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INTERNATIONAL ATOMIC ENERGY AGENCY
INTERNATIONAL CENTRE FOR THEORETICAL PHYSICS
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SMR.998d - 31

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

"Self-ordering of quantum wells, wires and dots by growth on a nonplanar substrate" PART I

and

"Electronic properties of low dimensional nanostructures grown on nonplanar substrates" PART II

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These are preliminary lecture notes, intended only for distribution to participants.

part I:

Self Ordering of Quantum Wells, Wires and Dots by Growth on a Nonplanar Substrate

part II:

Electronic Properties of Low Dimensional Nanostructures Grown on Nonplanar Substrates

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Mini workshop on Quantum Wells, Dots, Wires and Self-Organizing Nanostructures
International Center for Theoretical Physics, Trieste, Italy
August 11-22, 1997

Self Ordering of Quantum Wells, Wires and Dots by Growth on a Nonplanar Substrate

outline:

- Modified step flow growth on nonplanar substrates
- Nanofacet self ordering
- "Vertical" quantum wells
- V-groove quantum wires
- Dot-like potential landscape in V-groove wires
- Inverted-pyramid quantum dots

Self Ordering of Quantum Wells, Wires and Dots by Growth on a Nonplanar Substrate

Collaborators:

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A. Gustafsson, K. Leifer

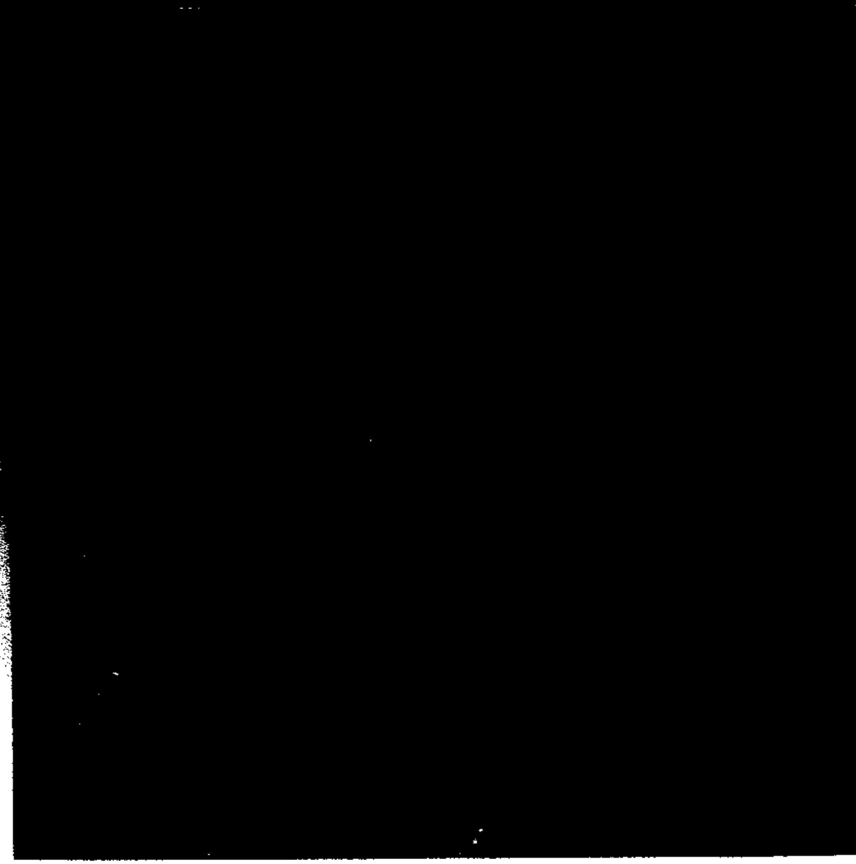
Morphology

ÉCOLE POLYTECHNIQUE
FÉDÉRALE DE LAUSANNE

GaAs(100) nominally ±

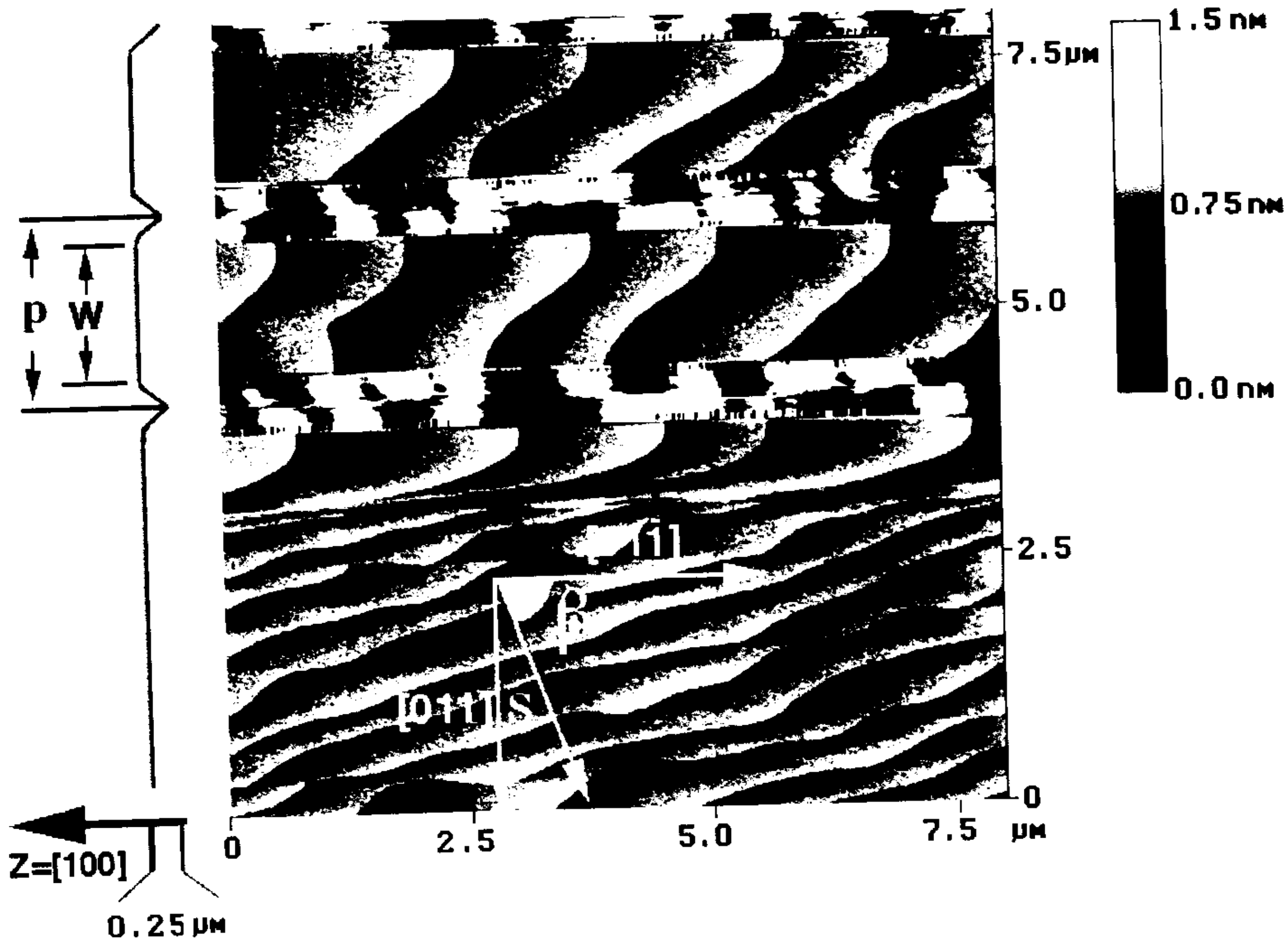
T = 680 °C

step height: 0.285 ± 0.005 nm
average terrace size: 280 nm
-> miscut 0.058 ° off



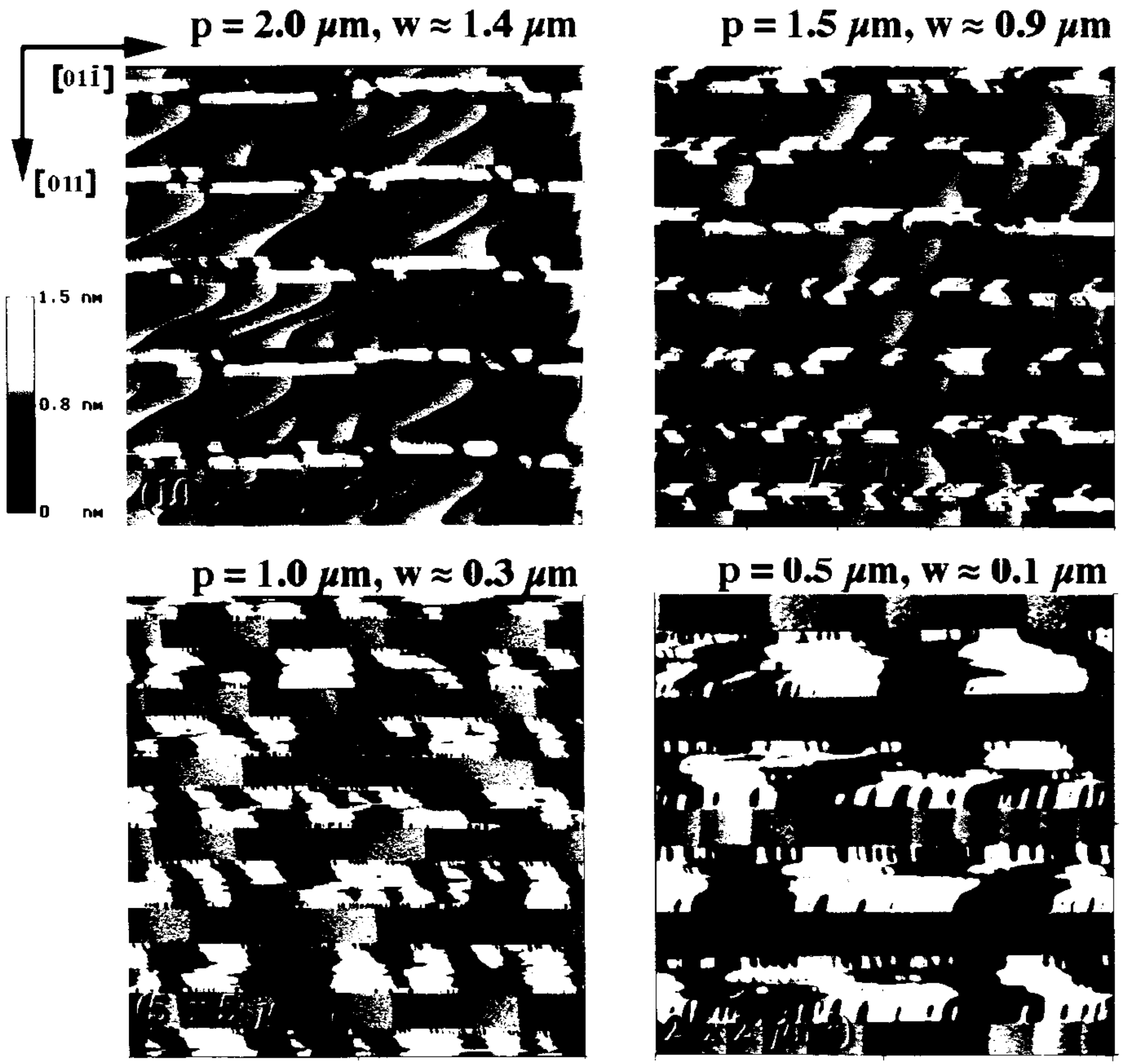
step height: 0.295 ± 0.005 nm
average terrace size: 430 nm
-> miscut 0.037 ° off

Step ordering on the (100)
between V-grooves



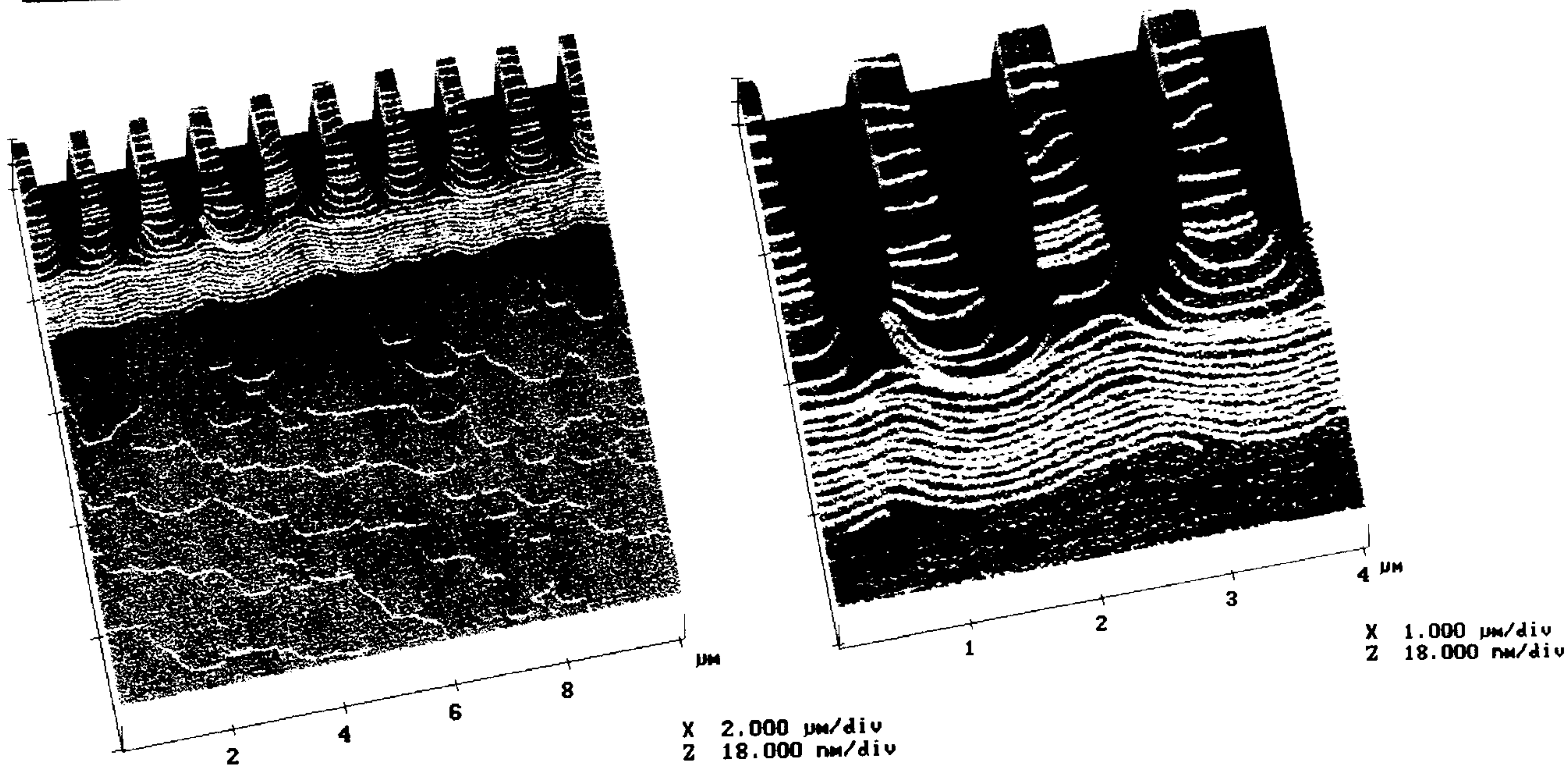
300 nm deep V-grooves in GaAs(100), spaced by different pitch p

Step ordering on the (100)

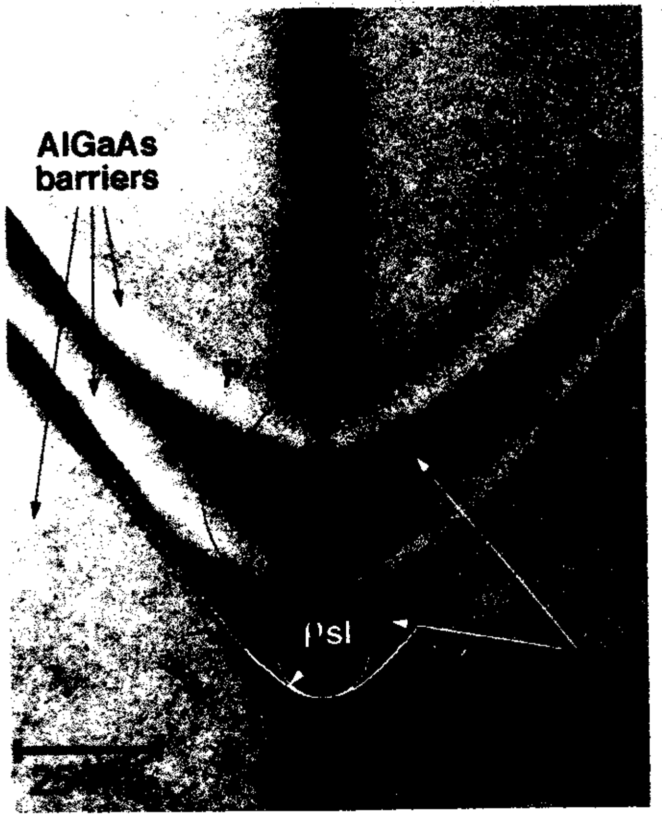


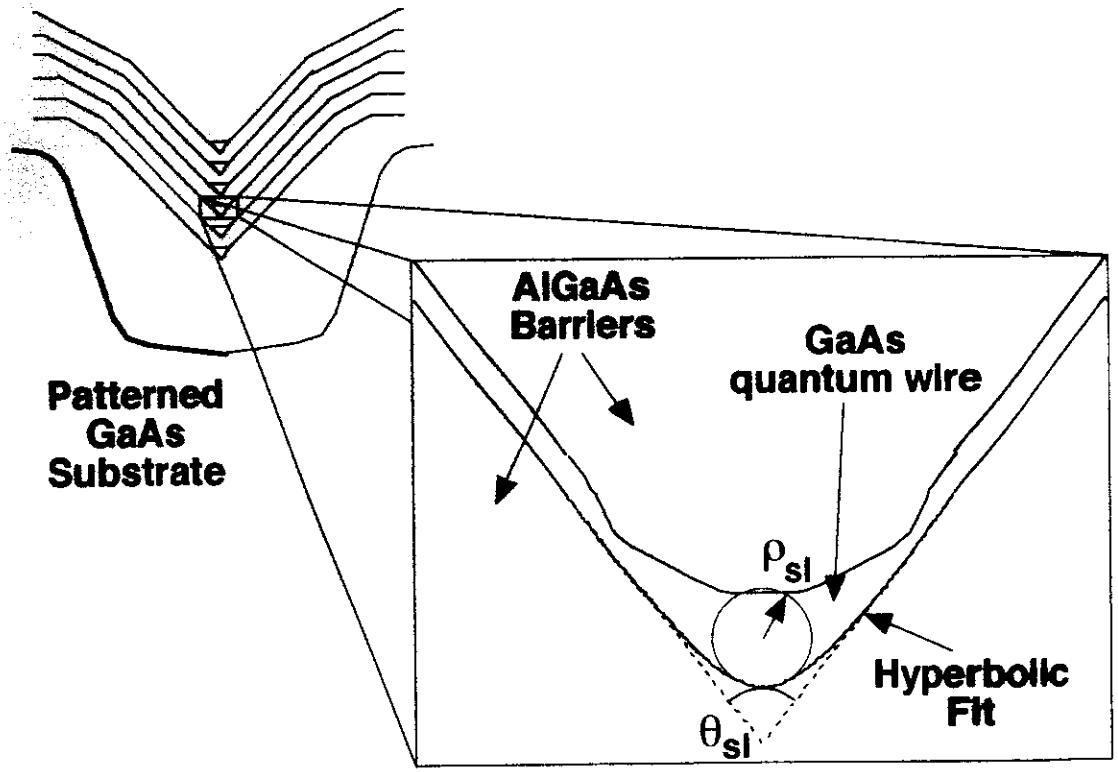
in GaAs(100), spaced by different pitch p

Monolayer Step Alignement on a Nonplanar Substrate

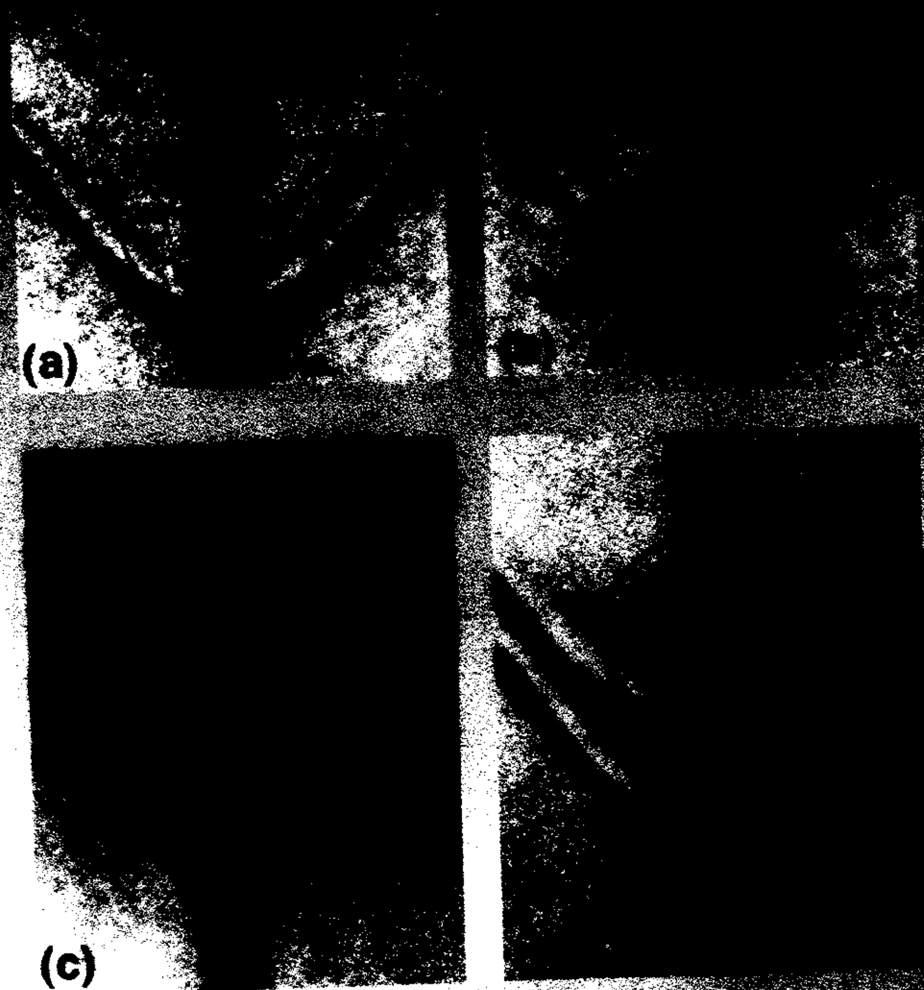


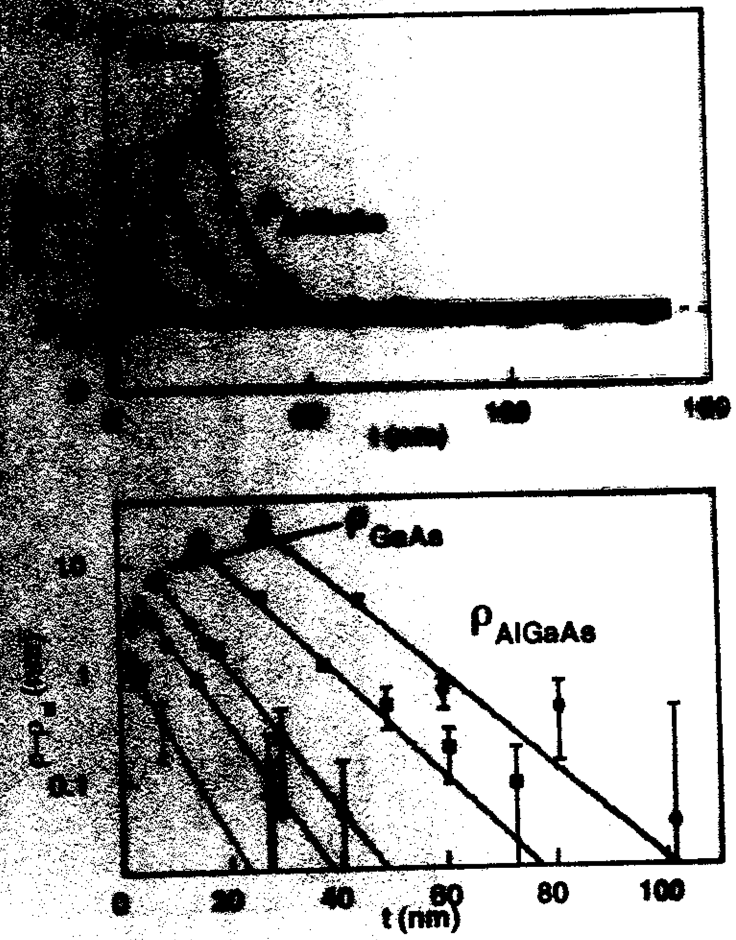
Formation of QWRs in a Self-Ordered V-Groove





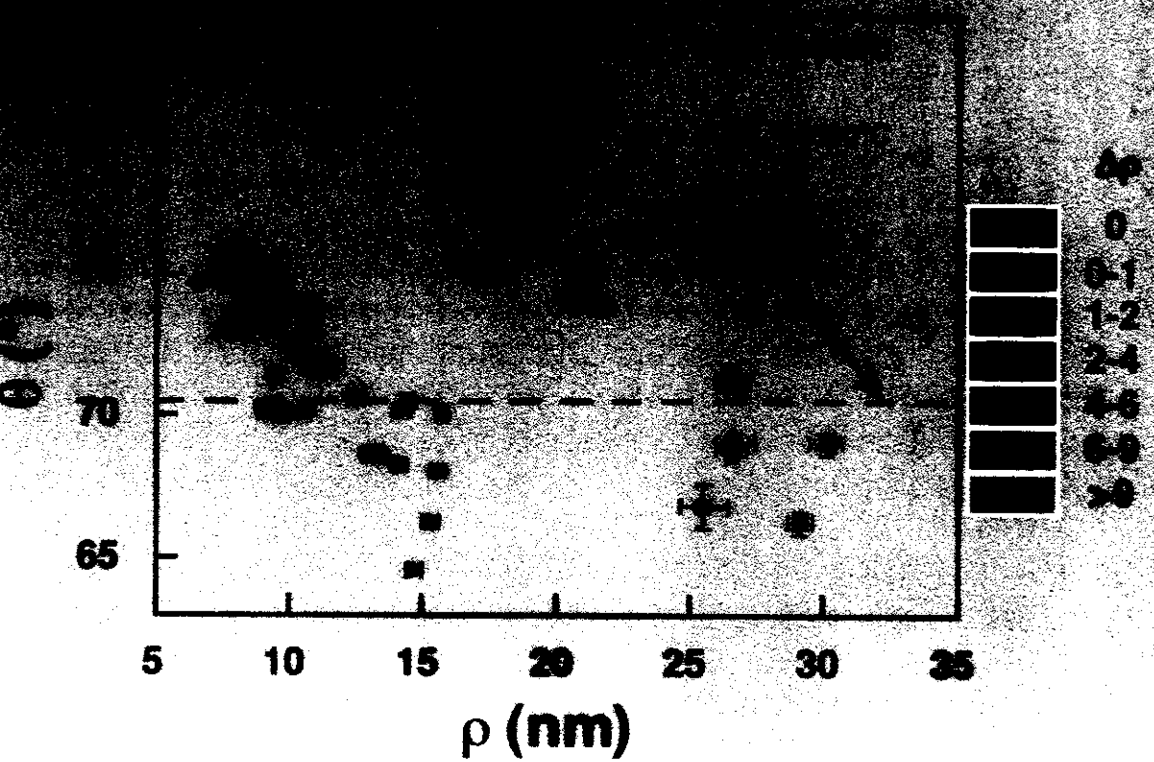
... Groove QWRs





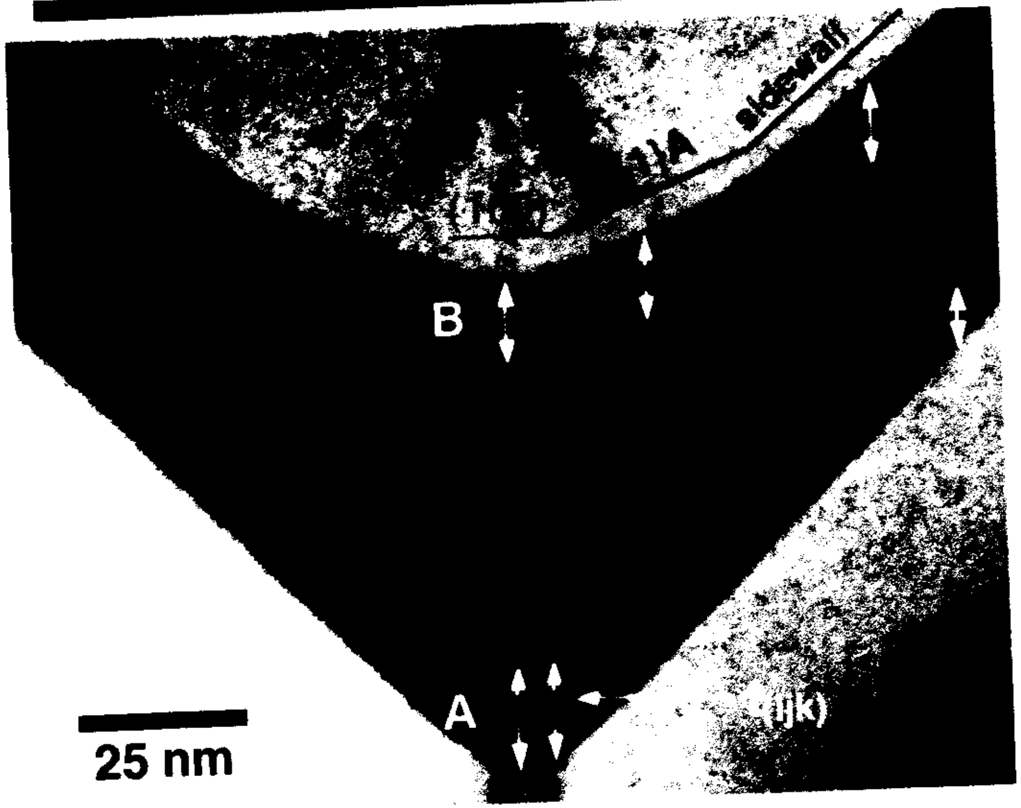
$$\rho(t_{GaAs}) = \rho_{sl} + \alpha \cdot t_{GaAs}$$

$$\rho(t_{GaAs}) = \rho_{sl} + (\rho_{GaAs} - \rho_{sl}) \ldots$$



$$\rho(t) = \rho_{sl} + \Delta\rho; \qquad \Delta\rho = \alpha t_{GaAs} \cdot e^{(-t_{AlGaAs}/\tau)}$$

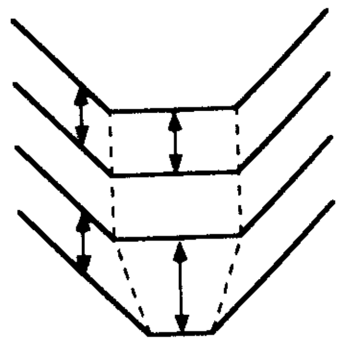
Evolution to a Self-Limiting GaAs Groove Profile



