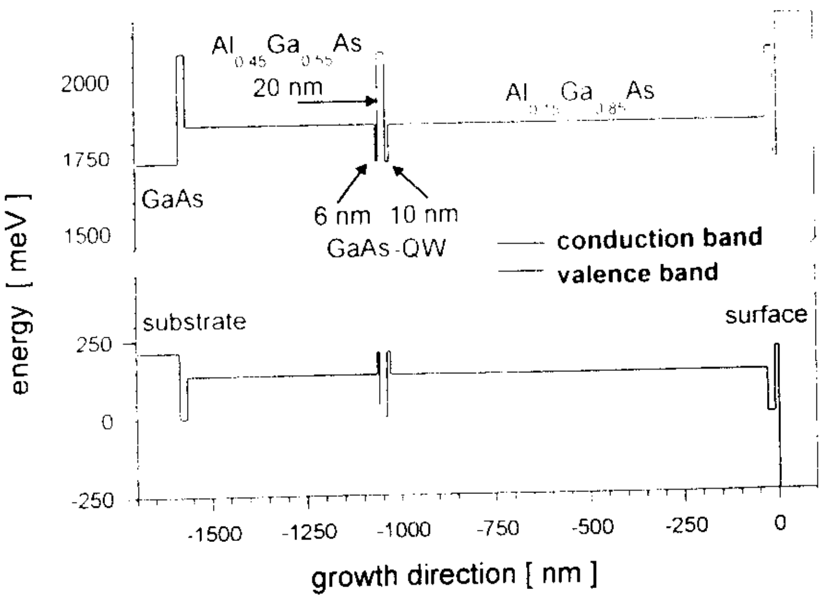
21

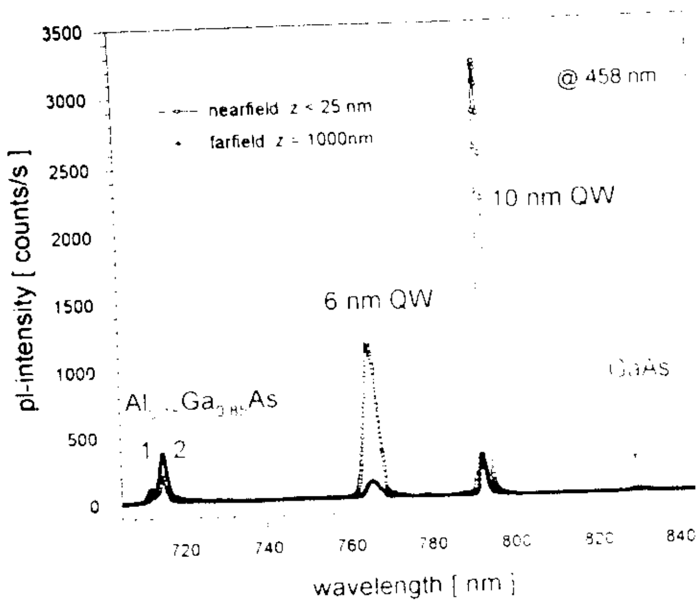


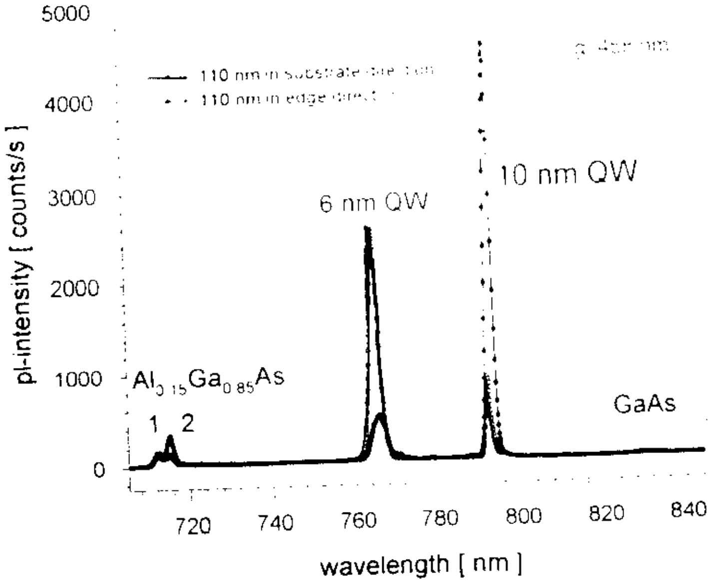


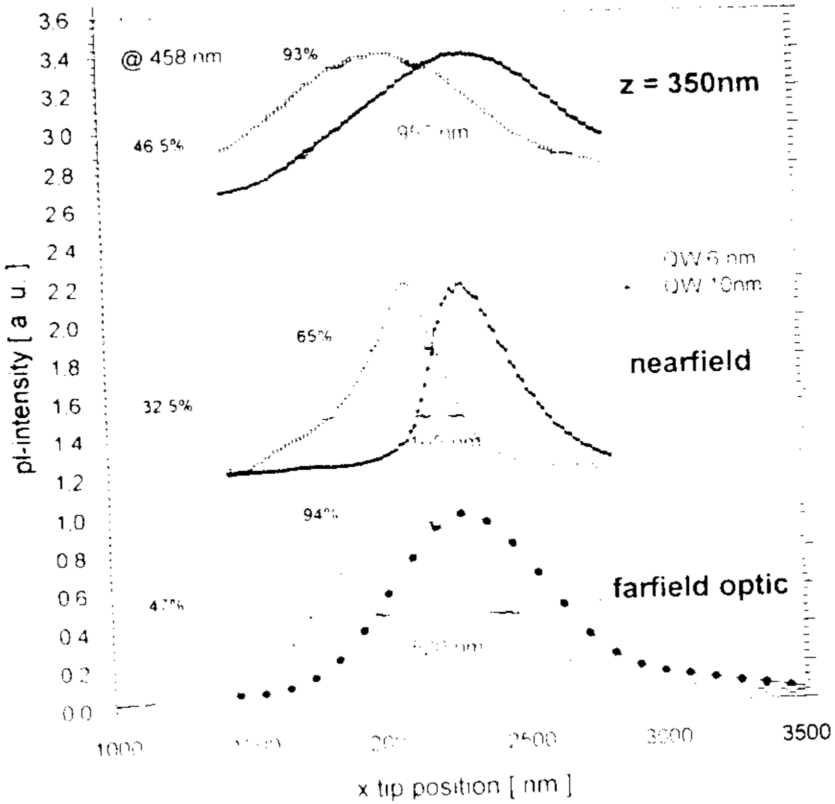
Optical Near Field Induced Current (ONIC)


tip
(001)
(110)
aluminium coating
scandirection
aluminium coating
surface
substrate
20nm $Al_{0.45}Ga_{0.55}As$
0.5 µm $Al_{0.15}Ga_{0.85}As$
6nm GaAs
20nm $Al_{0.45}Ga_{0.55}As$
10nm GaAs
1 µm $Al_{0.15}Ga_{0.85}As$
20nm $Al_{0.45}Ga_{0.55}As$

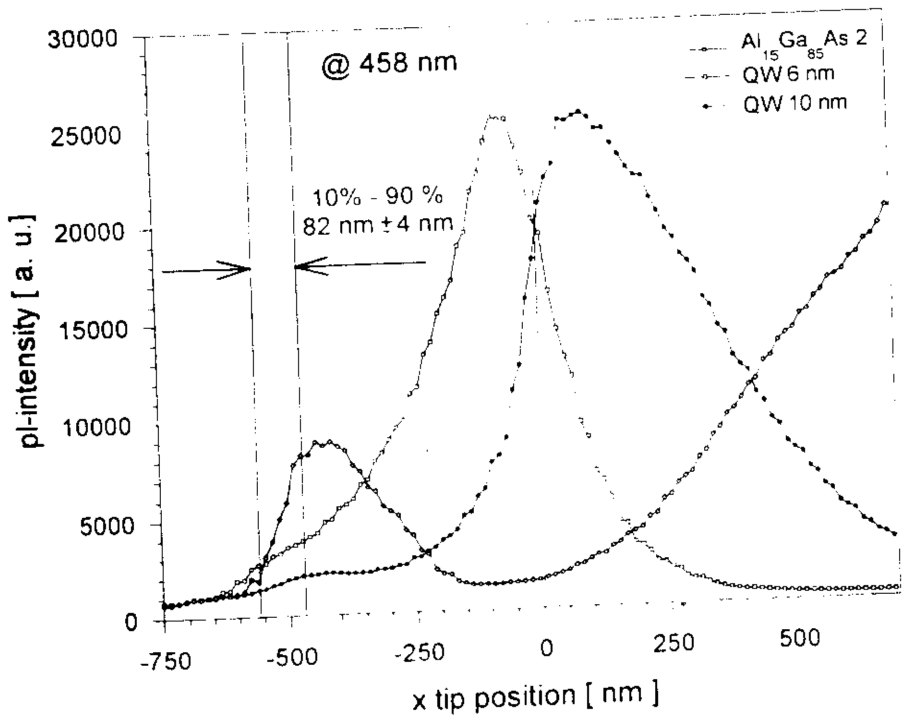

$Al_{0.45}Ga_{0.55}As$
20 nm
$Al_{0.15}Ga_{0.85}As$
GaAs
6 nm 10 nm
GaAs-QW
conduction band
valence band
substrate
surface
energy [meV]
growth direction [nm]


@ 458 nm
nearfield z < 25 nm
farfield z = 1000nm
10 nm QW
6 nm QW
GaAs
1 2
pl-intensity [counts/s]
wavelength [nm]


10 nm QW
6 nm QW
$Al_{0.15}Ga_{0.85}As$
1 2
GaAs
pl-intensity [counts/s]
wavelength [nm]



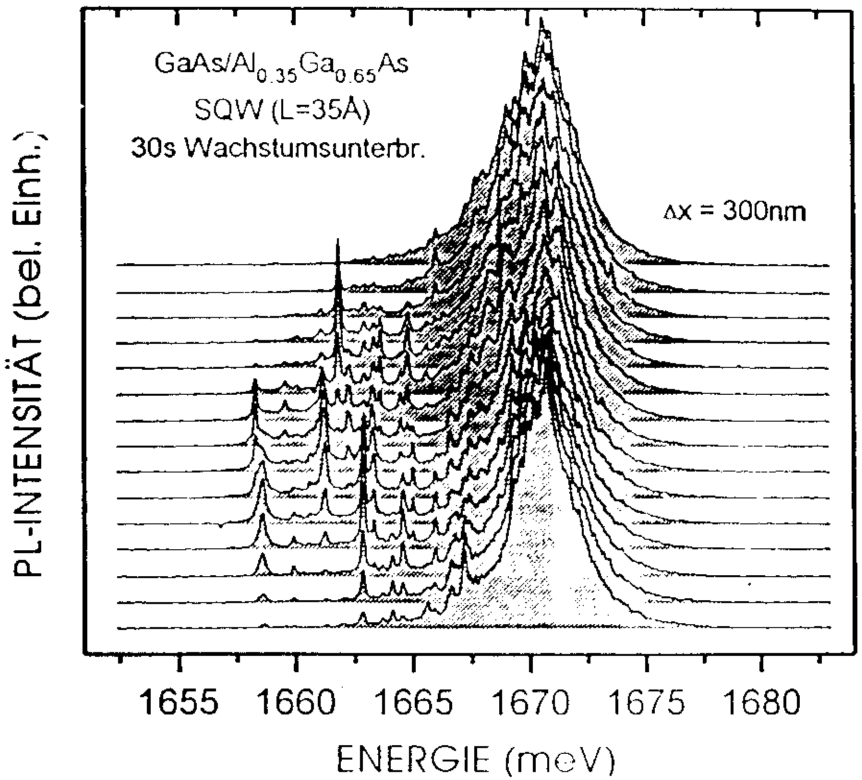
@ 458 nm
z = 350nm
93%
46.5%
nearfield
QW 6 nm
QW 10nm
65%
32.5%
94%
farfield optic
47%
pl-intensity [a. u.]
x tip position [nm]

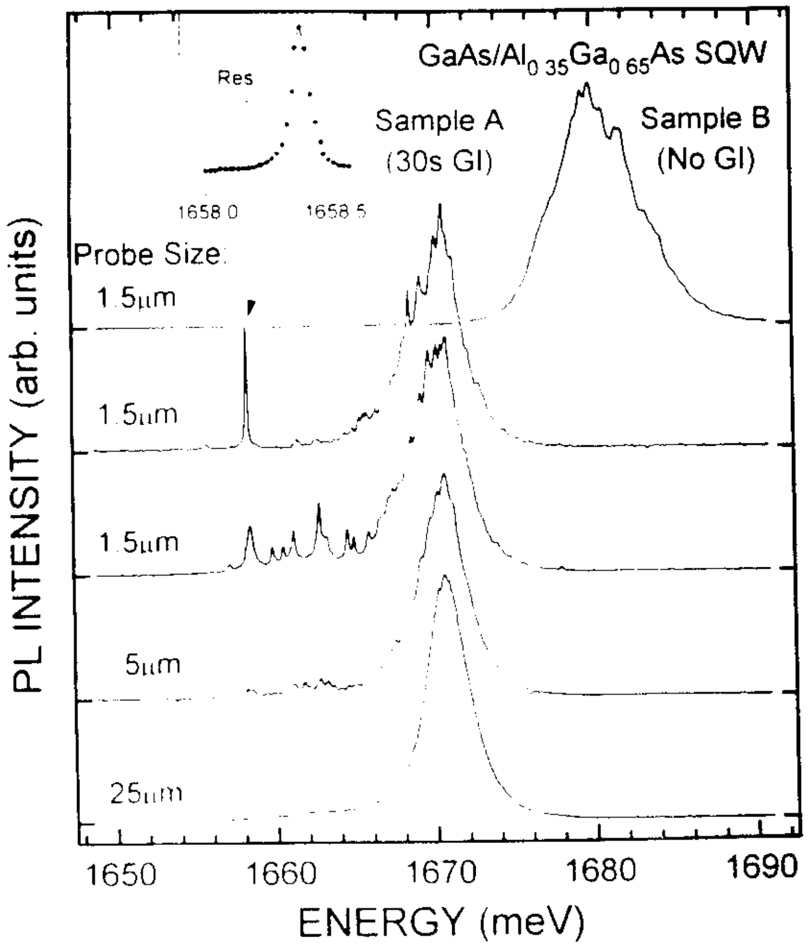


@ 458 nm
$Al_{15}Ga_{85}As$ 2
QW 6 nm
QW 10 nm
10% - 90 %
82 nm ± 4 nm
pl-intensity [a. u.]
x tip position [nm]

