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SMR.998d - 8

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

"Vertically coupled InGaAs-AlGaAs Quantum Dots: Growth, Characterization, High Power Lasers"

PART I

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

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QUANTUM DOTS: GROWTH, CHARACTERIZATION, HIGH POWER LASERS

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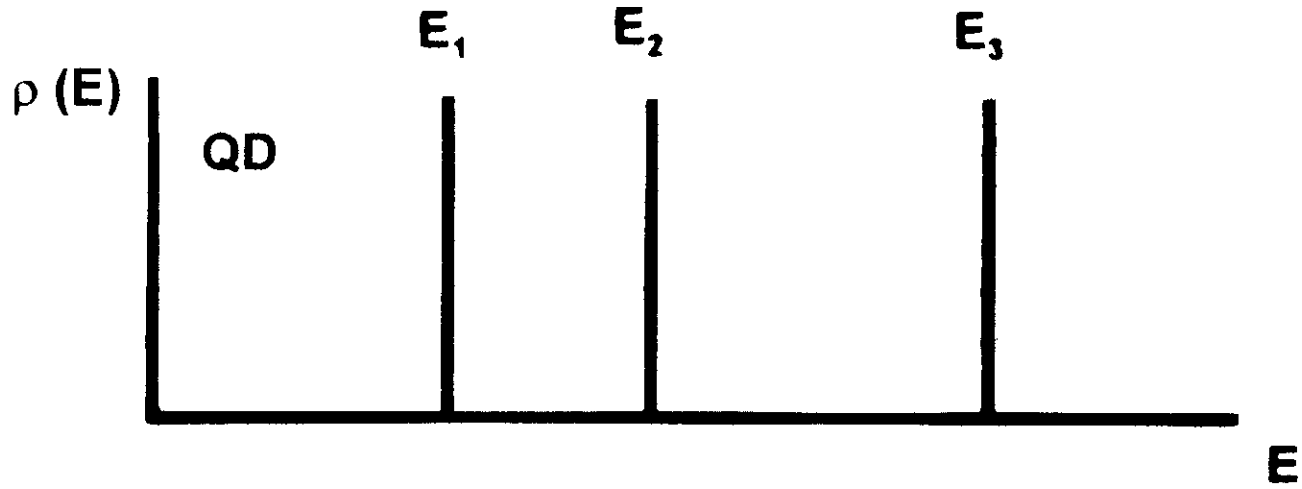
Deutsche Forschungsgemeinschaft (Sfb 296)

Contents:

Basic Advantages of Quantum Dots



ATOM like Energy Spectrum

- δ-function like density of states.

  No thermal broadening.
  No inhomogeneous broadening for single quantum dot

- Giant exciton oscillator strength.
  Ultrahigh material gain.
  Ultrahigh differential gain

- Lifting of *k*-selection rule

- ...

What Kind of Quantum Dots Do We Need?

- **At least one electron level should exist in the QD ($\Delta E_c > E_1^{QW}$)**

[redacted] Dot Size

- **Localization energies for electrons and holes should be larger than 3 kT at RT**

[redacted]ration

- **Energy separation between QD sublevels should be larger than 3 kT at RT:**
  ($kT < E_1^{QW}$)

  d^{QD} must be smaller than 14 nm (GaAs-QDs)
  d^{QD} must be smaller than 20 nm (InAs-QDs)

- **Dislocation free, low concentration of nonradiative recombination centers (direct growth methods)**

[redacted] efficiency

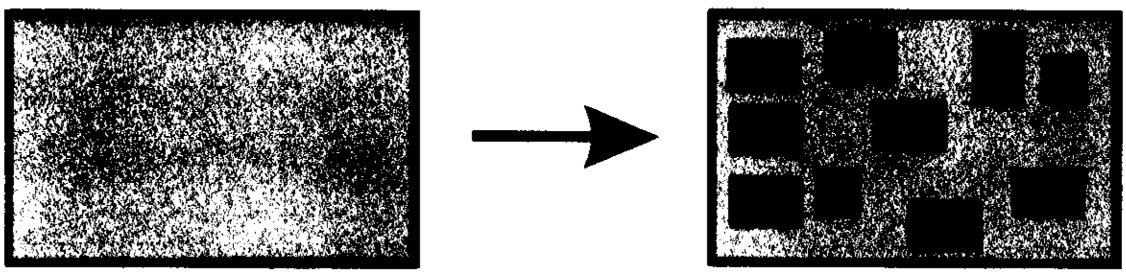
- **Uniformity in shape and in size. Dense arrays.**