T= 650°C

$x_{barrier} = 0.45$

concave contour



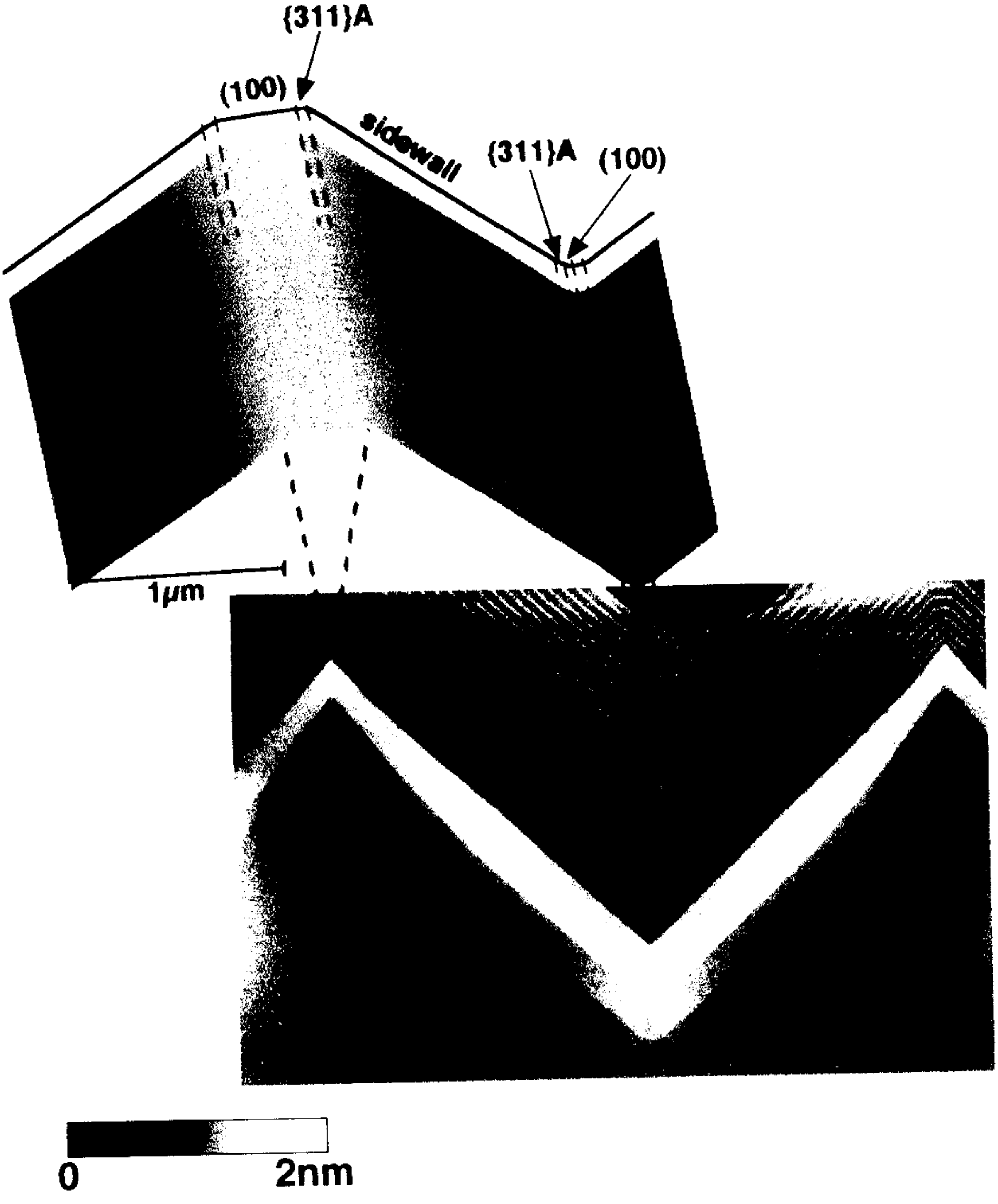
$r_{bottom} = r_{sidewalls}$ ⇓ conformal growth

$r_{bottom} > r_{sidewalls}$ ⇓ bottom expanding

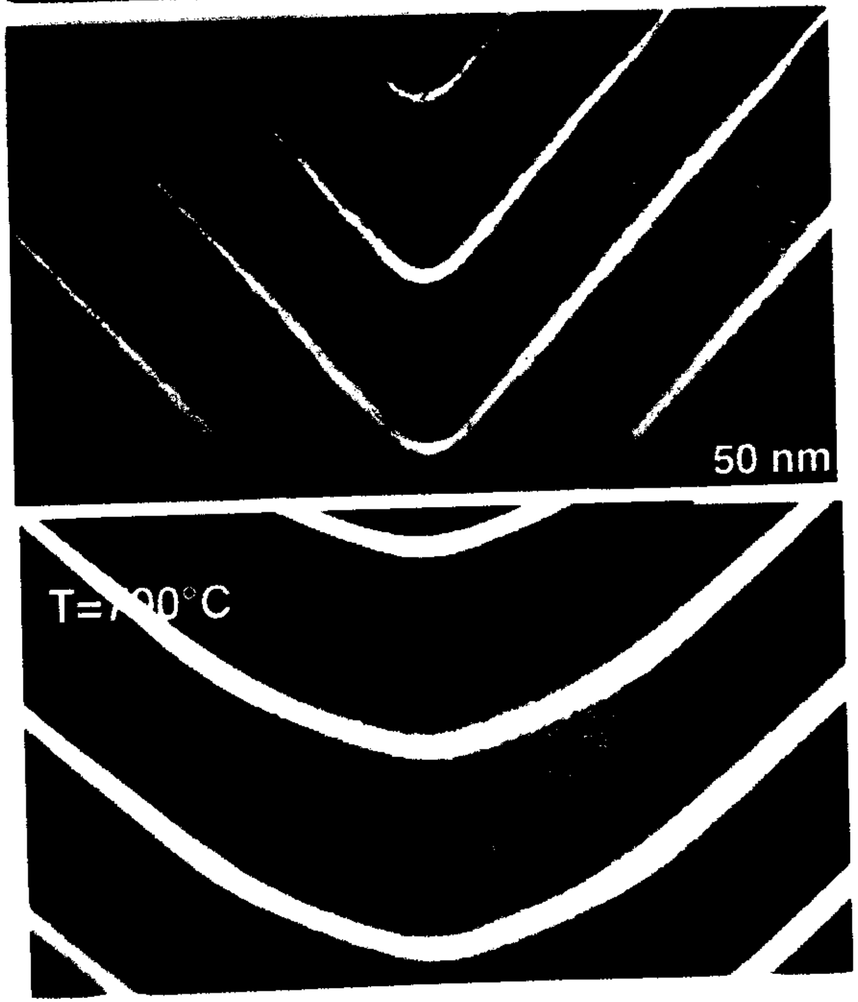
layer A: $t_{(100)} > t_{\{311\}A} > t_{sidewall} \Rightarrow$ expansion of (100) and {311}A facets

layer B: $t_{(100)} = t_{\{311\}A} = t_{sidewall} \Rightarrow$ stable facets, self-limiting growth

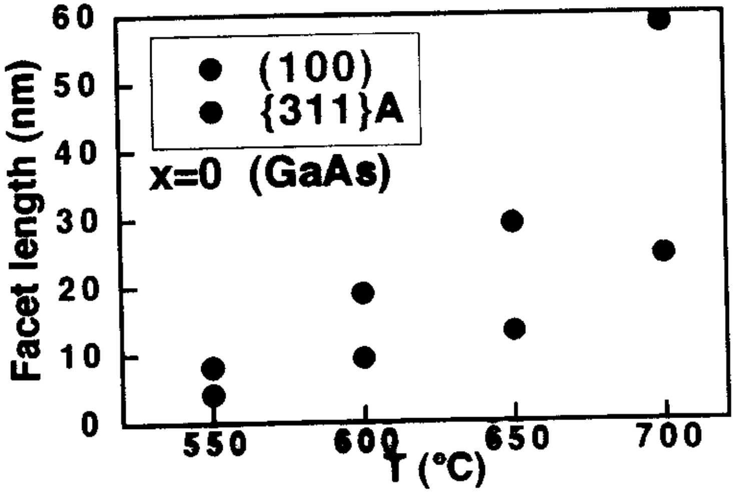
Surface of a Self-Limiting GaAs V-Groove

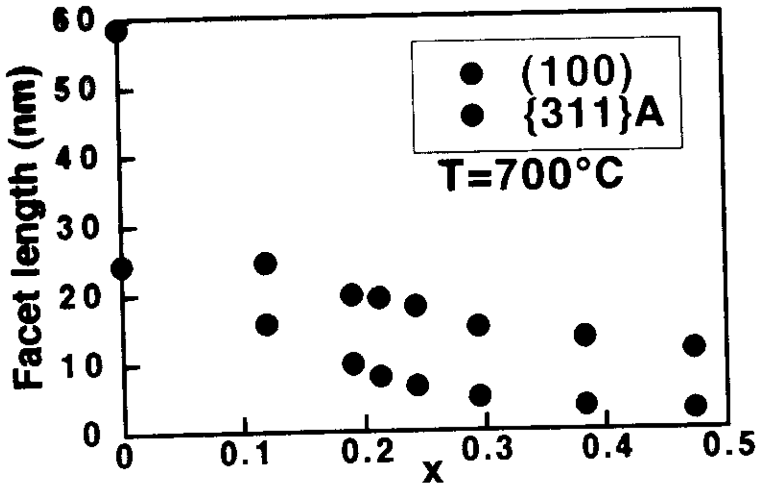


Self-Limiting Growth of GaAs on V-Grooves



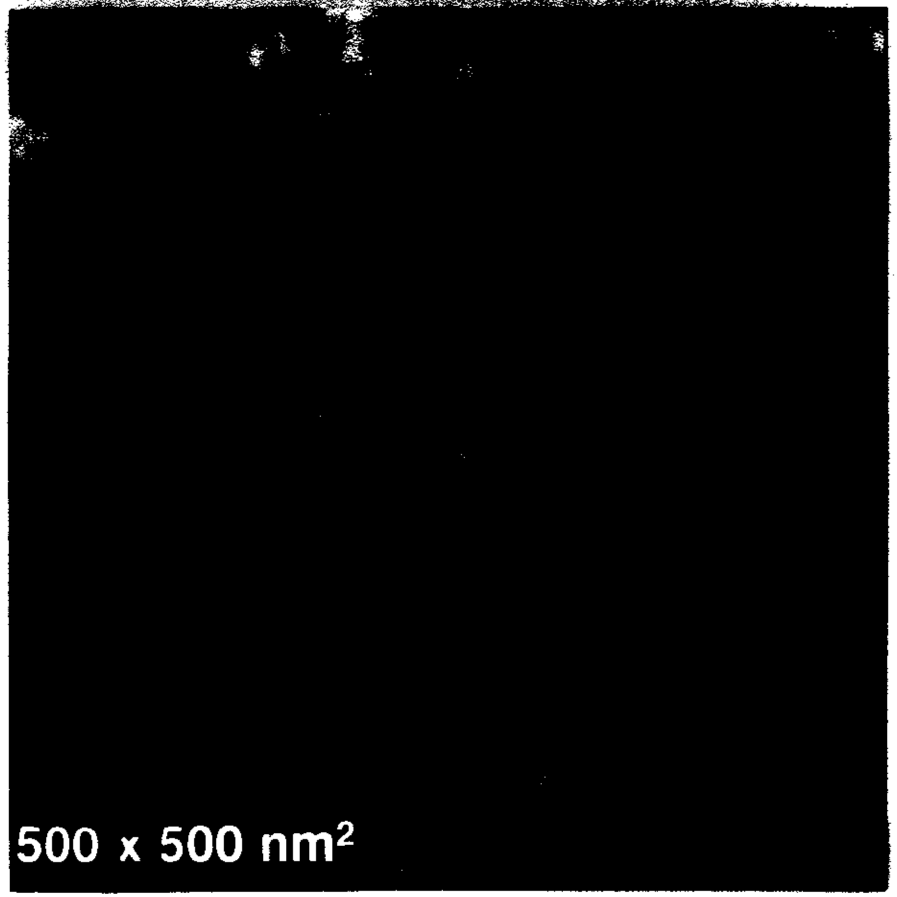
Self-limiting GaAs + AlGaAs markers



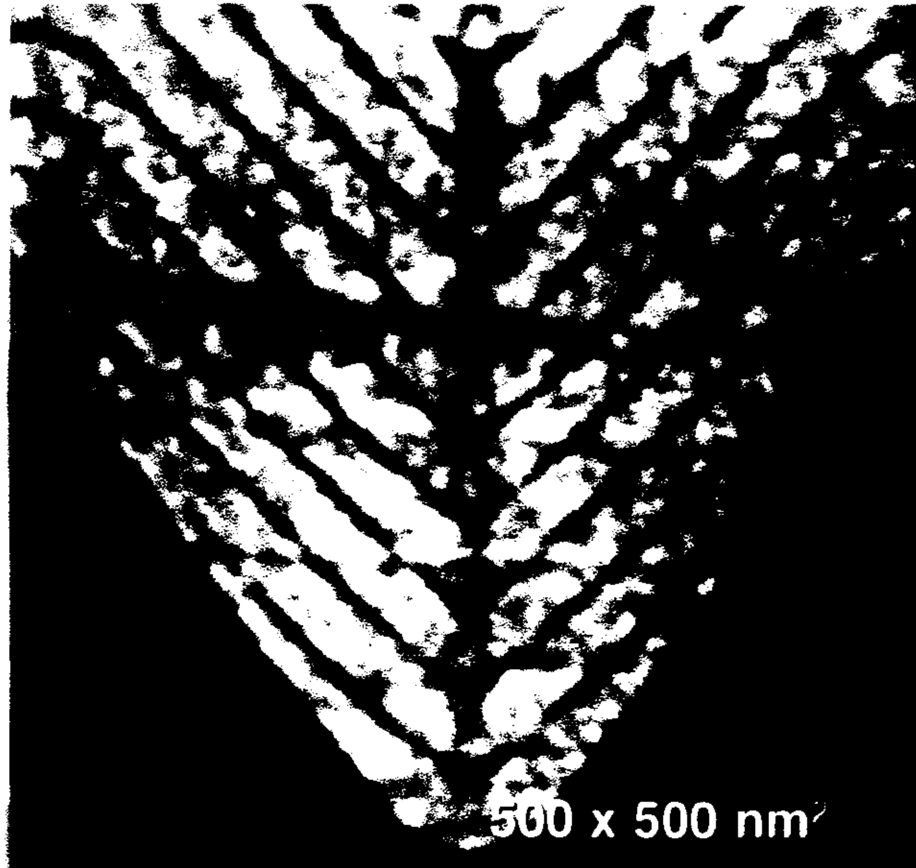


[illegible] of the initial shape of the groove

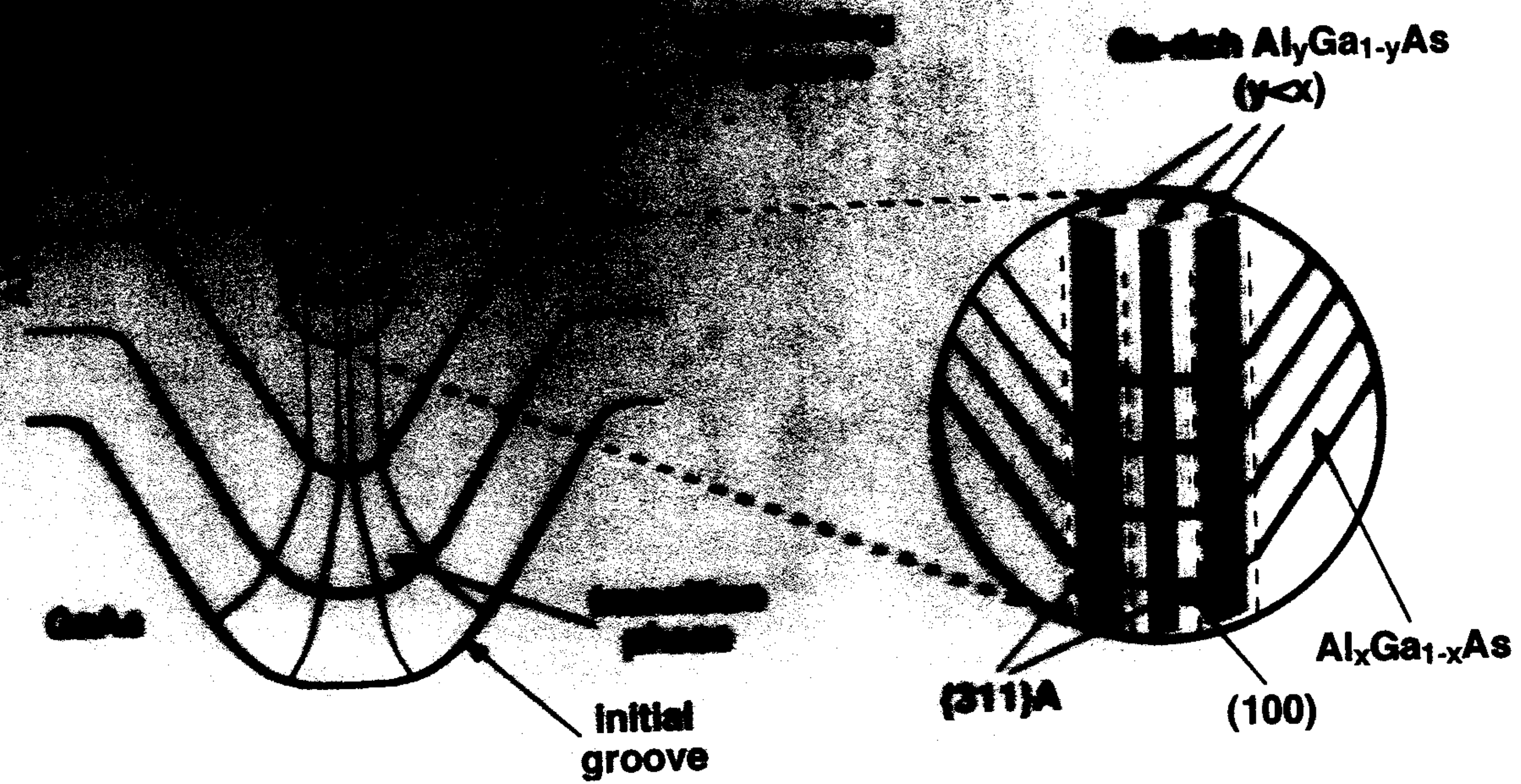
square-shaped groove



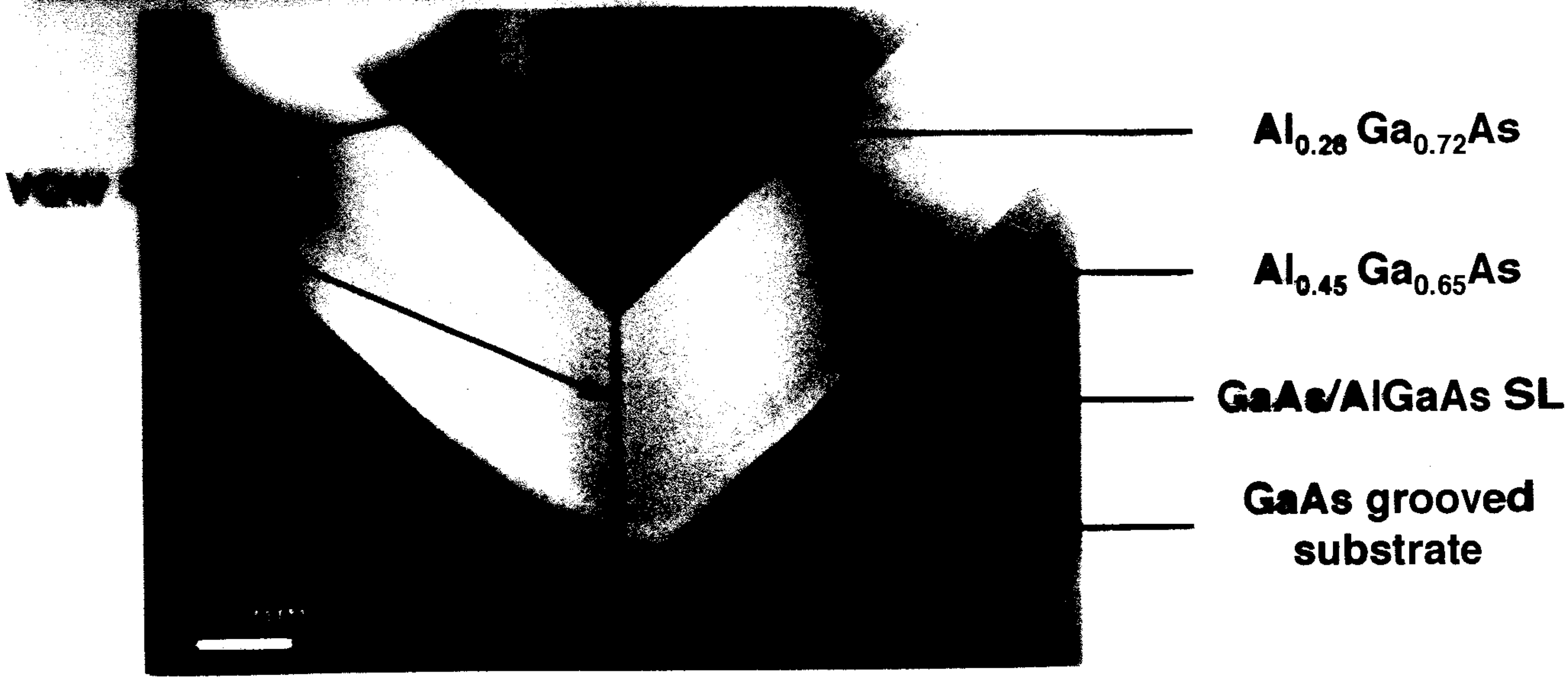
V-groove



structure

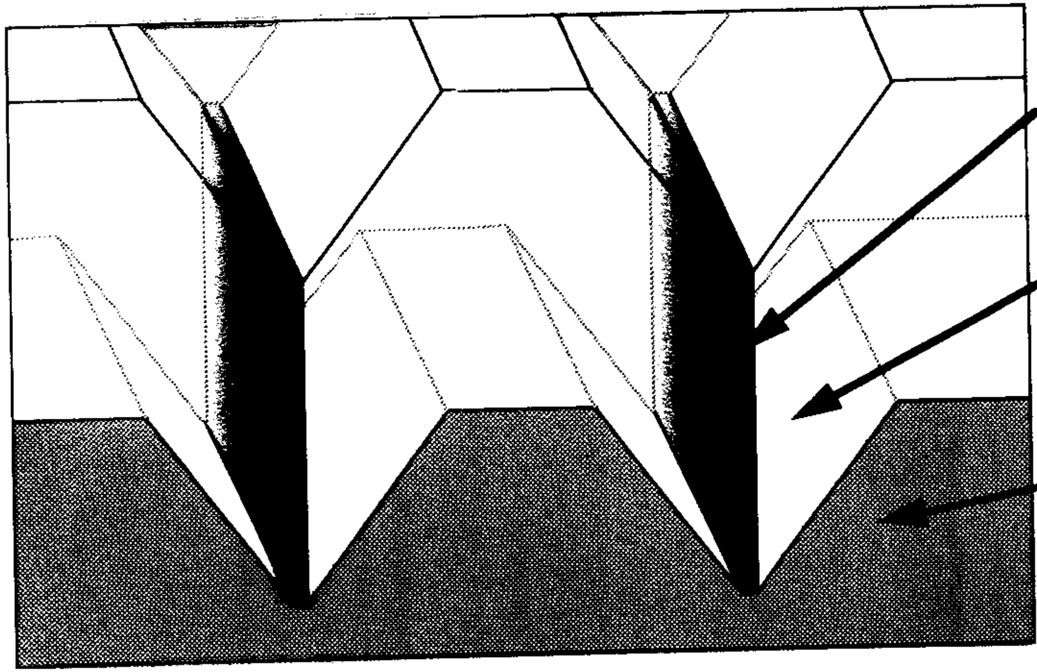


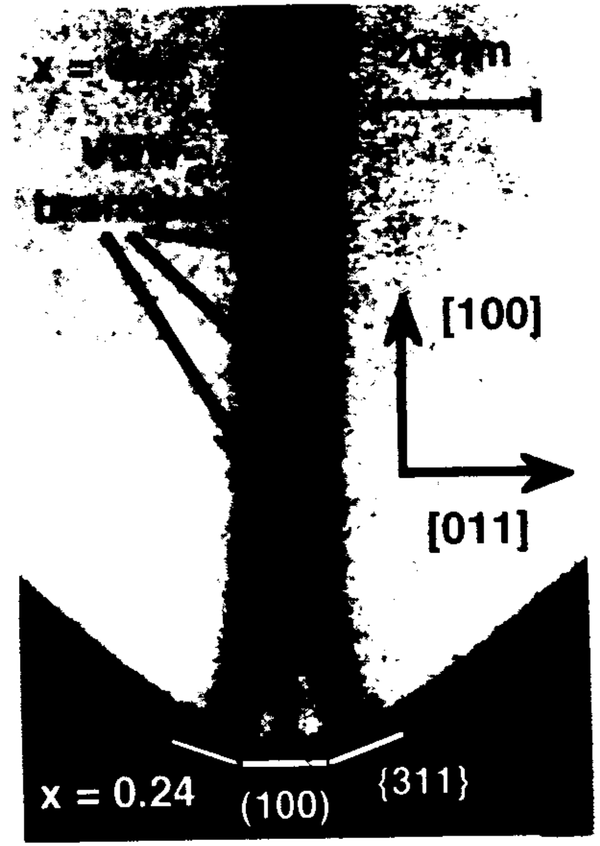
LP OMCVD growth of VQWs



- V-groove pitch $\Lambda = 3\ \mu m$ (by optical photolithography and wet chemical etching)
- Horizontal reactor; pressure = 20 mbar
- Growth temperature = 600 - 765 °C
- Al mole fraction = 0.13-0.75
- Growth rates = 0.28 - 0.45 nm/sec
- V/III ratios @ 160-200