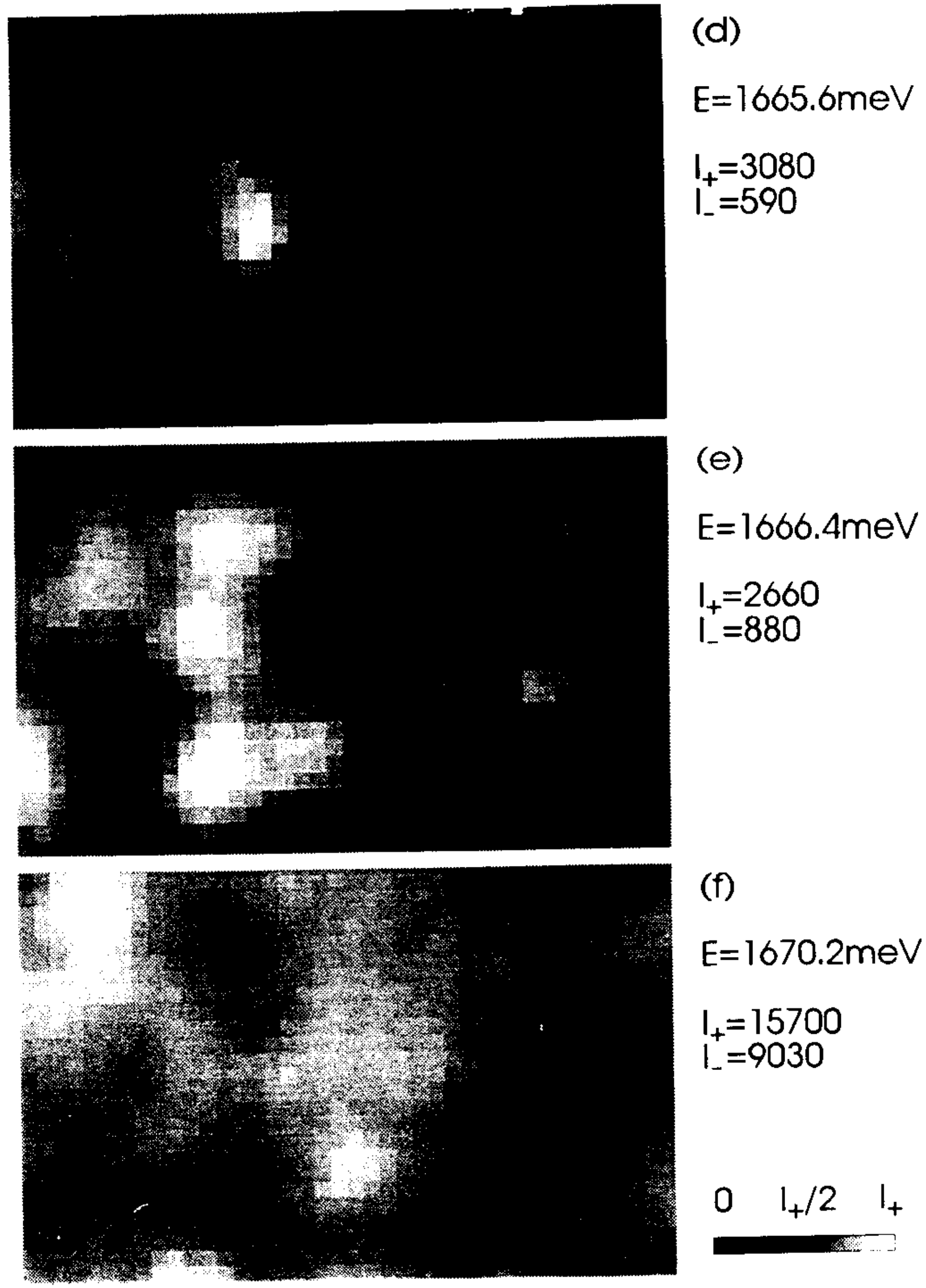
Sample

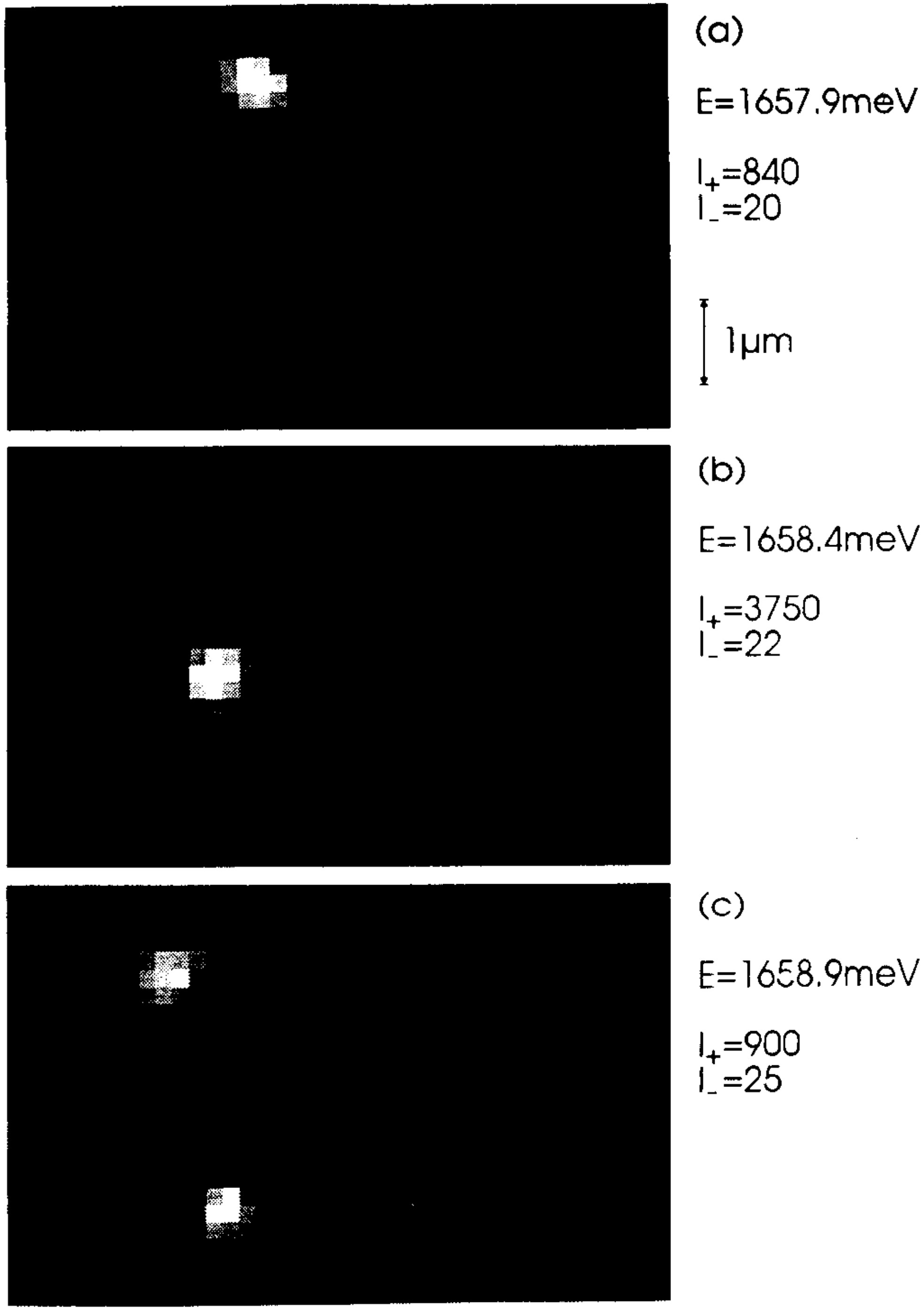
3.5 nm wide GaAs/AlGaAs quantum well.
Excitons are localized by monolayer width fluctuations

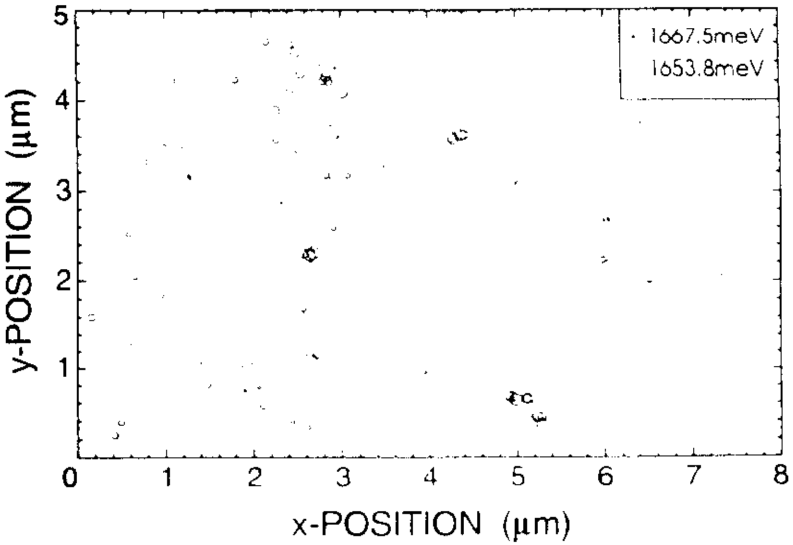


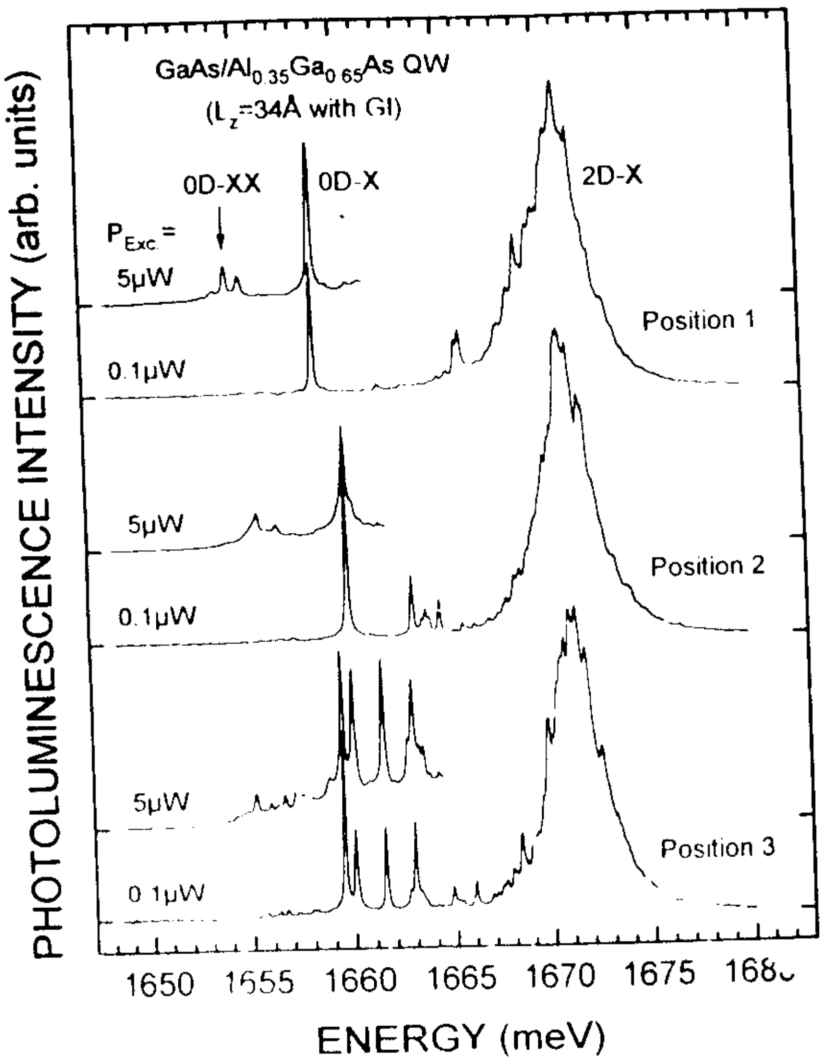


K. Brunner et al. Appl. Phys. Lett. 64, 3320 (1994)

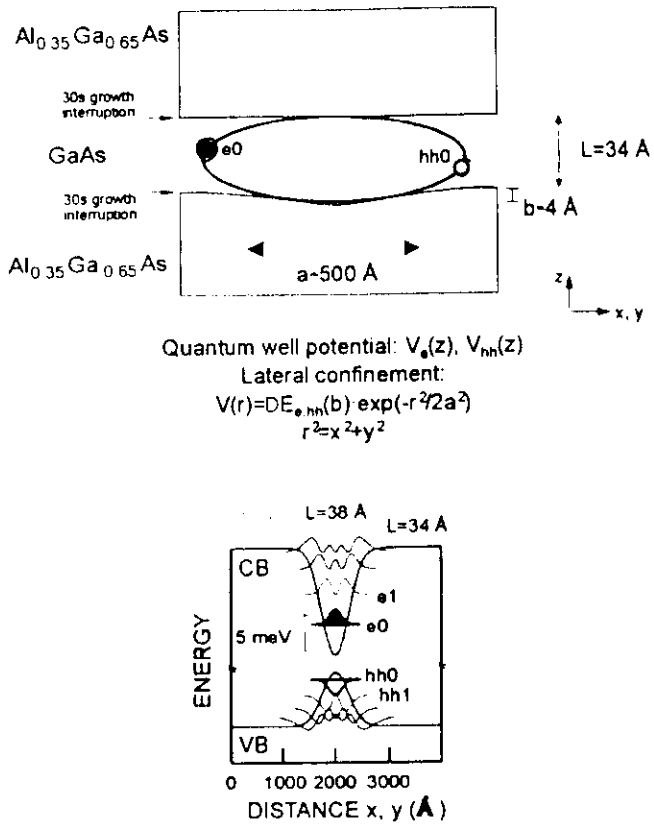



(a)
E=1657.9meV
I_+=840
I_-=20
1μm
(b)
E=1658.4meV
I_+=3750
I_-=22
(c)
E=1658.9meV
I_+=900
I_-=25


1667.5meV
1653.8meV
y-POSITION (μm)
x-POSITION (μm)
0
1
2
3
4
5
6
7
8

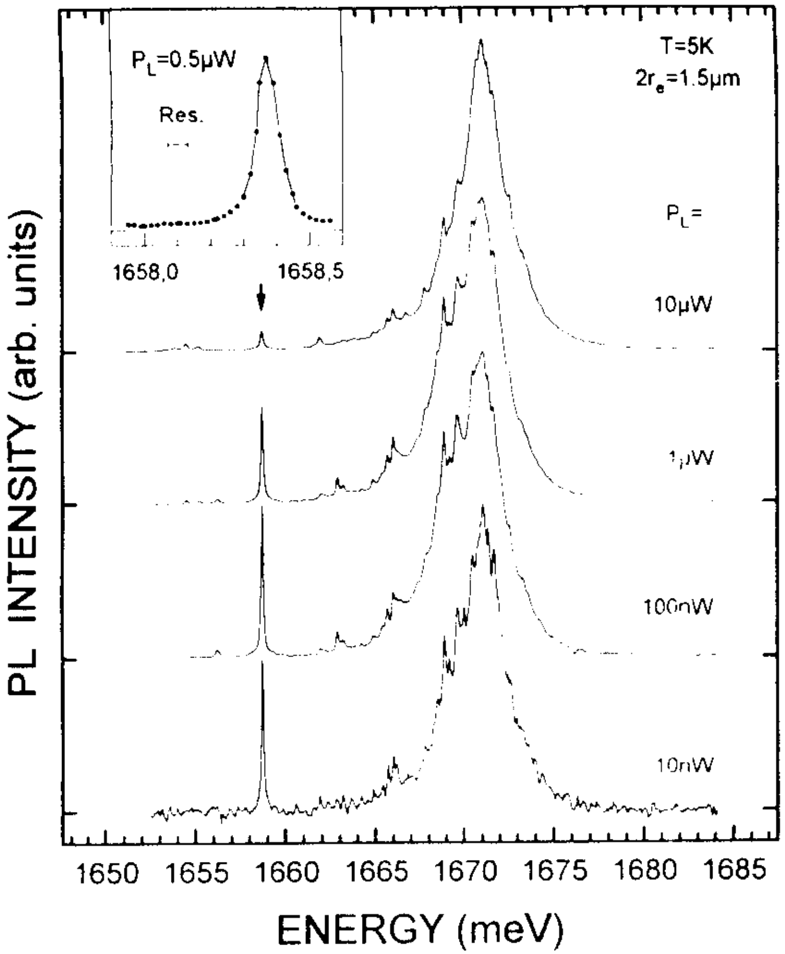


GaAs/$Al_{0.35}Ga_{0.65}As$ QW
(L_z=34Å with GI)
0D-XX
0D-X
2D-X
$P_{Exc.}$ =
5μW
0.1μW
Position 1
Position 2
Position 3
PHOTOLUMINESCENCE INTENSITY (arb. units)
1650
1655
1660
1665
1670
1675
ENERGY (meV)

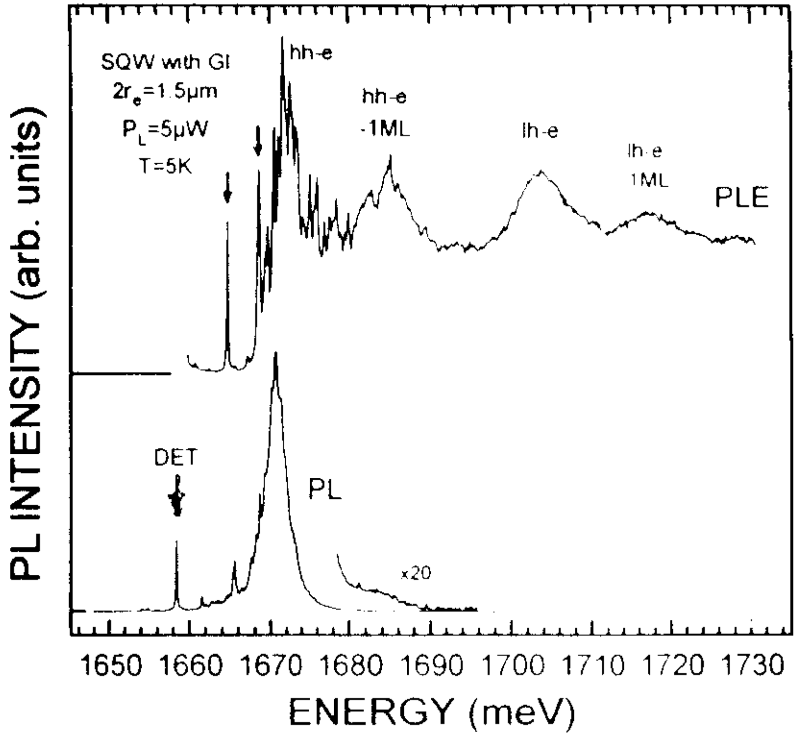


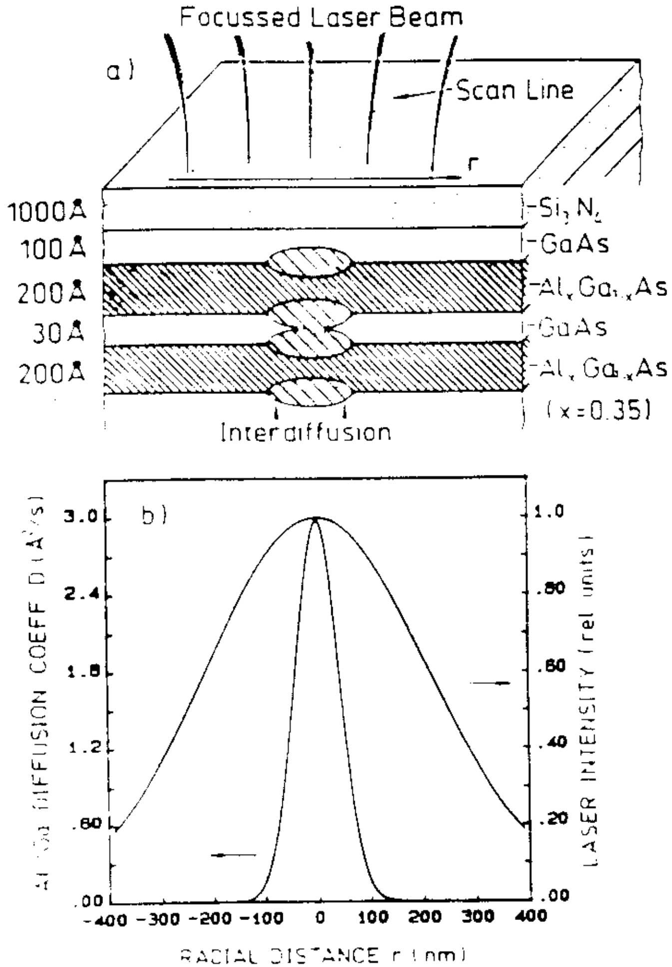
$Al_{0.35}Ga_{0.65}As$
30s growth interruption
GaAs
e0
hh0
L=34 A
b-4 A
a-500 A
z
x, y
Quantum well potential: $V_e(z)$, $V_{hh}(z)$
Lateral confinement:
$V(r)=DE_{e,hh}(b)\cdot exp(-r^2/2a^2)$
$r^2=x^2+y^2$
L=38 A
L=34 A
CB
e1
e0
5 meV
hh0
hh1
VB
ENERGY
0
1000
2000
3000
DISTANCE x, y (Å)