[redacted] for lasers

Selforganization of Quantum Wires and Dots

Nanofaceting

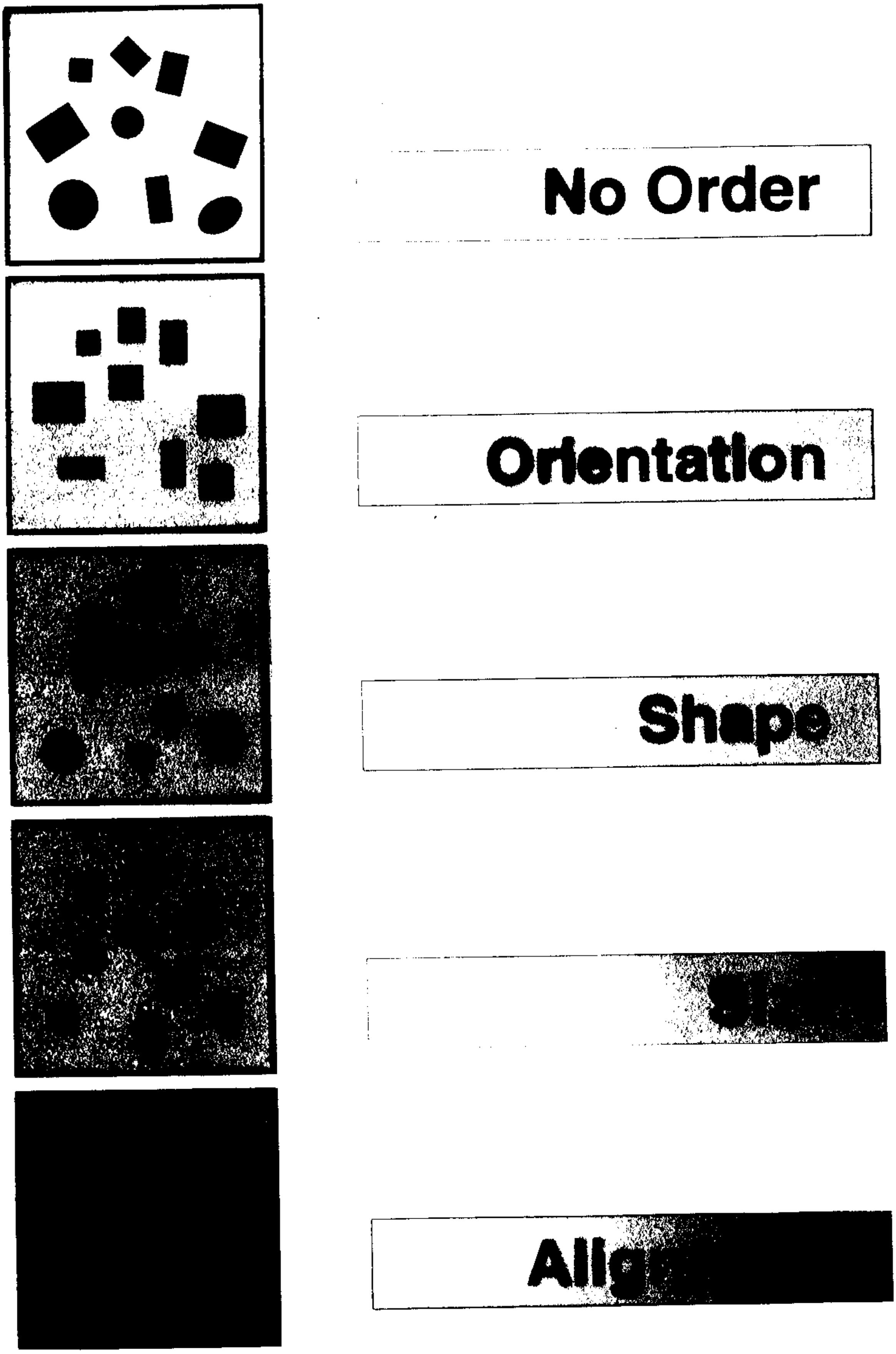
Alloy decomposition during growth



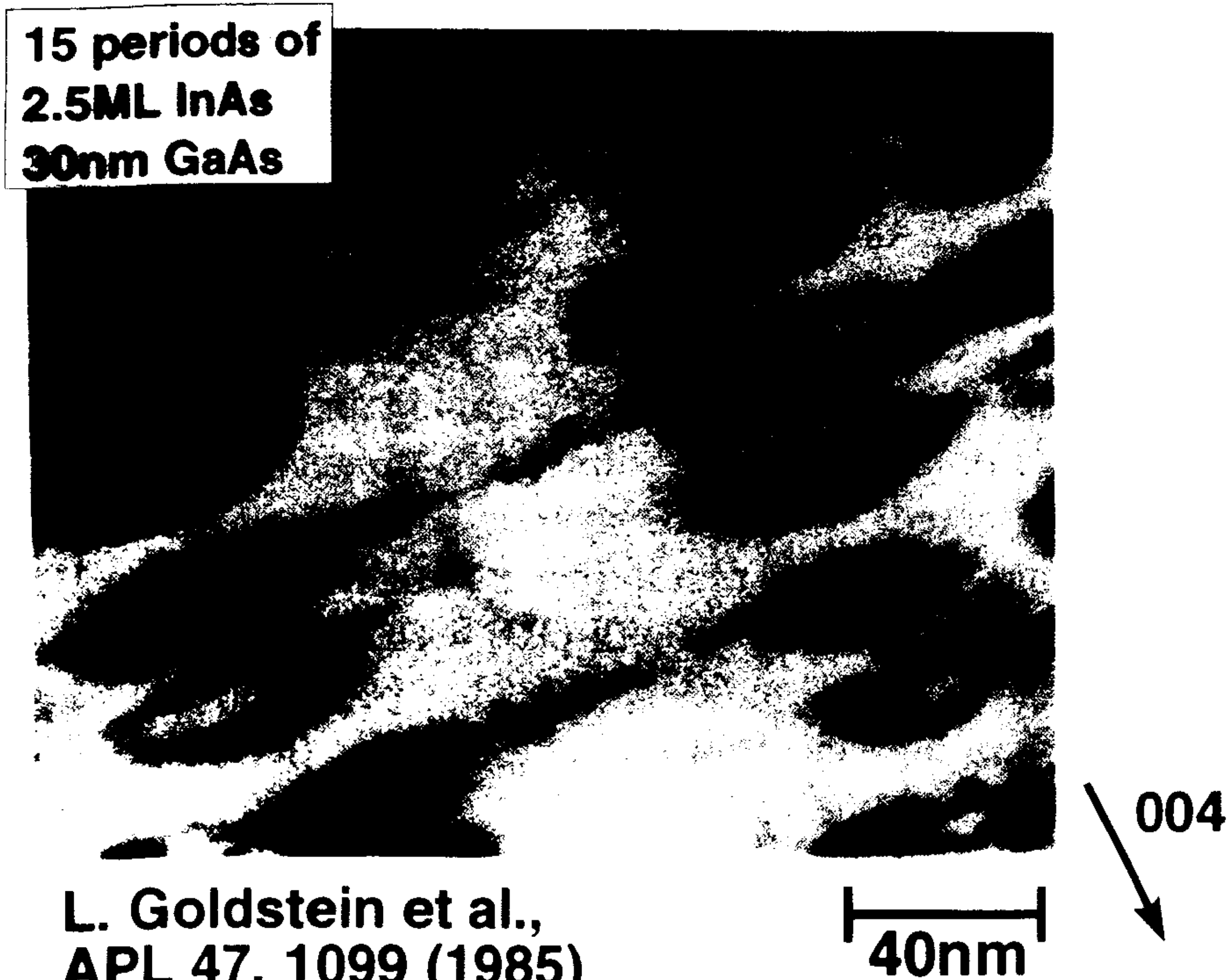
Alloy decomposition during annealing

Islanding

Hierarchy of Ordering



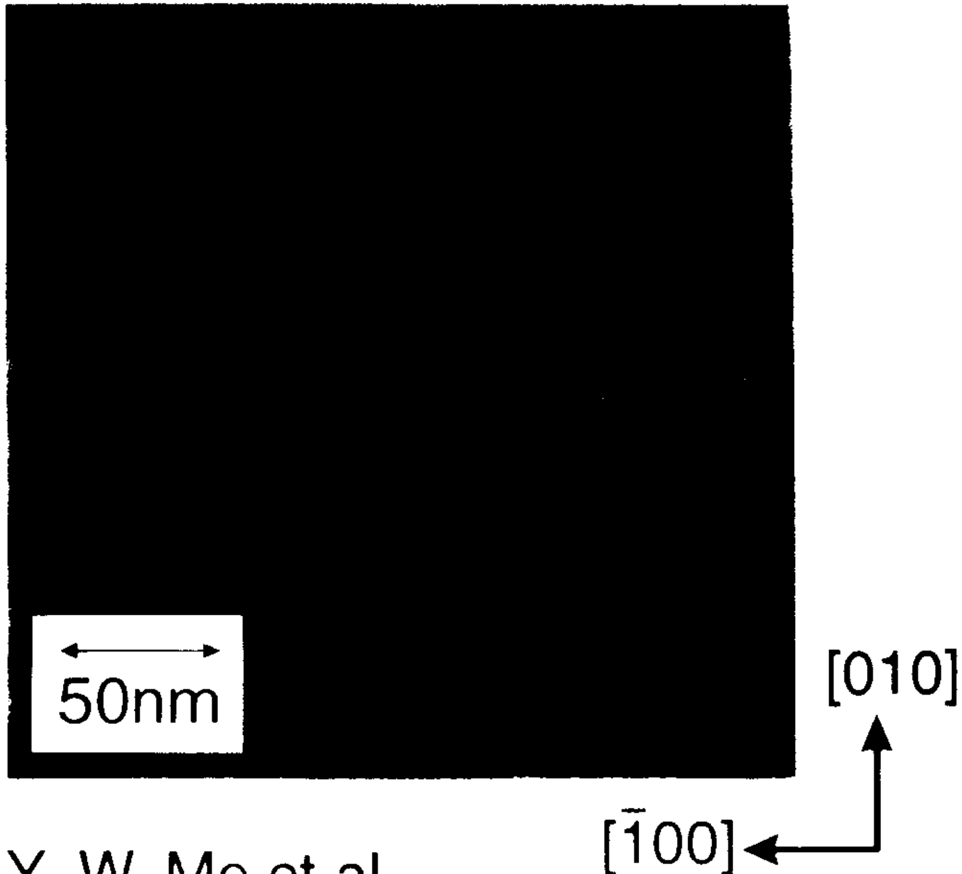
1985: First Observation of InAs/GaAs Islands and Vertical Ordering