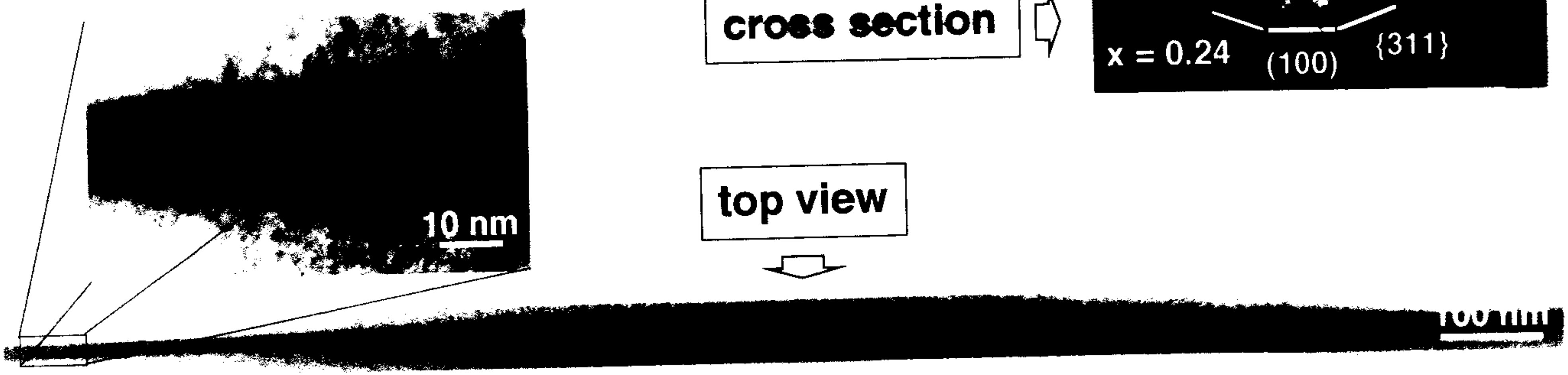
Self-Ordered AlGaAs VQW Heterostructure





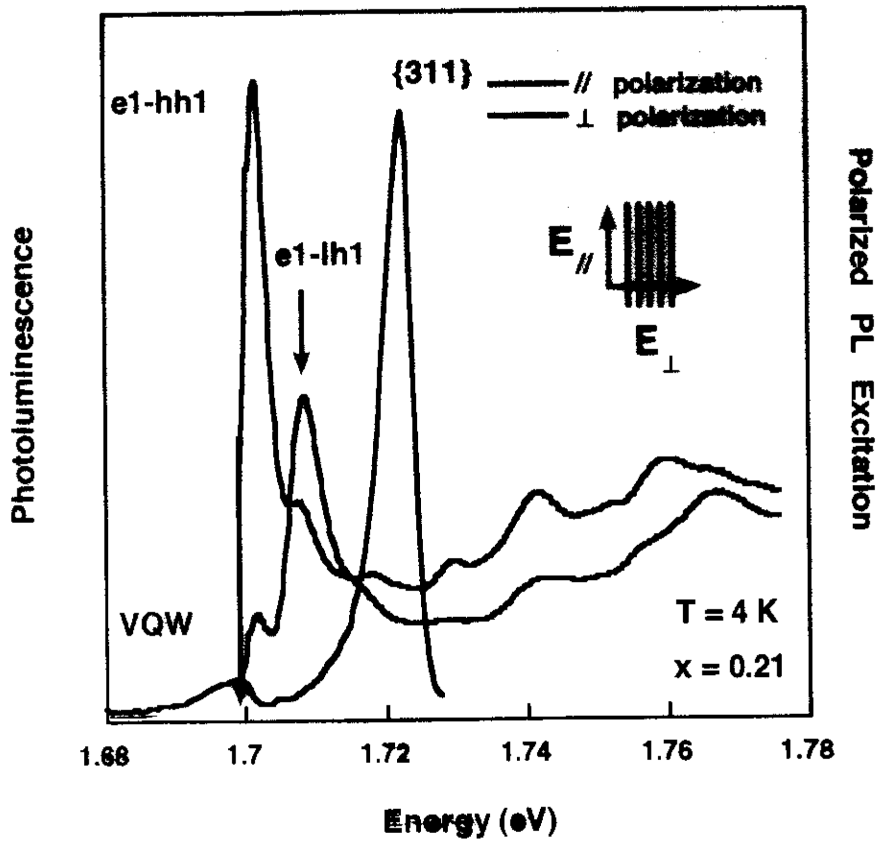
cross section

top view

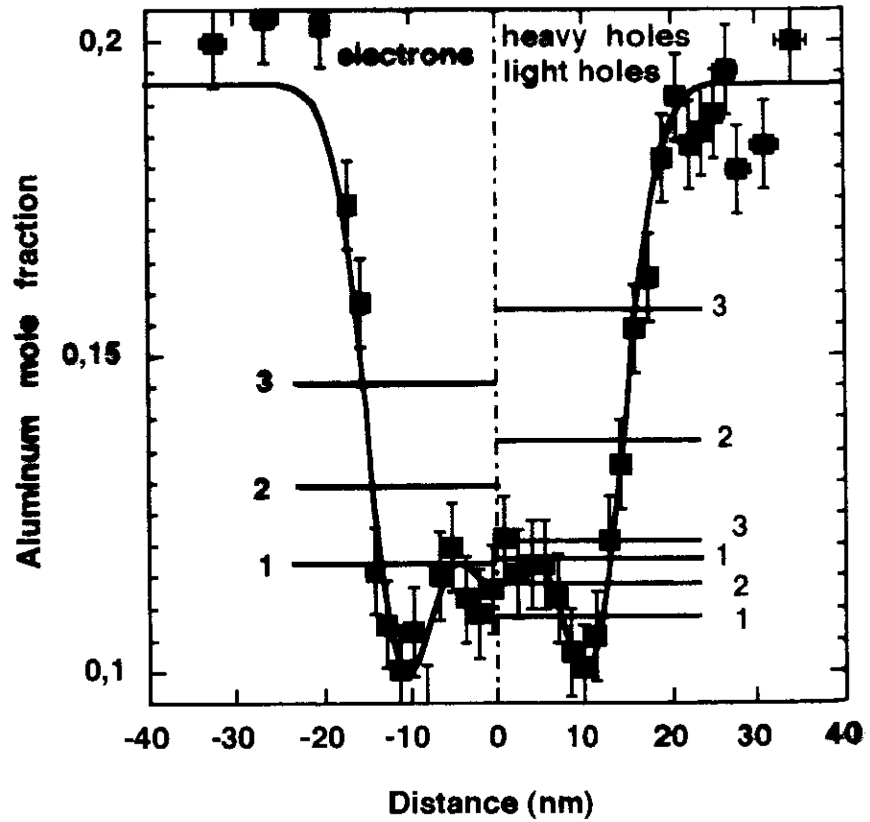


Quantum Confinement in V-Groove QWs

PL/PLE spectra

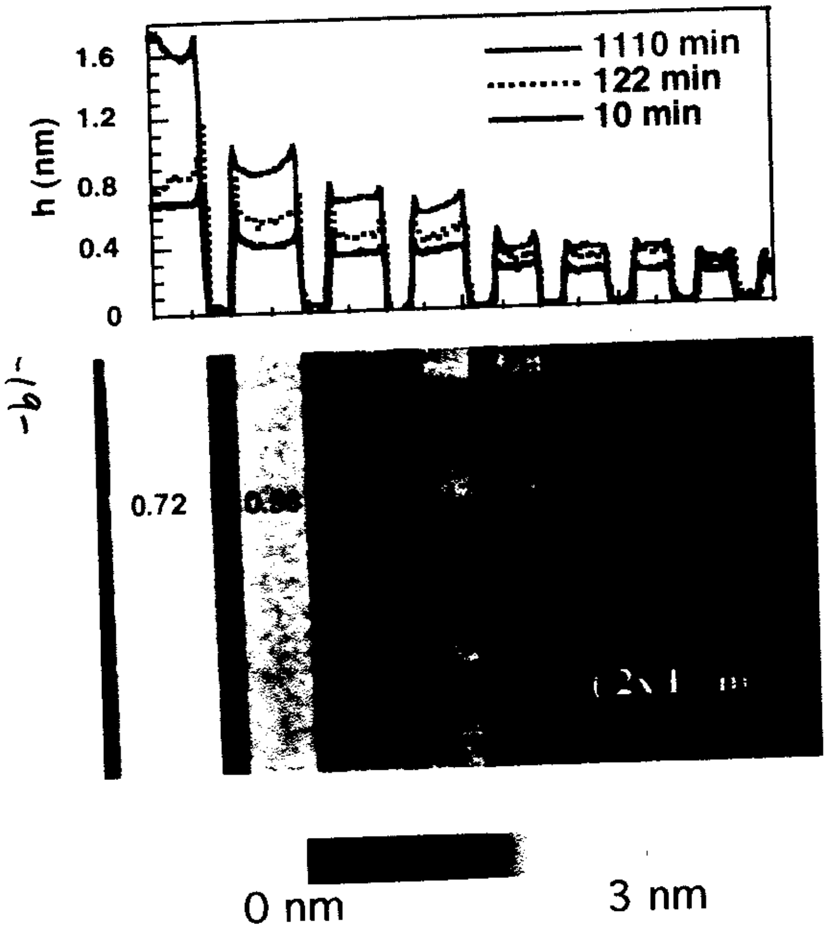


potential profile

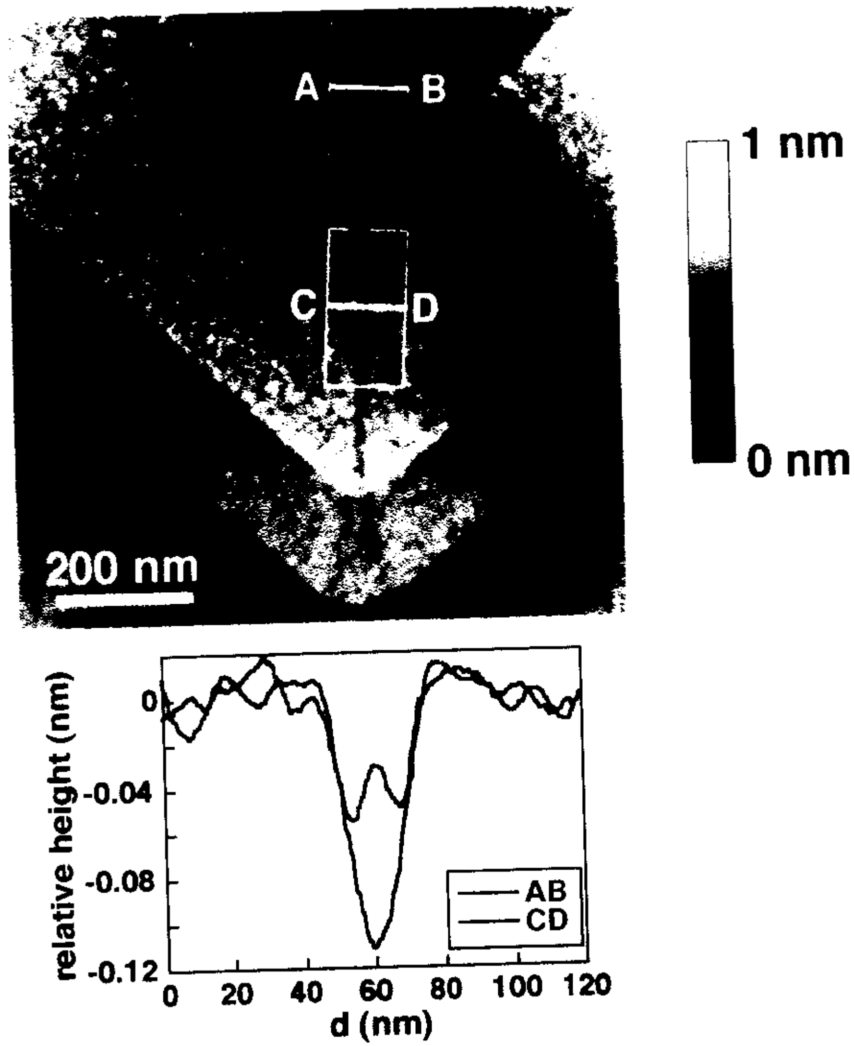


Cross-Sectional AFM Imaging of VQWs

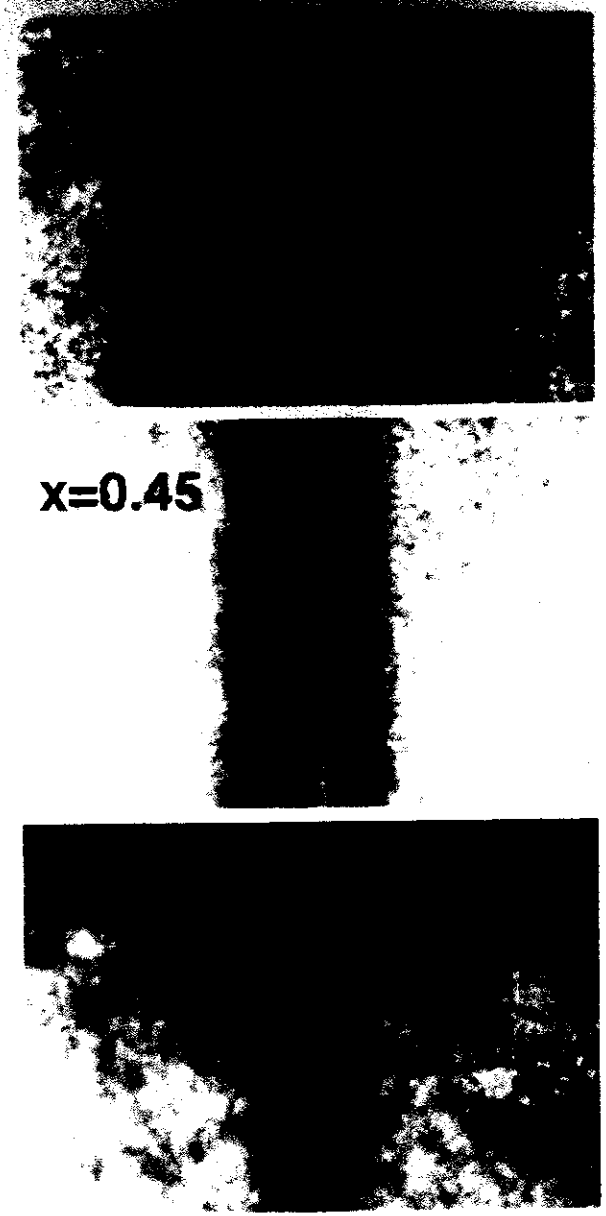
Method

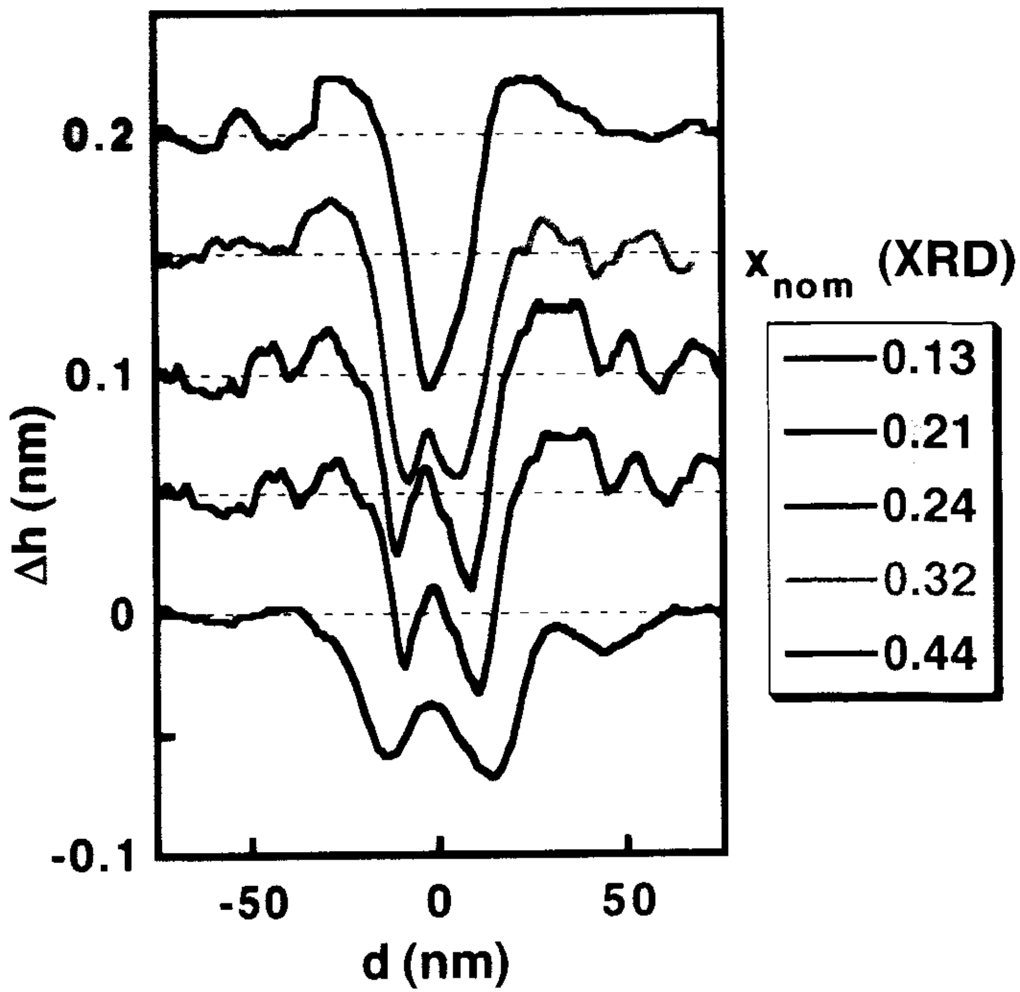


Application



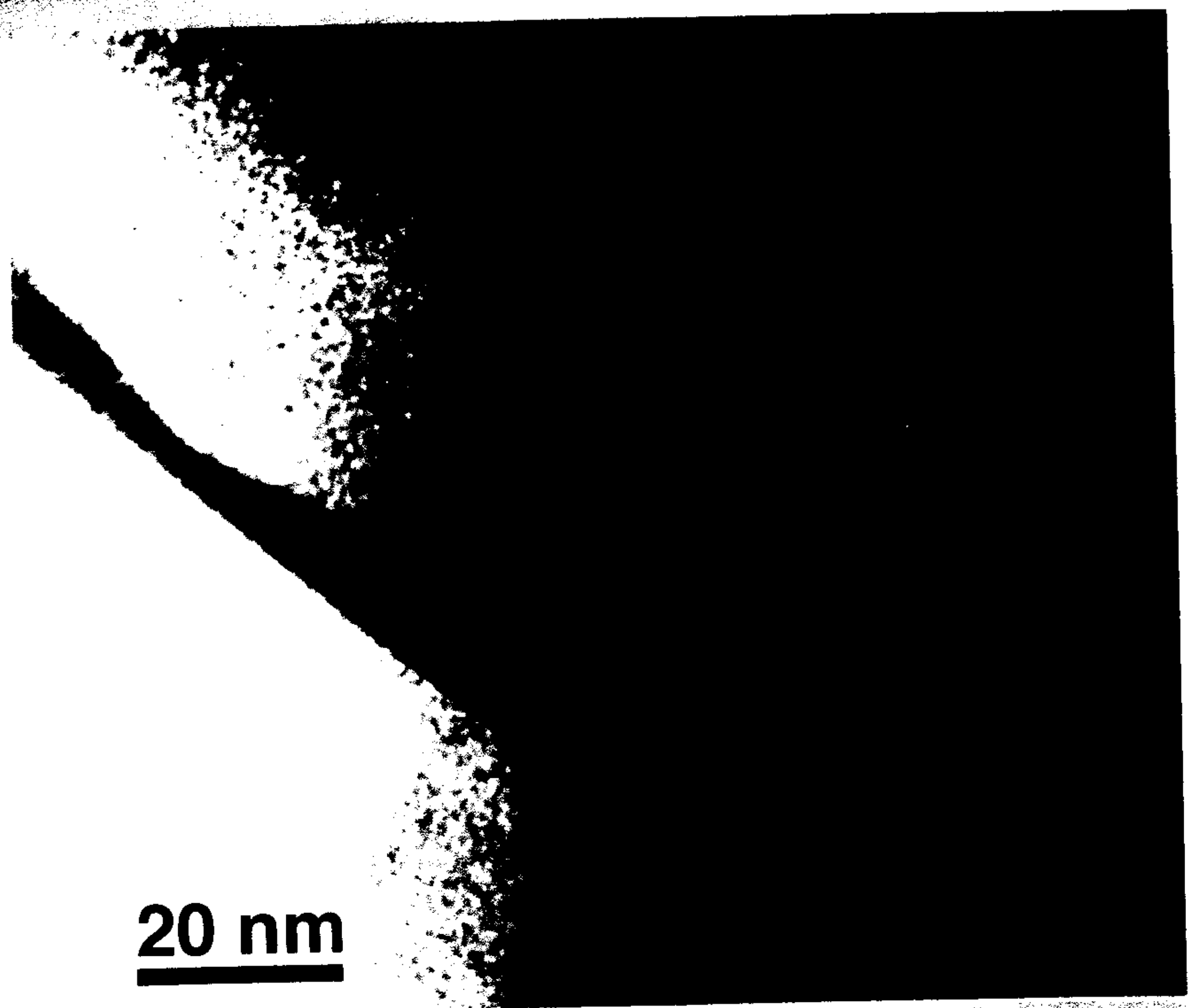
VQW profile in $Al_xGa_{1-x}As$ layers



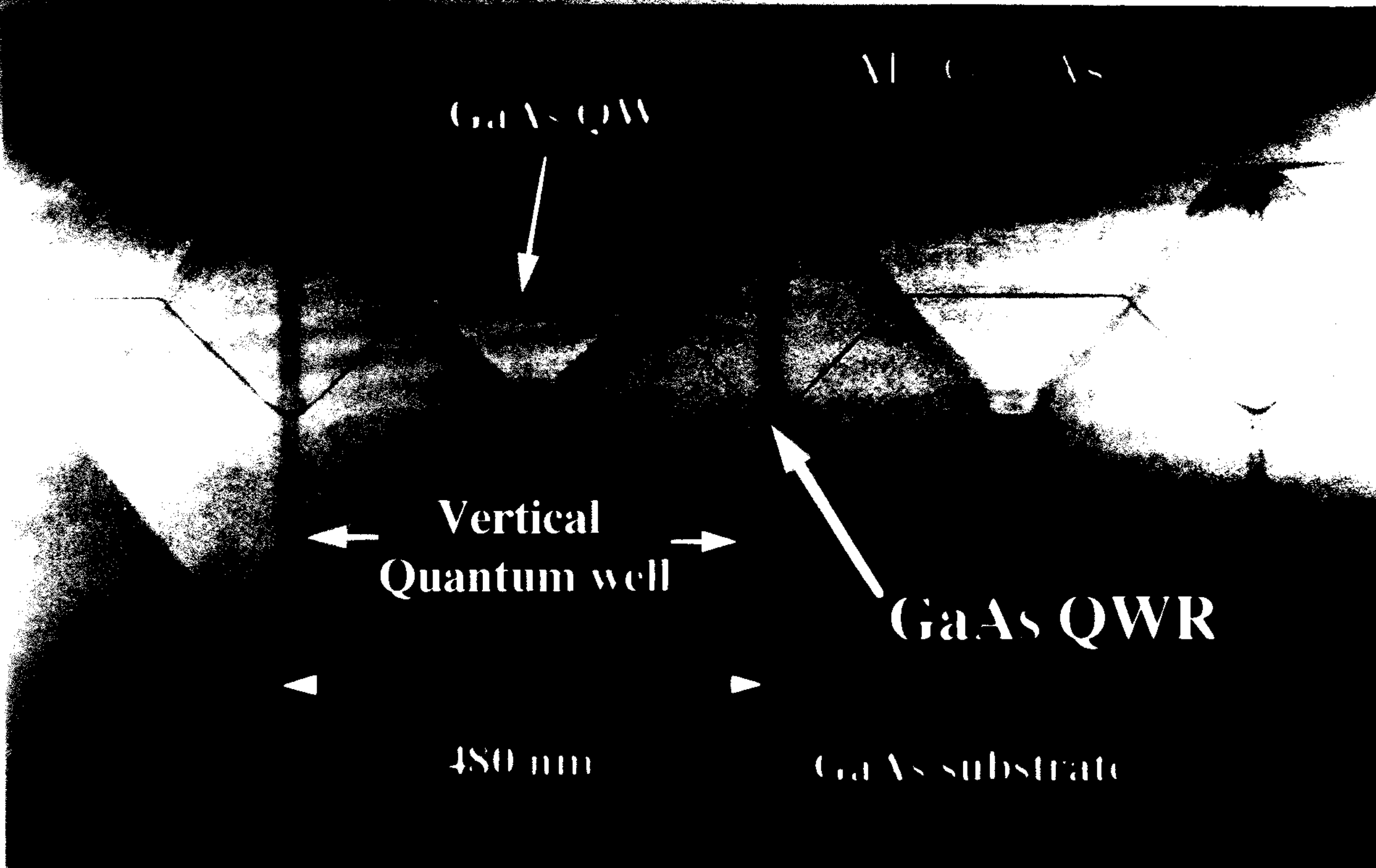


Atomic Force Microscopy: VQW x-section

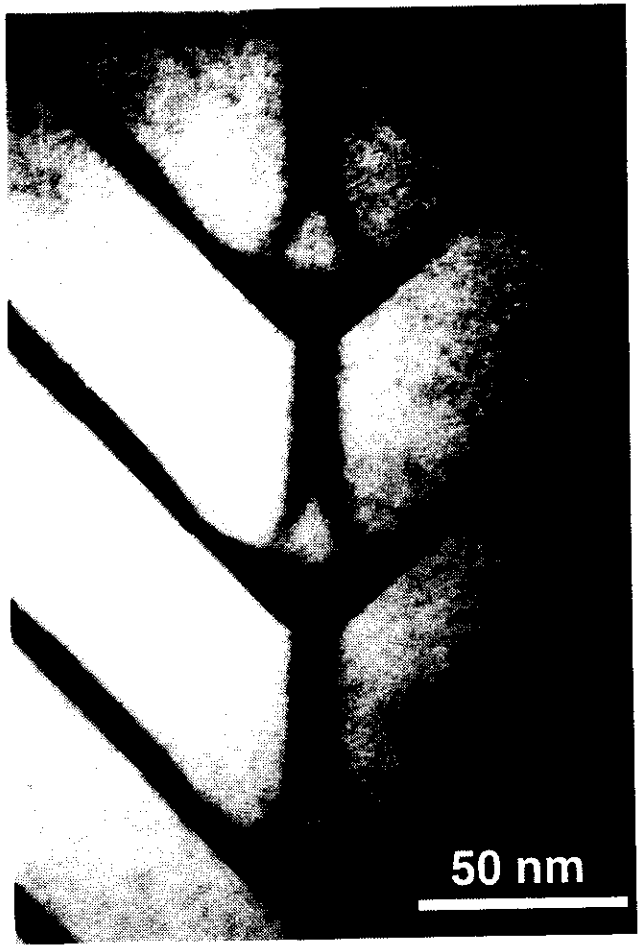
V-Groove Quantum Wire



Array of V-Groove QWRs



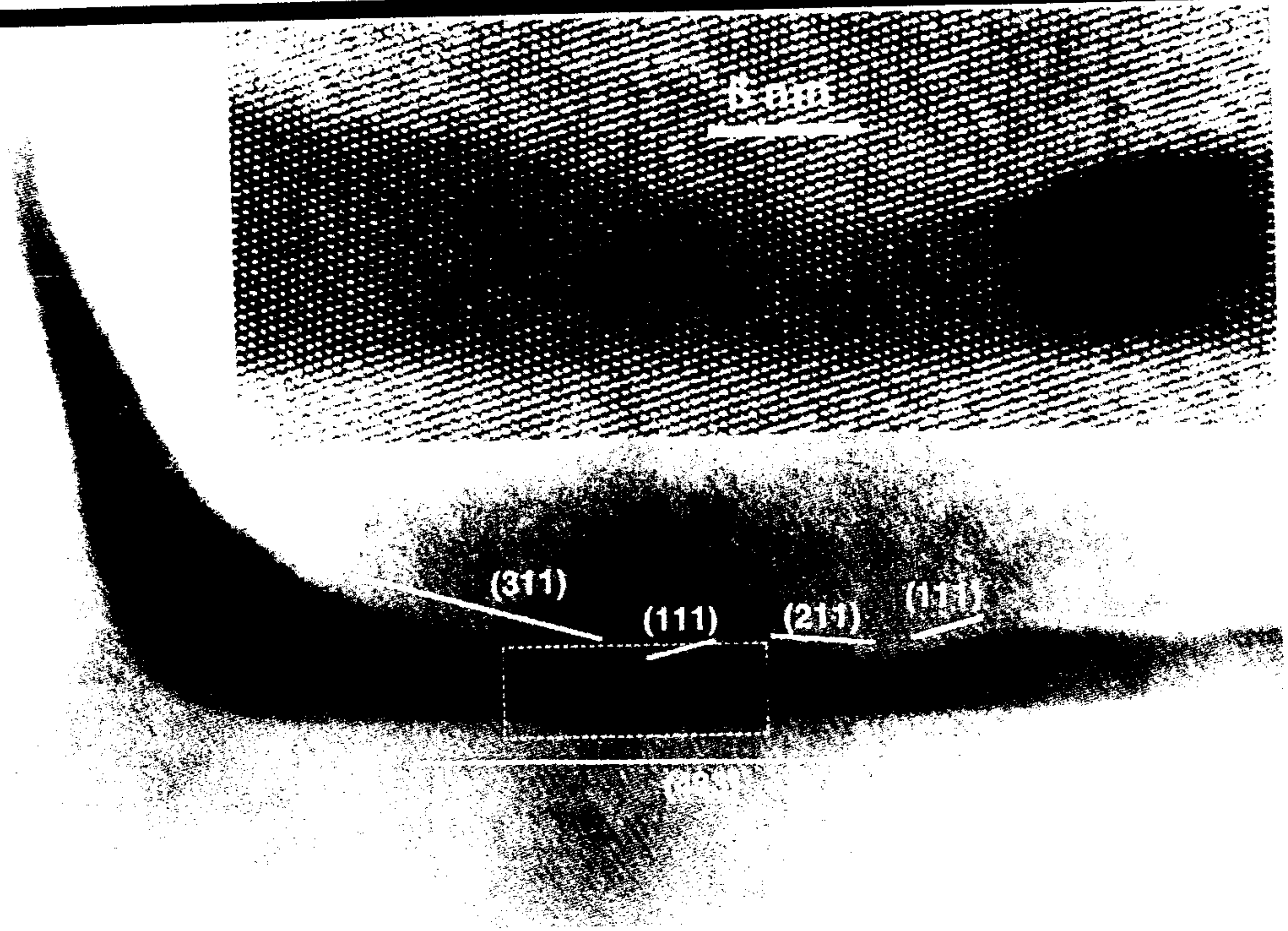
GaAs/AlGaAs QWRs Grown by Low-Pressure OMCVD



Dark field

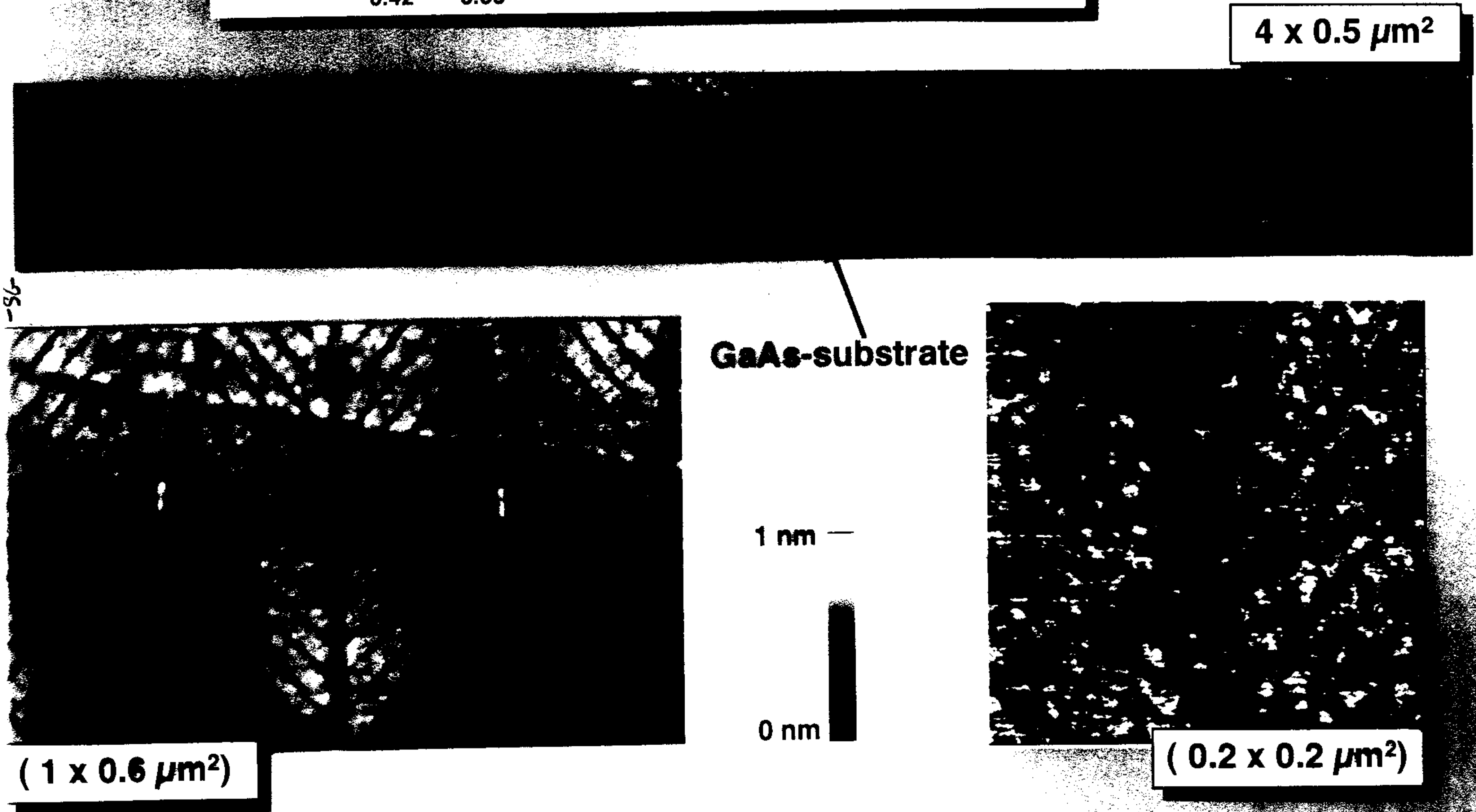
High resolution

Quantum Crescent:
high resolution TEM



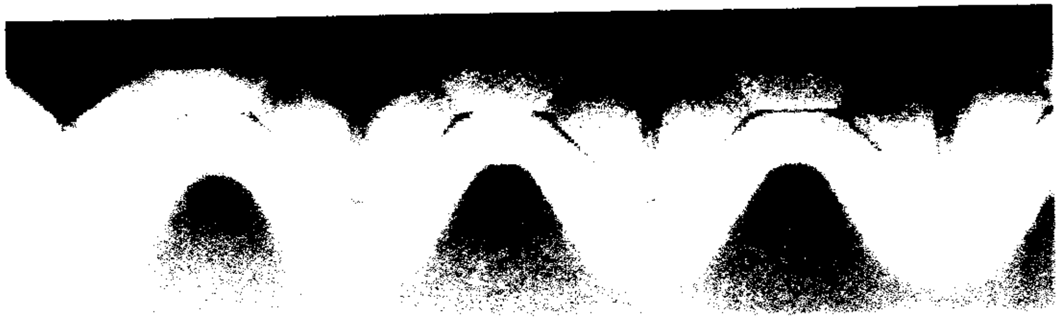
Sections of a QWR Growth Study

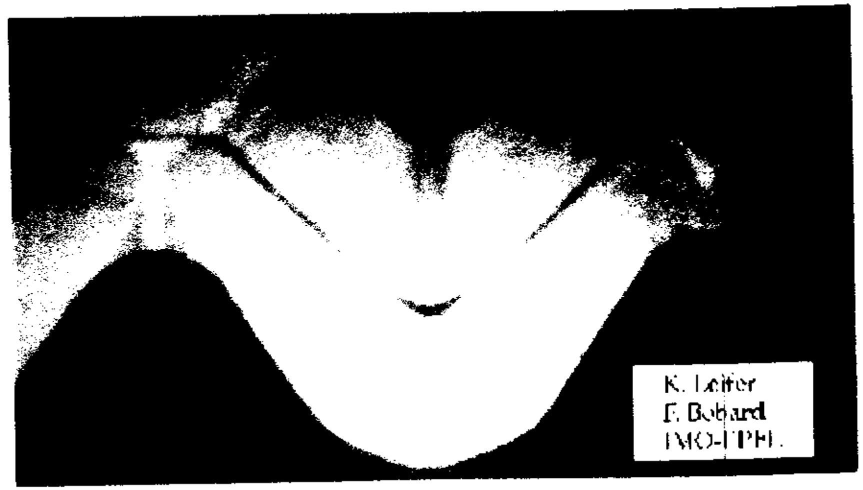
40 nm-$Al_{0.42}Ga_{0.58}As$/3.5 nm-GaAs heterostructure