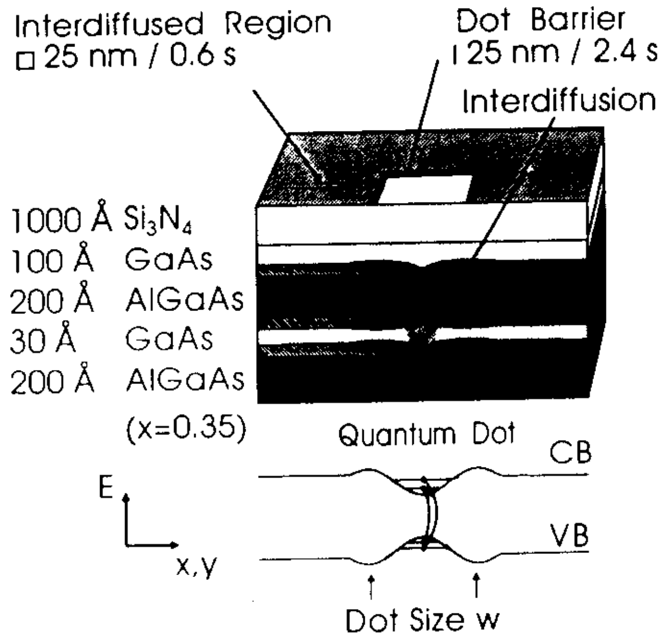
Fig. 7



→ excitation spectroscopy







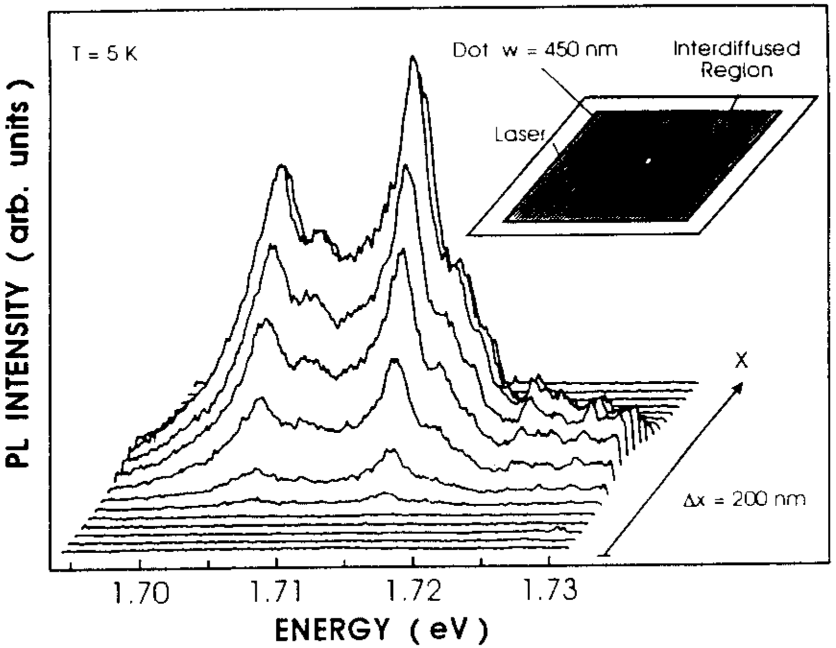
→ K. Brunner et al. Phys. Rev. Lett. 69, 3216 (1992)

→ local doping: Zn in n-AlGaAs/GaAs

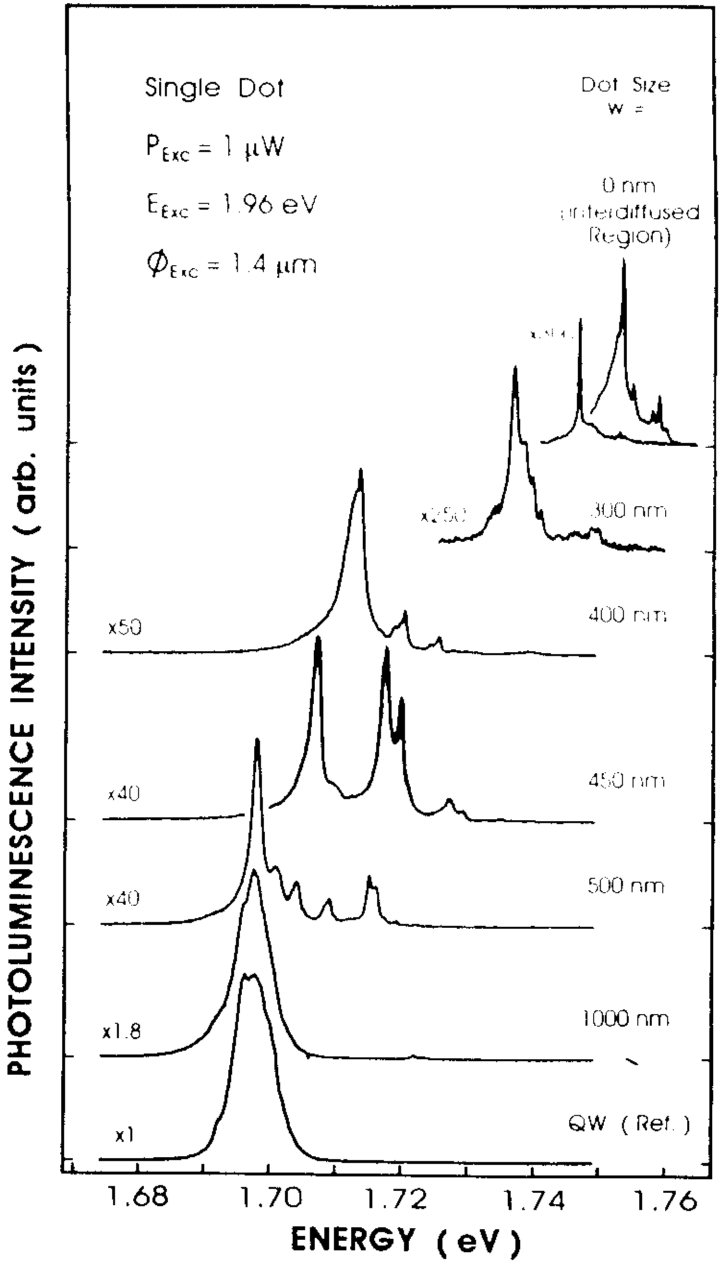
"in-plane gate transistor" P. Baumgartner et al.
Appl. Phys. Lett. 64, 592 (1994)

"lateral npn-transistor"
P. Baumgartner, C. Engel et al.
Appl. Phys. Lett. [illegible] (1995)

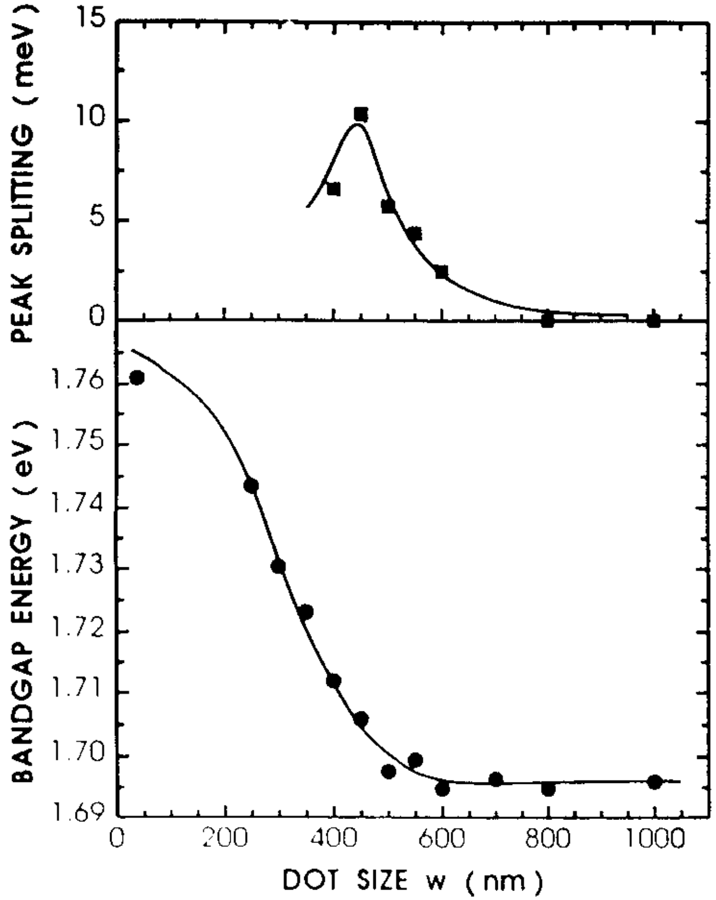
narrow $GaAs / Al_x Ga_{1-x} As$ quantum well

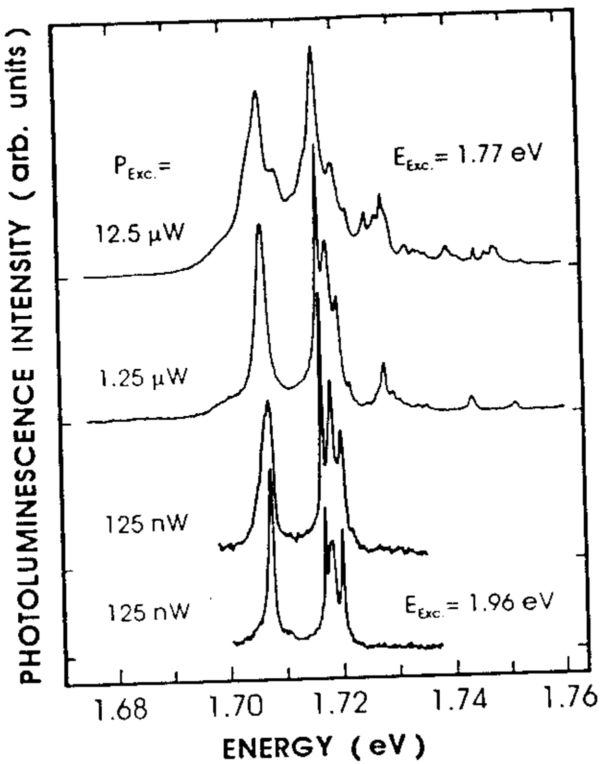


K. Brunner et al. Phys. Rev. Lett. 69, 3216 (1992)

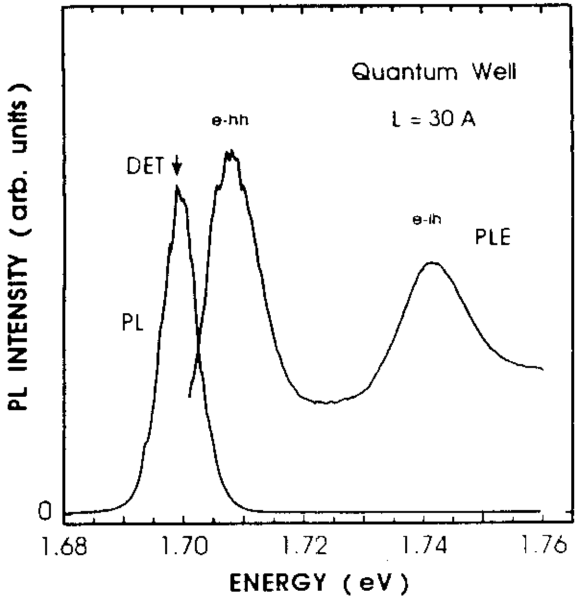


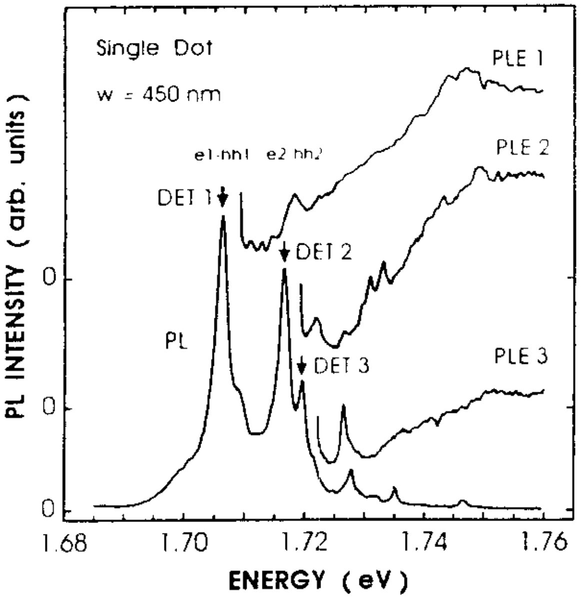
K. Brunner et al. Phys. Rev. Lett. 69, 3216 (1992)



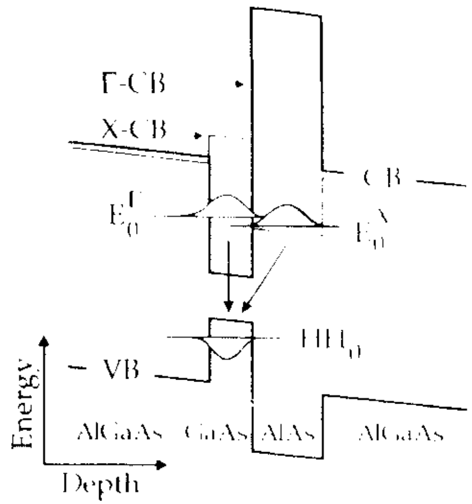


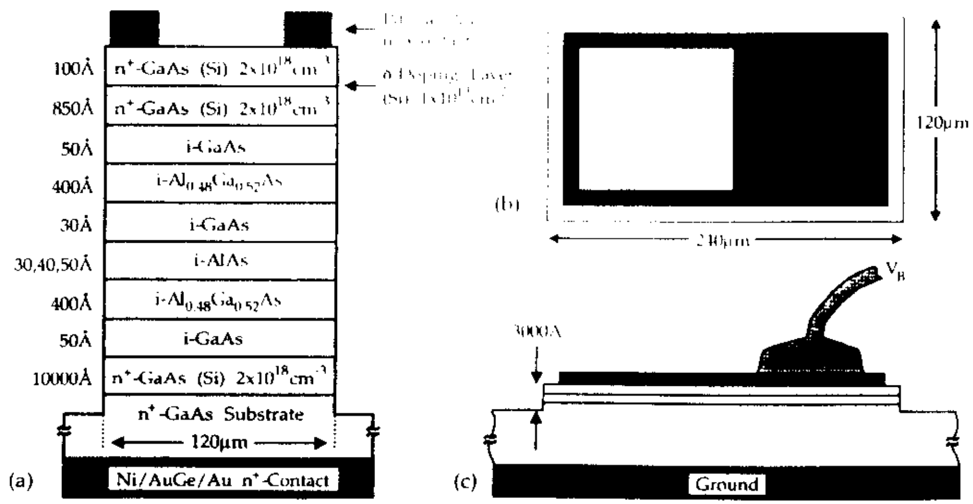
K. Brunner et al., Phys. Rev. Lett. 69, 3216 (1992)