L. Goldstein et al.,
APL 47, 1099 (1985)

"These kind of structures are thus proved to be of interest to study low-dimensional (<2) objects showing good optical properties"

1990: Rectangular Ge "Hut" Clusters on Si(001)

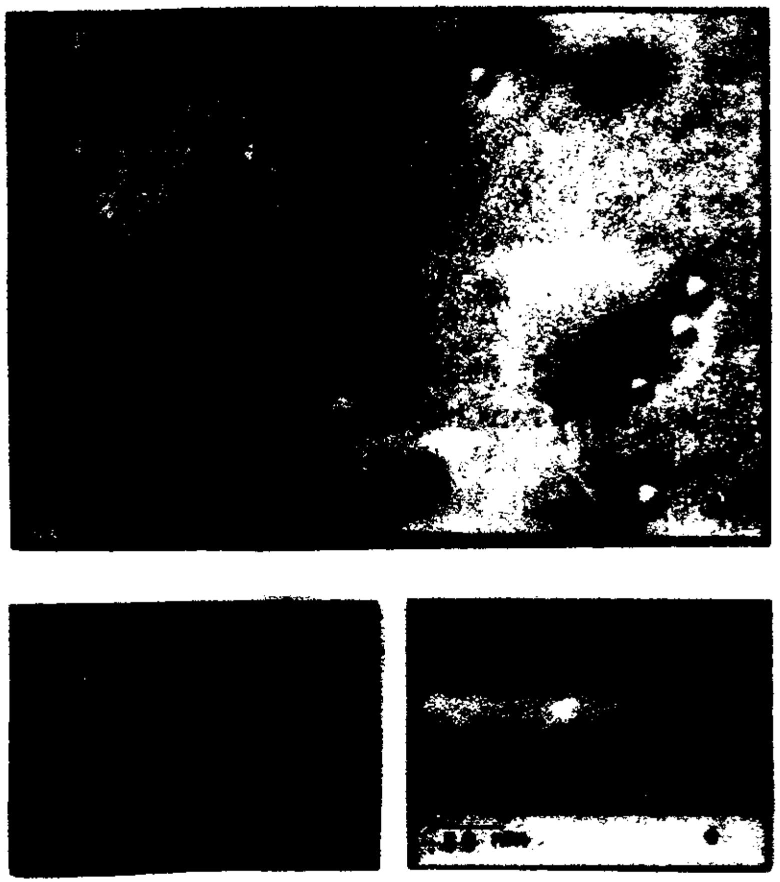


Y.-W. Mo et al.
PRL 65, 1020 (1990)

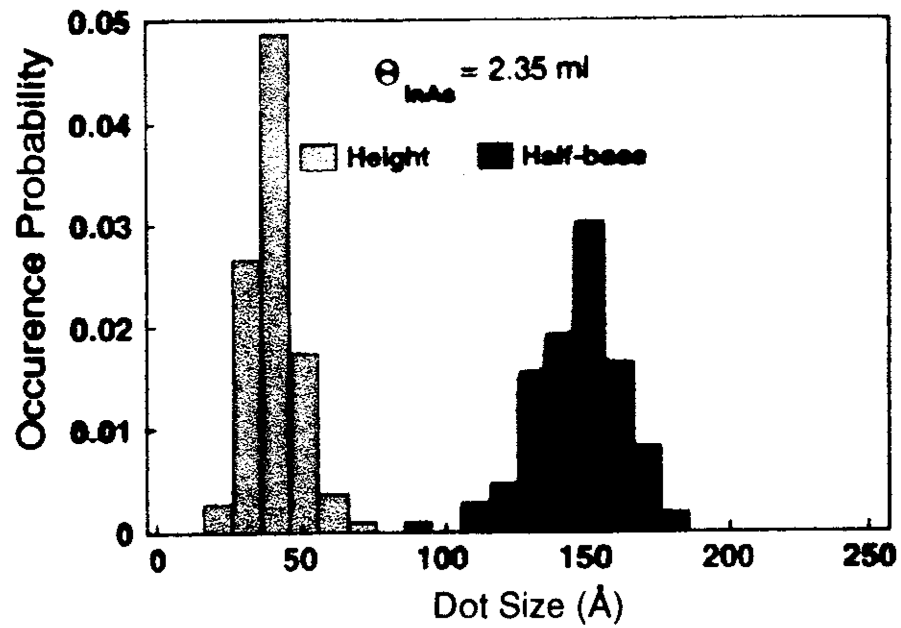
- No size ordering
- No shape ordering

1993/4: Self-ordered InAs/GaAs Quantum Dots

- Size ordering
- Shape ordering



D. Leonard et al.
APL 63, 3203 (1993)

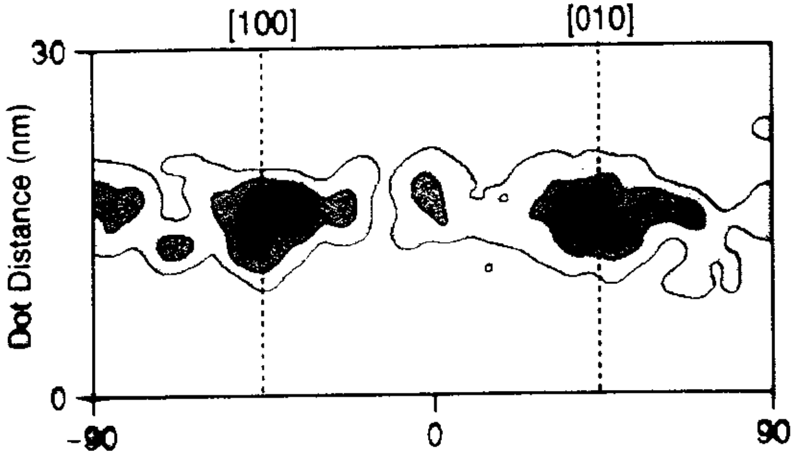


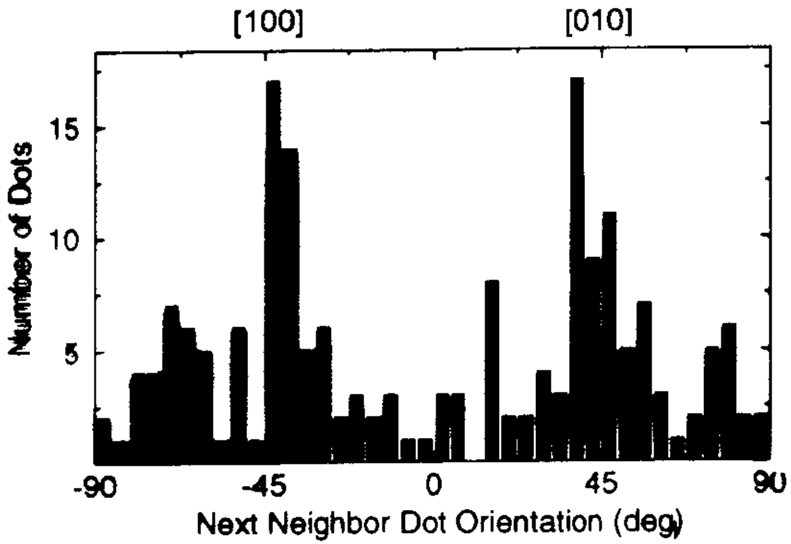
J.M. Moison et al.
APL 64, 197 (1994)