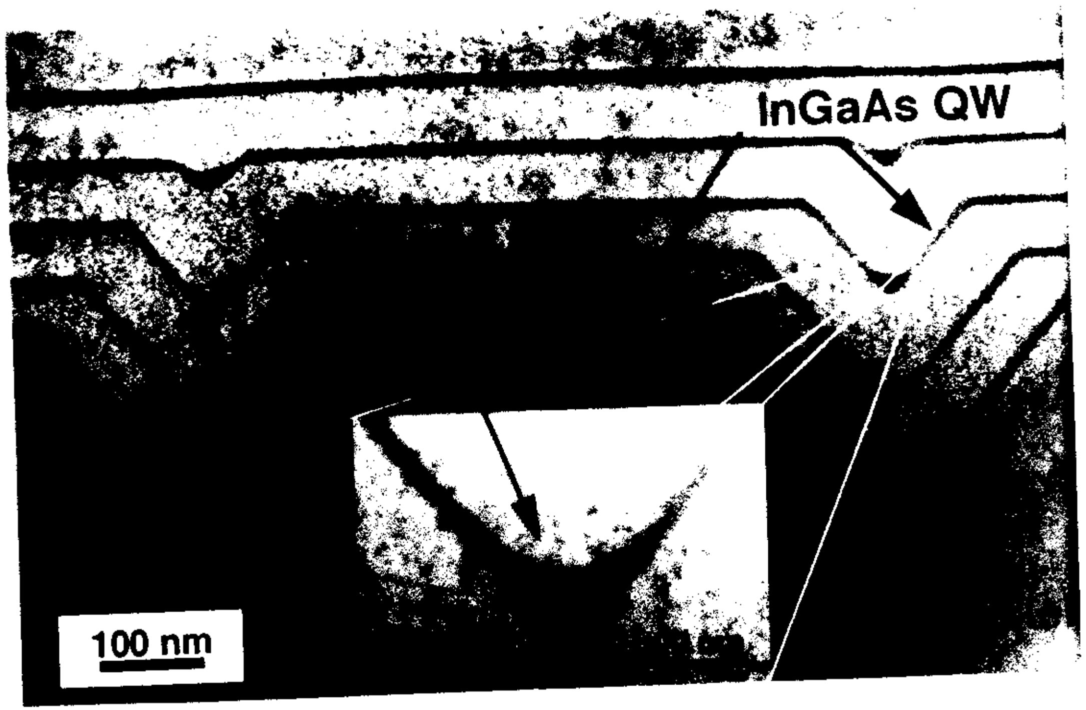
GaAs/AlGaAs V-Groove QWRs

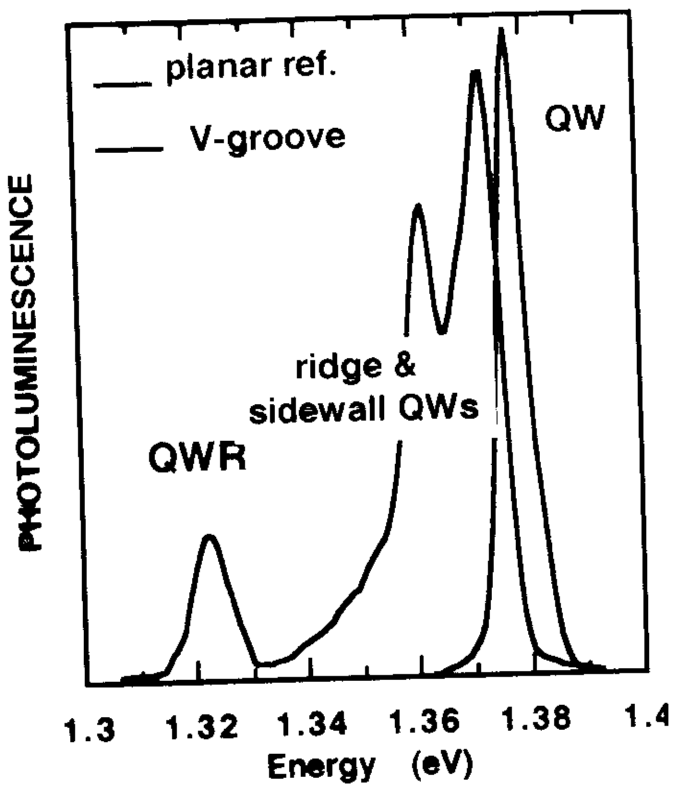
0.25 μm-pitch





InGaAs/GaAs Strained QWRs on 0.5μm-pitch Grating

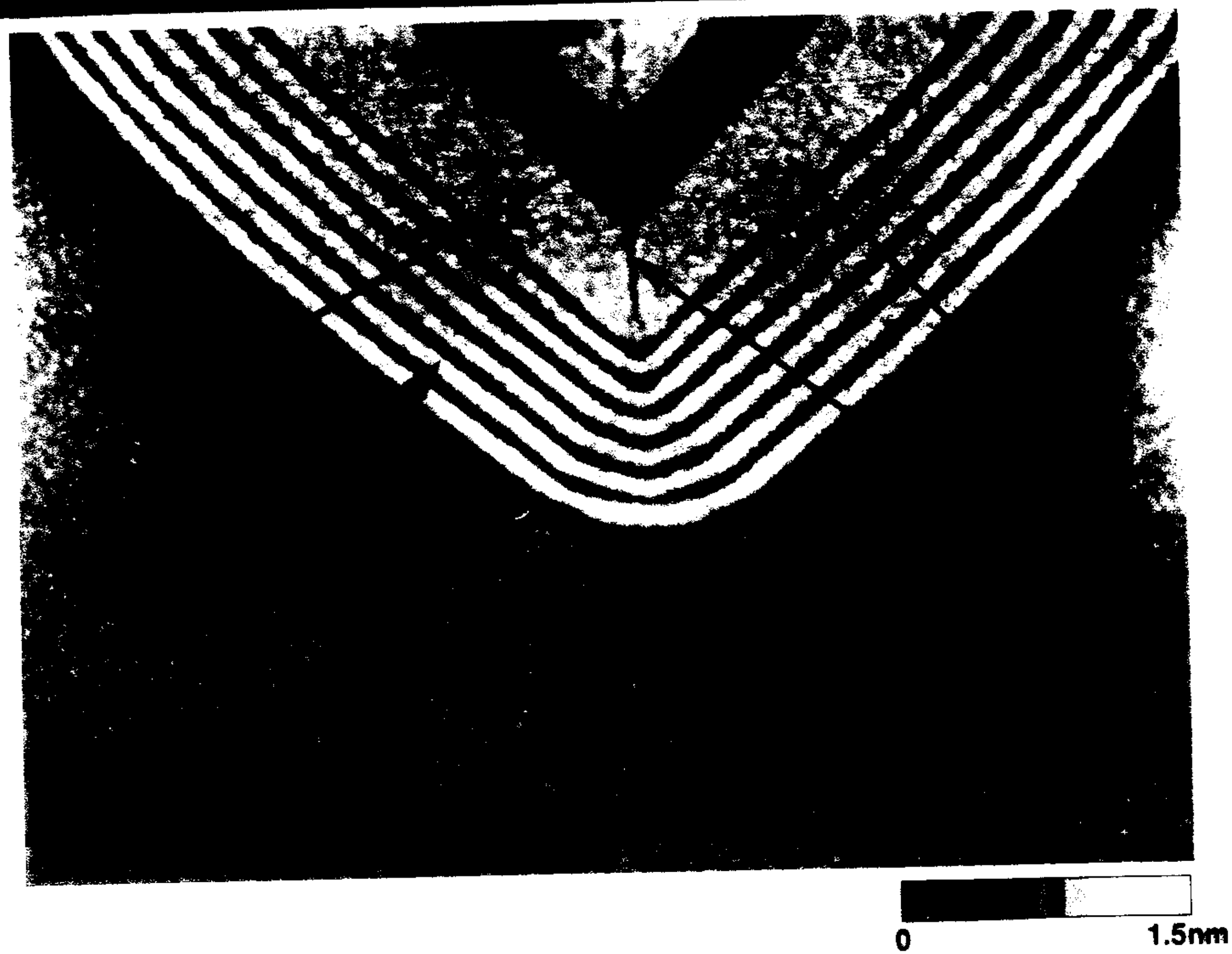




- uniform sub-10nm QWR size
- Self-limiting GaAs profile recovery < 25nm

- narrow linewidth (10meV)
- efficient carrier capture

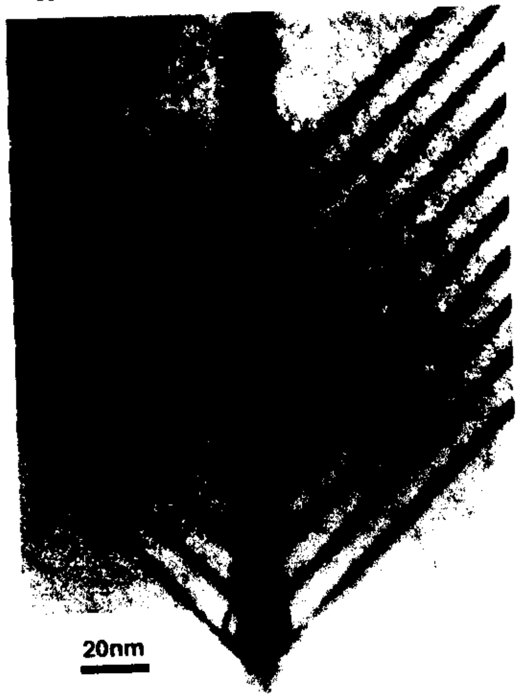
Self-Ordering of a V-Groove Surface



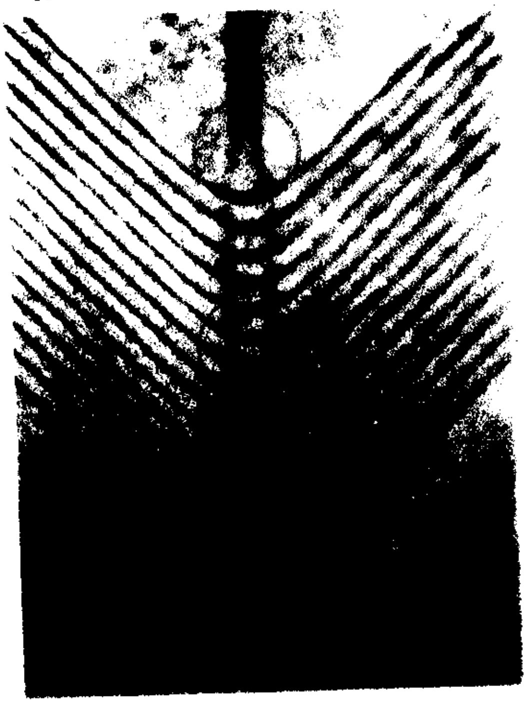
From Multiple QWRs to QWR SLs

t_w=4.5nm; t_b=60nm

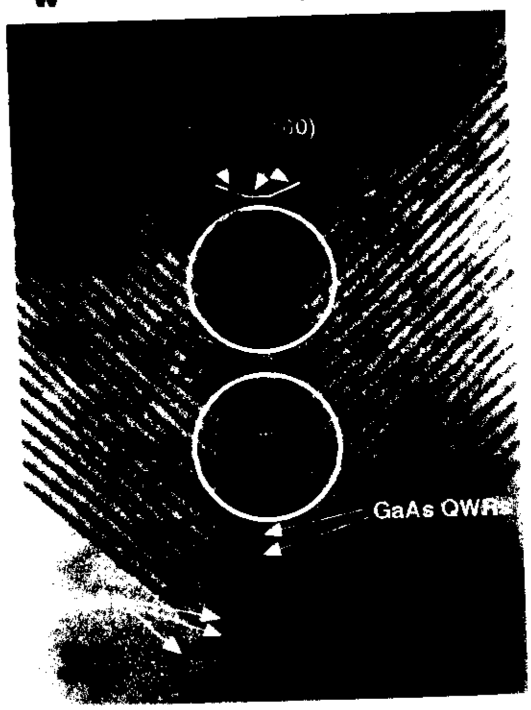
t_w=4.5nm; t_b=9.3nm



t_w=3.9nm; t_b=5.3nm

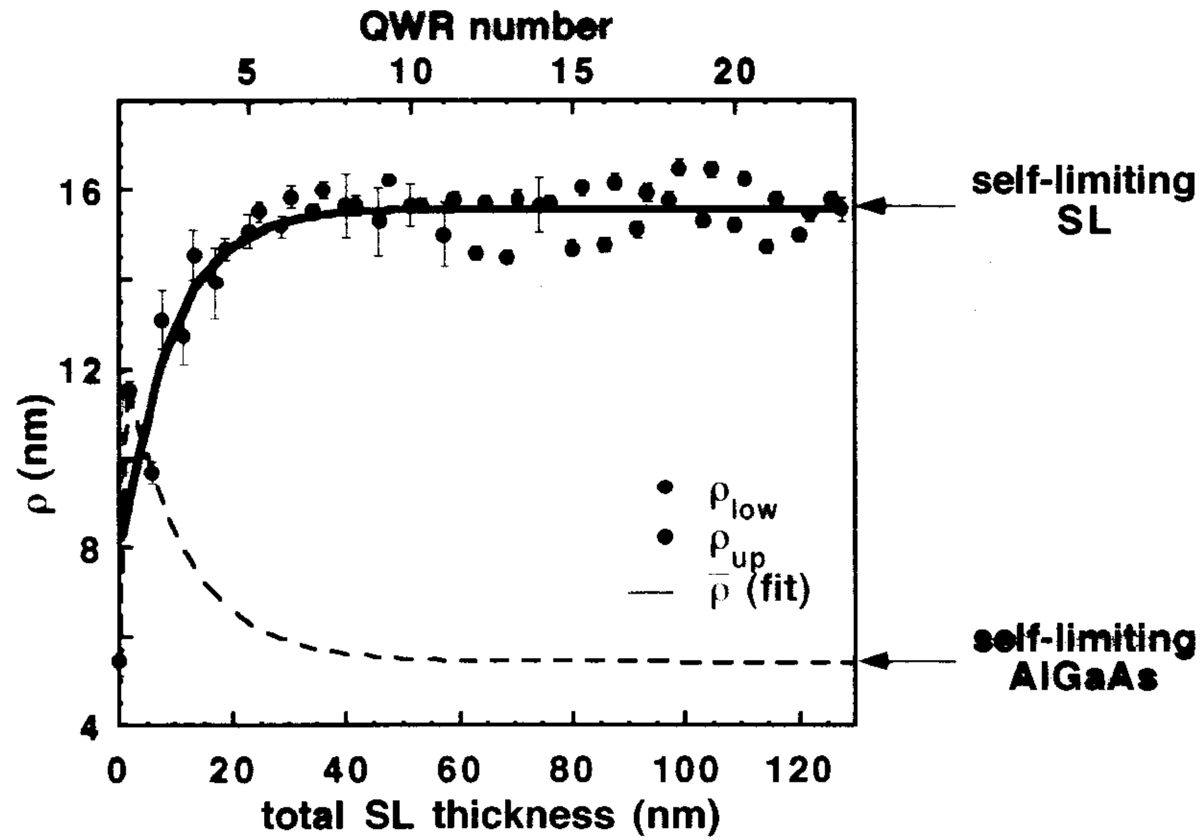


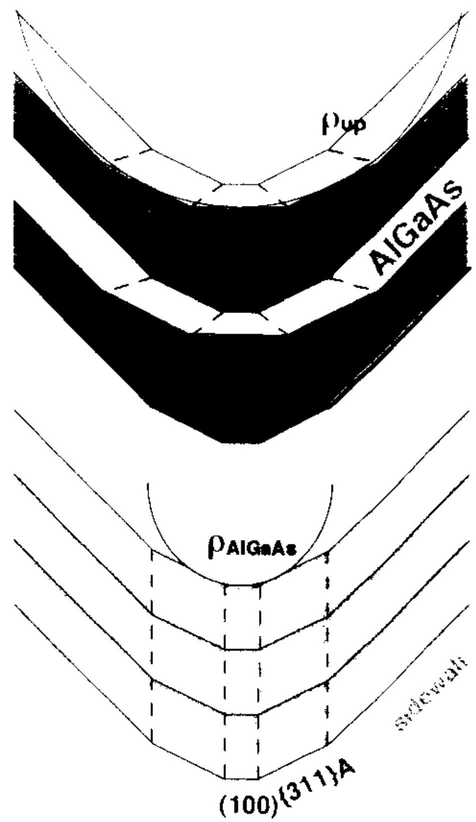
t_w=2.3nm; t_b=1.8nm



GaAs/$Al_{0.45}$ $Ga_{0.55}$As; T_{sub}=650°C

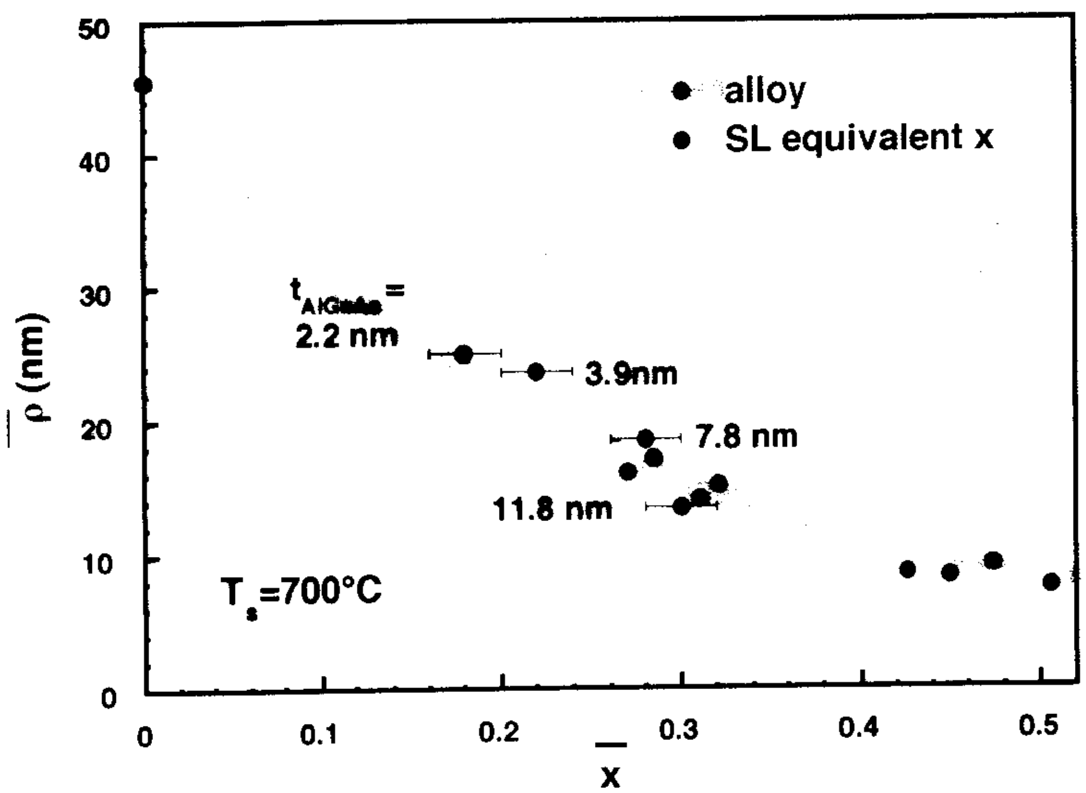
Self Ordering of a V-Groove QWR-SL

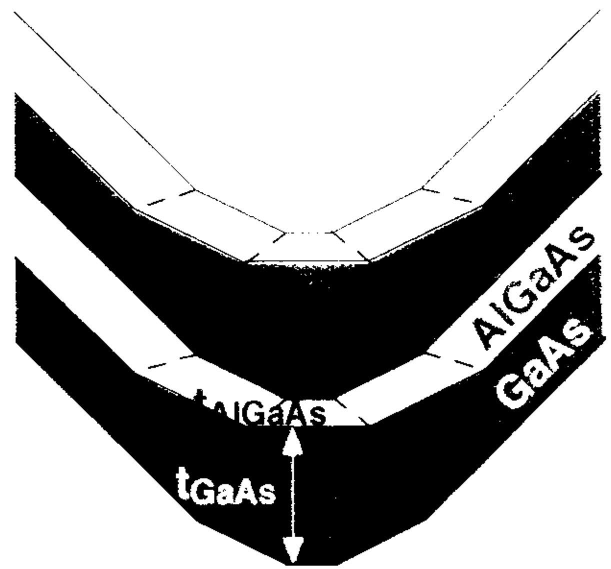




t_w=1.8nm; t_b=3.9nm; T_{sub}=650°C

Comparison of Alloy and SL V-Groove Ordering

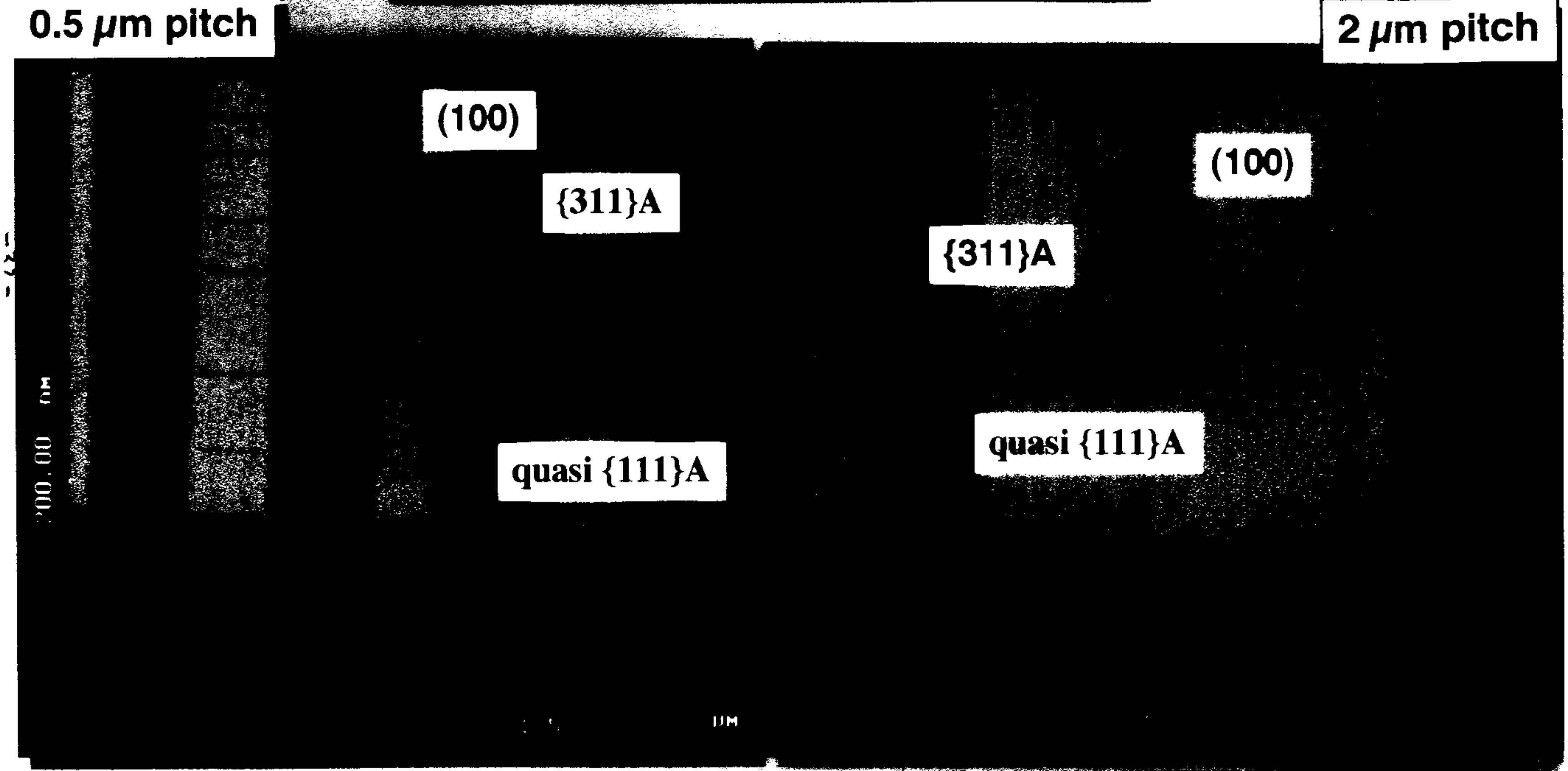




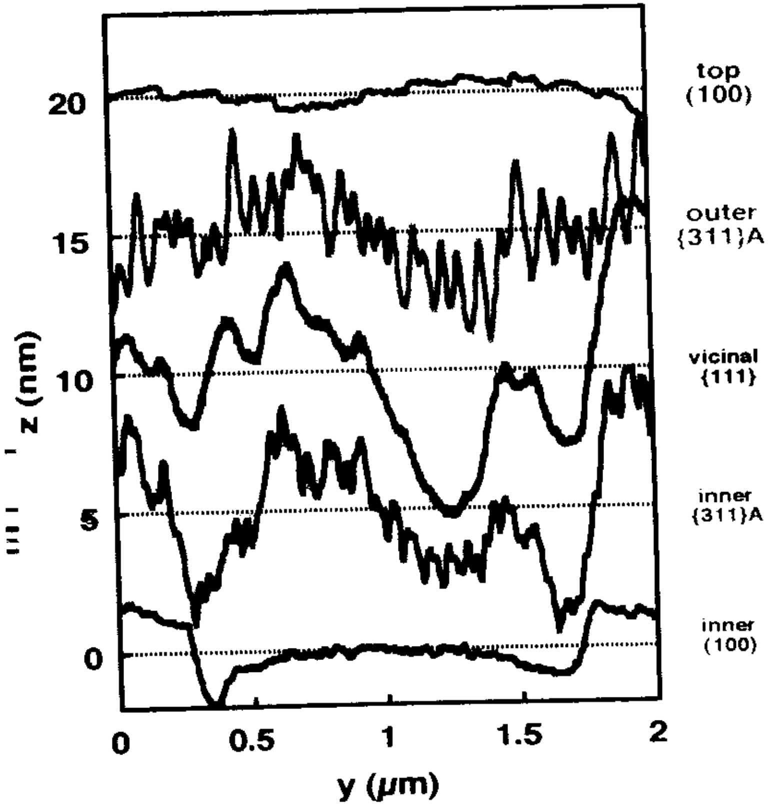
$$\bar{x} = \frac{x_{AlGaAs} \cdot t_{AlGaAs}}{t_{GaAs} + t_{AlGaAs}}$$

(100) Surface After Growth

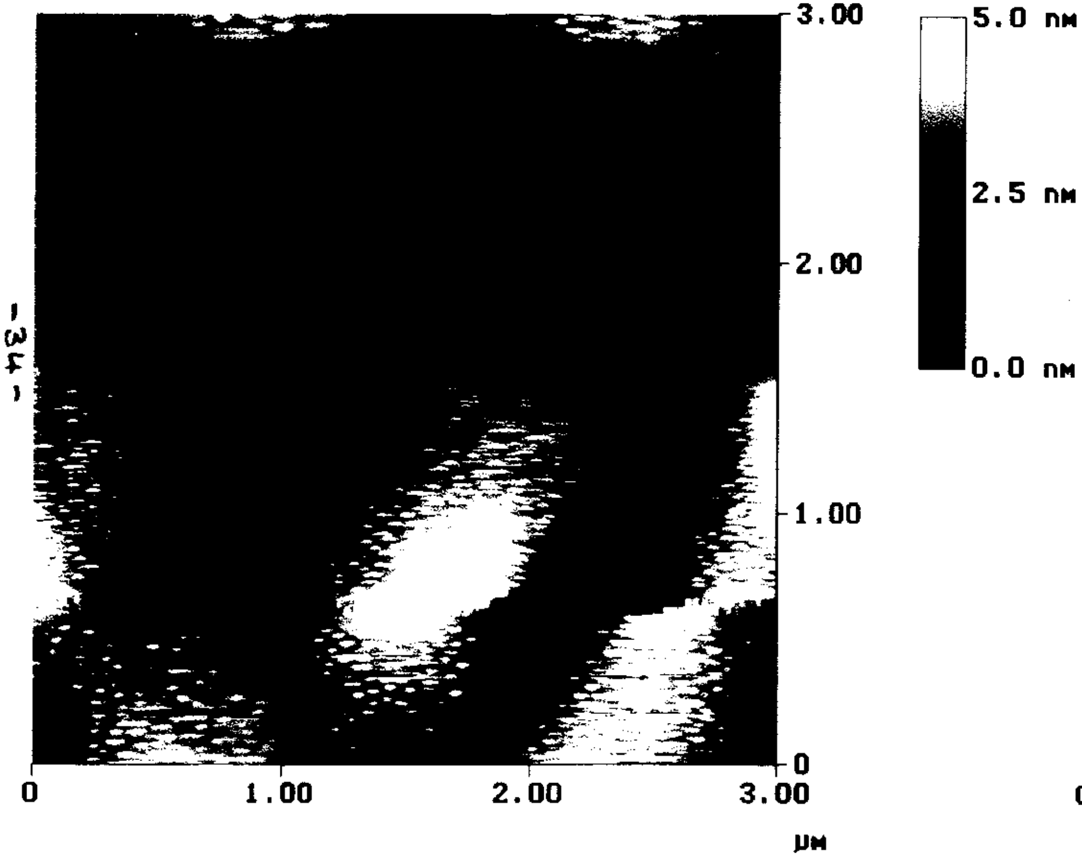
- Monolayer steps on the (100) surface
- Step bunching on the (311)A surface