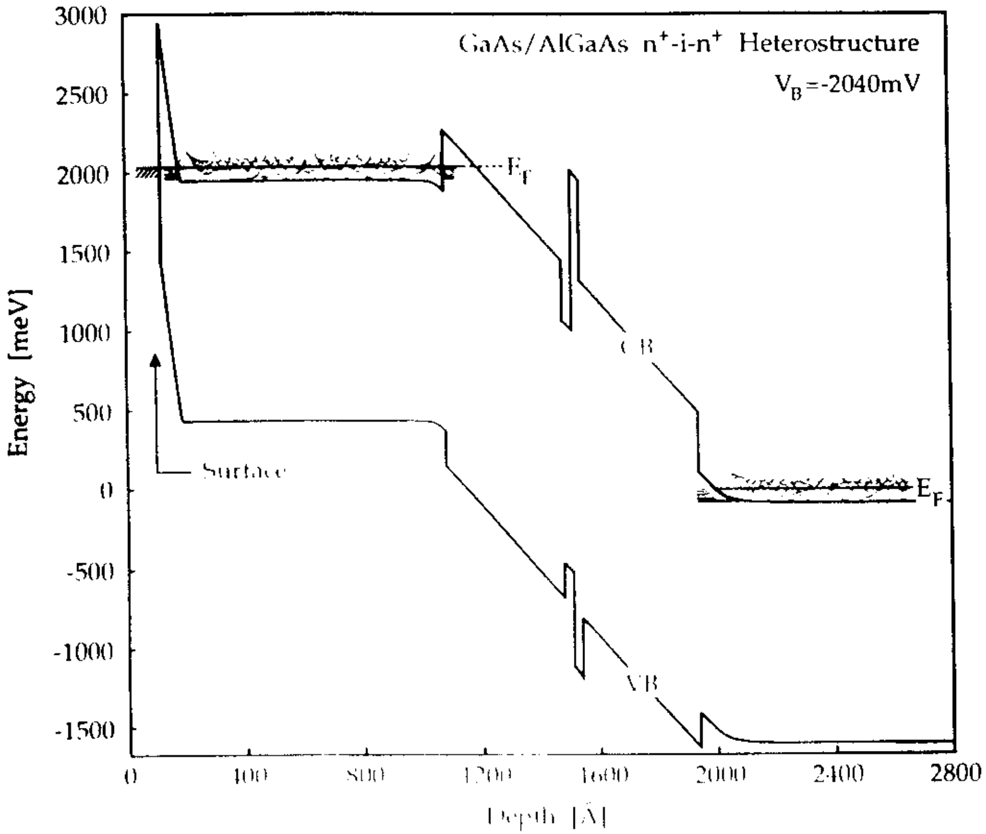


Electric-field-tunable GaAs/AlAs CQW Structures





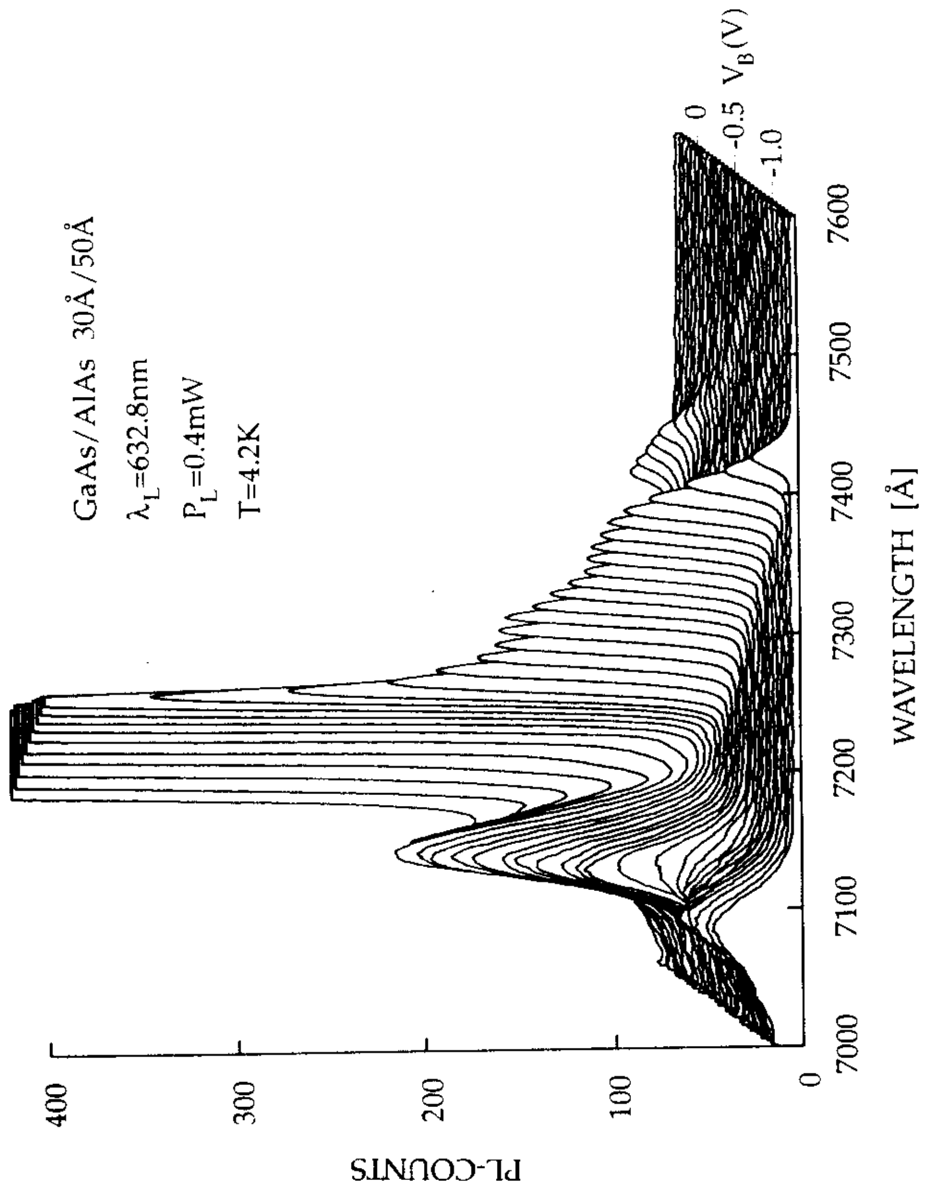
Selfconsistent Description of an n^+-i-n^+ Structure



Schrodinger Equation $\quad -\frac{\hbar^2}{2}\frac{d}{dz}\frac{1}{m^*(E,z)}\frac{d}{dz}\Psi(z)+V(z)\Psi(z)=E\Psi(z)$

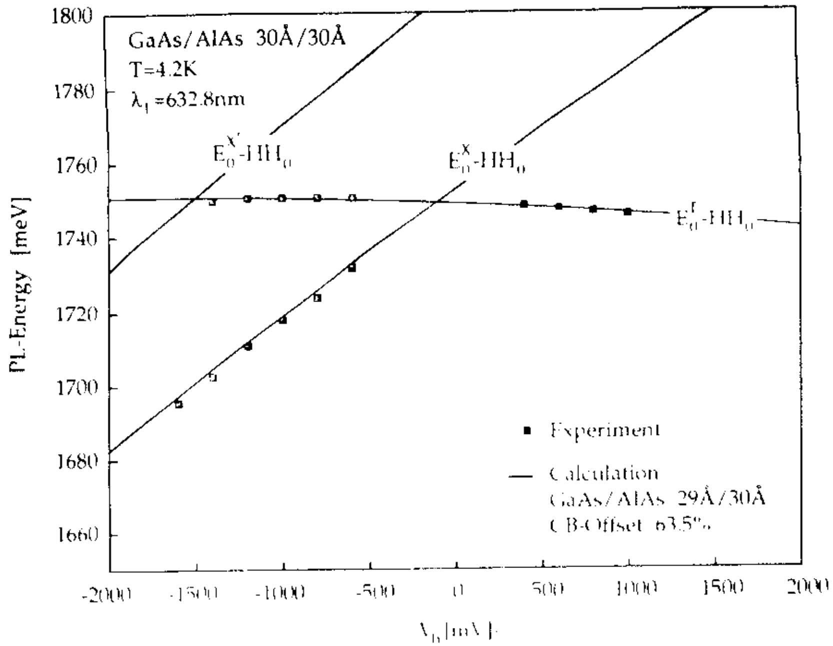
$$m^* = \left[1 + C + \frac{E_p}{3}\left(\frac{2}{E_{\Gamma}} + \frac{1}{E_{\Gamma}+\Delta}\right) + \frac{E_p'}{3}\left(\frac{2}{E_{\Gamma}'} + \frac{1}{E_{\Gamma}'+\Delta'}\right)\right]^{-1} m_e$$

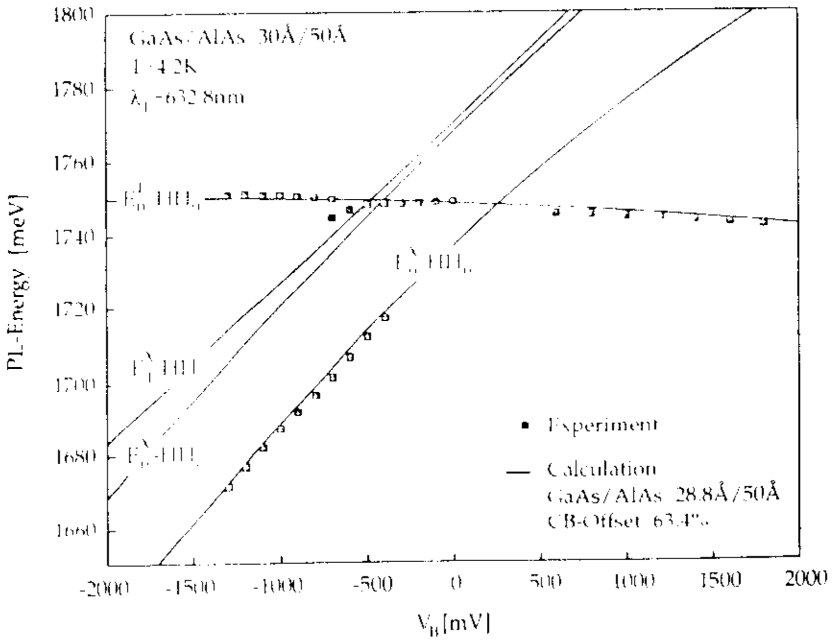
- correct description of the electrostatic screening
- relates the external voltage V_B to the internal electric field



A. Zrenner, Advances in Solid State Physics 32 (1992)

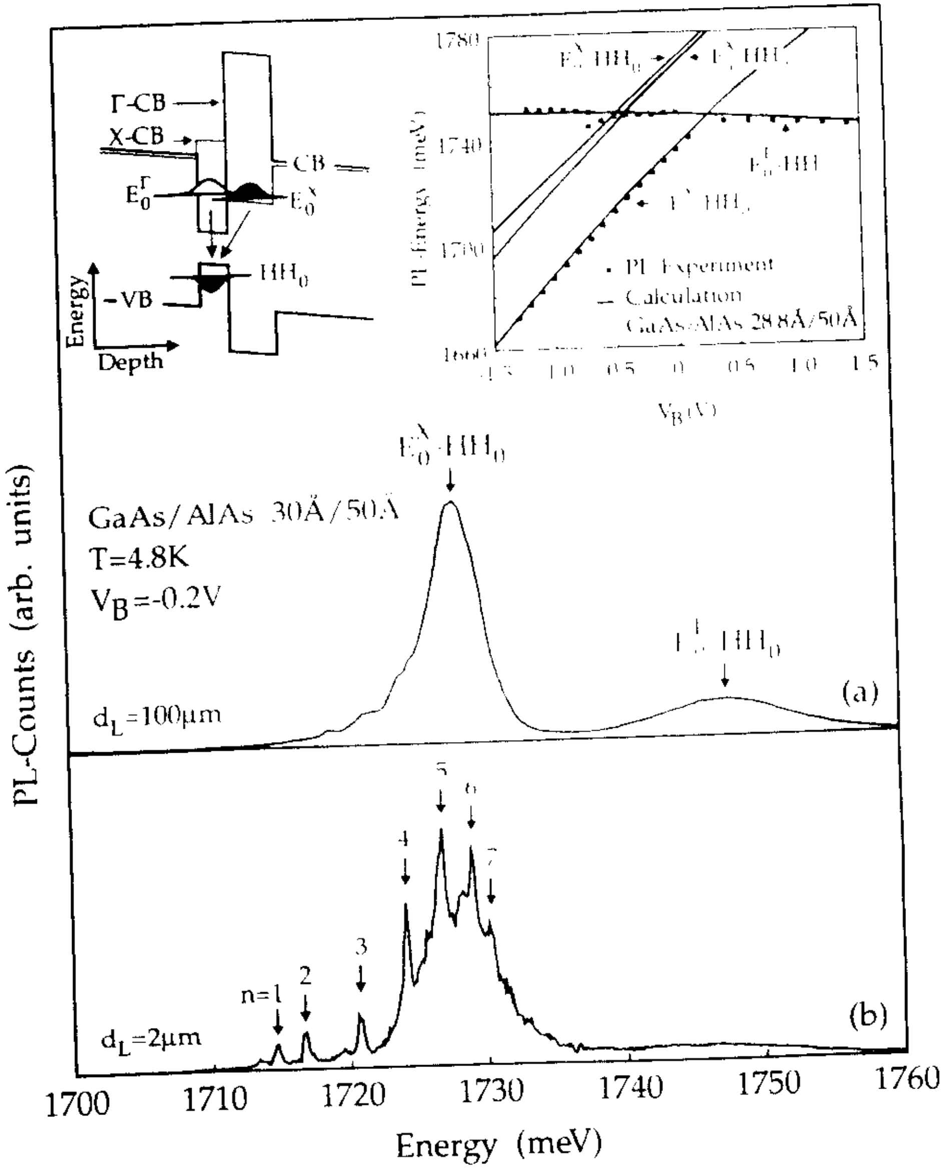
Comparison: PL-Experiment - Modelcalculation

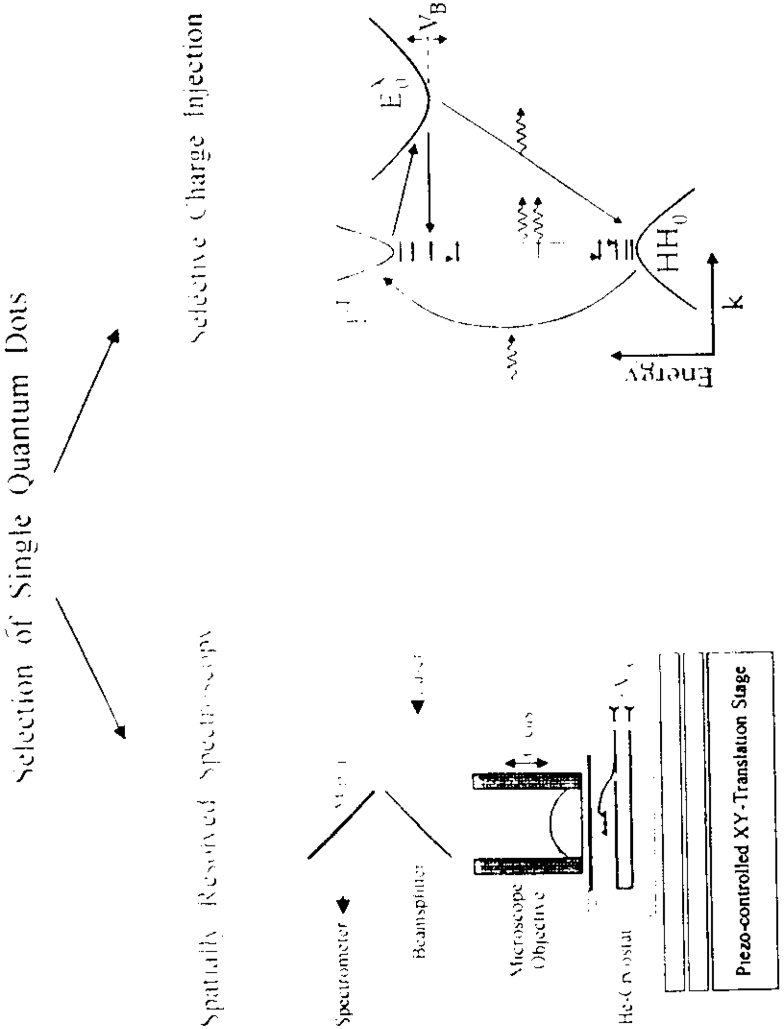


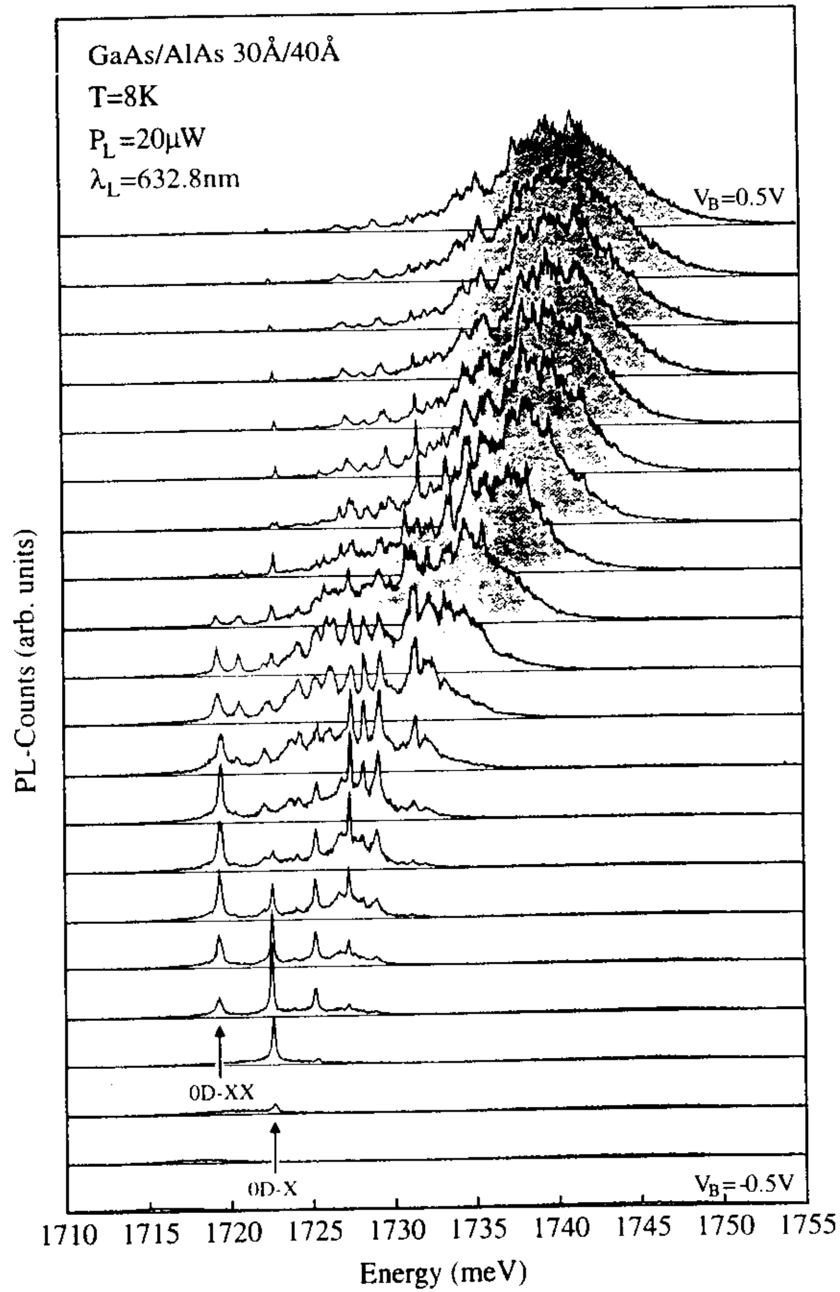


from A. Zrenner,
Festkörperprobleme 32 (1992)