Lateral Ordering of Quantum Dots in a 2D Square Lattice

plan-view TEM

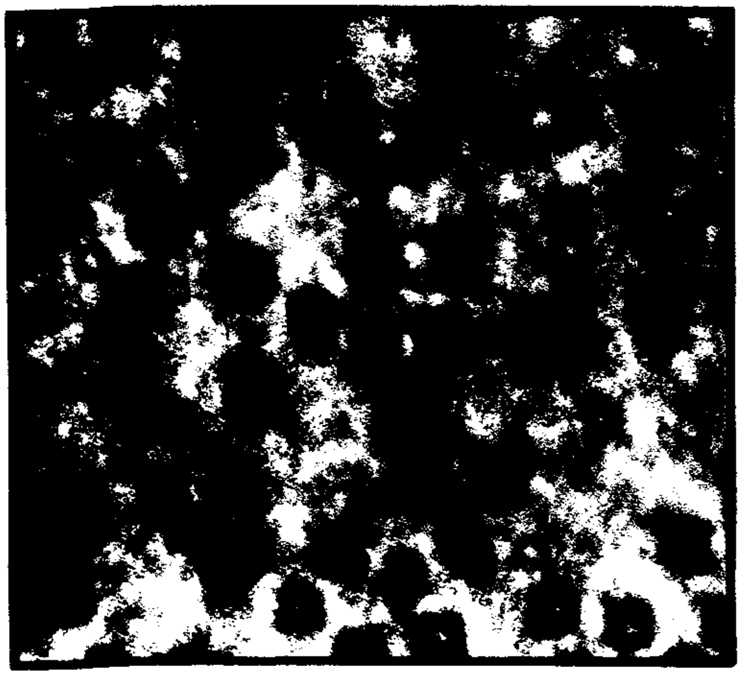
Statistical Evaluation





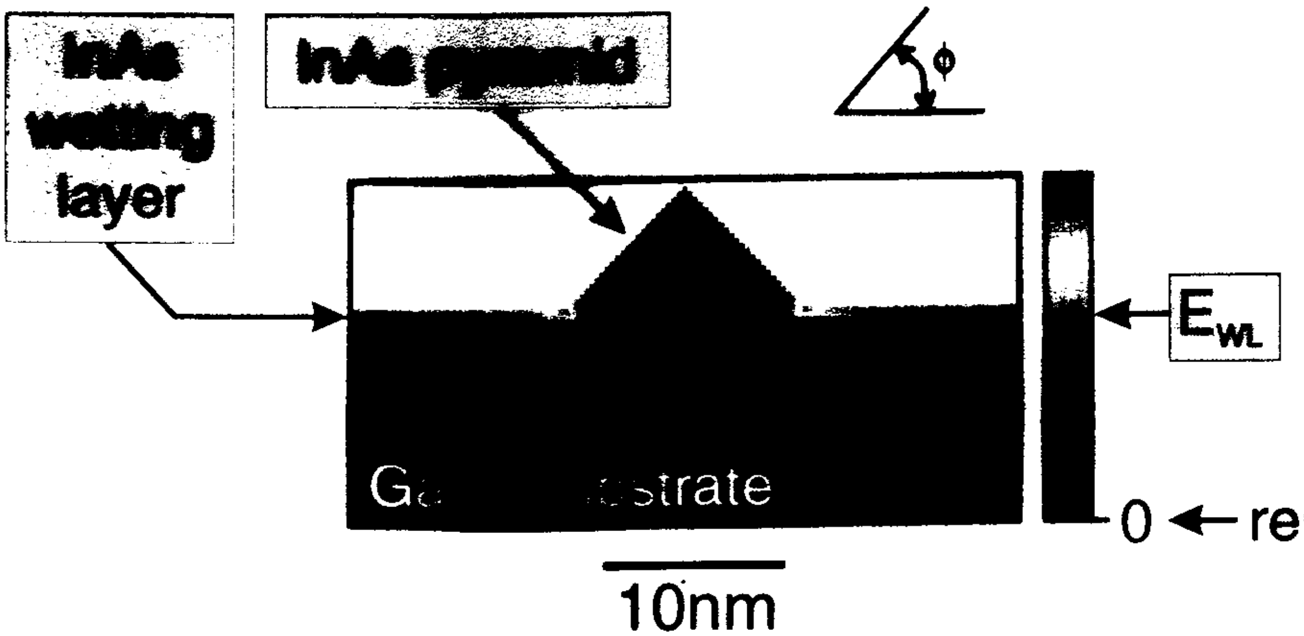
Self-organized Growth of Quantum Dots

Plan view TEM of ordered array of InAs/GaAs quantum dots grown using MBE



- Why do 3D objects of similar size and shape develop ?
- What is their shape?
- Why are they ordered ?
- What are the optimal growth conditions ?

Relaxation of Elastic Energy



$\phi=45^\circ$: $\Delta E = -60\%\ E_{WL}$

$\phi=5^\circ$: $\Delta E = -8\%\ E_{WL}$

- Top of pyramid is strain free

M. Grundmann, V.A. Shchukin, 1995

Energetics of 3D Islanding

Energy Decrease due to the Island Elastic Relaxation ($-\Delta E_v$)

and

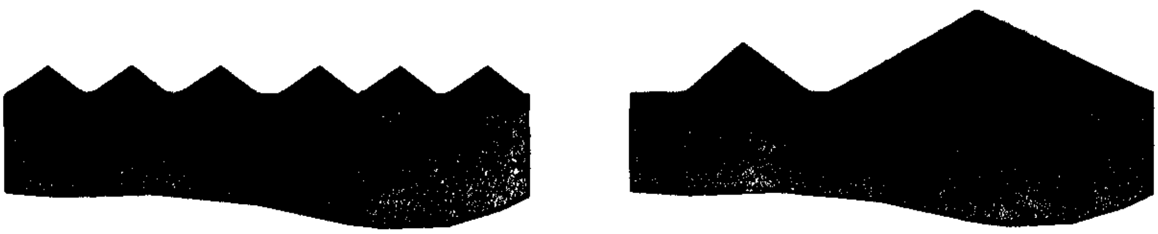
Increase in Surface Area

Change of surface energy ΔE_s

Positive and large

Critical island size ($\Delta E_v > \Delta E_s$) is large
Dislocations are formed before islands appear