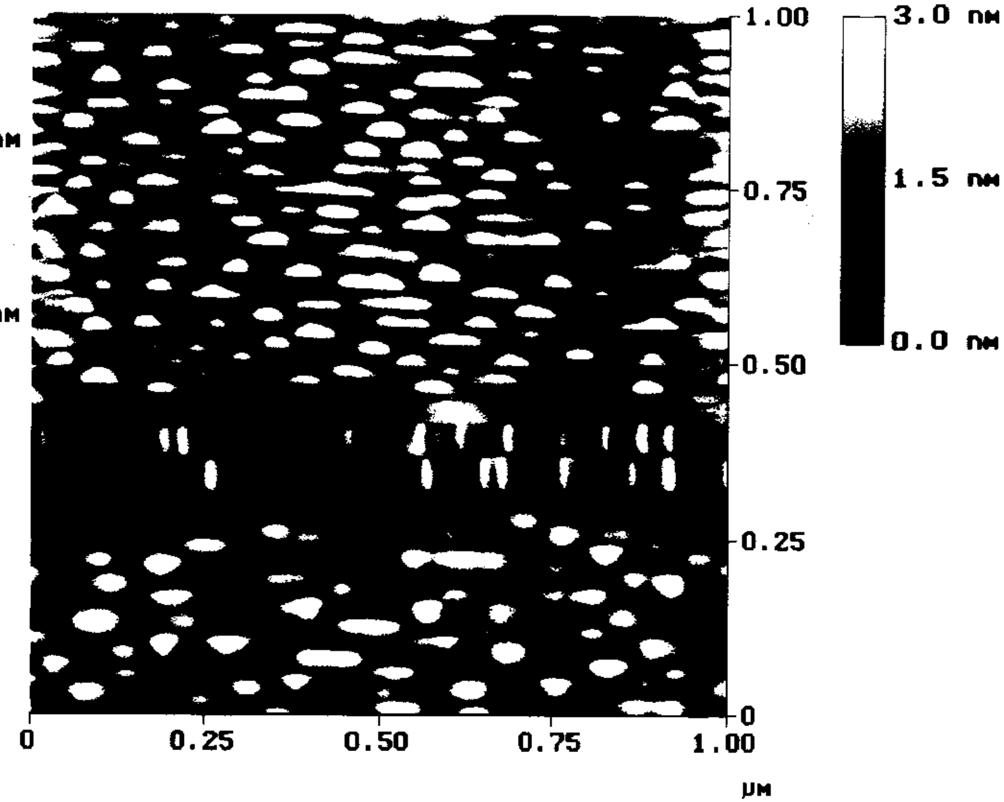


Topography of a V-Groove Surface-QWR

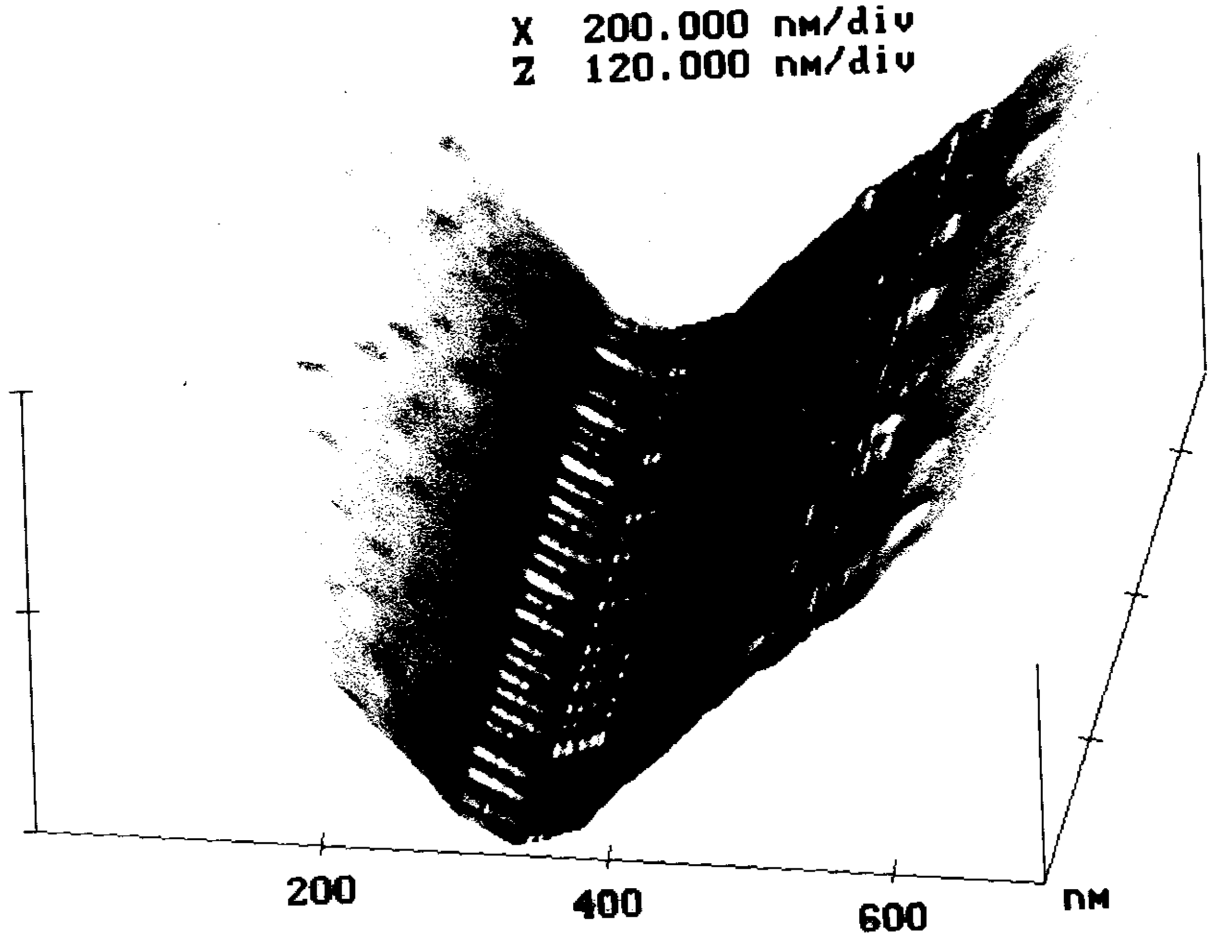


InGaAs/AlGaAs V-groove Surface



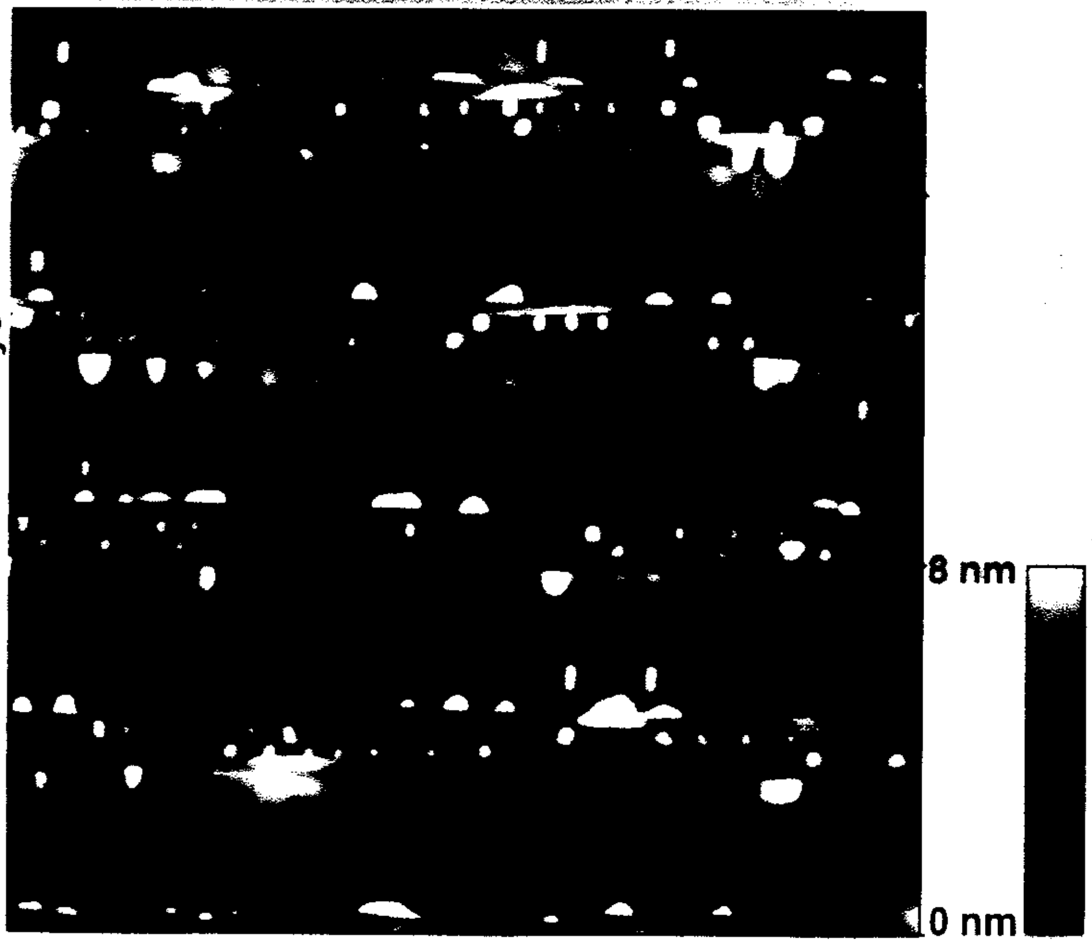


Surface of InGaAs/AlGaAs V-Groove

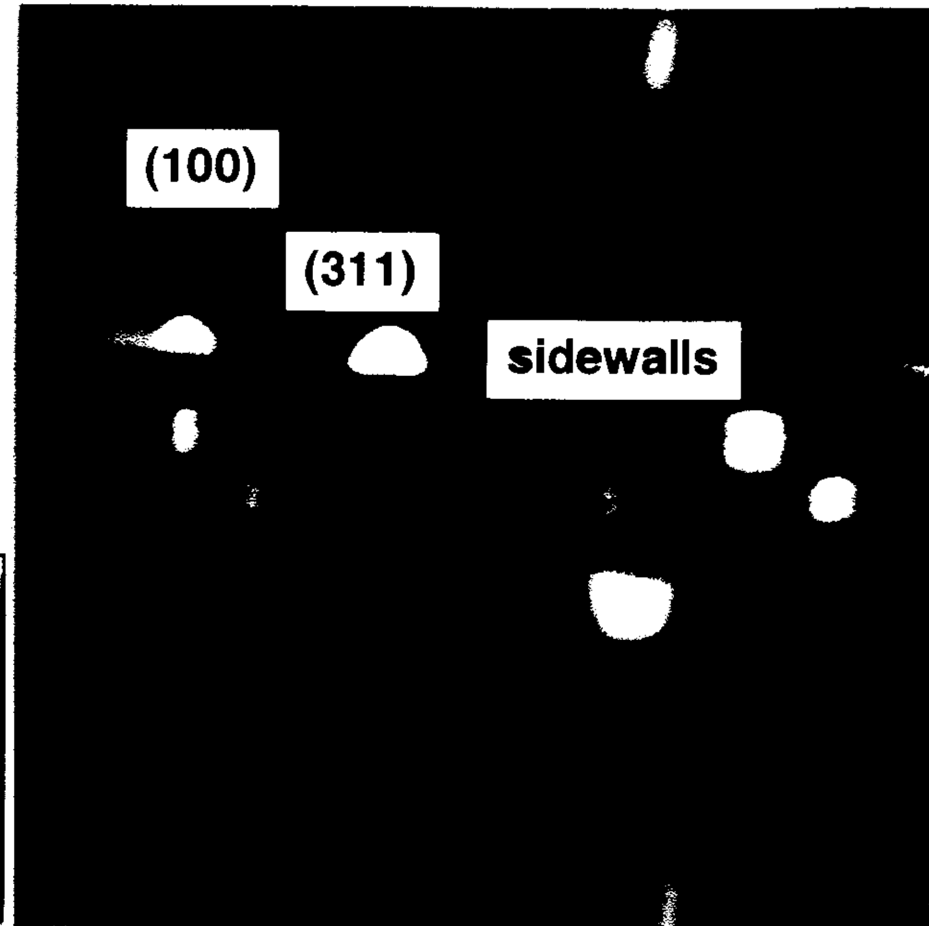


Surface Quantum Wire (p= 0.5 μm)

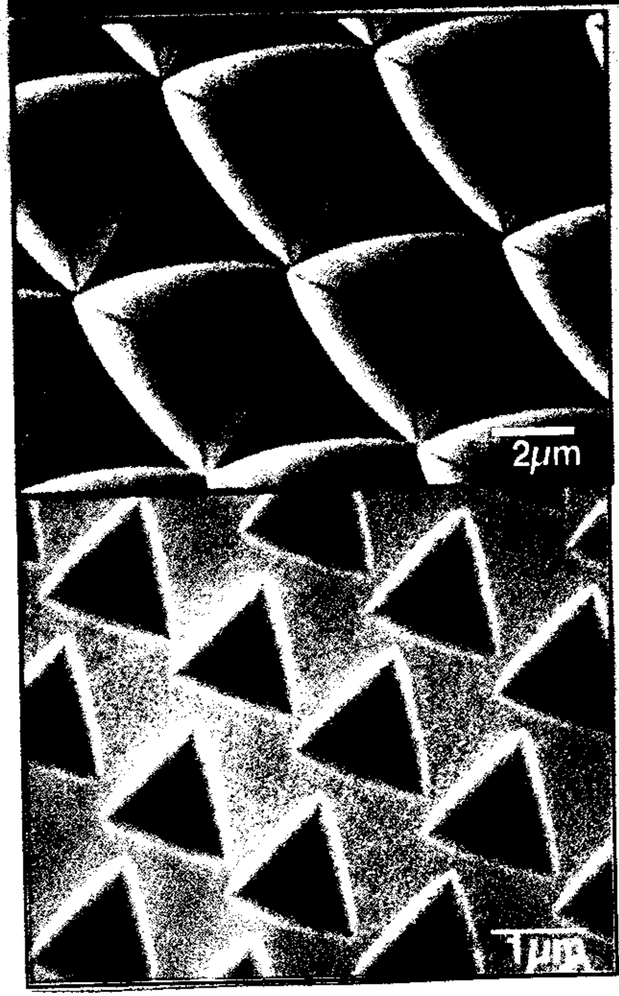
(2.5 x 2.5μm^2)



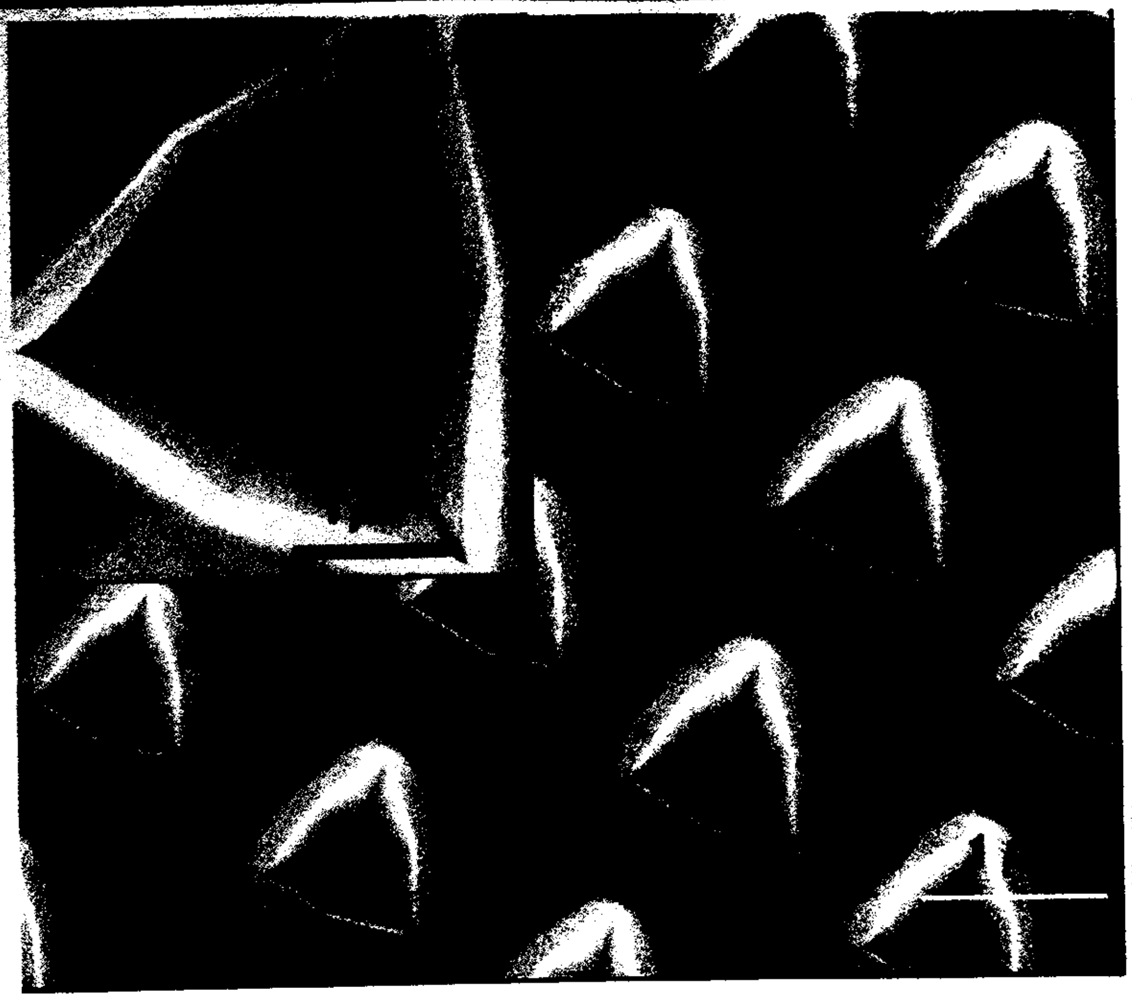
(0.7 x 0.7 μm^2)



Growth of QDs in Inverted Tetrahedral Pyramids

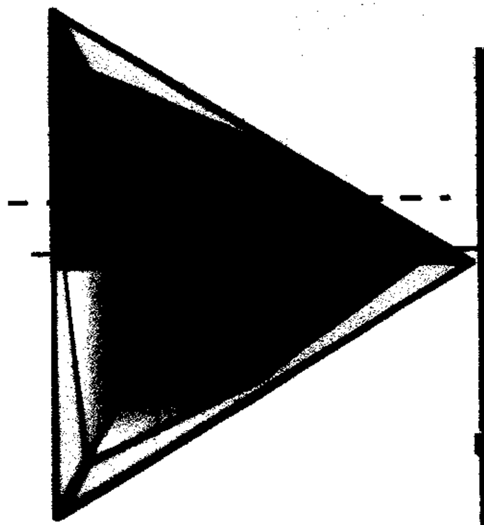


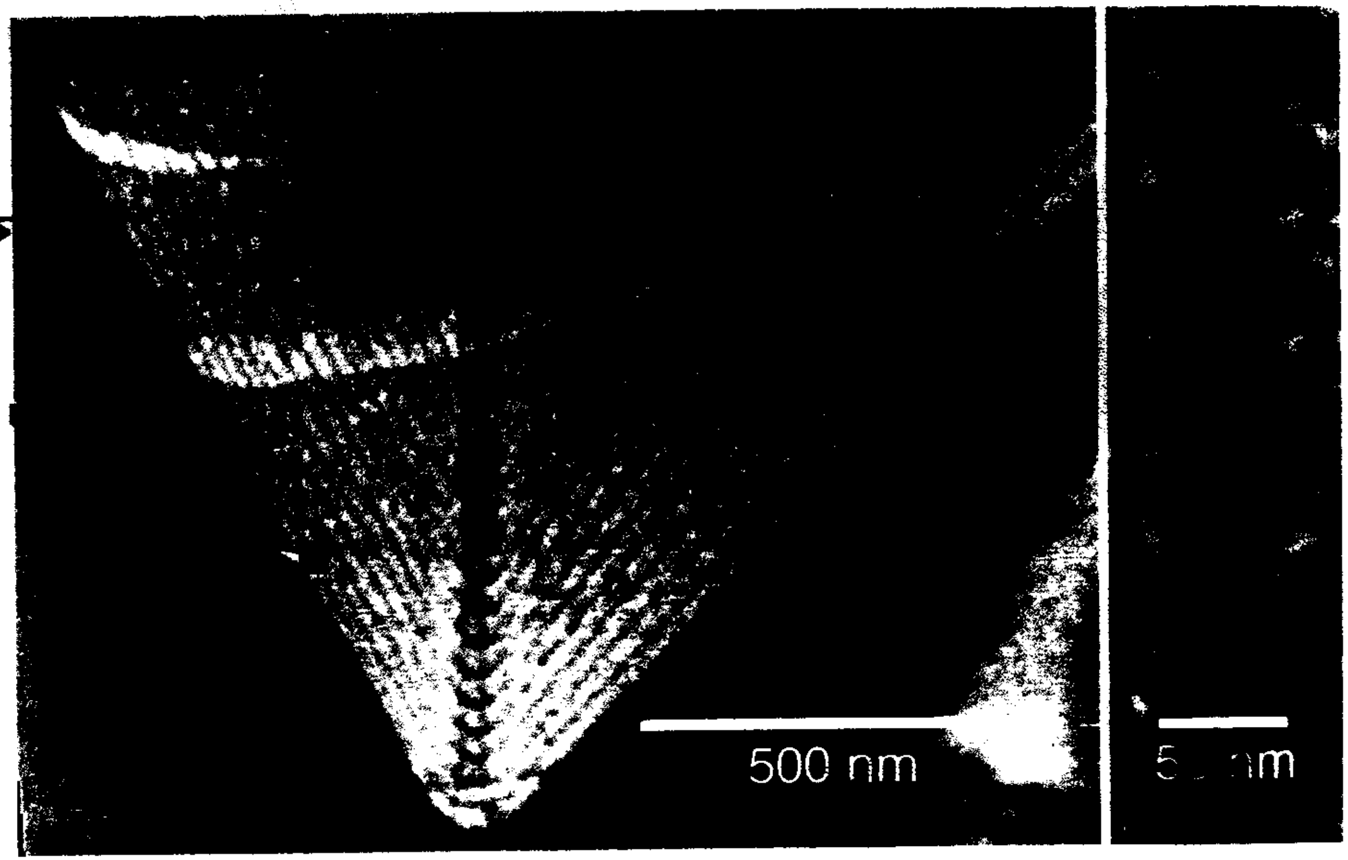
Etched (111)B GaAs substrate



Regrown heterostructure

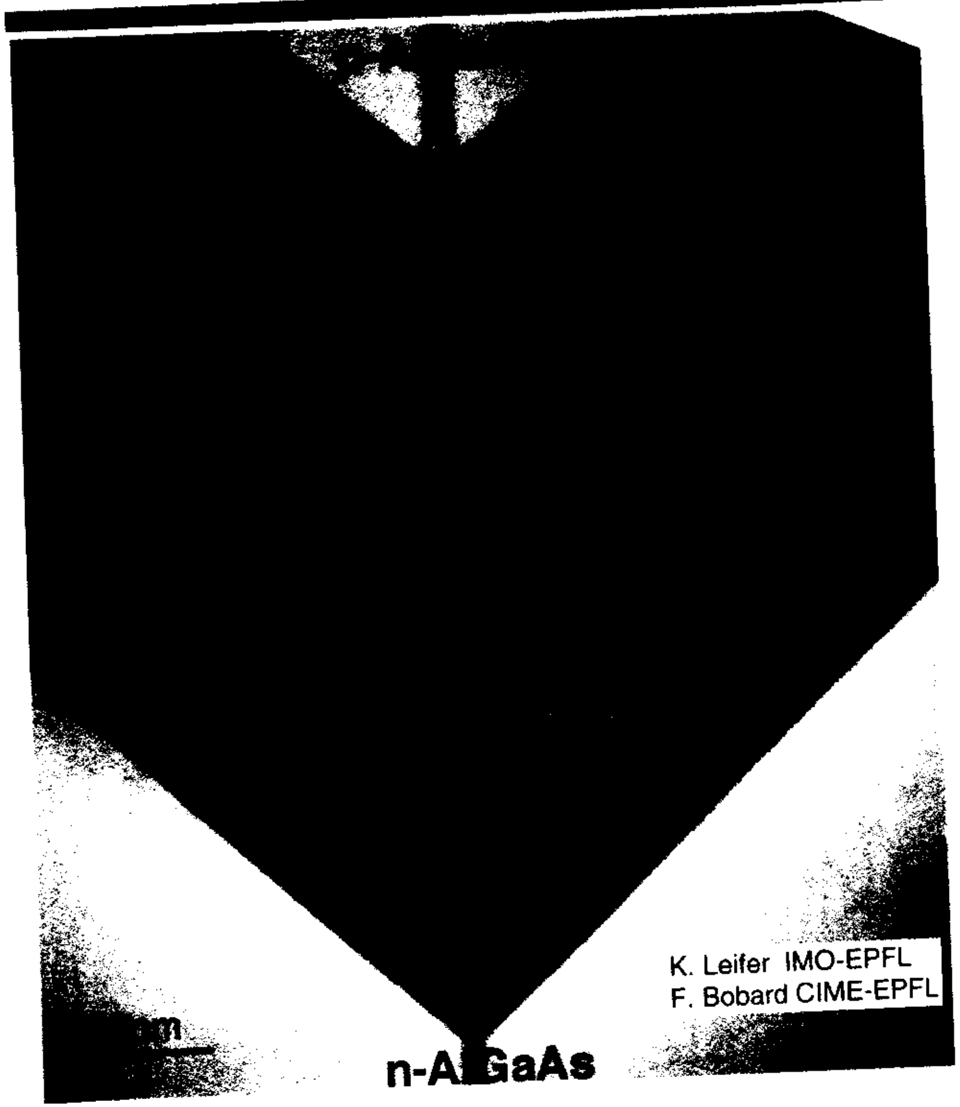
AFM Cross Section at Center of a QD Pyramid

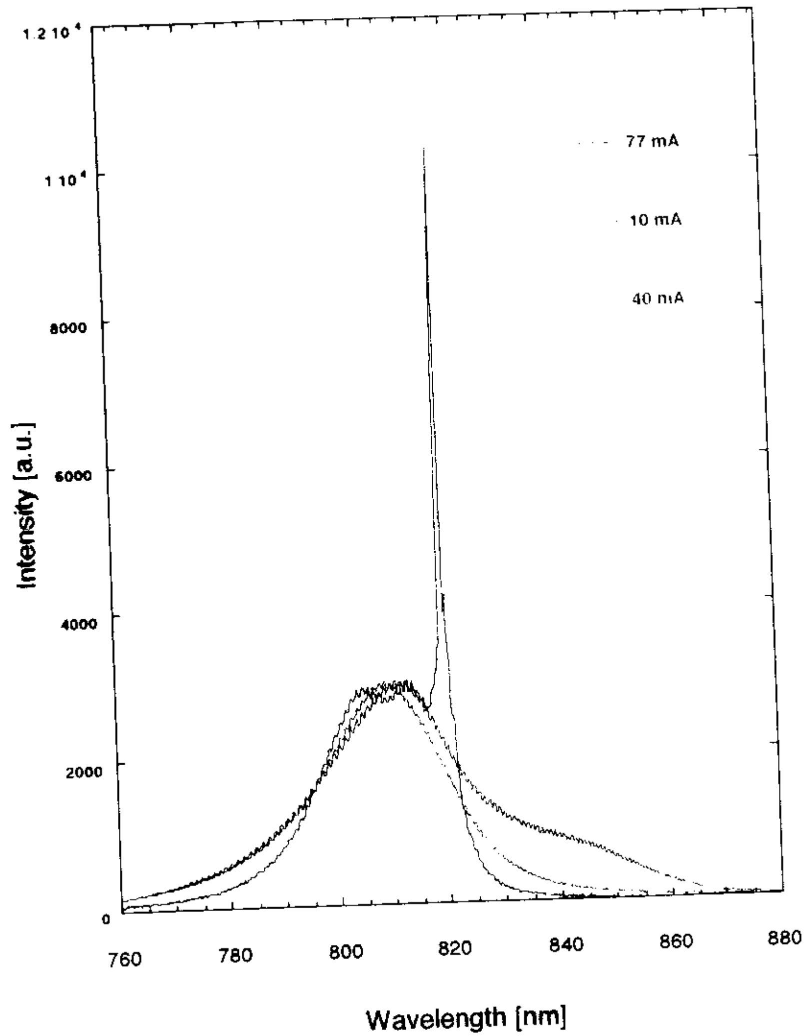




- vertically-stacked QWRs and QDs
- vertical QWR

Multiple-QWR V-Groove Laser





Electronic Properties of Low Dimensional Nanostructures Grown on Nonplanar Substrates

outline:

- Quantum confinement in vertical QWs
- Valence band mixing in QWRs
- Coupling and tunneling in double QWRs
- Localized and delocalized states in QWR superlattices
- Localized excitons in QWRs
- 1D excitons at high densities

Electronic Properties of Low Dimensional Nanostructures Grown on Nonplanar Substrates

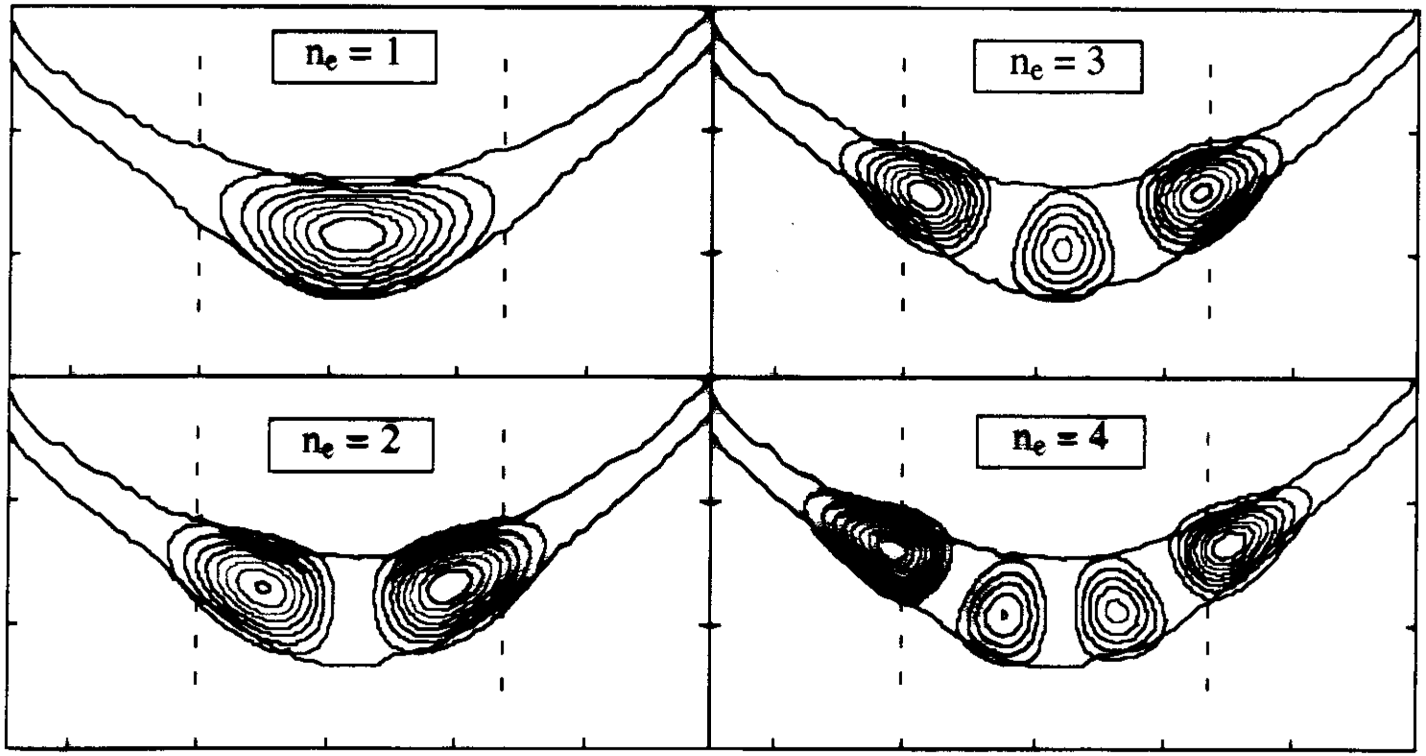
Collaborators:

D. Oberli, F. [redacted], M.-A. Dupertuis

E. Martinet, A. Gustafsson, H. We[redacted], Y. [redacted]

Electron Subband in a V-Groove QWR

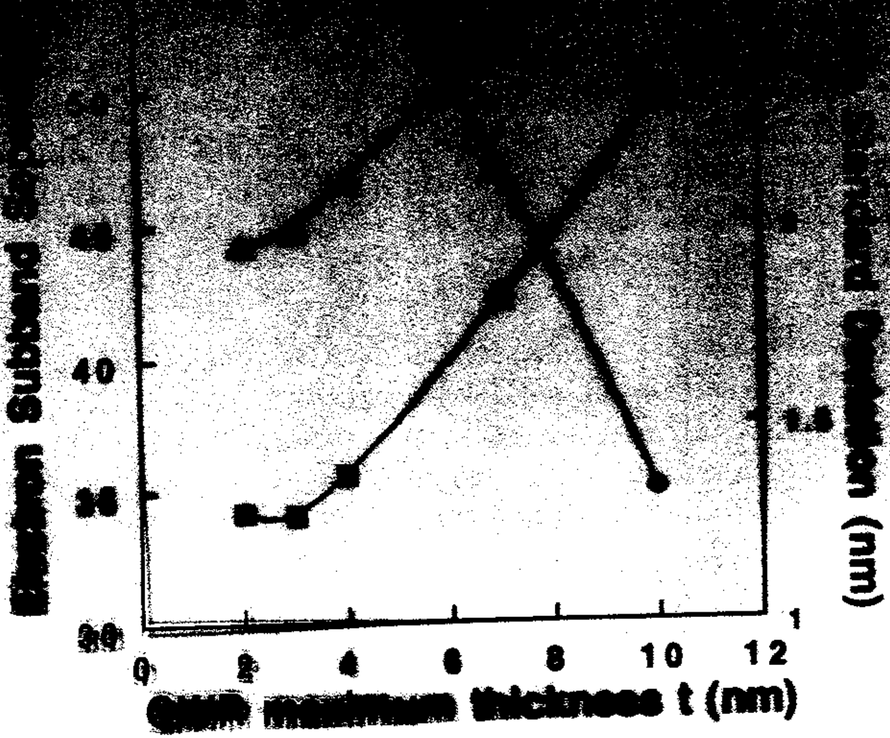
(Probability Density Distribution)

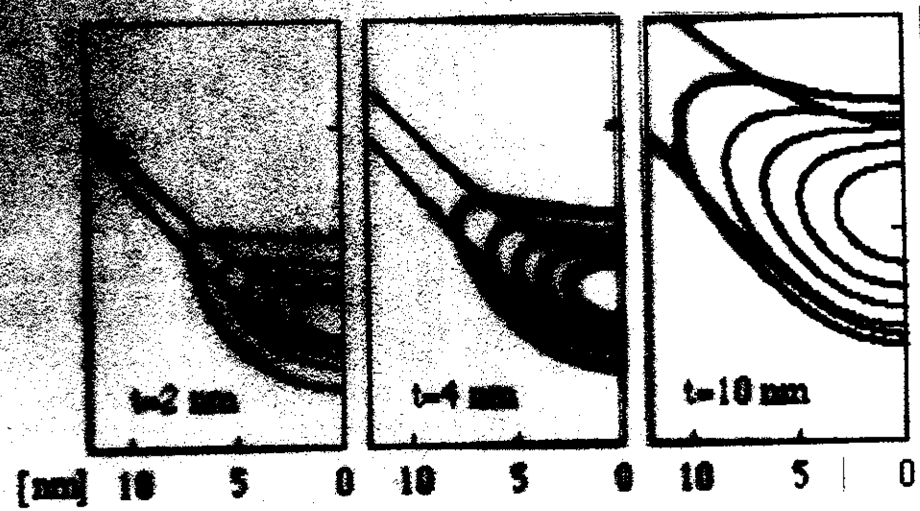


10 nm / div.