Ortsaufgelöste Photolumineszenz

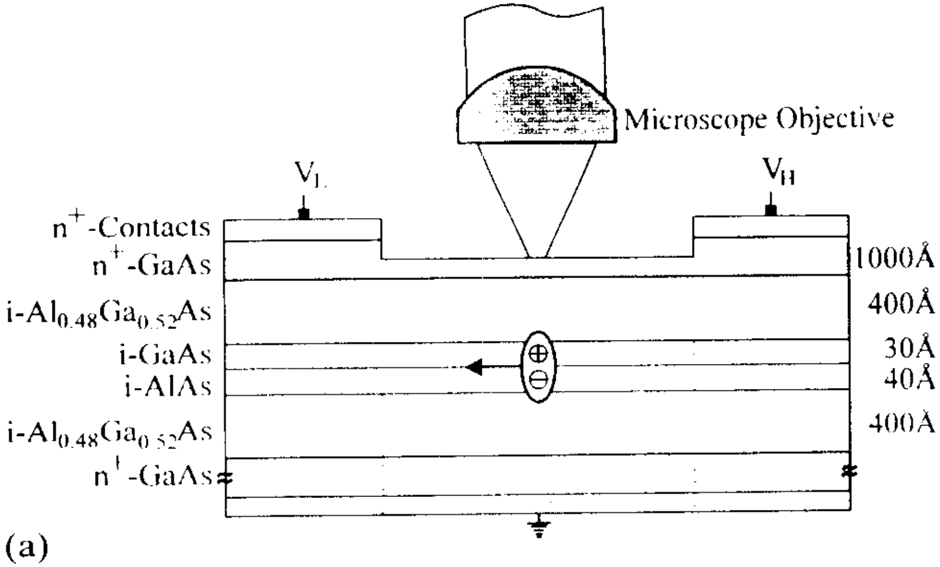




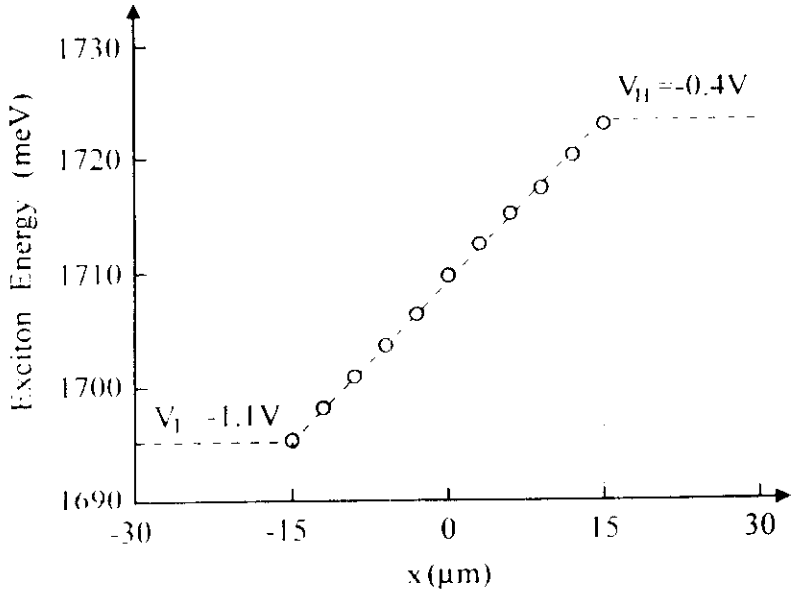


A Zrenner et al Phys. Rev. Lett. 72 3382 (1994) and Surf. Science

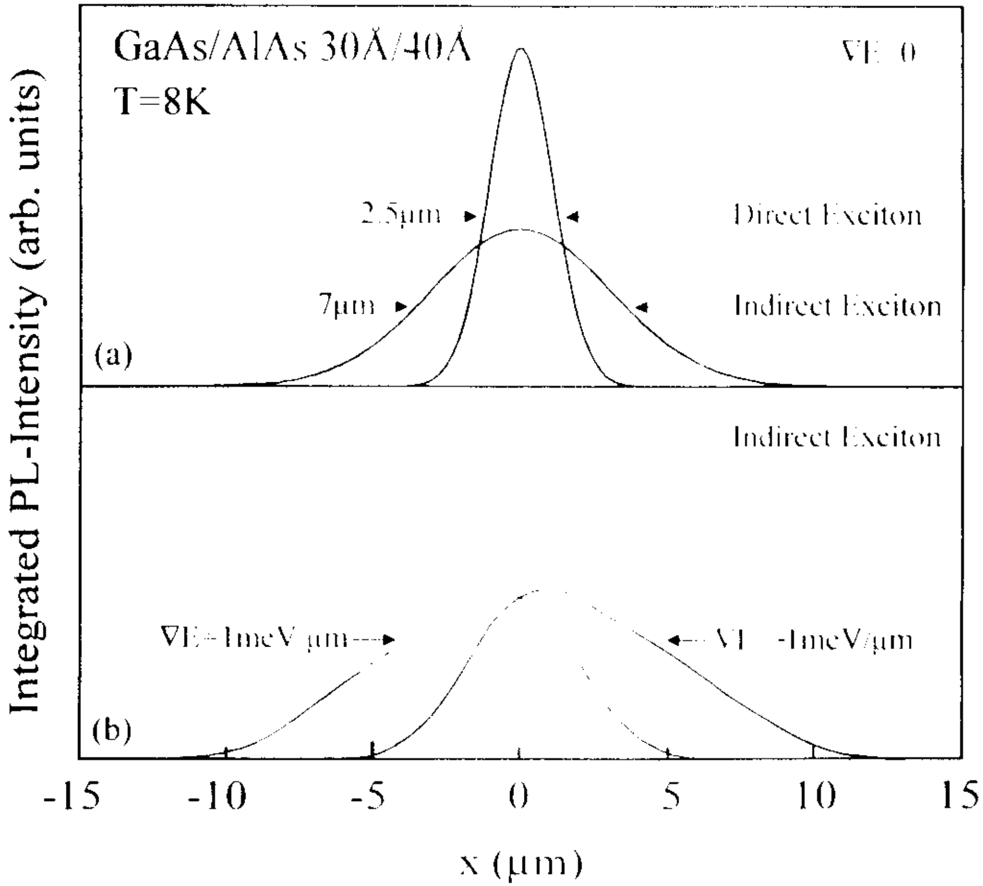
3-terminal CQW Device for Exciton Transport



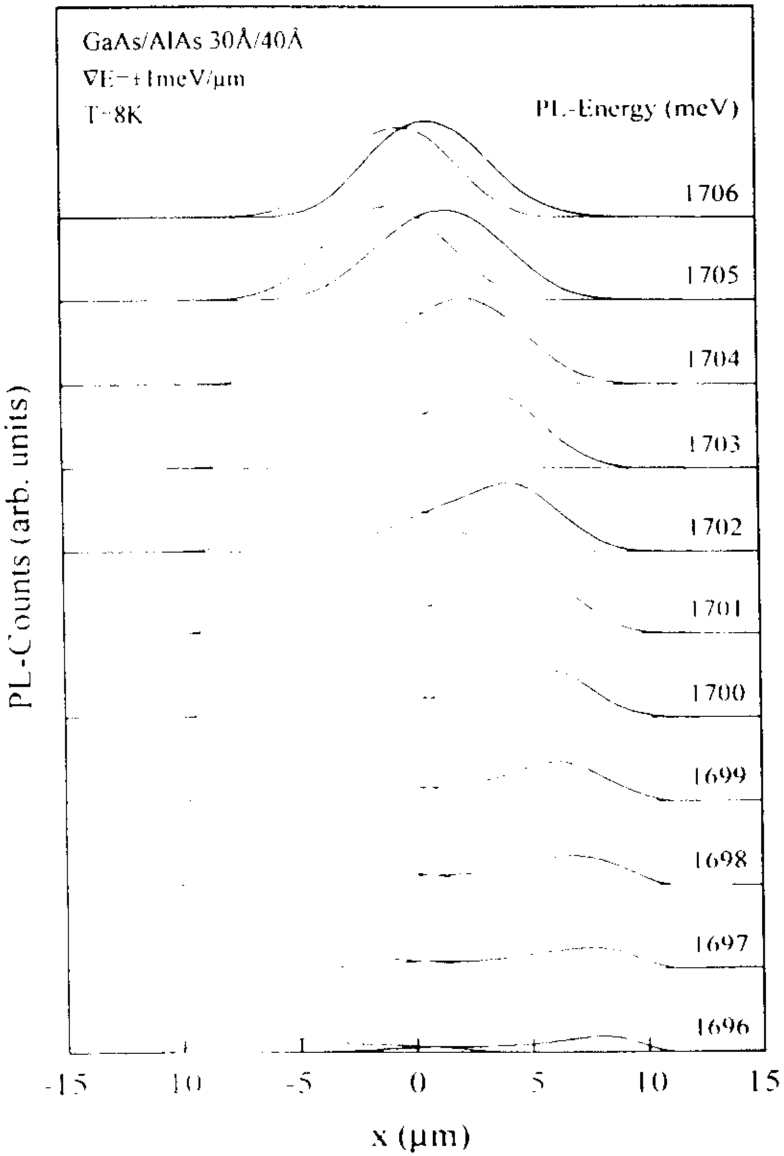
(a)

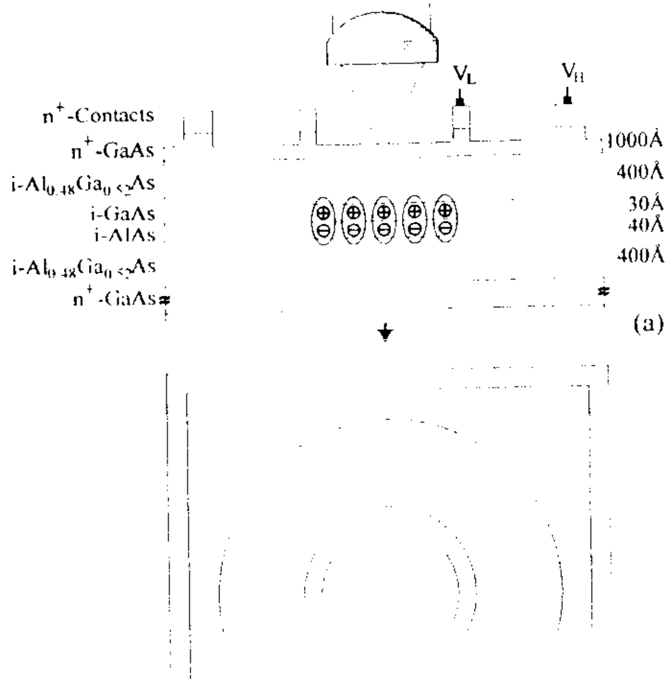


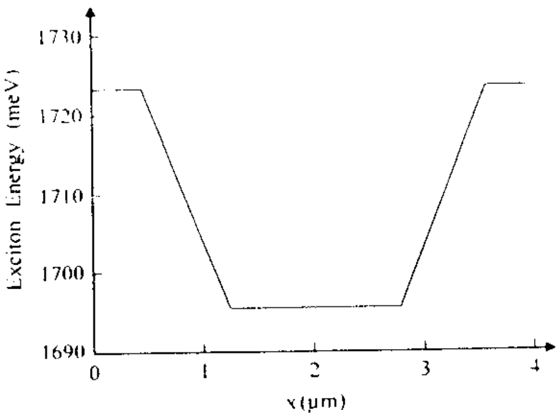
(b)



M. Hagn, A. Zrenner, G. Böhm and G. Weimann, APL July 10 (1995)







Exciton - Trap

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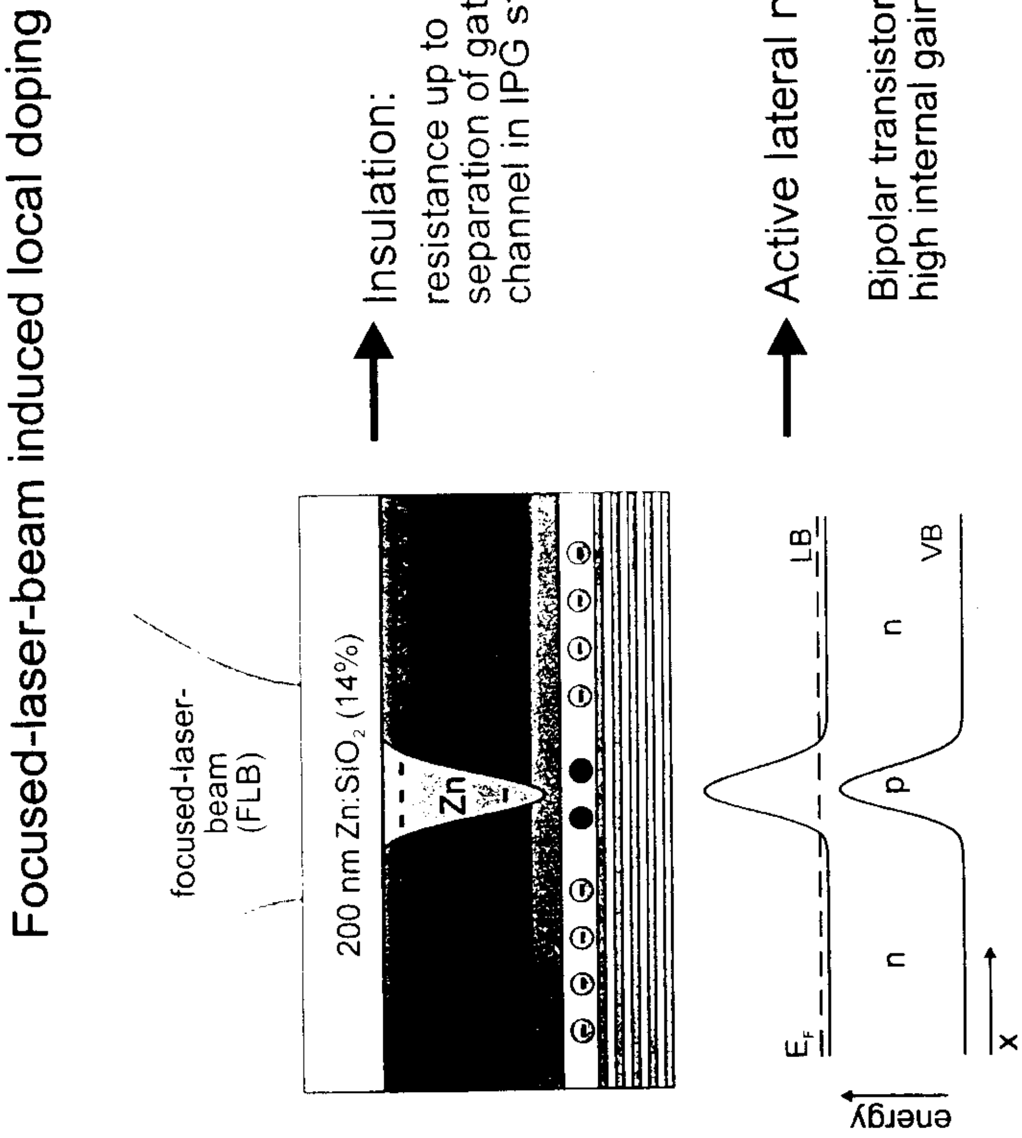

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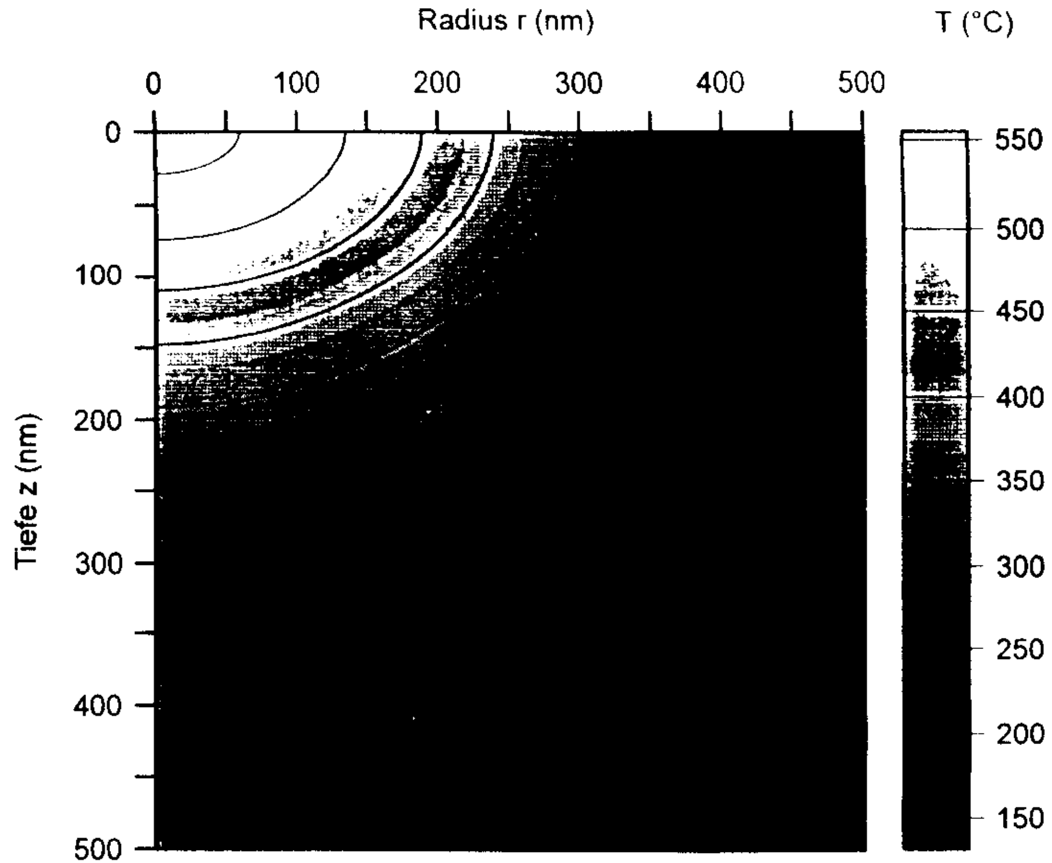
Temperaturverteilung in der Probe