Positive and small



Islands of critical size appear and undergo ripening

Negative

At some size ripening is energetically unfavorable

Strain-induced Renormalization of Surface Energy

Concept of intrinsic surface strain (ε^{INT})

V.I. Marchenko, A.Ya. Parshin, 1980

1/2 λ $(\varepsilon^{INT})^2$ — surface — **1/2 λ $(\varepsilon + \varepsilon^{INT})^2$**

strained film ε

Change of surface energy per unit area

$$\Delta E_{SURFACE} = -\tau\varepsilon + S\varepsilon^2$$

Intrinsic surface stress (τ) can be positive or negative (~100 meV / Å^2)

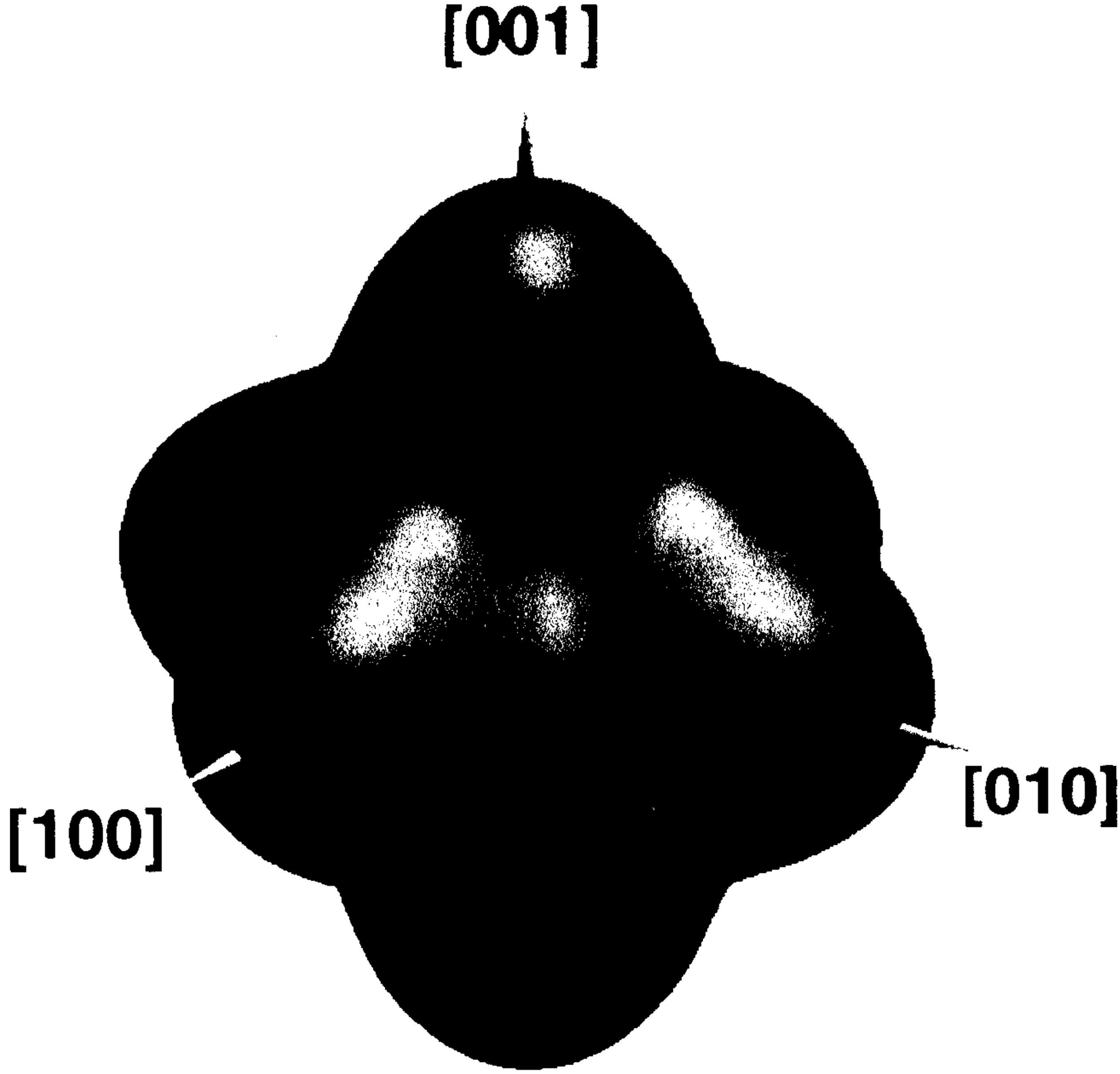
[illegible] (~3000 - [illegible])

Surface energy of a strained wetting layer can be larger than that of the relaxed island