Separation

- lower ra ρ= 5 nm
- Al mole fr

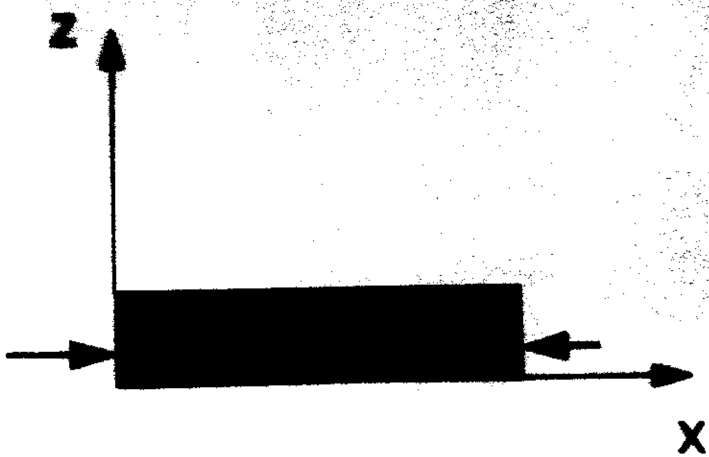




ground state wave functions

Valence Band Mixing in a 1D Semiconductor:

Luttinger Hamiltonian



$$\begin{bmatrix} H_{hh} & c & b & 0 \\ c^* & H_{lh} & 0 & -b \\ b^* & 0 & H_{lh} & c \\ 0 & -b^* & c^* & H_{hh} \end{bmatrix} \begin{matrix} \left|\frac{3}{2},\frac{3}{2}\right\rangle \\ \left|\frac{3}{2},-\frac{1}{2}\right\rangle \\ \left|\frac{3}{2},\frac{1}{2}\right\rangle \\ \left|\frac{3}{2},-\frac{3}{2}\right\rangle \end{matrix}$$

heavy hole

light hole

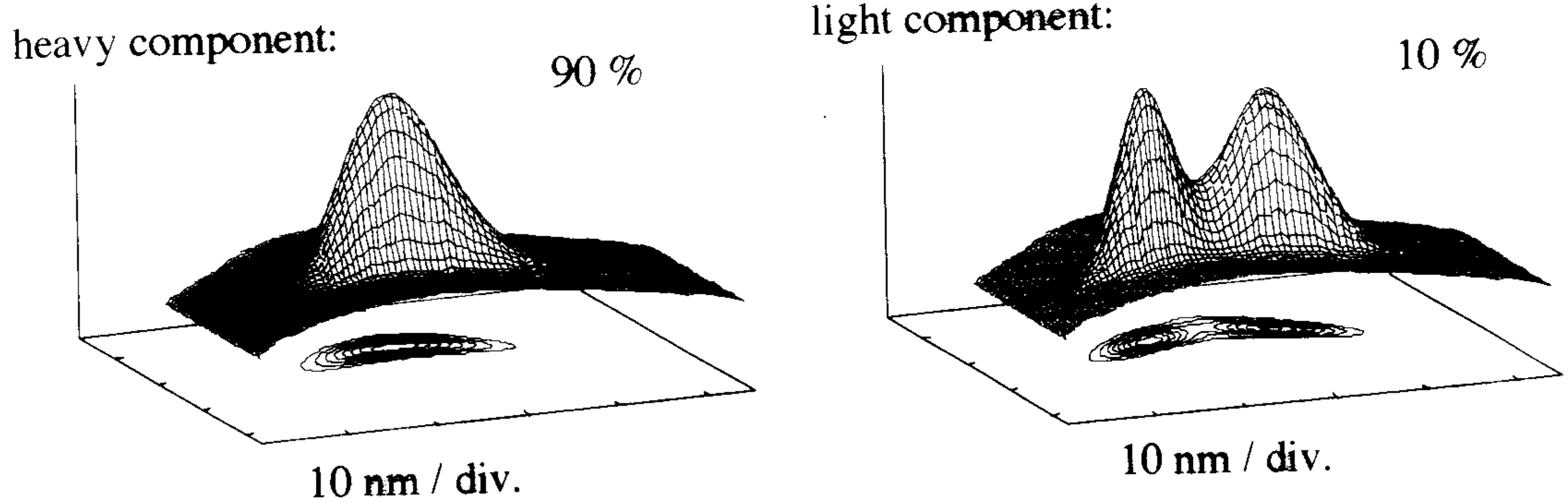
lateral confinement

$c=c(k_x, k_y)$, $c(0,0)=0$
$b=b(k_x, k_y)$, $b(0,0)=0$

⇨ heavy hole- light hole mixing

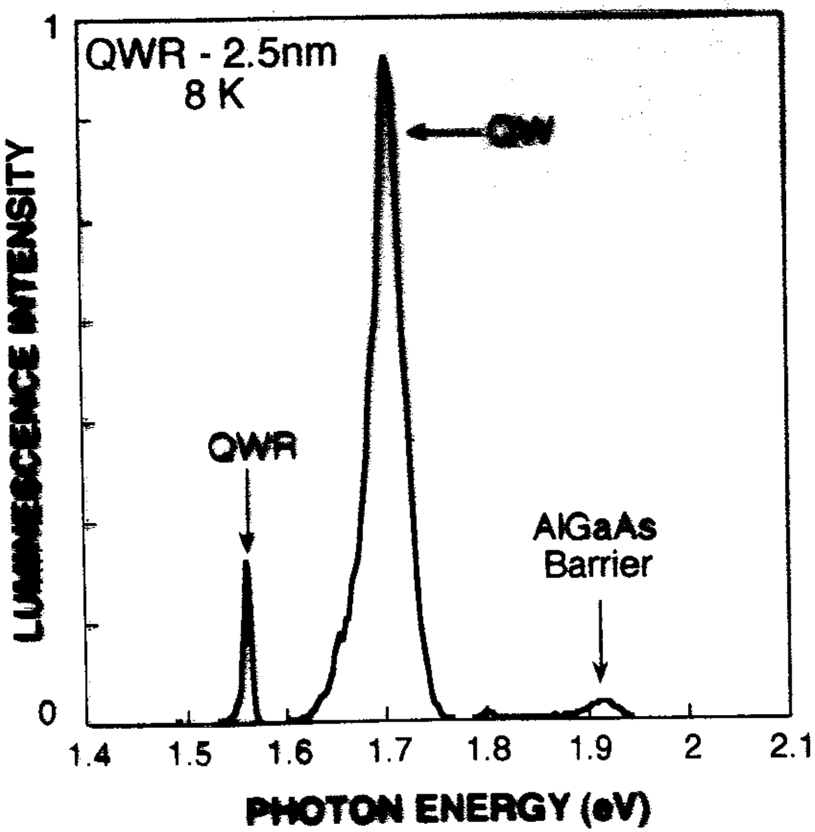
Valence Band Mixing in QWRs

(2.5 nm V-Groove QWR; nh = 1)



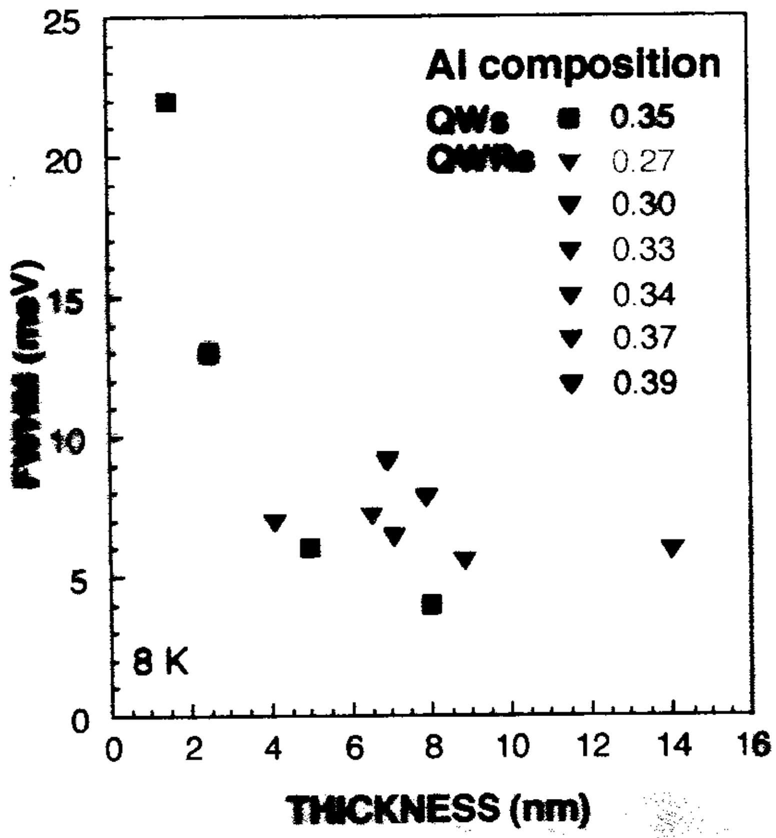
Low-Temperature PL Spectra of V-Groove QWRs

PL spectrum of a V-Groove QWR

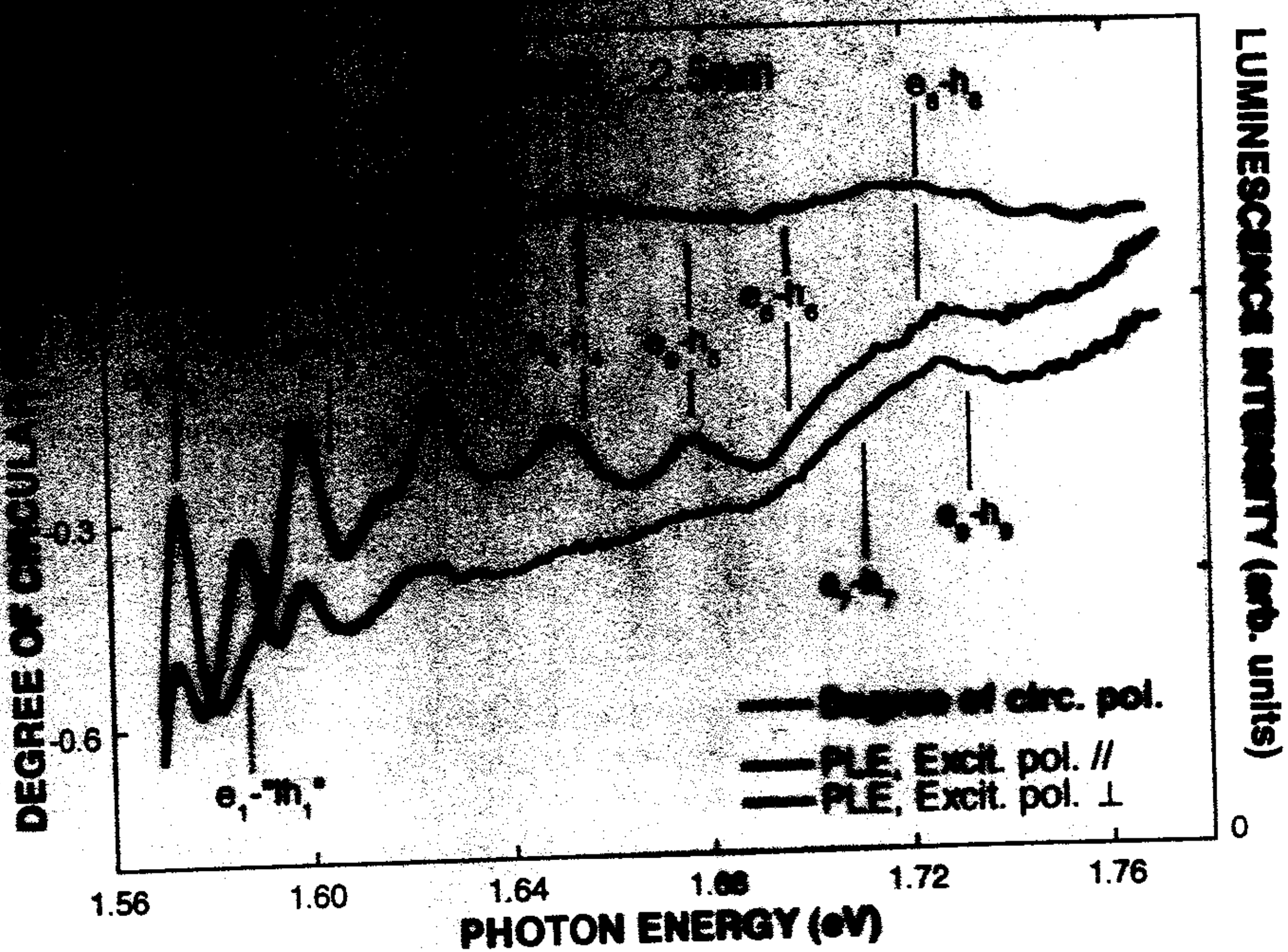


QWR vs QW Linwidths

Linewidth of QWs and QWRs



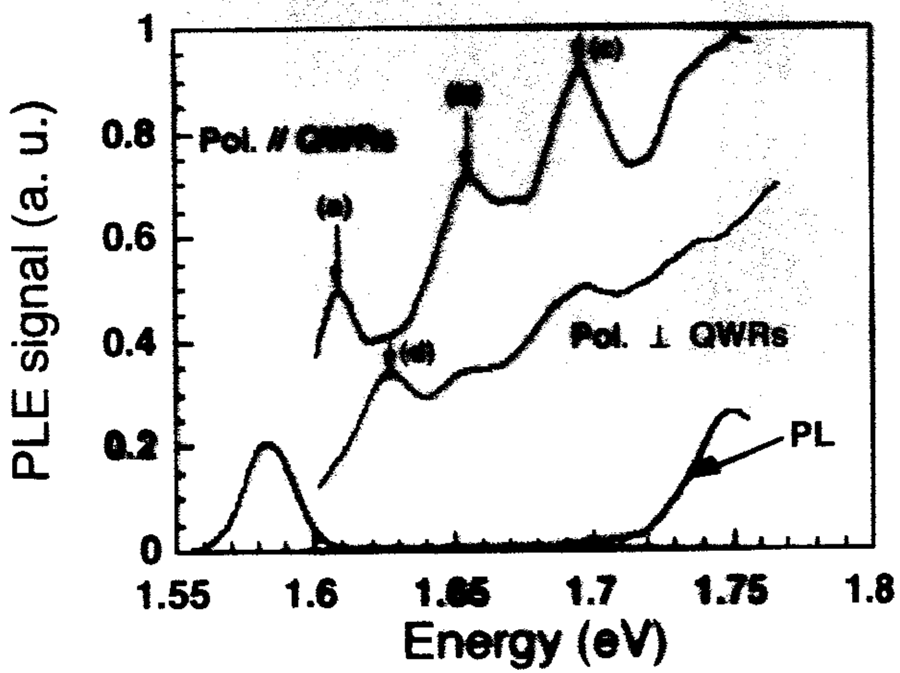
...y in V-Groove QWRs



☆ hh <u>and</u> lh related transitions observed

☆ polarization anisotropy in e-lh/e-hh ratio

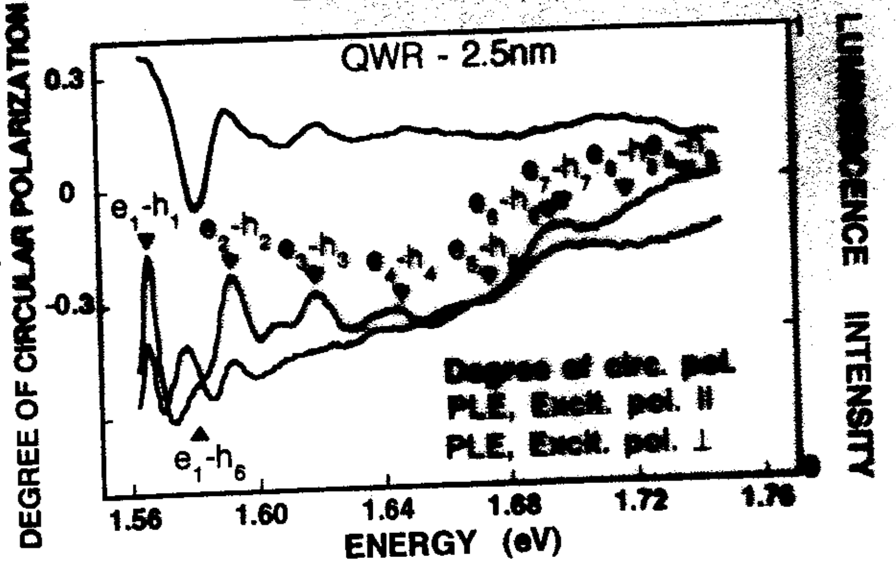
Large (45 meV) Subband Separation in V-Groove QWRs



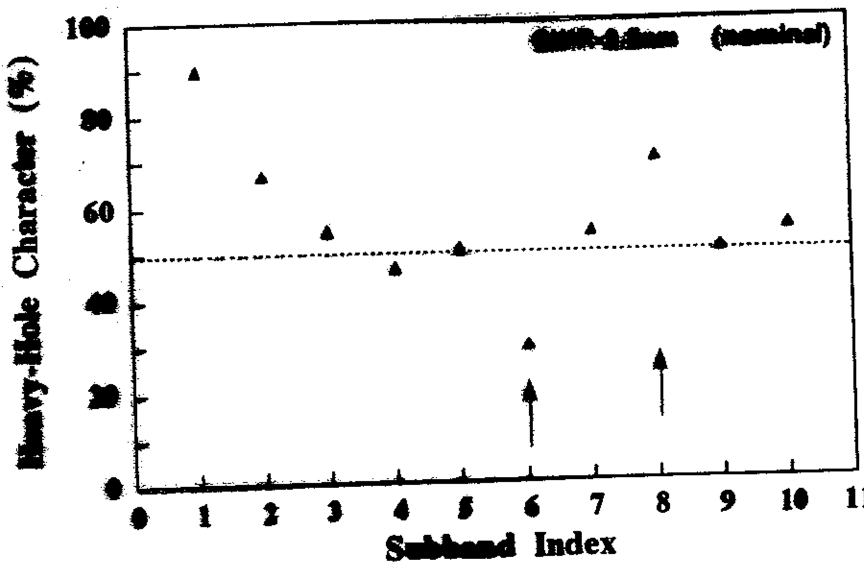
PLE Spectra:
-45 meV e-"hh" subband separation
-large "hh"-"lh" polarization anisotropy