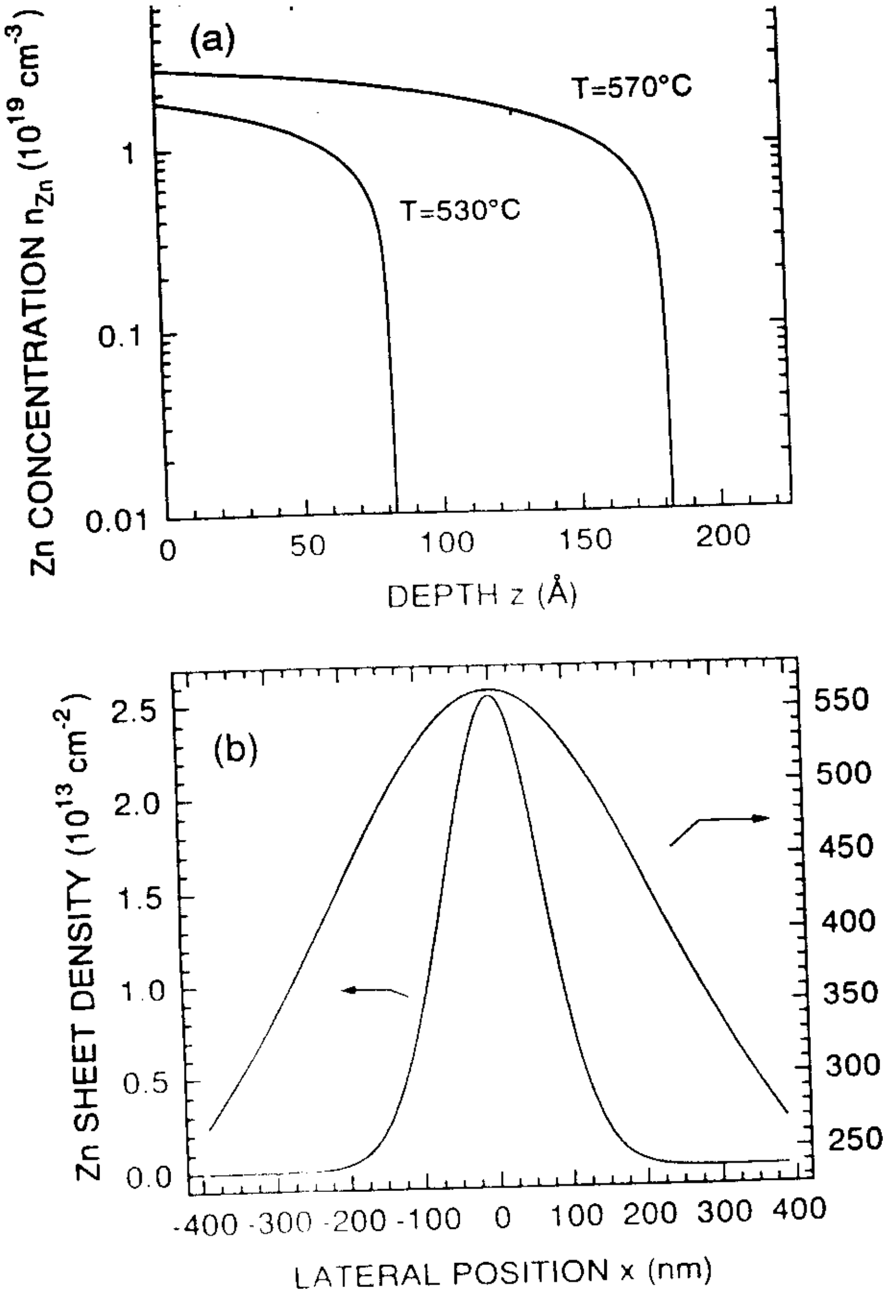


P_{Laser}=4.5mW

Laserspotdurchmesser $2 \cdot r_e$=600nm

Wärmeleitfähigkeit $\kappa \propto 1/T$

Temperaturgleichgewicht nach $\tau = c \cdot r_e^2/\kappa < 1\mu s$



P. Baumgartner, C. Engel et al Appl. Phys. Lett $\underline{64}$, 592 (1994)
- in-plane gate transistor
- phototransistor

and $\underline{66}$, 751 (1995)

- concentration dependent diffusion coefficient:

$$\underline{D_{Zn} = c_0 (n_{Zn})^2 \exp(-E_a / k_B T)}$$

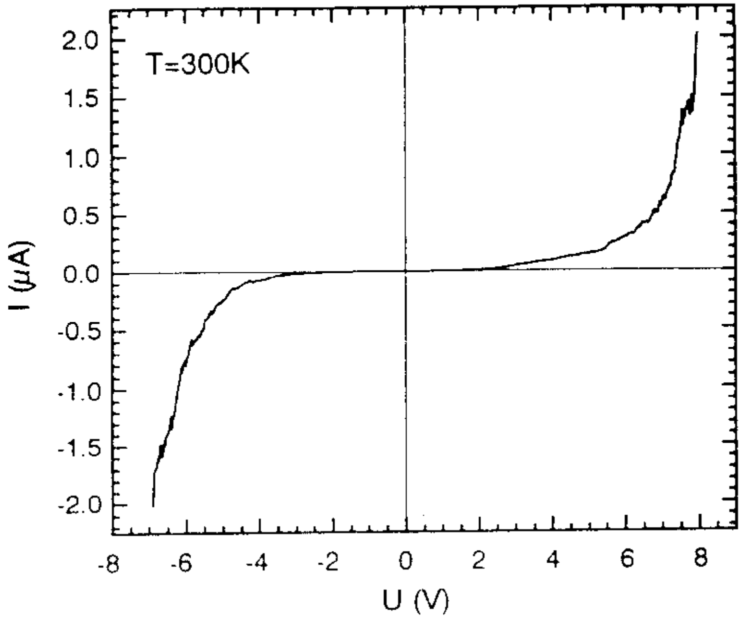
- temperature dependent Zn solubility:

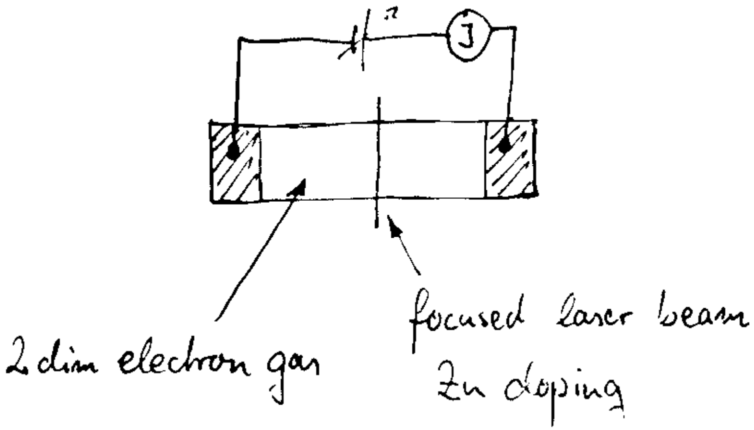
$$\underline{n_{Zn,max} = n_0 \exp(-E_s / k_B T)}$$

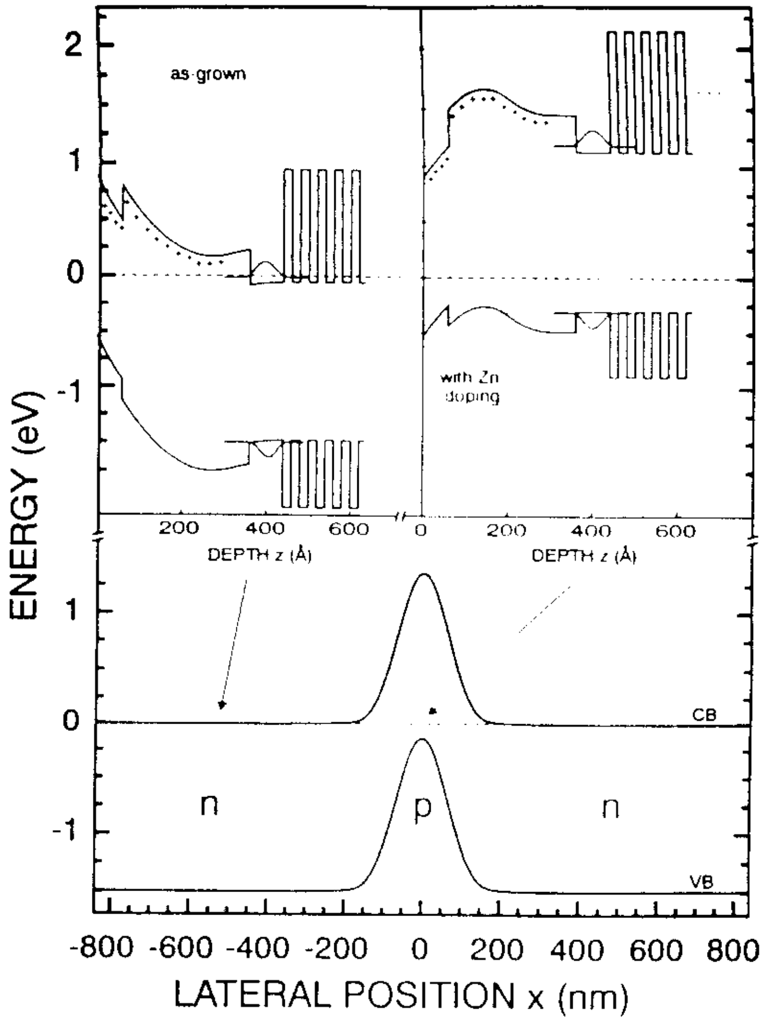
Lit.: $c_0 = 2.3 \times 10^{-44}\ \text{cm}^8/\text{s}$
$E_a = 1.1$ eV
$n_0 = 9.5 \times 10^{22}\ \text{cm}^{-3}$
$E_s = 0.57$ eV

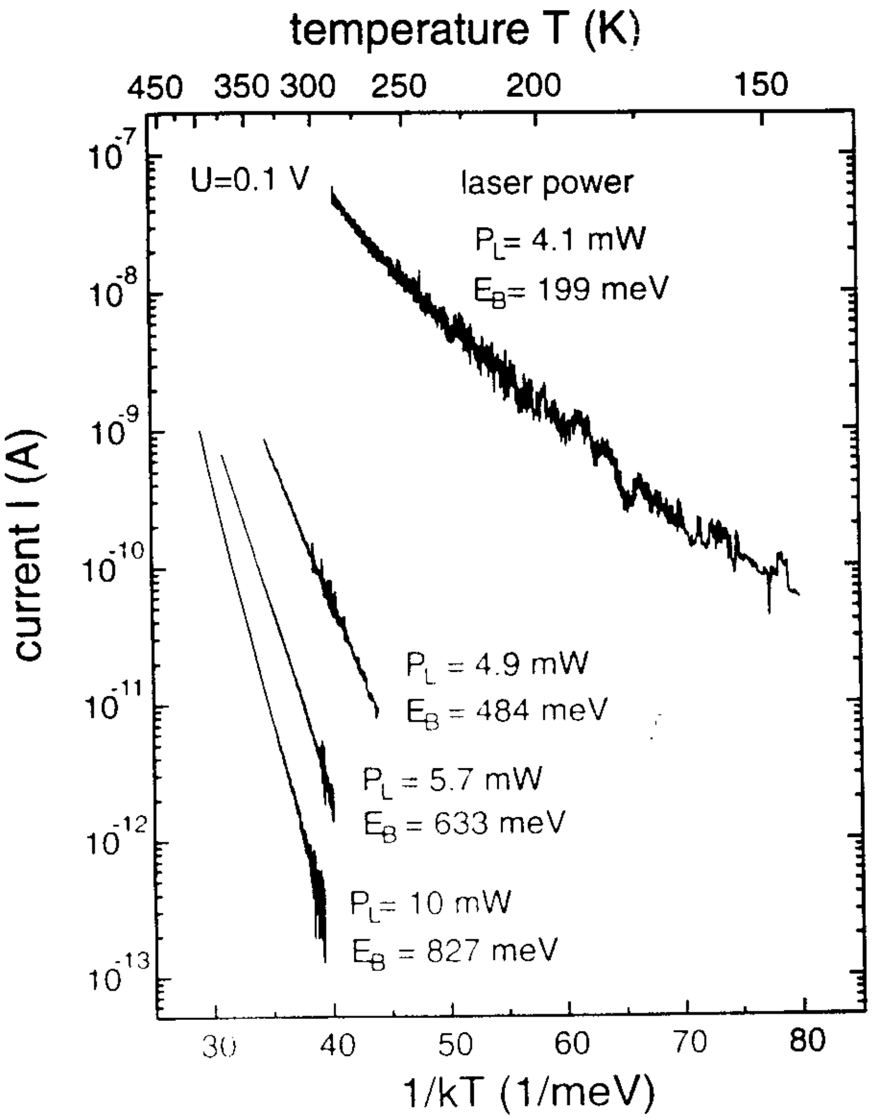
H.C. Casey Jr, in Atomic Diffusion in Semiconductors
ed. D. Shaw, Plenum, NY, 1973

$\underline{2r_e = 600\ \text{nm}}$, $\underline{P_L = 4.5\ \text{mW}}$, $\underline{\Delta t = 1\ \text{s}}$


T=300K
I (μA)
U (V)
2.0
1.5
1.0
0.5
0.0
-0.5
-1.0
-1.5
-2.0
-8
-6
-4
-2
0
2
4
6
8


J
2 dim electron gas
focused laser beam
Zn doping


as-grown
with Zn doping
ENERGY (eV)
DEPTH z (Å)
DEPTH z (Å)
CB
VB
n
p
n
LATERAL POSITION x (nm)
-800 -600 -400 -200 0 200 400 600 800


temperature T (K)
450 350 300 250 200 150
U=0.1 V
laser power
P_L= 4.1 mW
E_B= 199 meV
P_L = 4.9 mW
E_B = 484 meV
P_L = 5.7 mW
E_B = 633 meV
P_L= 10 mW
E_B = 827 meV
current I (A)
10^{-7} 10^{-8} 10^{-9} 10^{-10} 10^{-11} 10^{-12} 10^{-13}
30 40 50 60 70 80
1/kT (1/meV)