Coverage of surface with islands of optimal size, no ripening

Anisotropy of Young's Modulus in GaAs

$$\varepsilon_{\vec{n}\vec{n}} = \frac{1}{Y(\vec{n})}\sigma_{\vec{n}\vec{n}}$$



Kinetically Limited and Equilibrium Size Islands

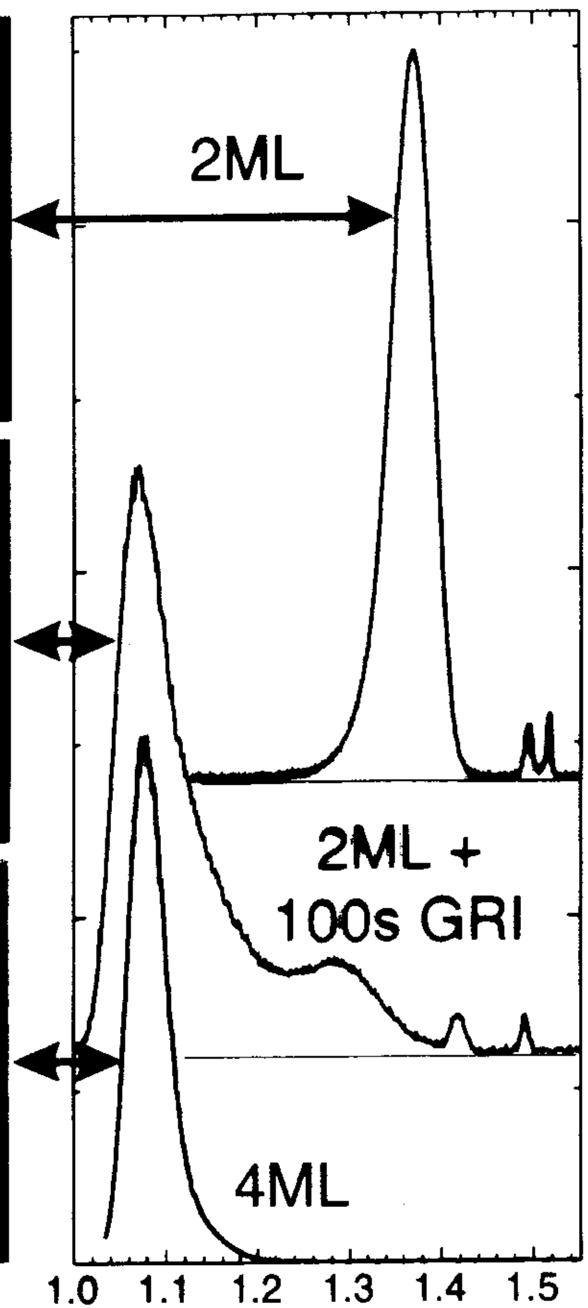
Kinetically Limited Quantum Dot Size

100s Growth Interruption

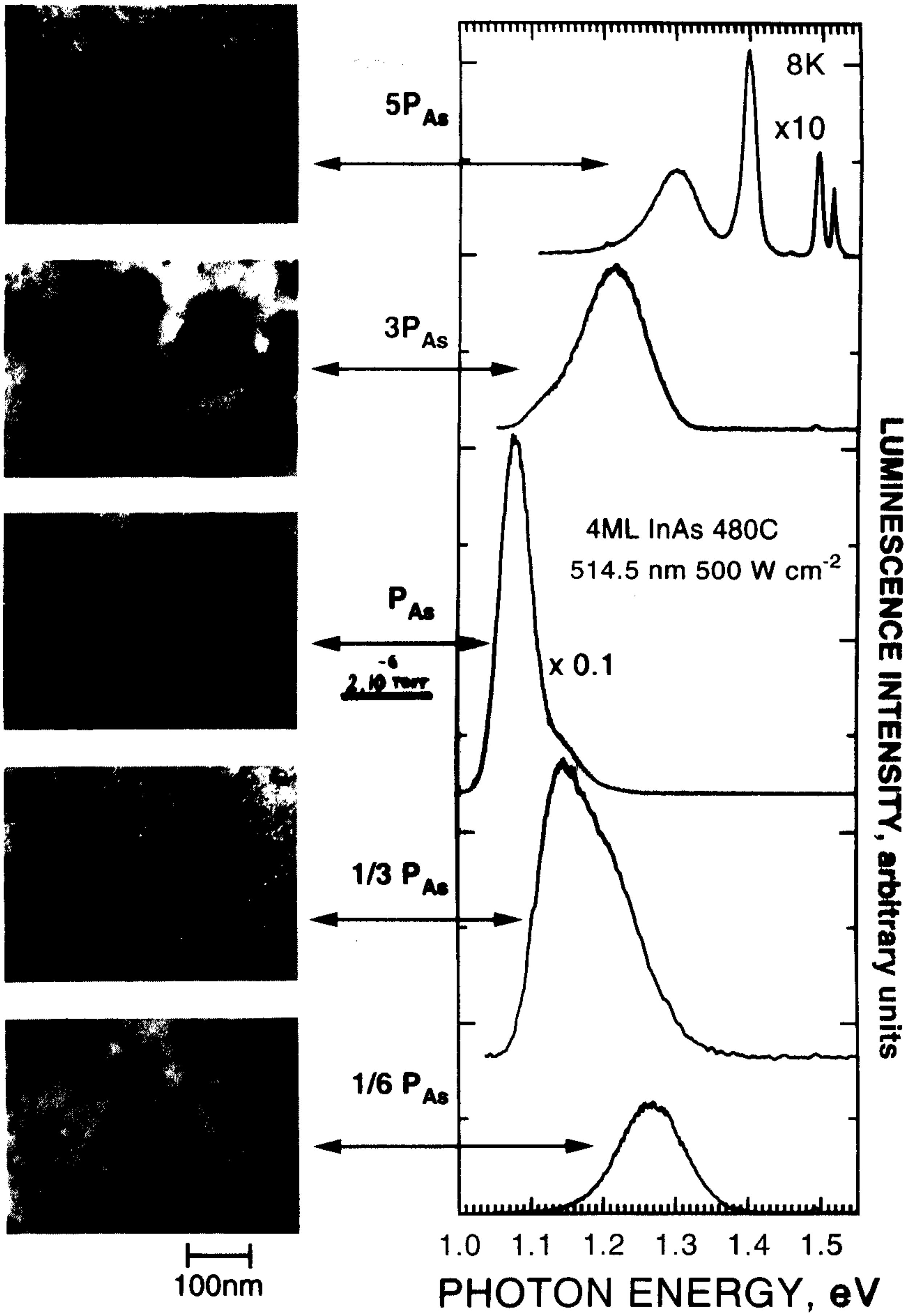
Formation of 12nm Size Pyramids

Equilibrium Dot Size