Observation of Valence Band Mixing in 1D Wires

PHOTOLUMINESCENCE EXCITATION



CALCULATED CHARACTER of VALENCE SUBBAND STATES at K=0

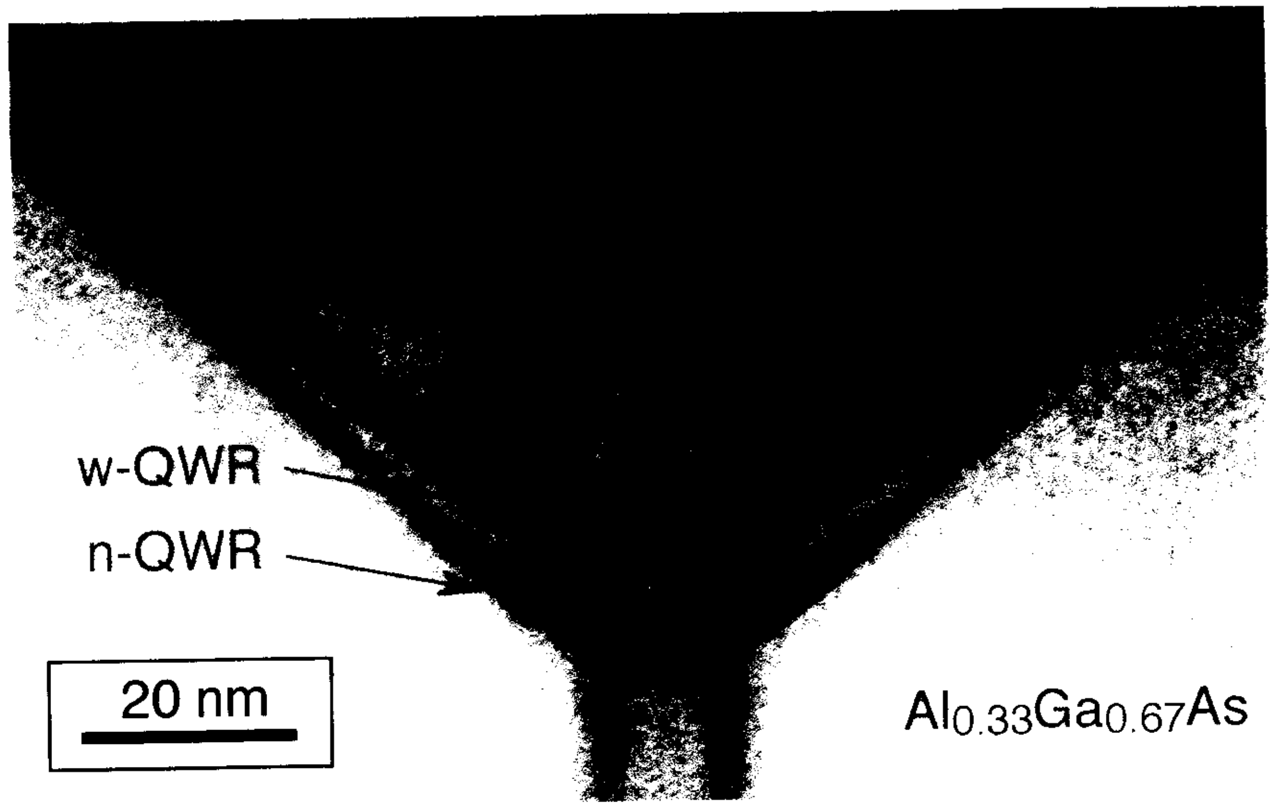


- polarization anisotropy
- heavy/light hole mixing

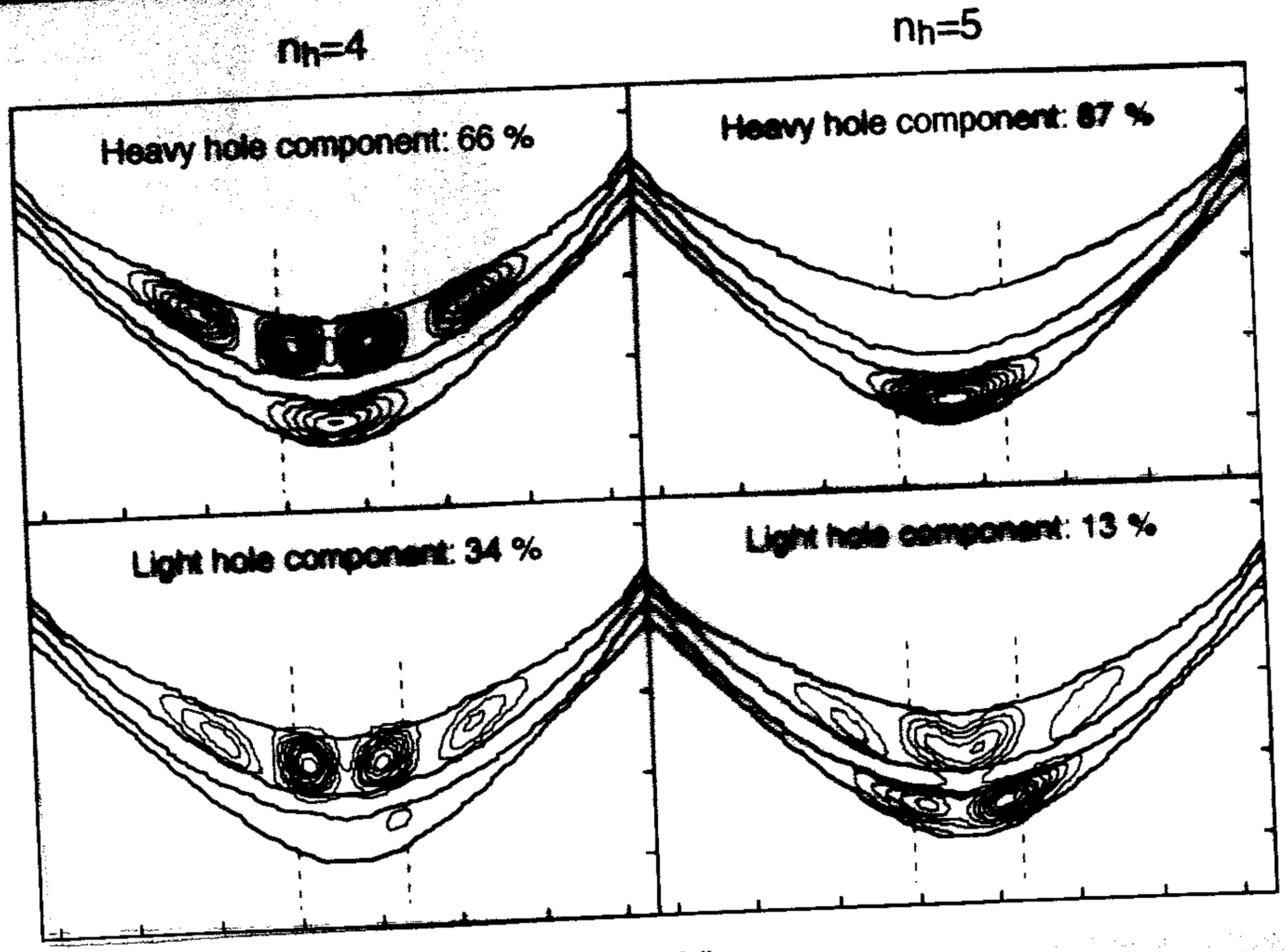
Heavy Hole Character =

$$< F_{3/2}(r) | F_{3/2}(r) >^2 + < F_{-3/2}(r) | F_{-3/2}(r) >^2$$

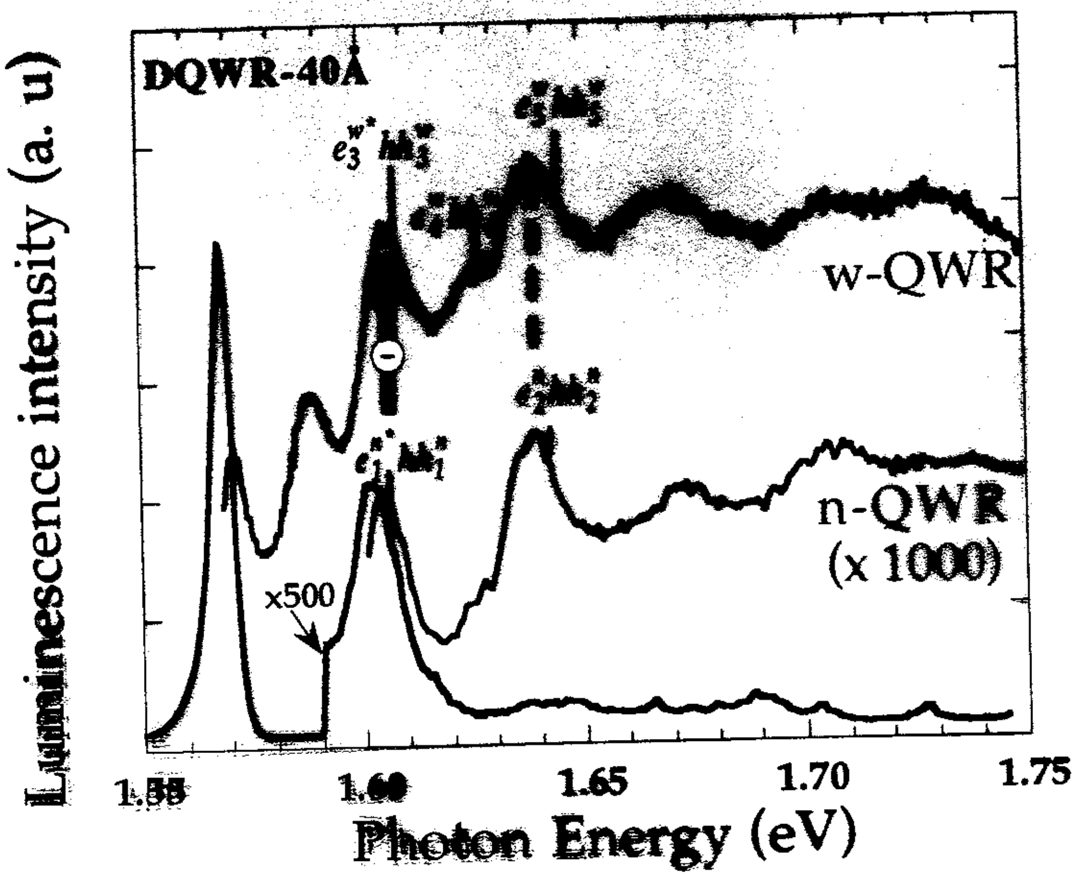
Coupled V-Groove Quantum Wires

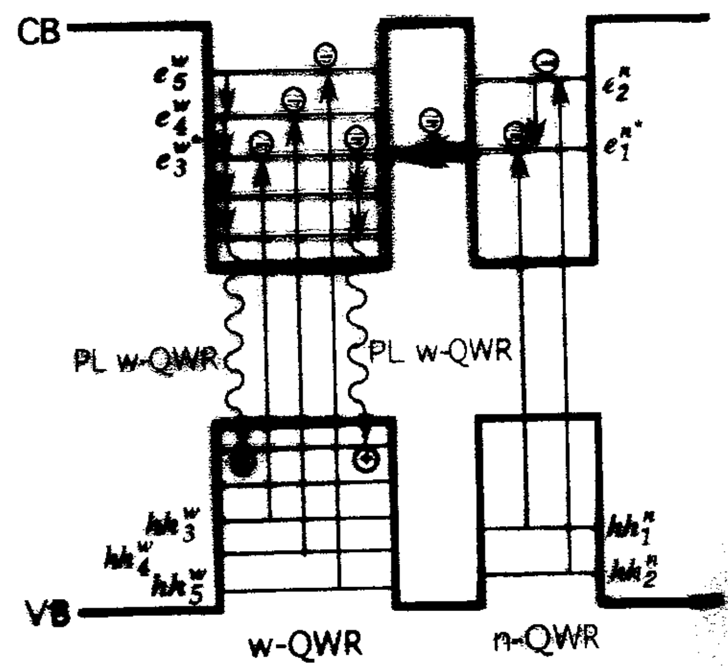


Coupled Hole States in Double V-Groove QWRs

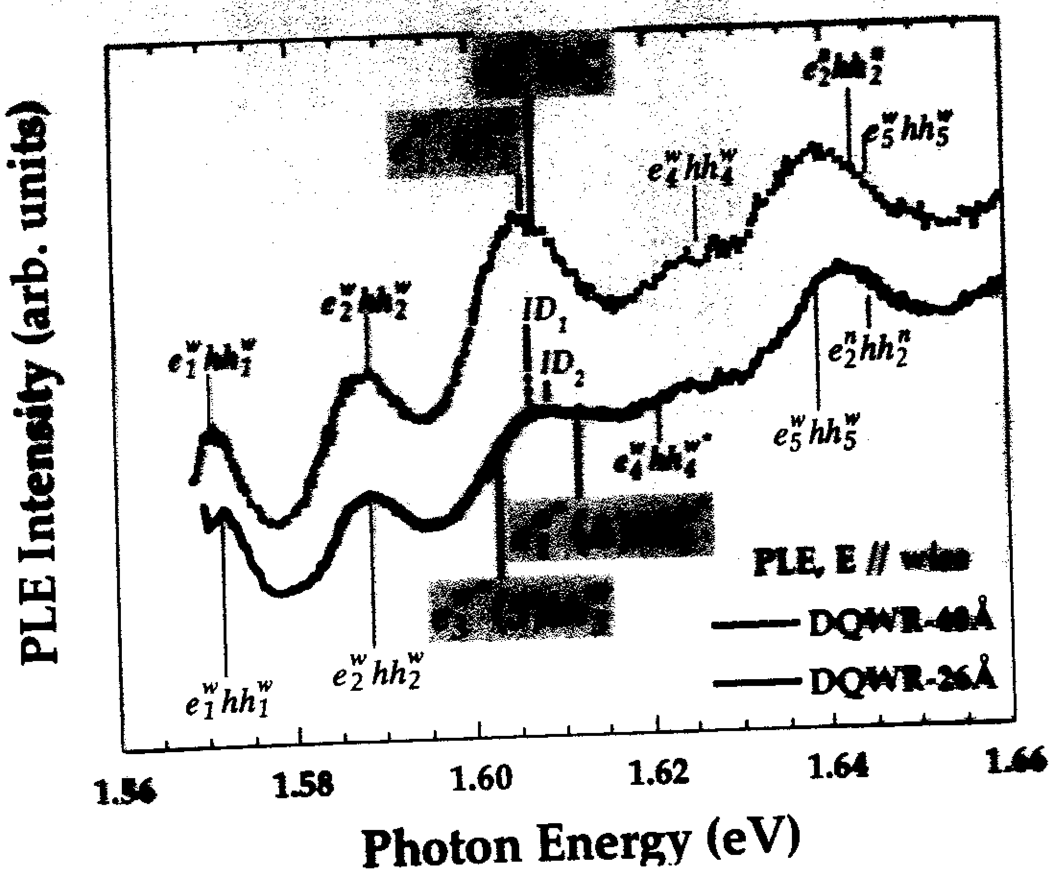


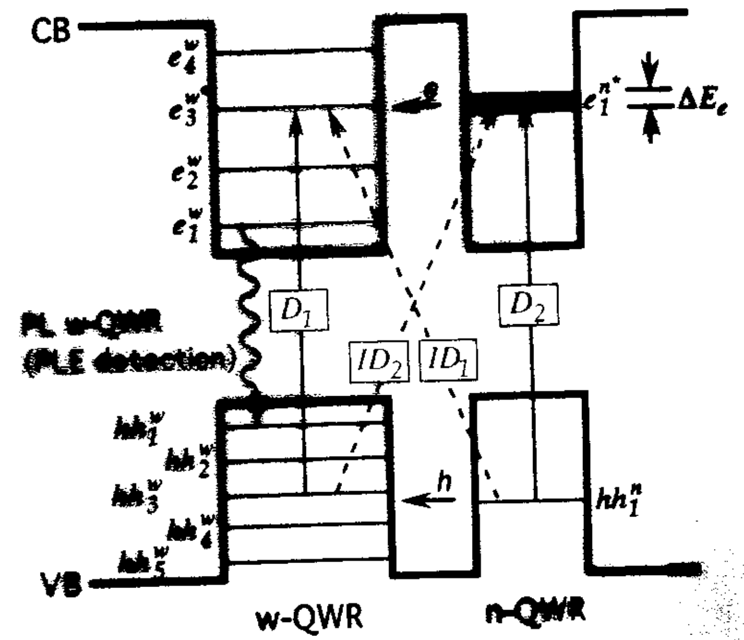
Evidence for Tunneling between 1D States



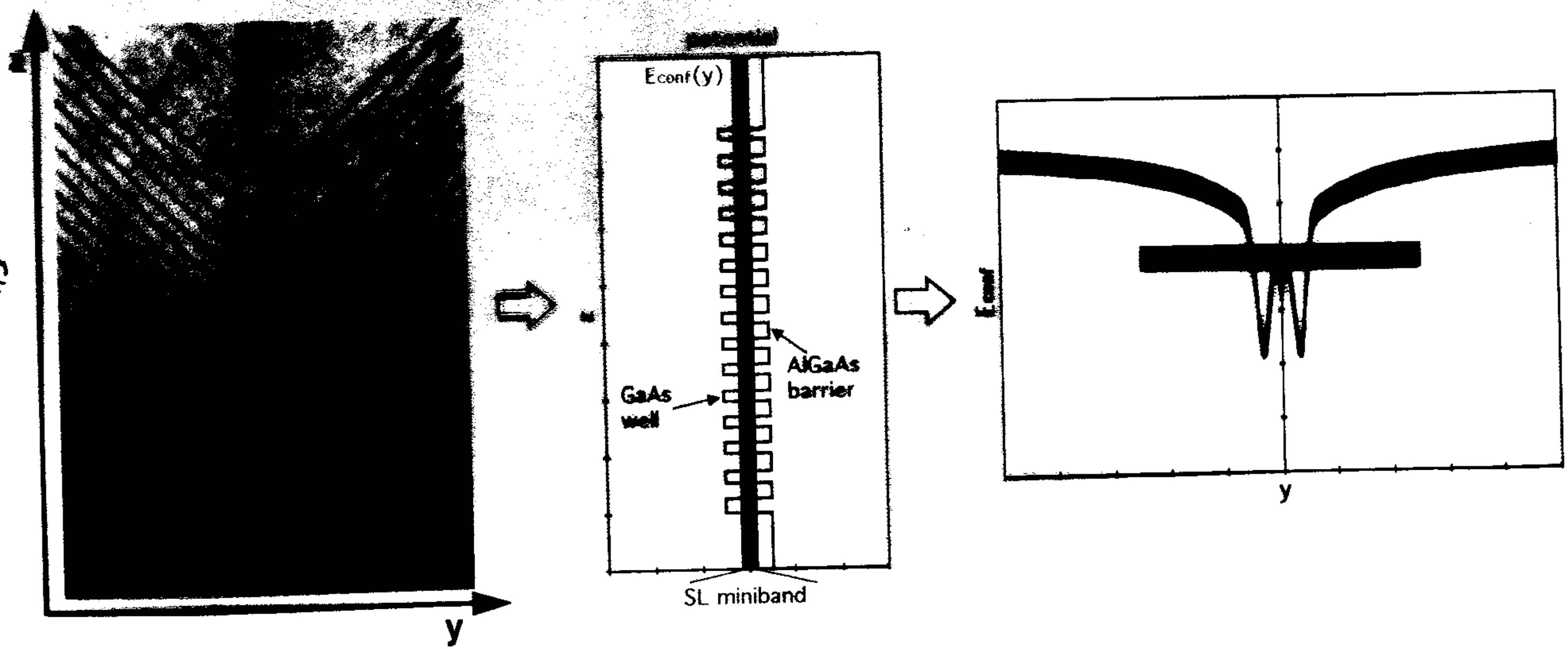


Evidence for Elctronic Coupling in a Double QWR





Adiabatic Model for QWR-SLs



TEM cross section

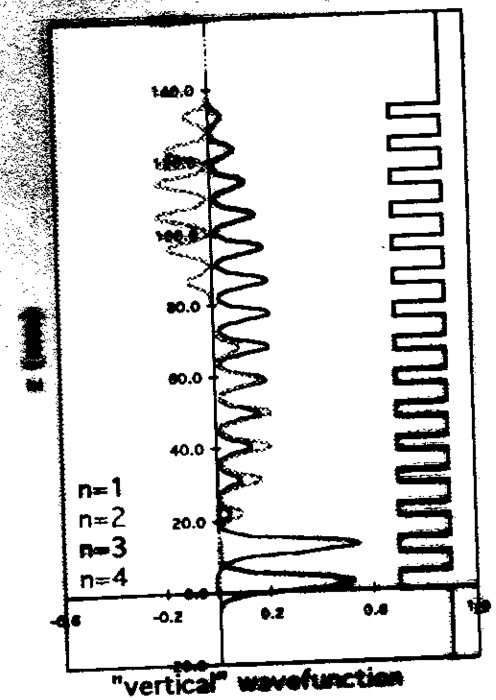
transverse wavefunctions

lateral wavefunctions

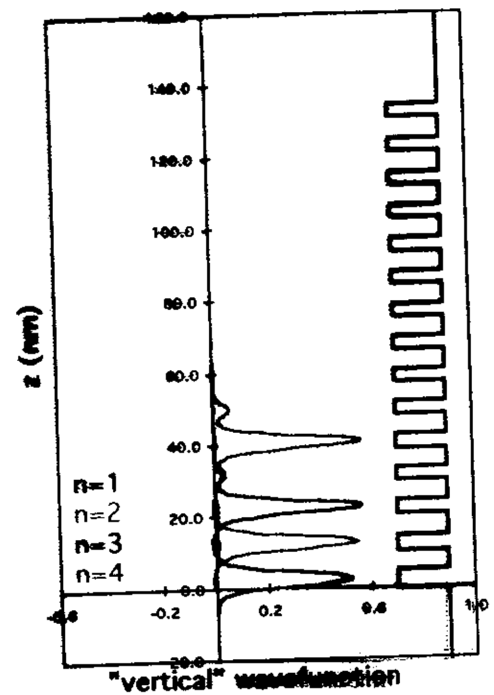
Localization of QWR-SL States:
thick barriers

t_w = 3.0 nm
t_b = 5.2nm

T_s = 650°C

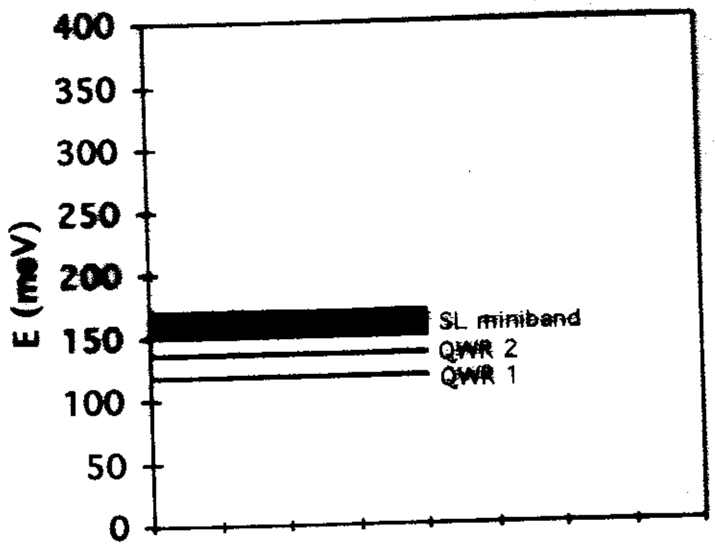


ideally uniform QWR-SL

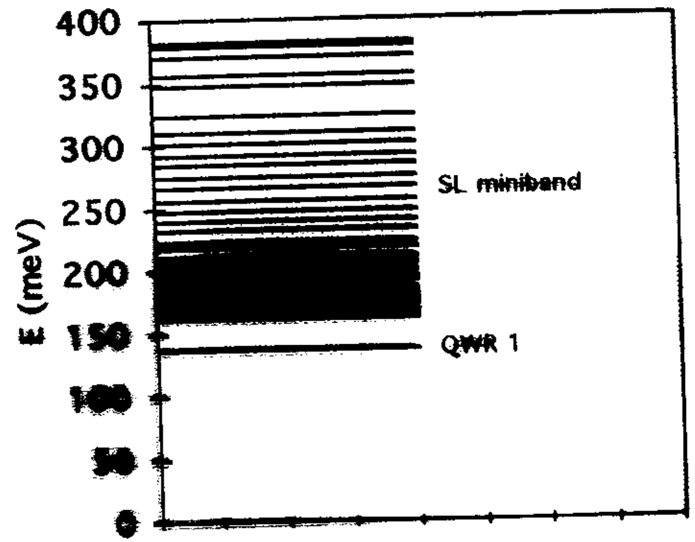


disordered QWR-SL

Calculated QWR-SL Minibands (electrons)

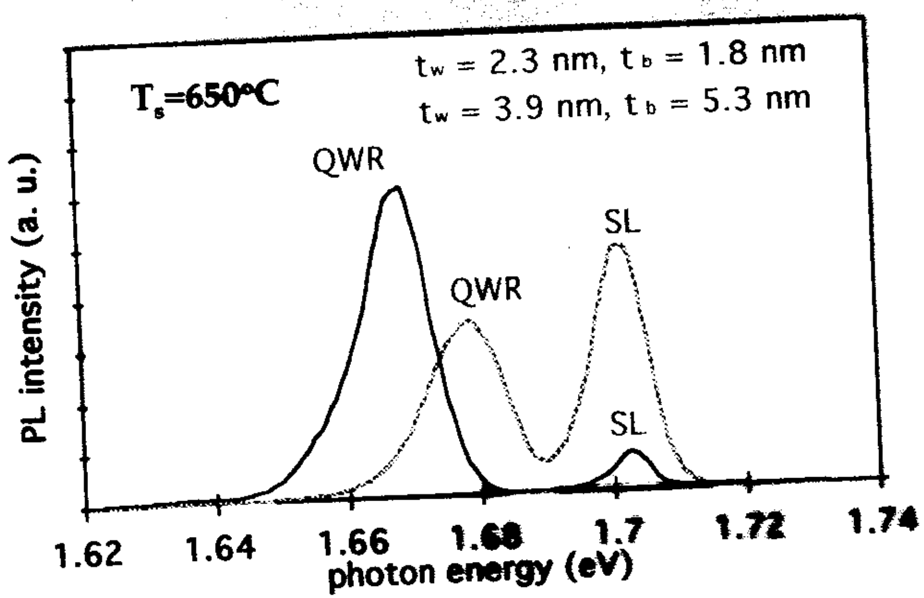


$t_w = 3.9$ nm
$t_b = 5.3$ nm

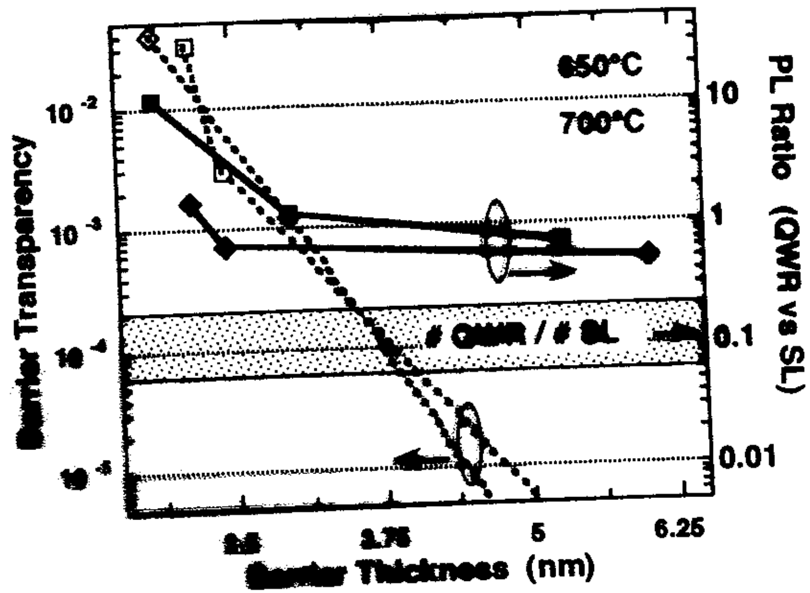


$t_w = 2.3$ nm
$t_b = 1.8$ nm

Photoluminescence Spectra of QWR-SLs

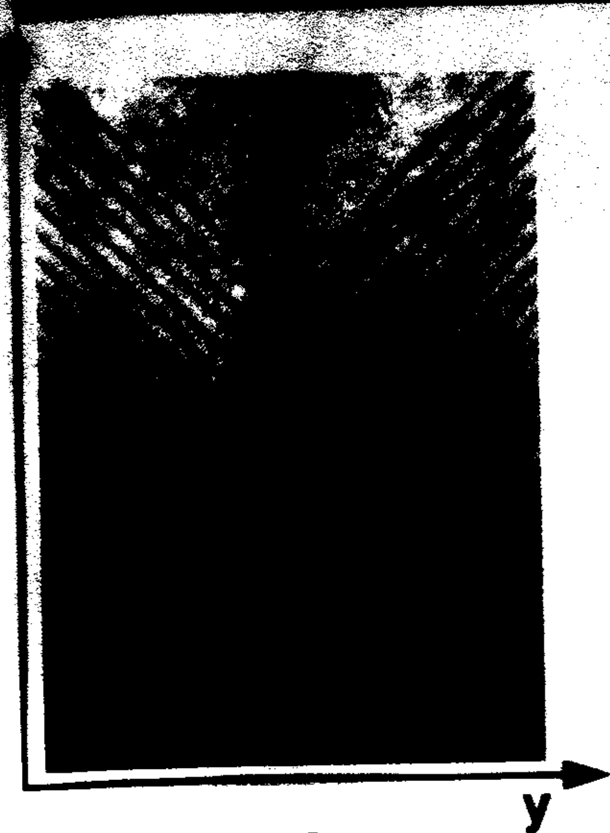


PL Spectra (T=10K)

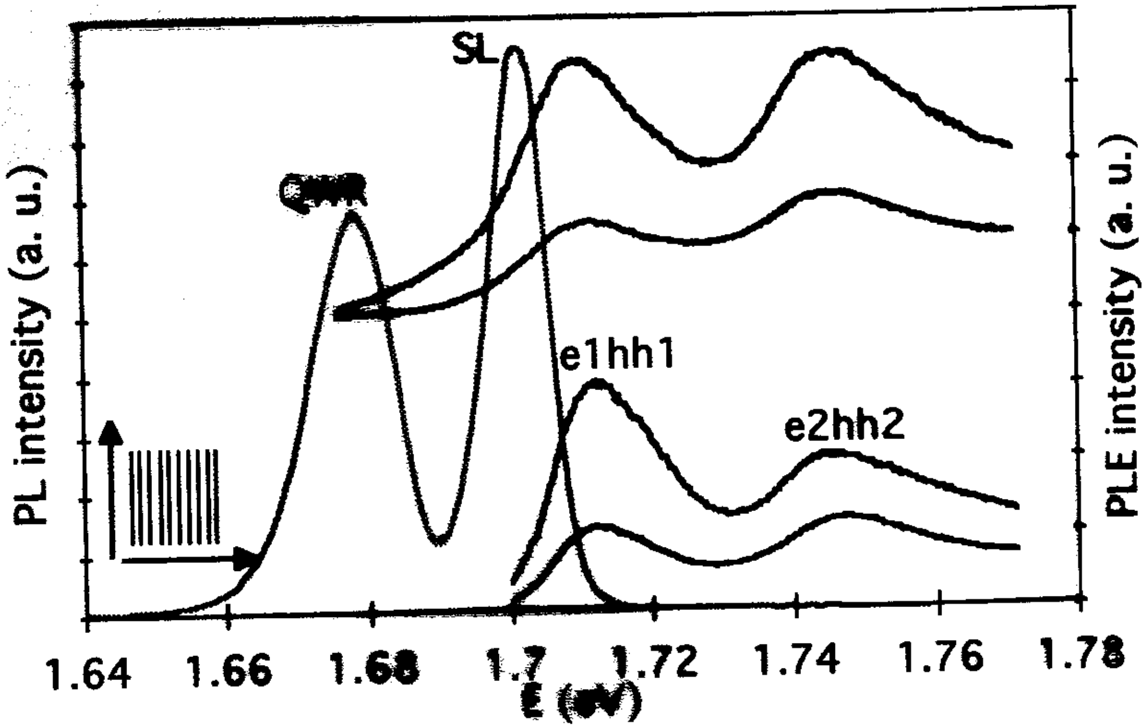


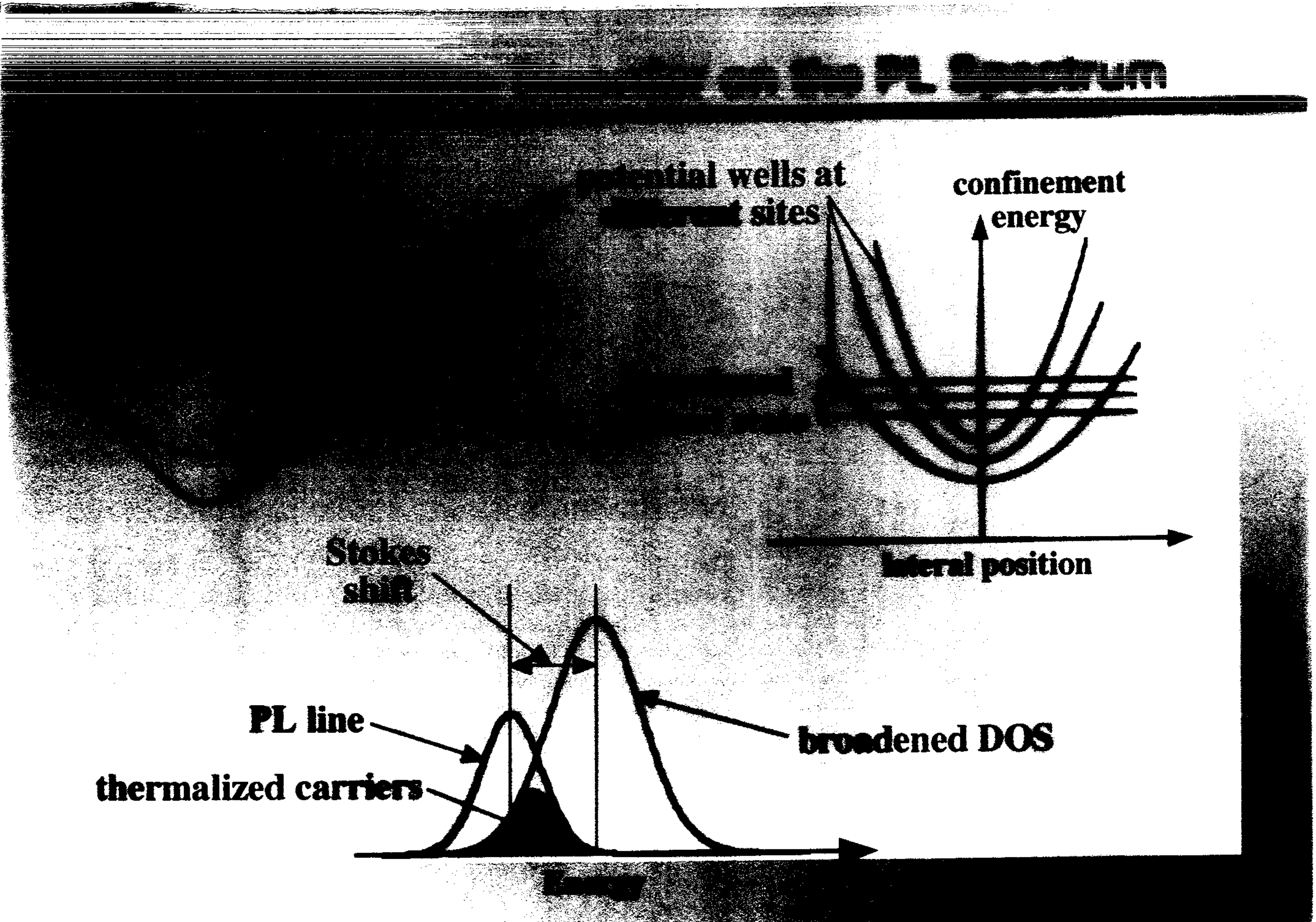
Effect of barrier thickness on QWR/SL intensity ratio

PL-Excitation Spectra of QWR-SLs:

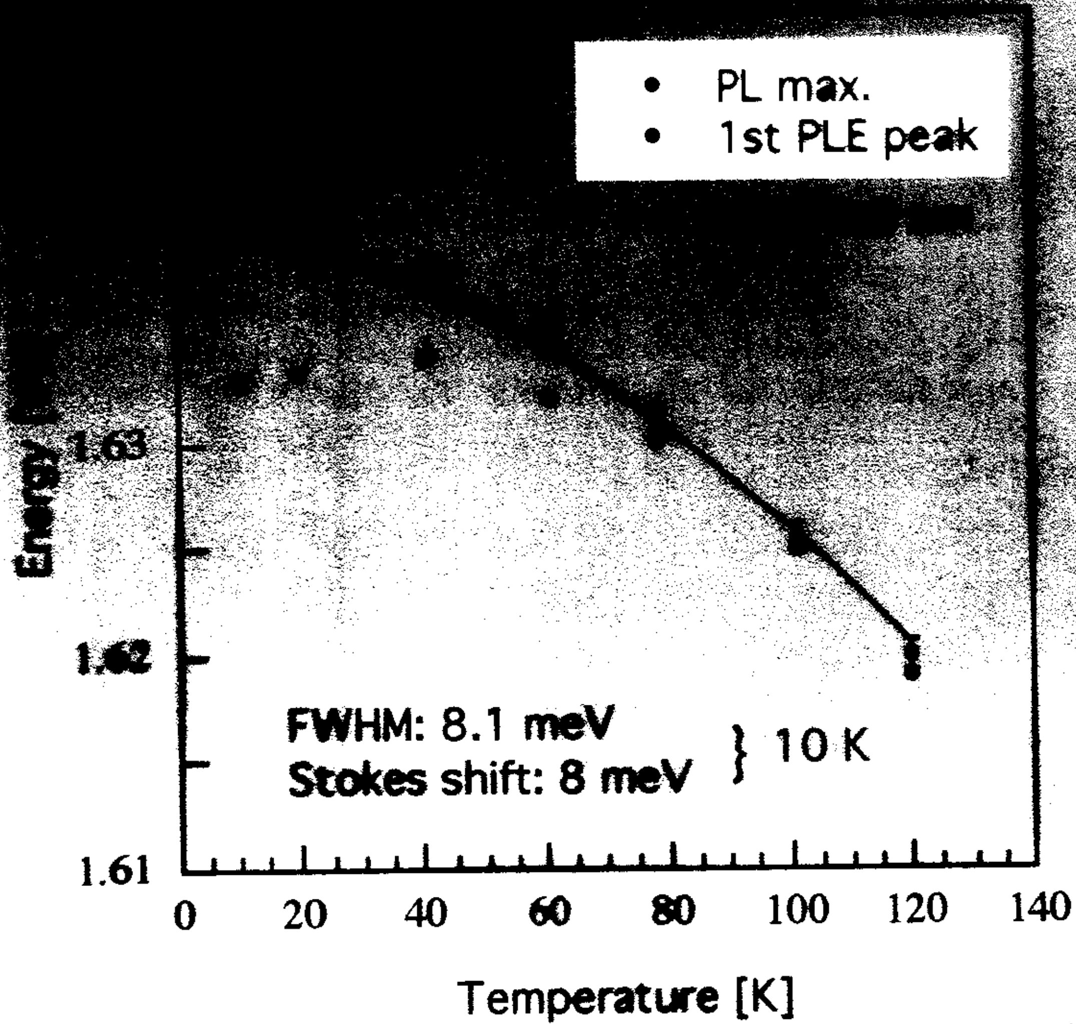


$t_w = 3.9$ nm
$t_b = 5.3$nm
$T_s = 650°C$



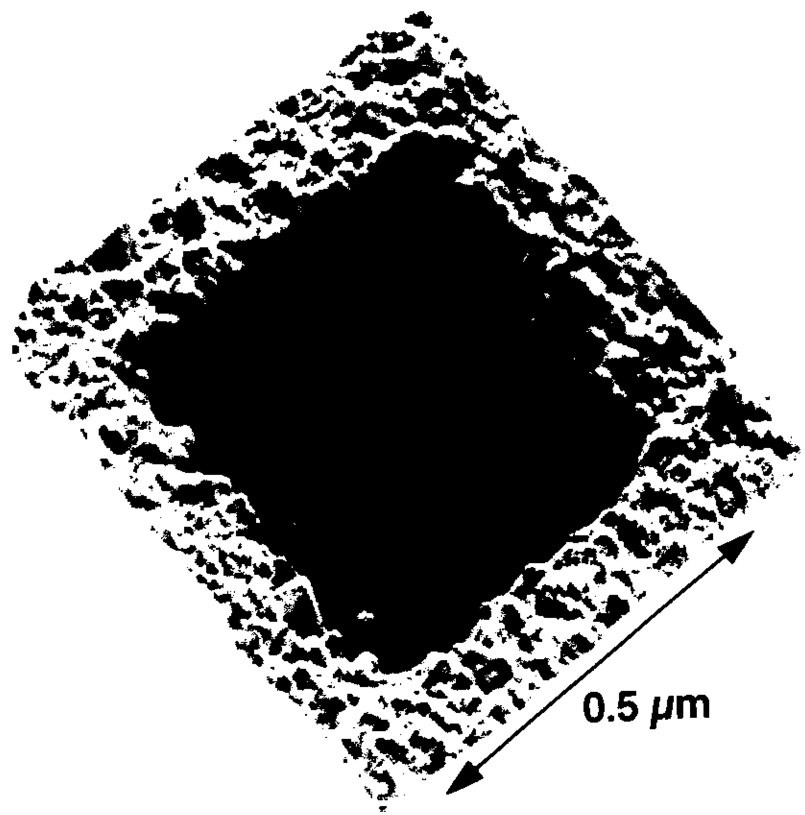

wells at
sites
confinement
energy
position
Stokes
shift
PL line
thermalized carriers
broadened DOS