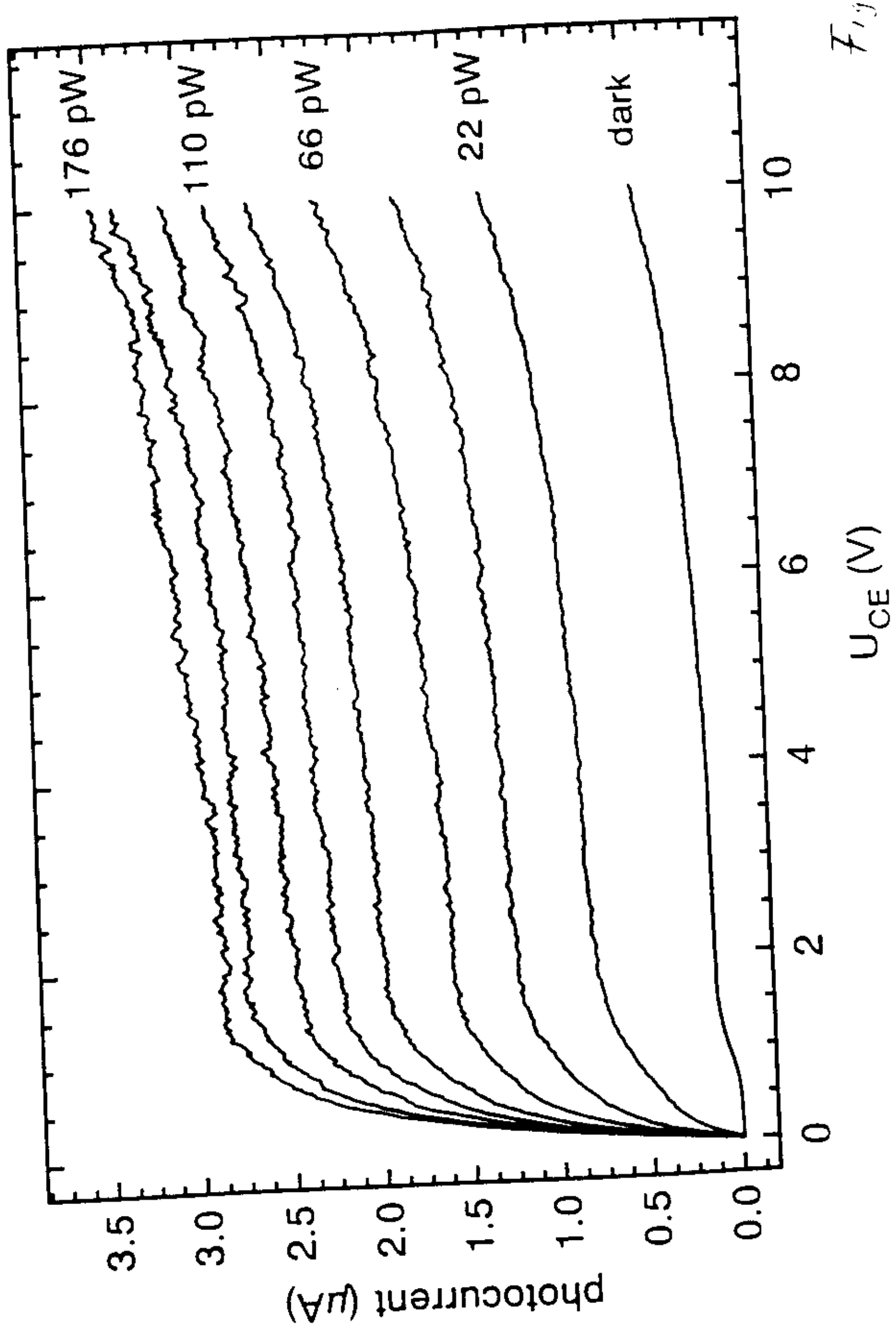
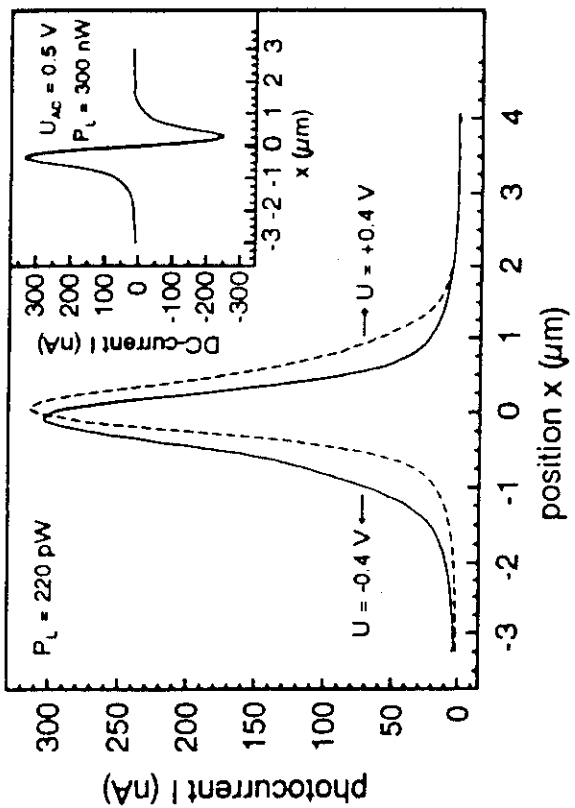
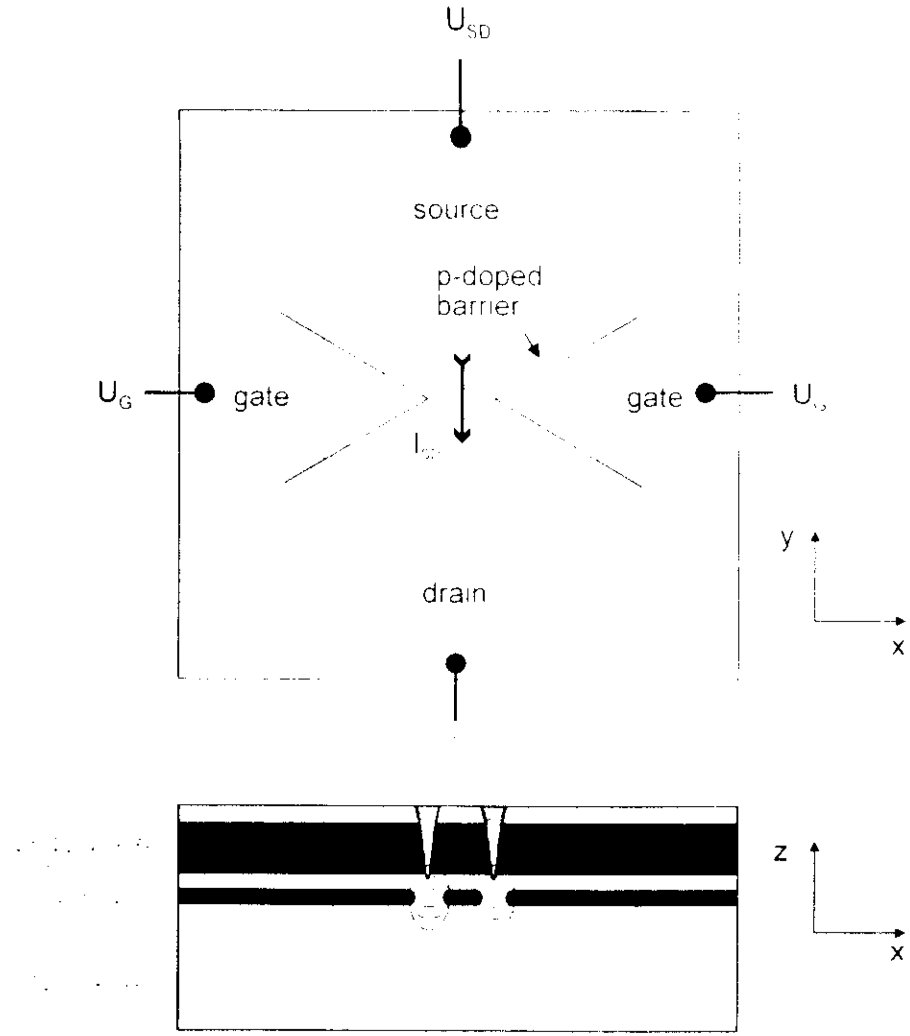

176 pW
110 pW
66 pW
22 pW
dark
U_{CE} (V)
0 2 4 6 8 10
photocurrent (μA)
0.0 0.5 1.0 1.5 2.0 2.5 3.0 3.5

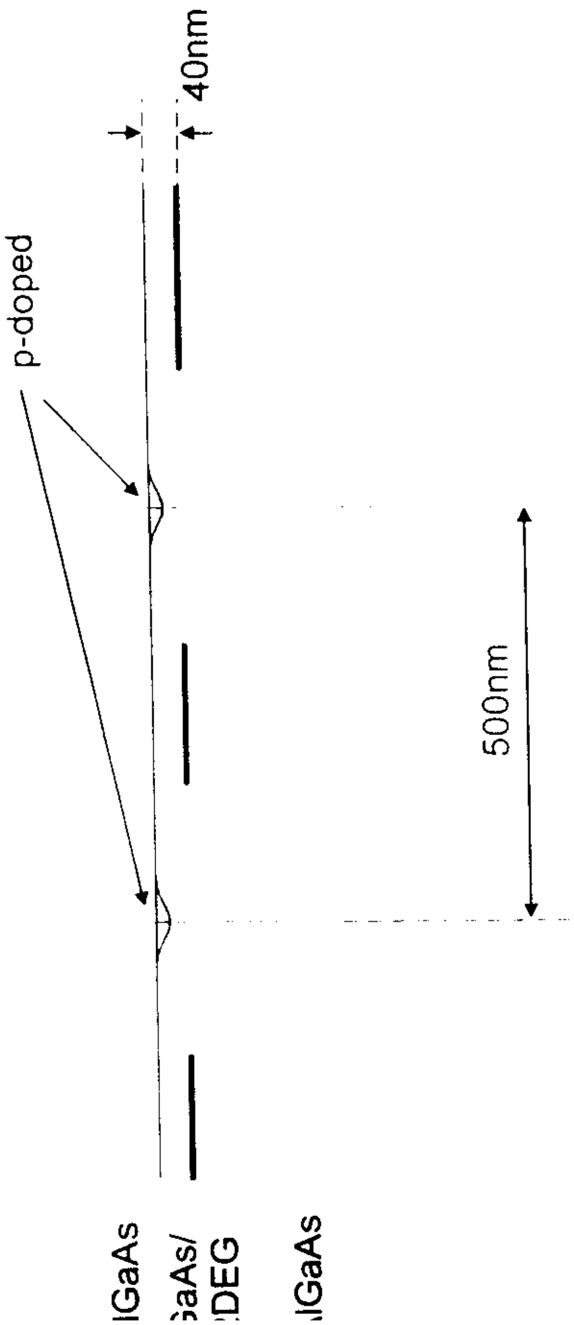
Fig 63

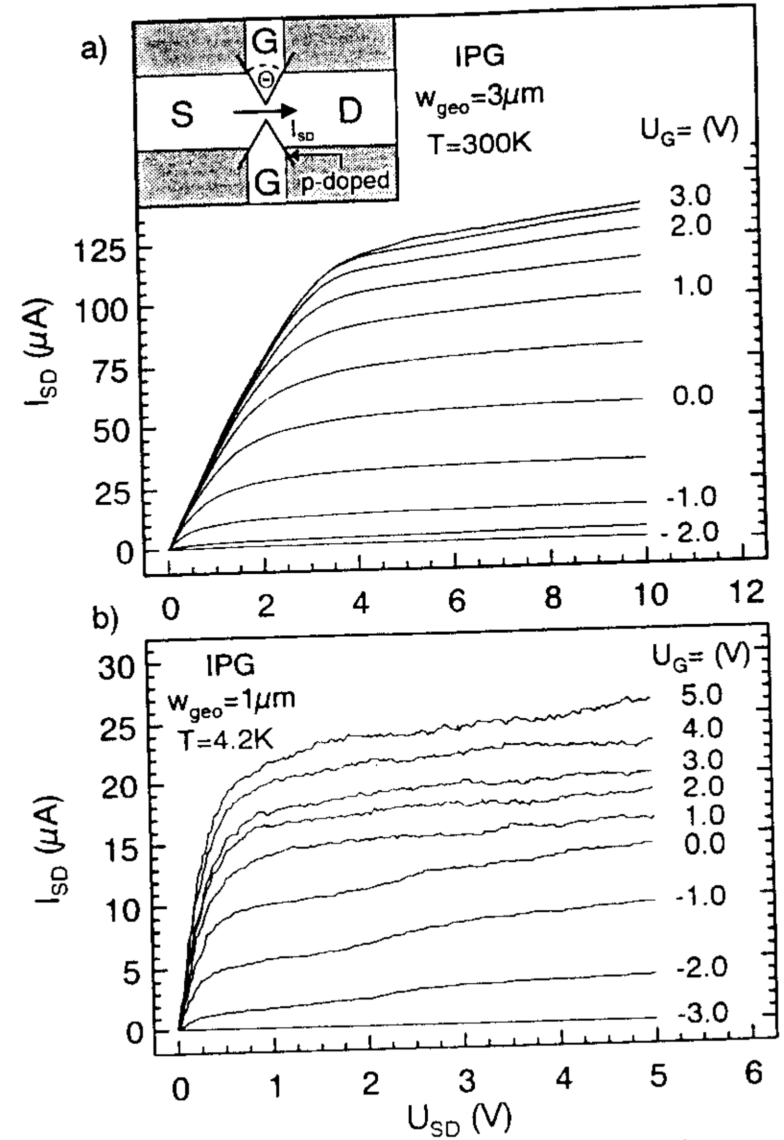


In-Plane-Gate Transistor



in-plane-gate structure to scale:



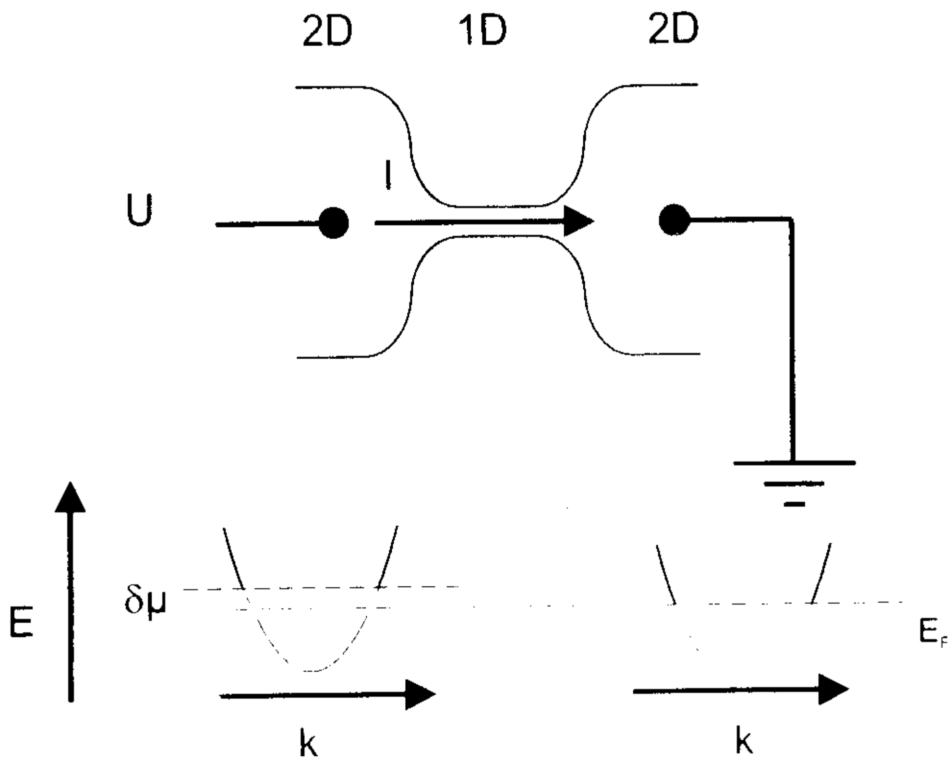


"in-plane gate transistor"

"point contact"

P. Baumgartner et al. Appl. Phys. Lett. 64, 592 (1994

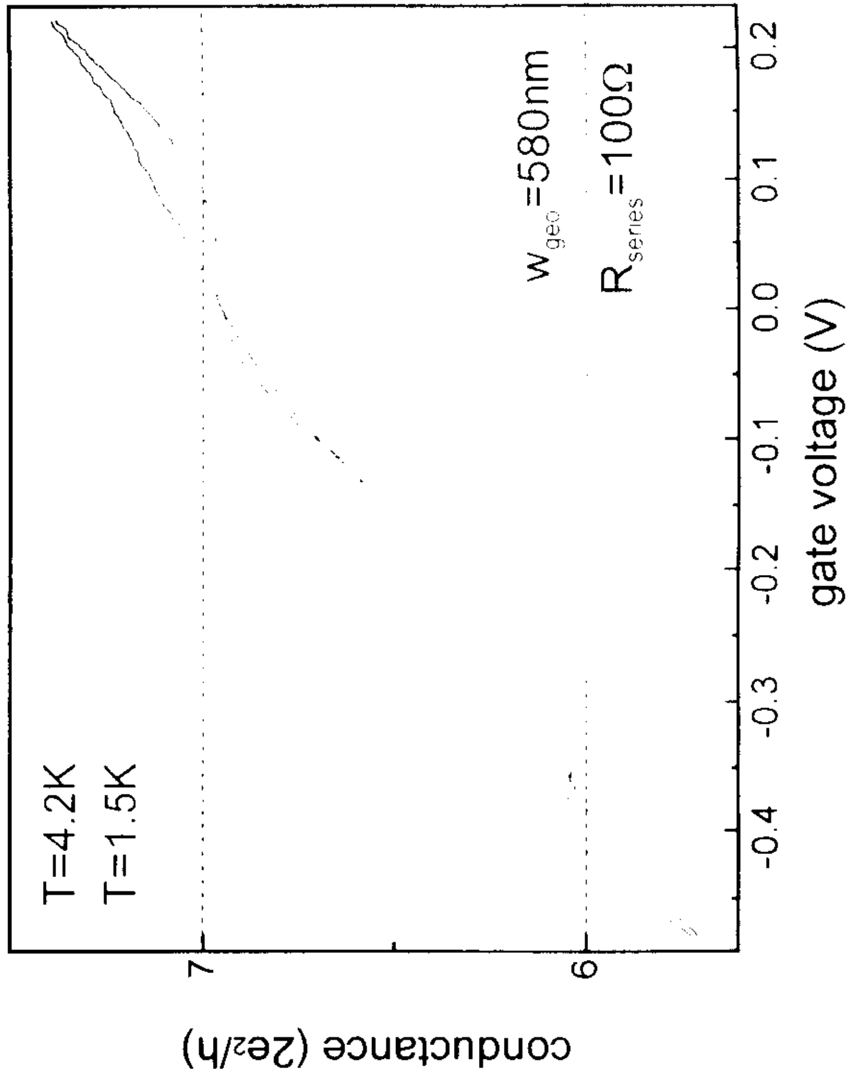
Ballistischer Transport in Quanten-Punktkontakten