Formation of 12nm Size Pyramids

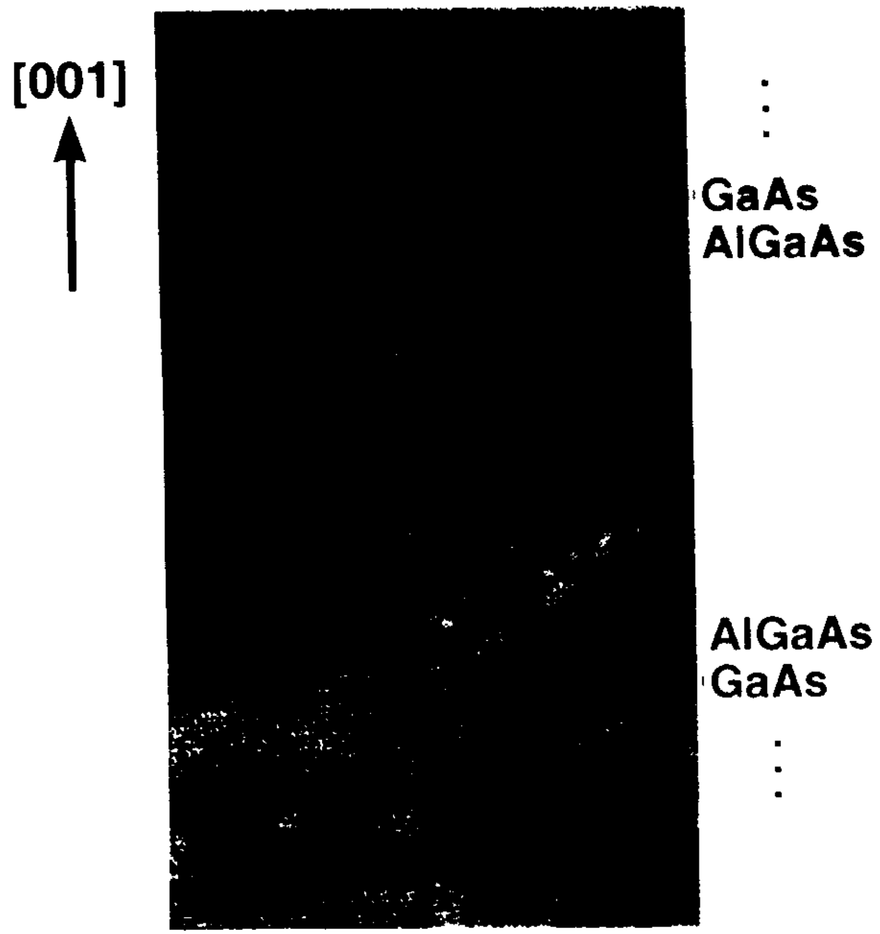


Arsenic Pressure Dependence of Dot Formation

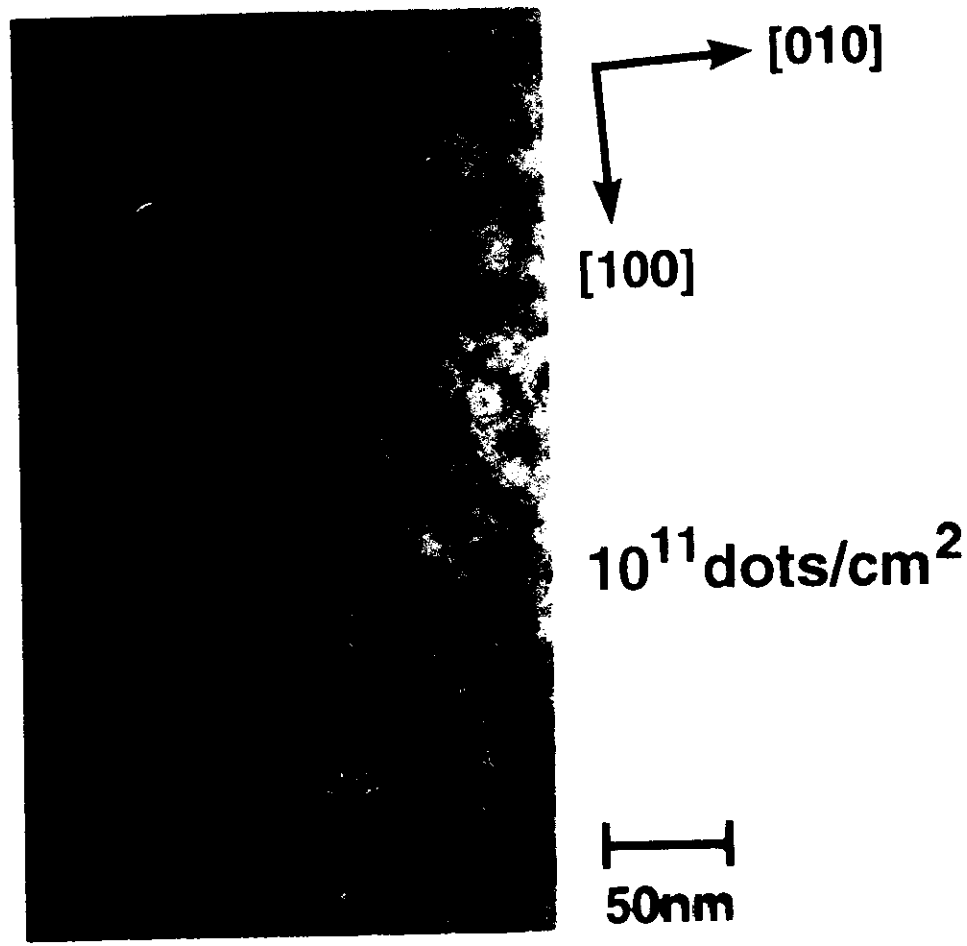


Transmission Electron Microscopy of InAs/GaAs Quantum Pyramids

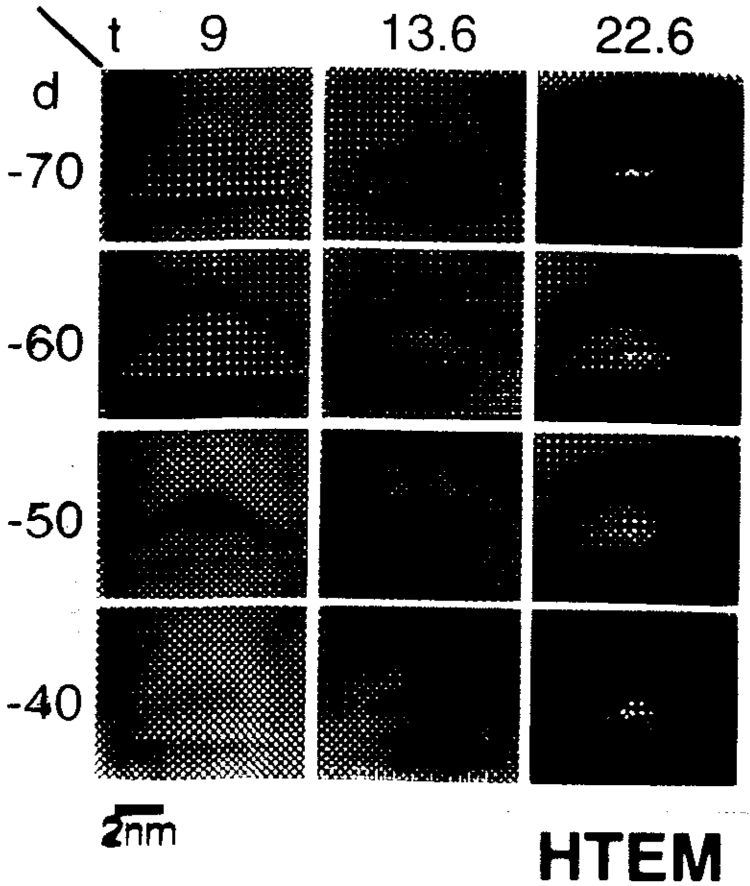
Cross section

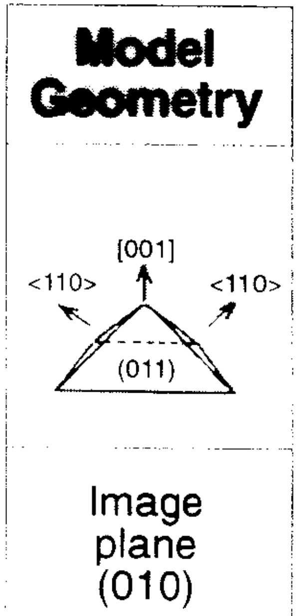


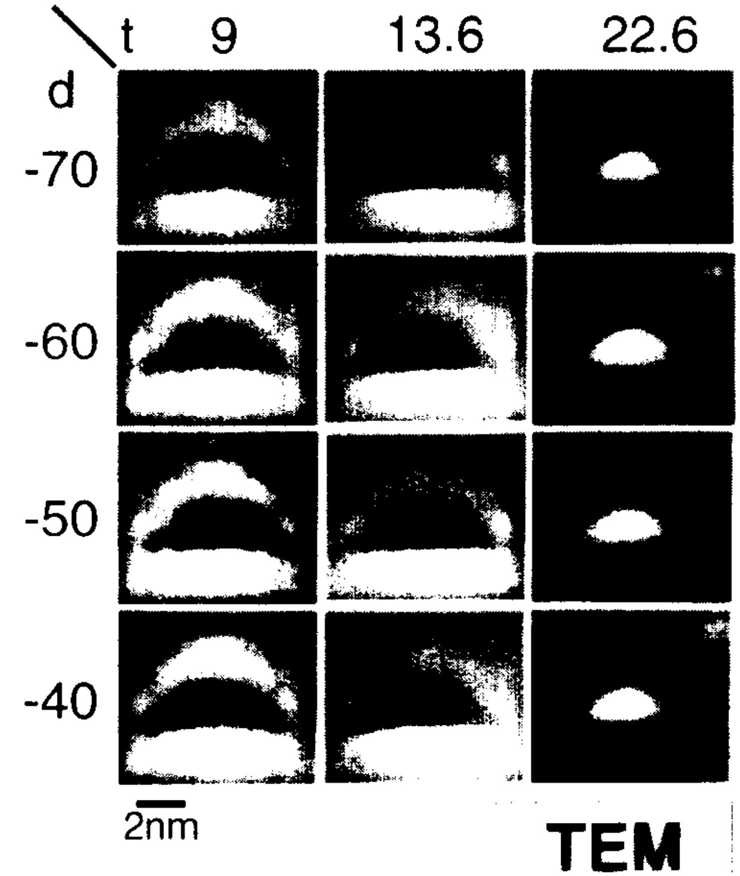
Plan view



Simulation of TEM of InAs/GaAs Pyramid