... V-Groove QWRs



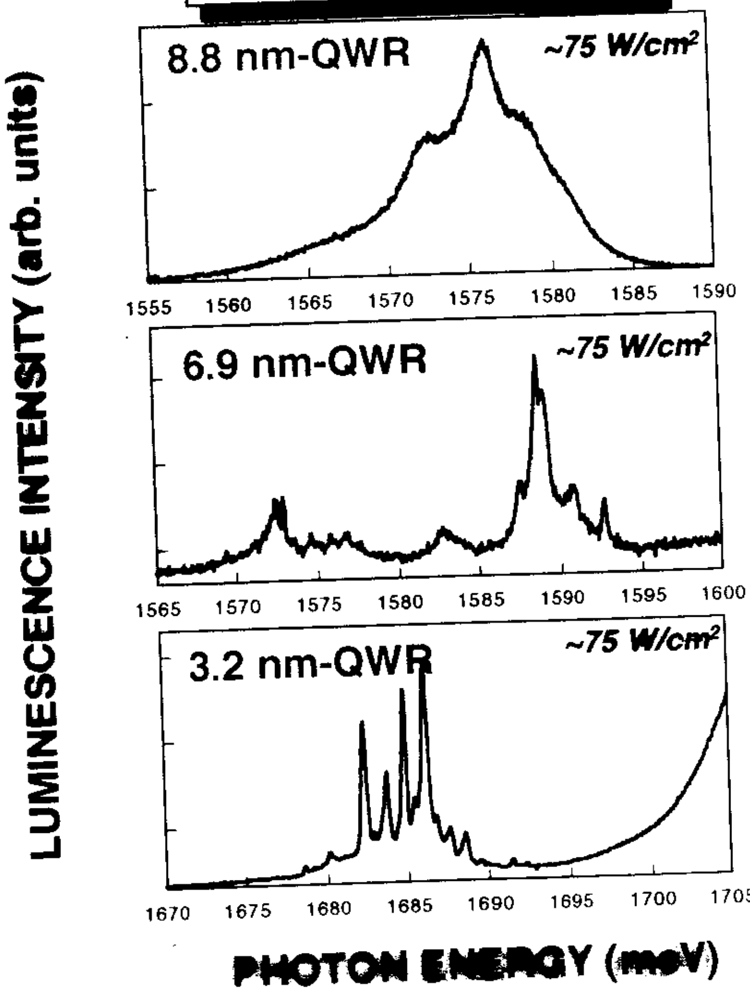
- Stokes shift increases with decreasing wire size at low temperatures
- Stokes shift vanishes at higher temperatures

Apertured Micro-PL Spectra of V-Groove QWRs

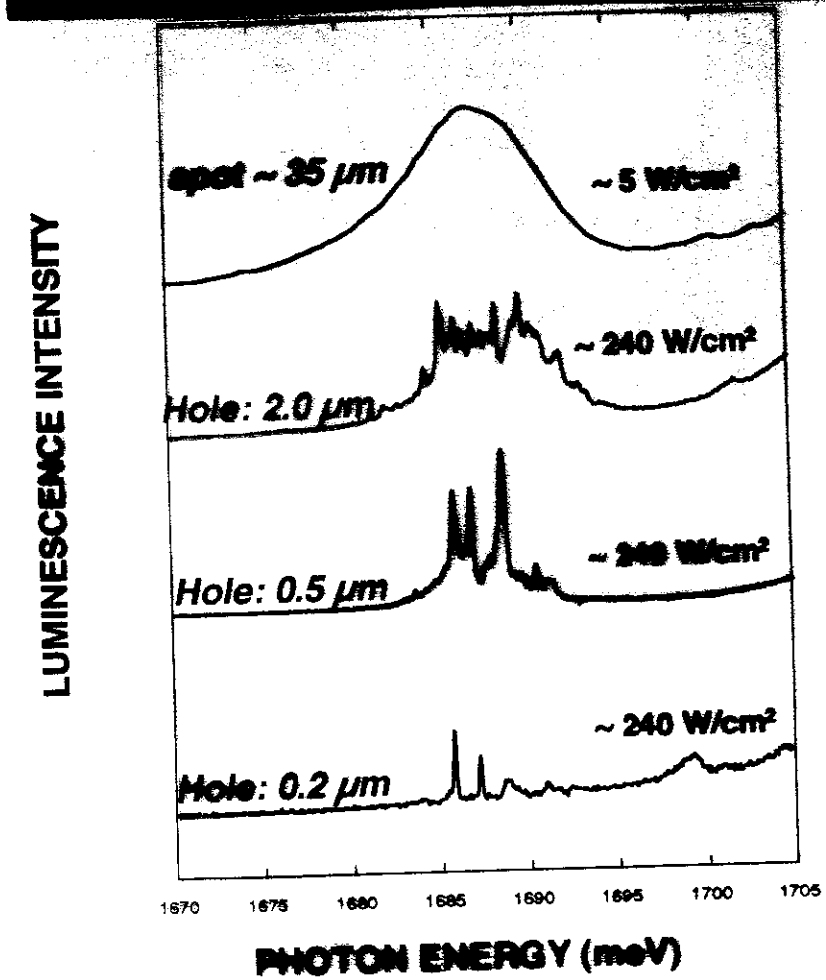


square holes in Al masks

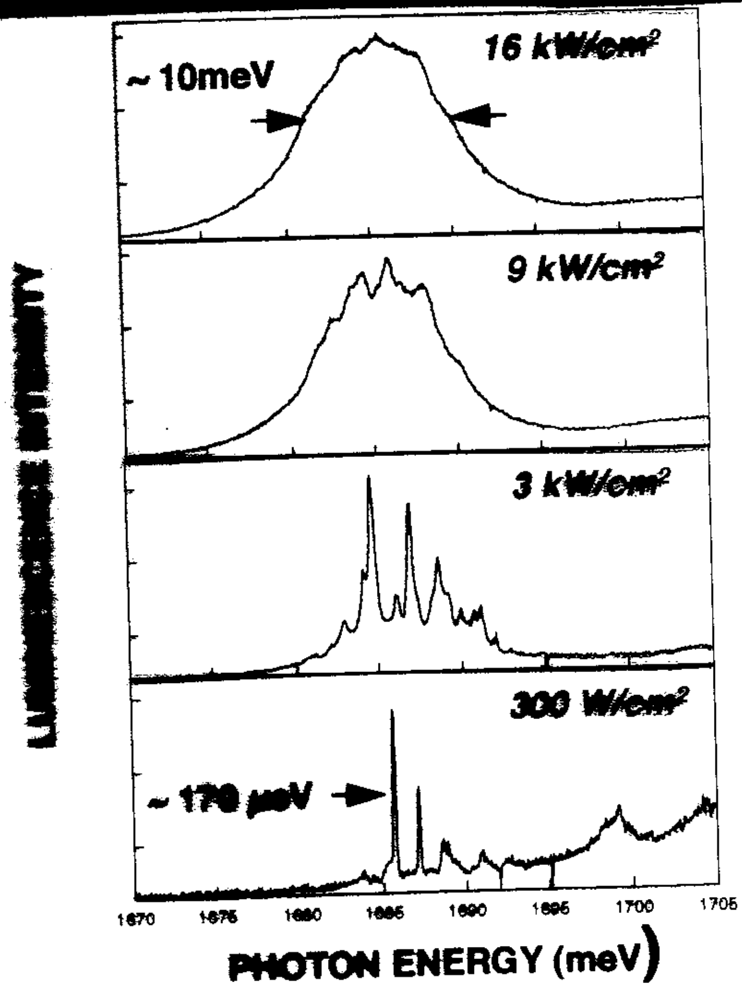
0.5 μm hole; T=8K



Spatially-Resolved PL Spectra of V-Groove QWRs
(3.2-nm QWR; 8K)



versus aperture size



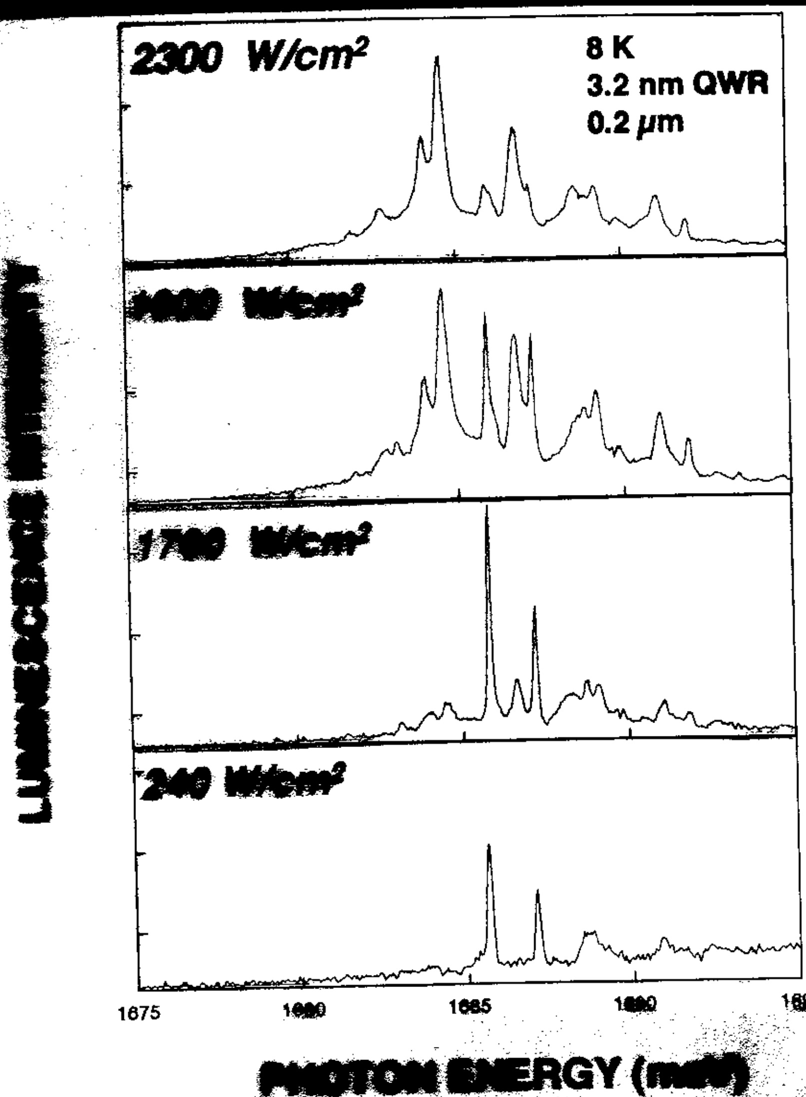
versus power (0.2μm aperture)

1D Localized Exciton Spectra- Density Dependence

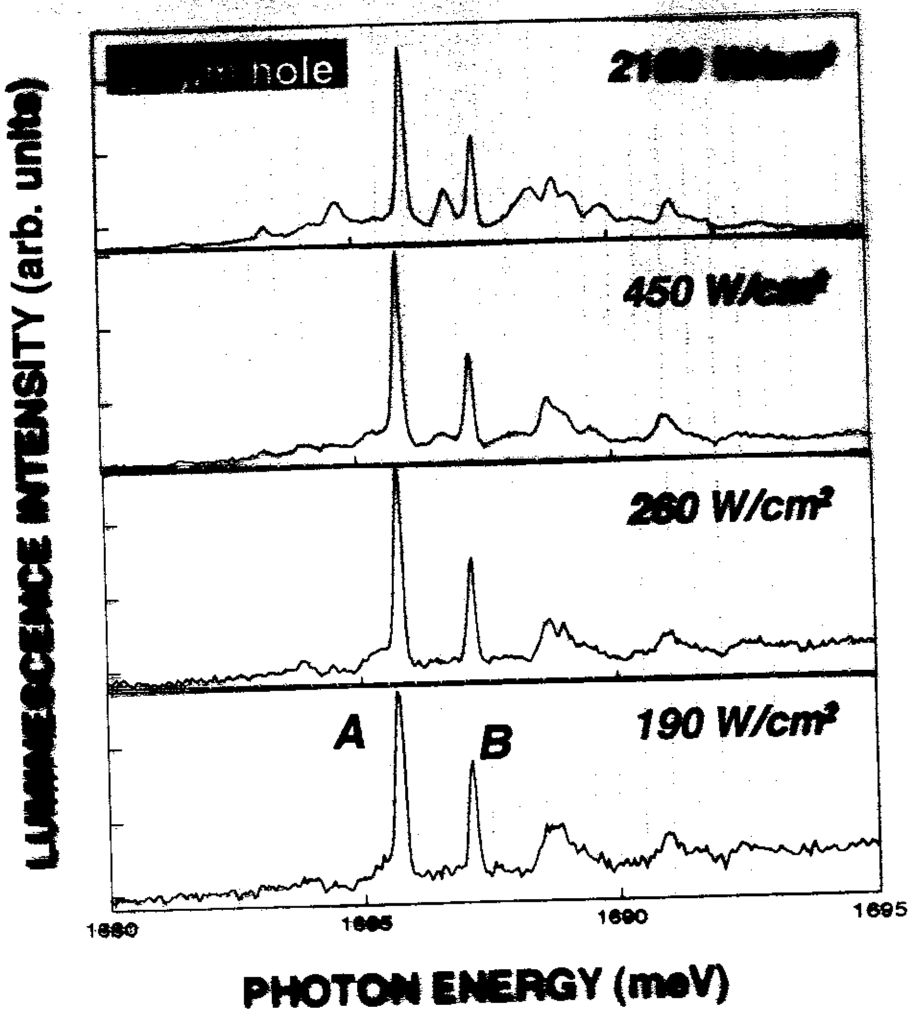
- low density lines saturate
- new lines appear on low energy side
- stronger exciton correlation in 1D

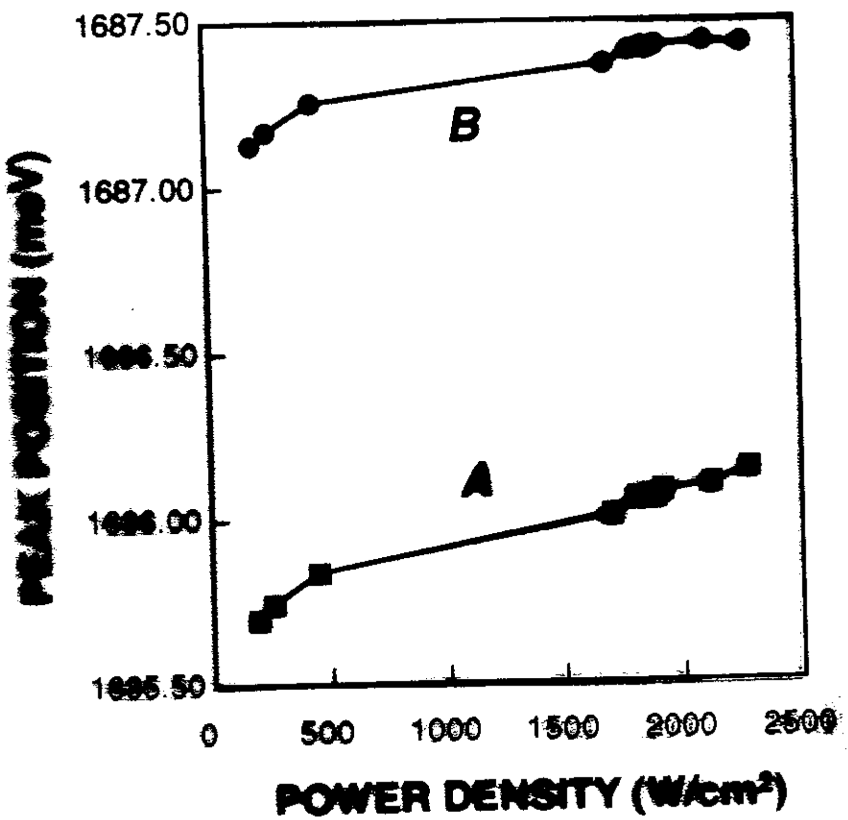
⇨

observation of 1D biexcitons

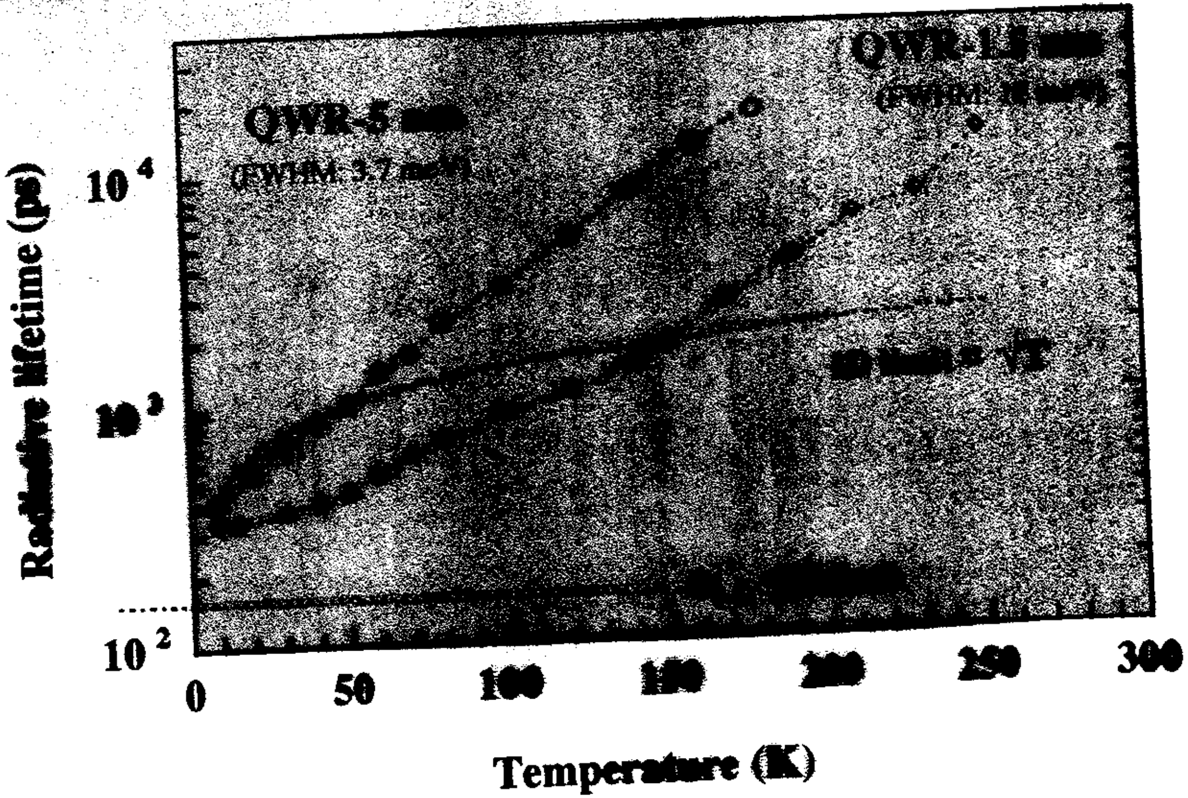


Blue Shift of 1D Excitons at Increasing Densities



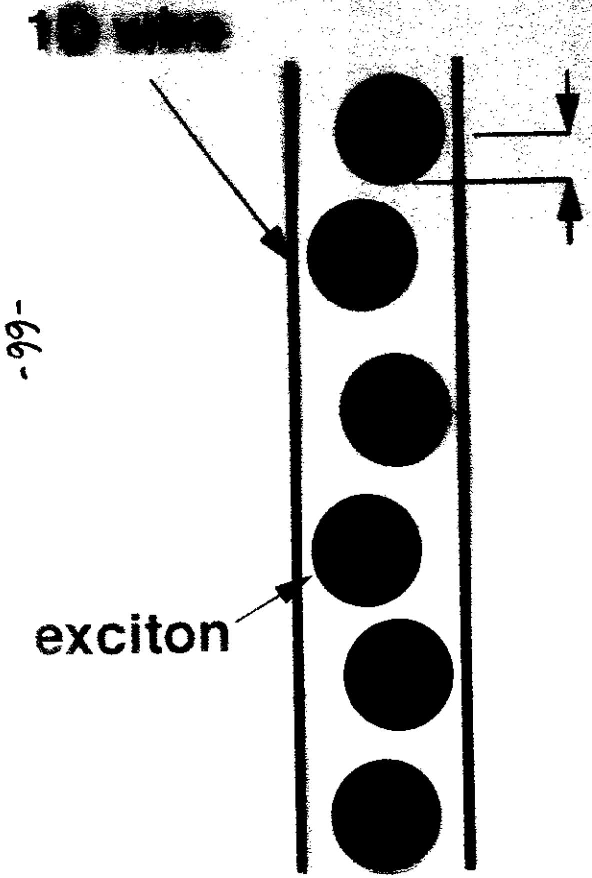


Radiative Lifetime of 1D Excitons- Effect of Localization



- Exponential T-dependence of radiative lifetime observed
- Variation with T increases with decreasing localization effects

Metal-Insulator Transition in a 1D Gas of Excitons

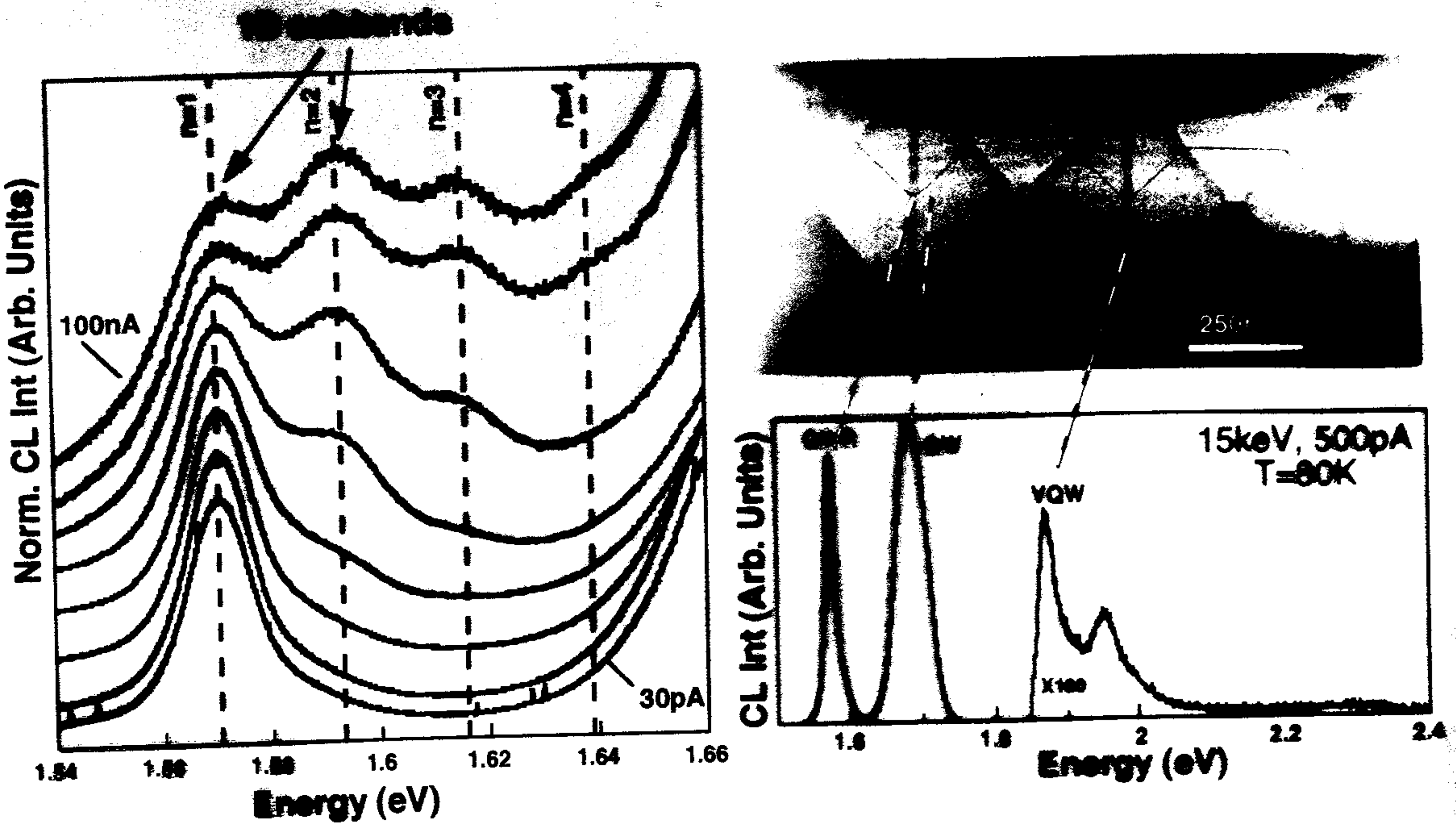


exciton Bohr radius

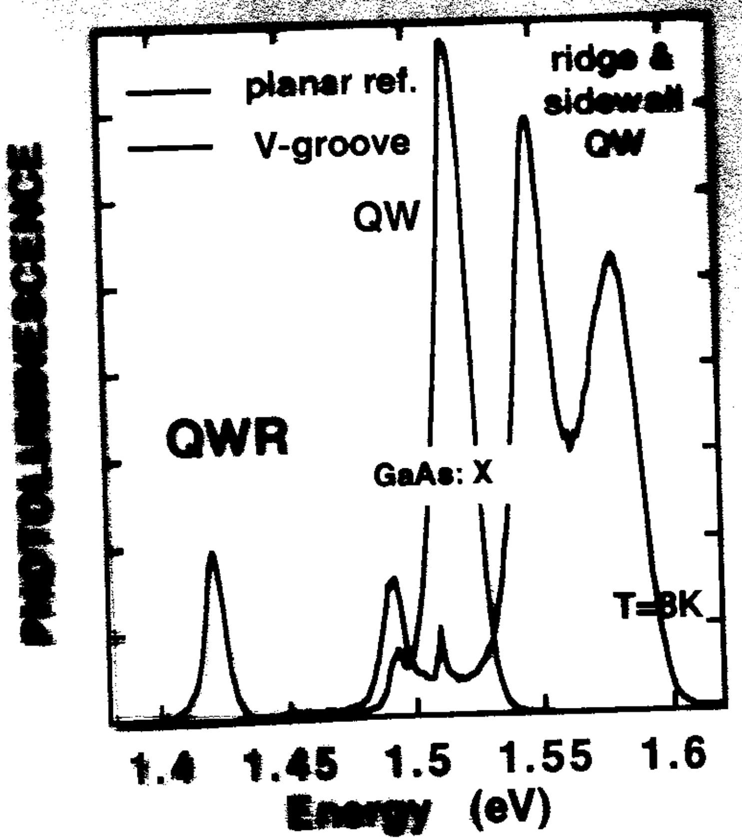
$a_B = \frac{\hbar^2 \varepsilon}{\mu e^2}$ ~10 nm in GaAs/AlGaAs

Mott transition at ~5 10^5 cm^{-1}

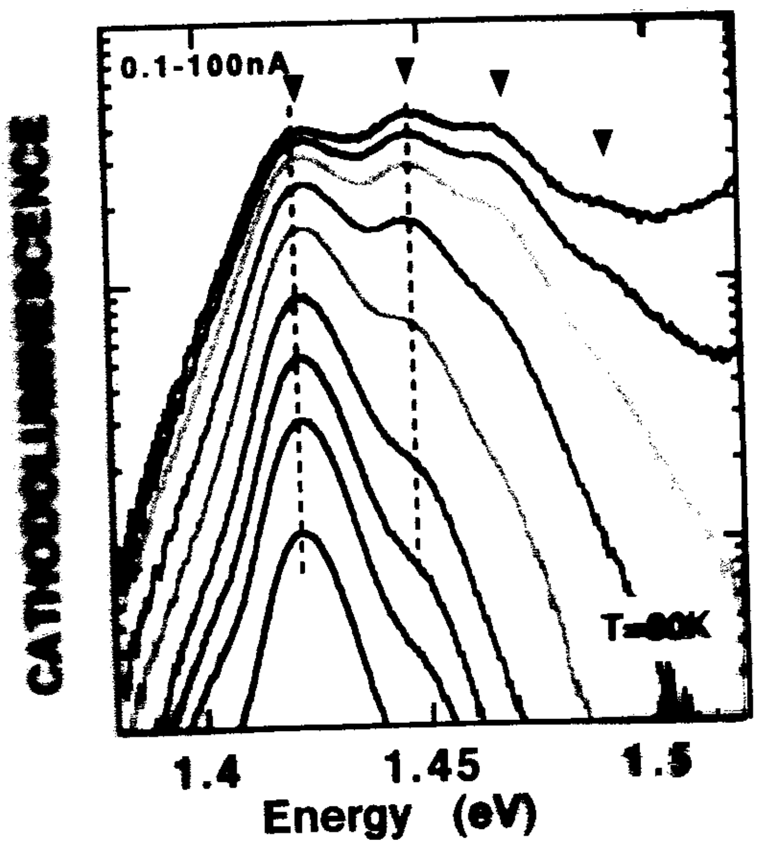
CL Spectra of a V-Groove QWR Array



Luminescence of InGaAs/AlGaAs QWRs



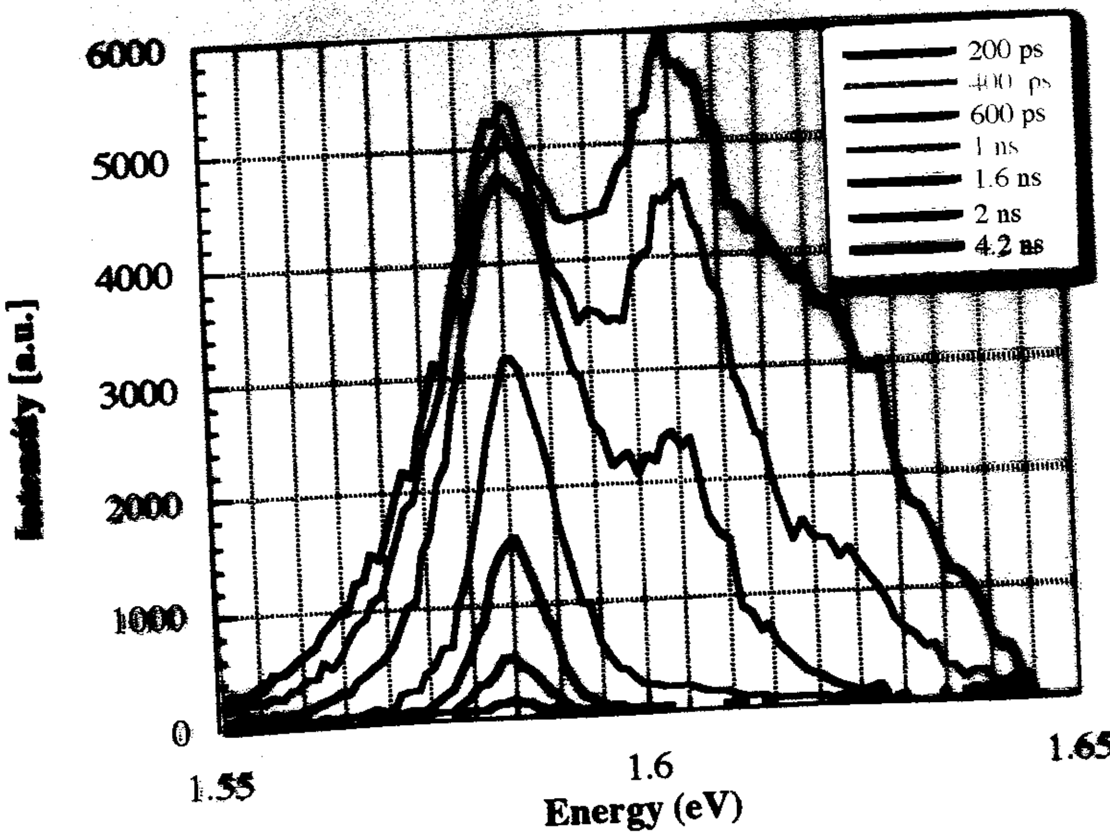
In = 0.16
Al = 0.27



- narrow linewidth (<10meV)
- efficient carrier capture

- 1D-subband filling
- No 1D subband energy shift

Electron-Hole Plasma in 1D Wires



☆ no shift in 1D-subband energies up to ~3 10^6 cm^{-1}

⇨ -radiative recombination dominated by excitons

-Mott transition not observed

-bandgap renormalization <10-15 meV