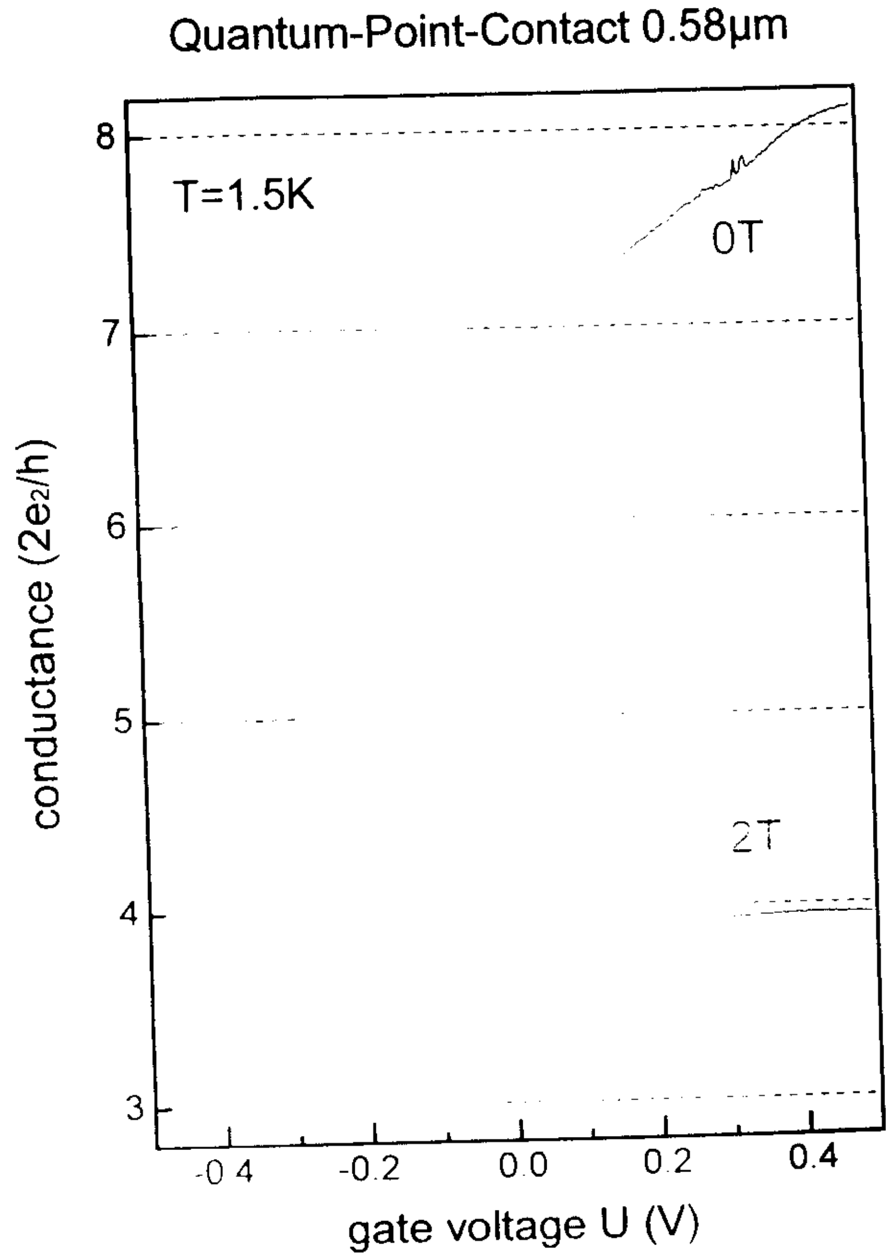


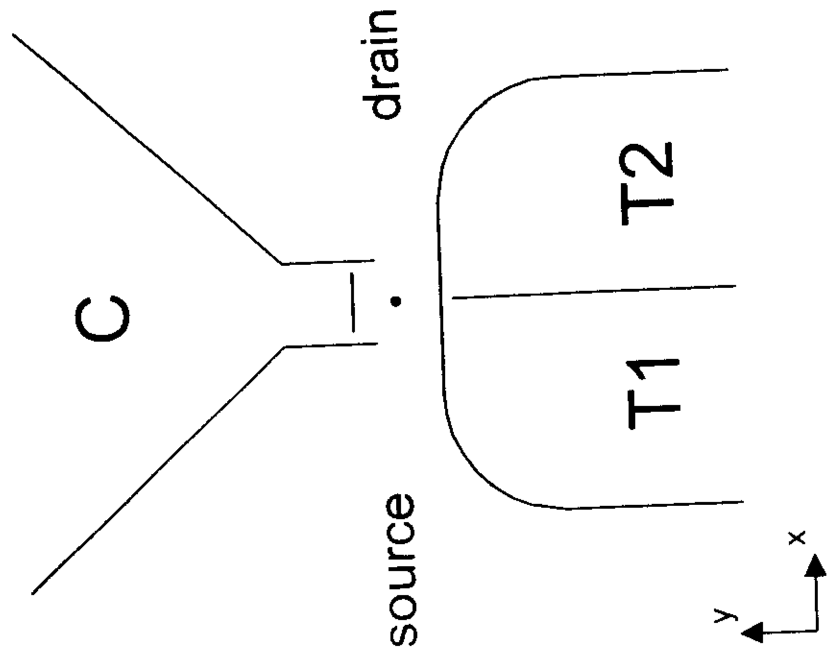
$$I = e \cdot n \cdot v \qquad n = 2 \cdot \delta\mu \cdot \frac{2\pi \cdot dk}{dE}$$

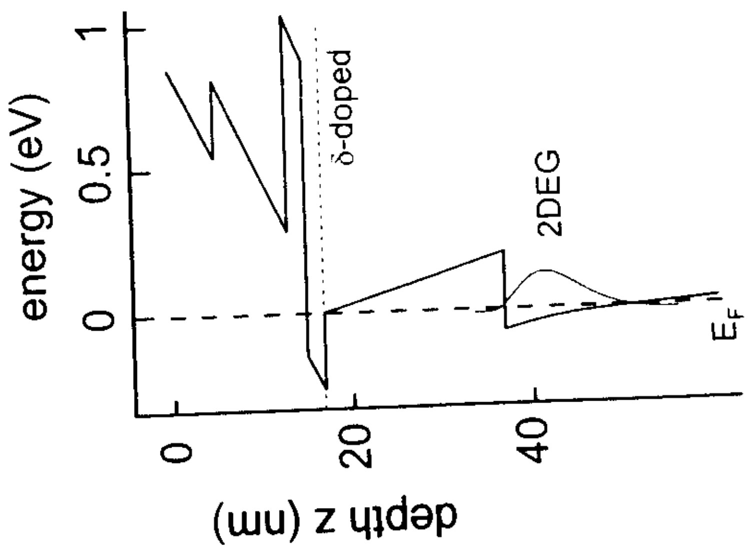
$$v = \frac{dE}{\hbar \cdot dk}$$

$$G = \frac{I}{U} = \frac{e \cdot I}{\delta\mu} = \frac{2e^2}{h}$$

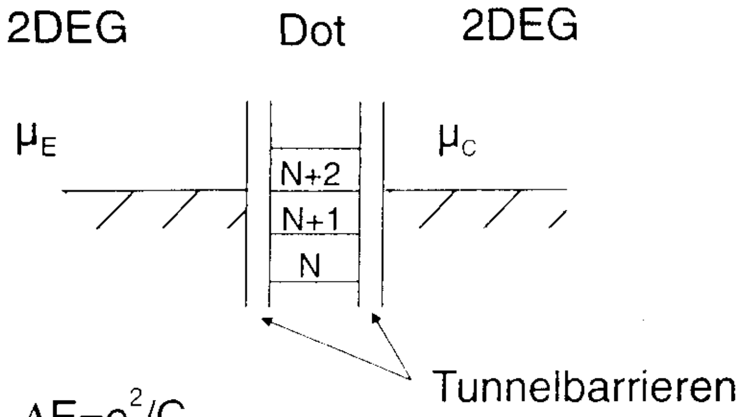



Quantum-Point-Contact 0.58μm
T=1.5K
0T
2T
conductance (2e2/h)
gate voltage U (V)

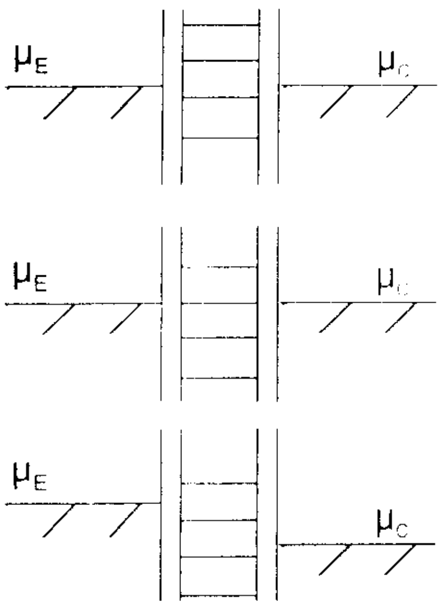

C
drain
source
T2
T1
x
y


energy (eV)
depth z (nm)
δ-doped
2DEG
E_F

Coulomb-Blockade und Einzelelektron-Tunneln



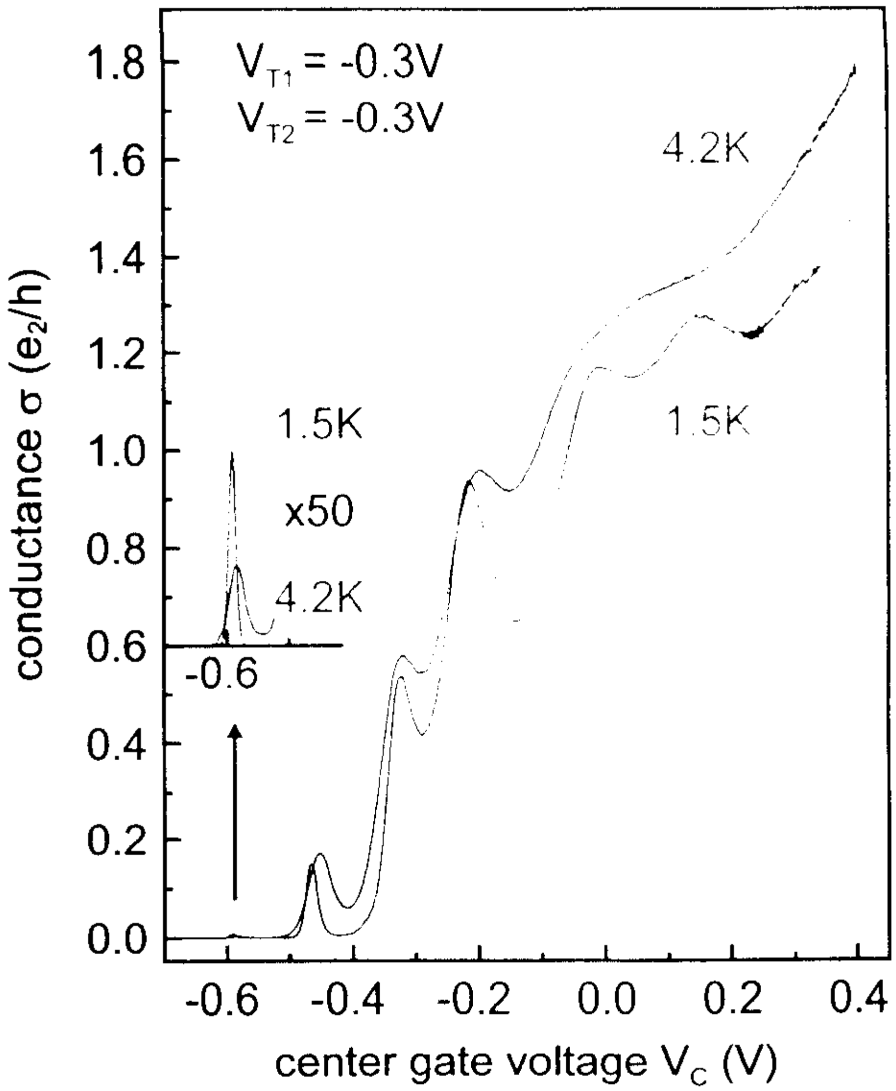
$\Delta E = e^2/C$

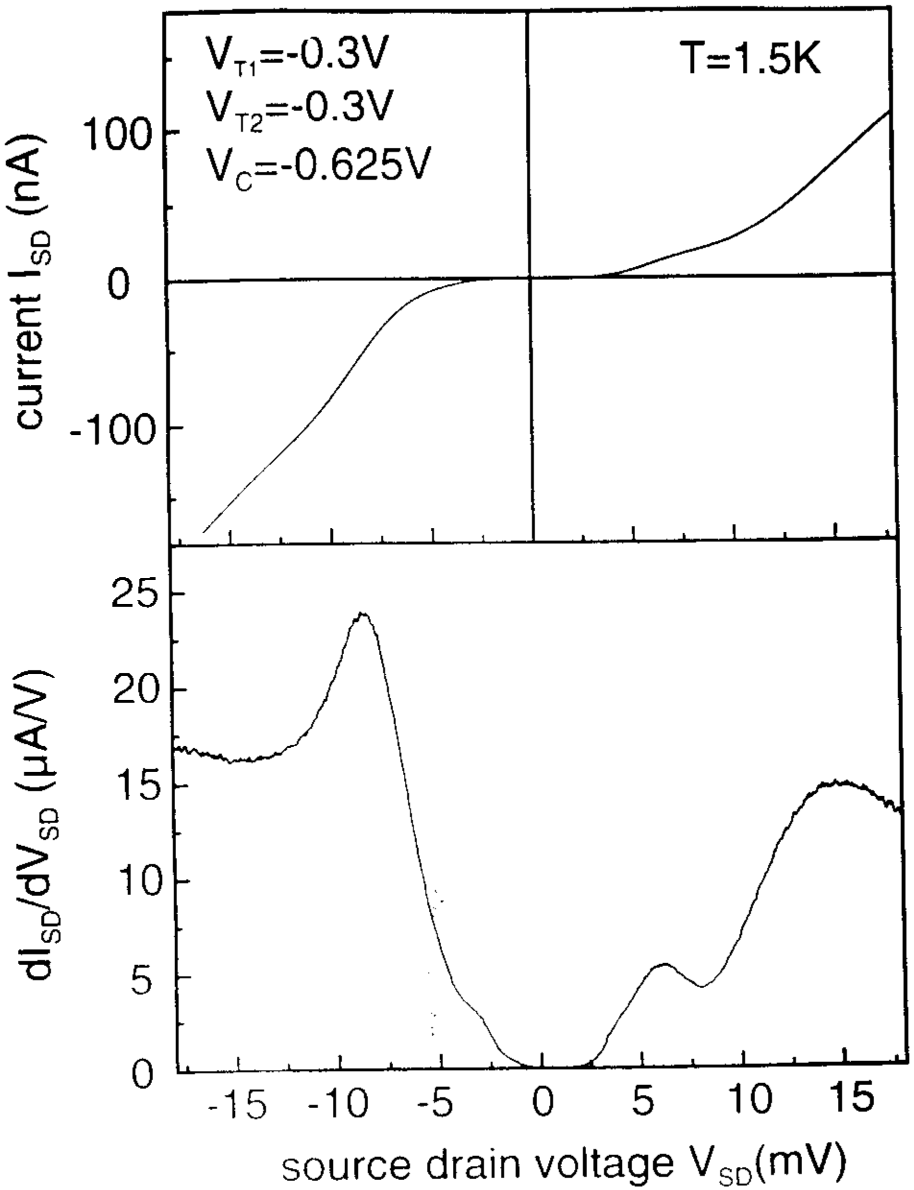


Coulomb-Blockade

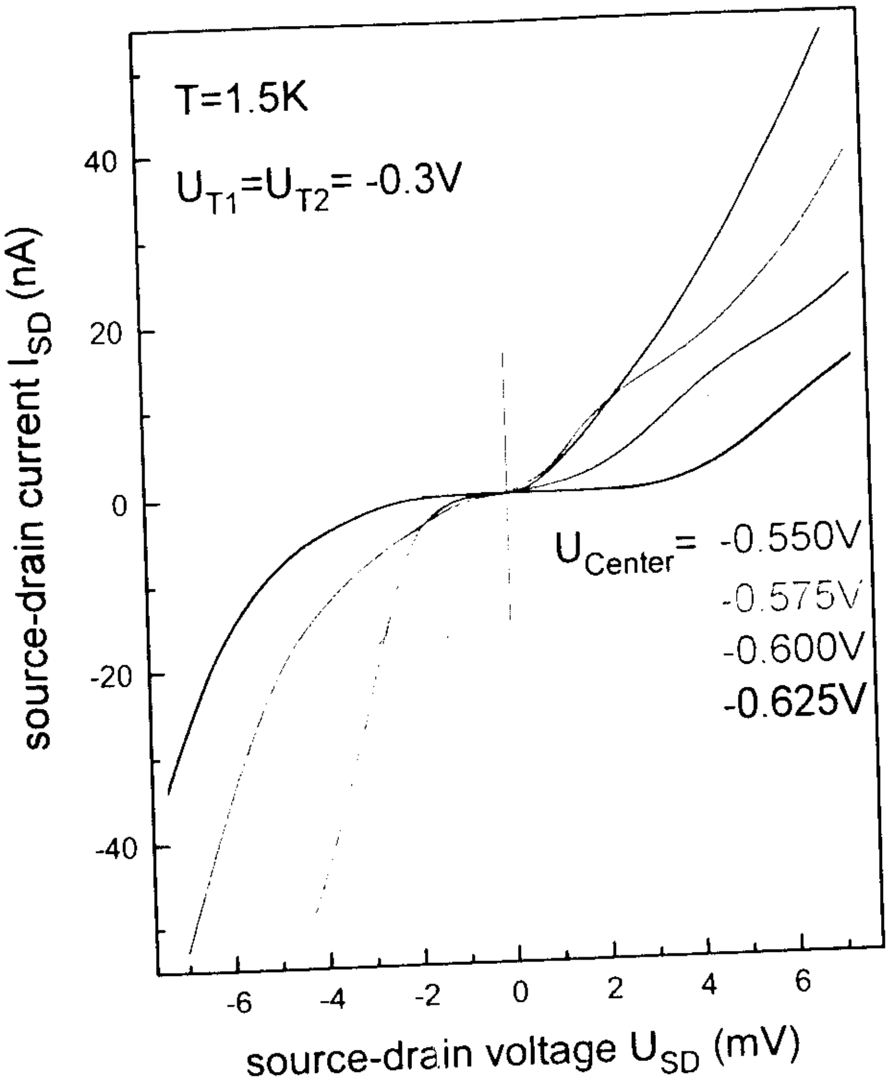
Einzelektron-Tunneln

endliche Biasspannung





V_T1=-0.3V
V_T2=-0.3V
V_C=-0.625V
T=1.5K
current I_SD (nA)
100
0
-100
dI_SD/dV_SD (μA/V)
25
20
15
10
5
0
-15 -10 -5 0 5 10 15
source drain voltage V_SD(mV)



T=1.5K
U_T1=U_T2= -0.3V
source-drain current I_SD (nA)
40
20
0
-20
-40
U_Center= -0.550V
-0.575V
-0.600V
-0.625V
-6 -4 -2 0 2 4 6
source-drain voltage U_SD (mV)

Aharonov-Bohm Ring