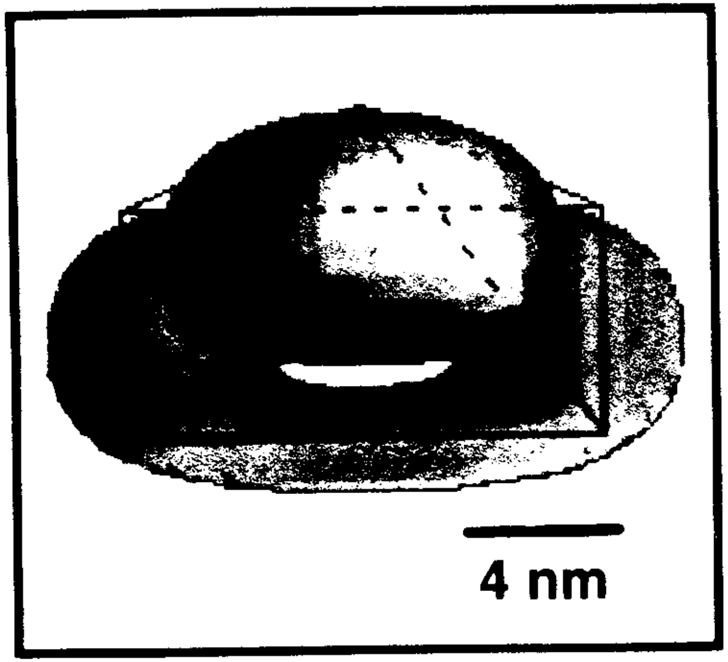


- depends strongly on foil thickness and defocus
- optimal defocus (d=-60nm at t=9nm) reveals true shape

- almost no dependence on defocus
- height is underestimated shape appears truncated/lens

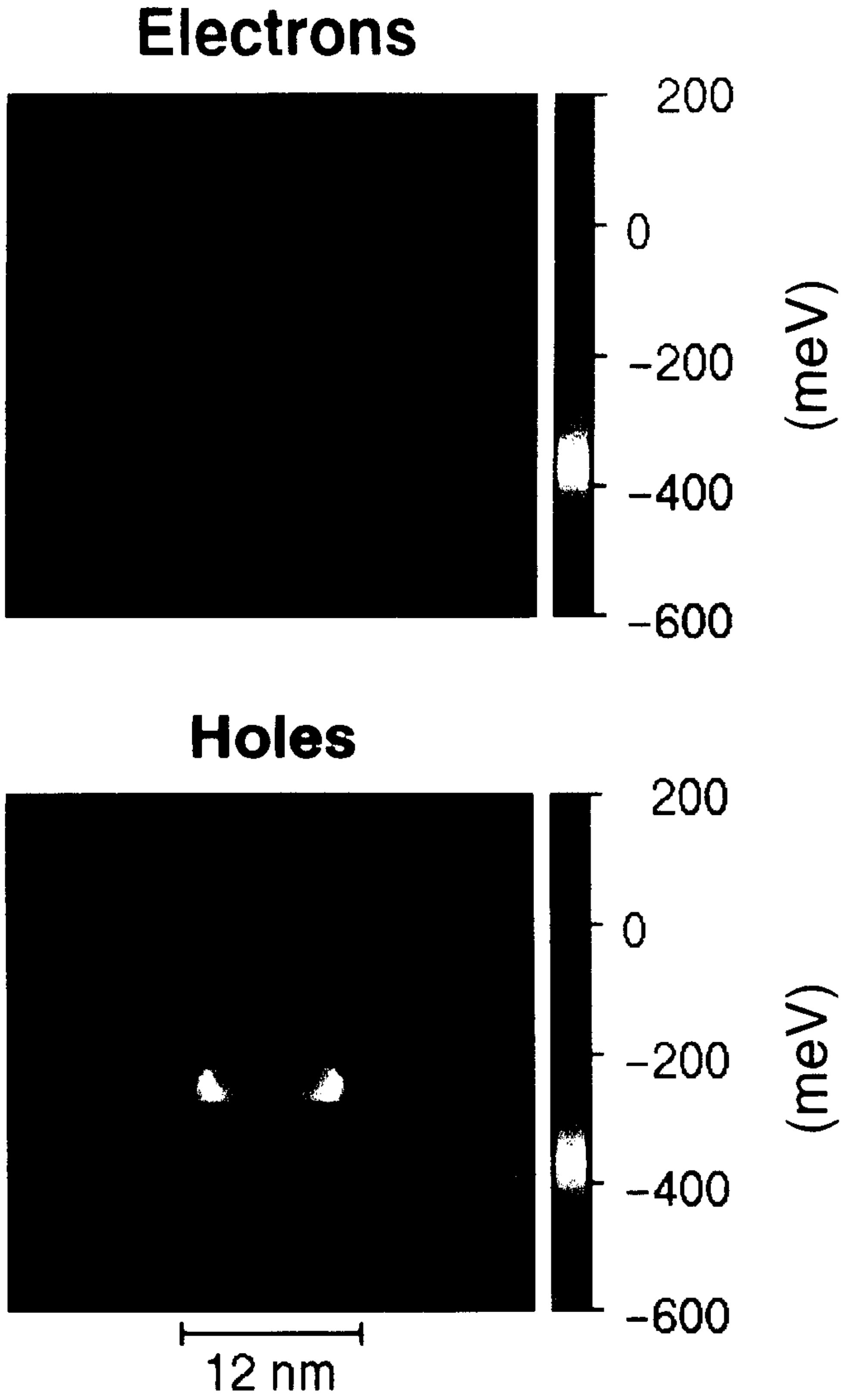
Simulation of Pyramidal Quantum Dots

Wavefunction of (001) excited hole state in pyramidal InAs/GaAs quantum dot

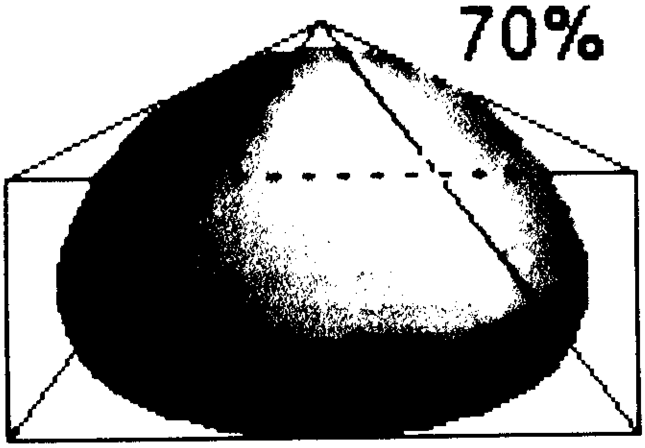


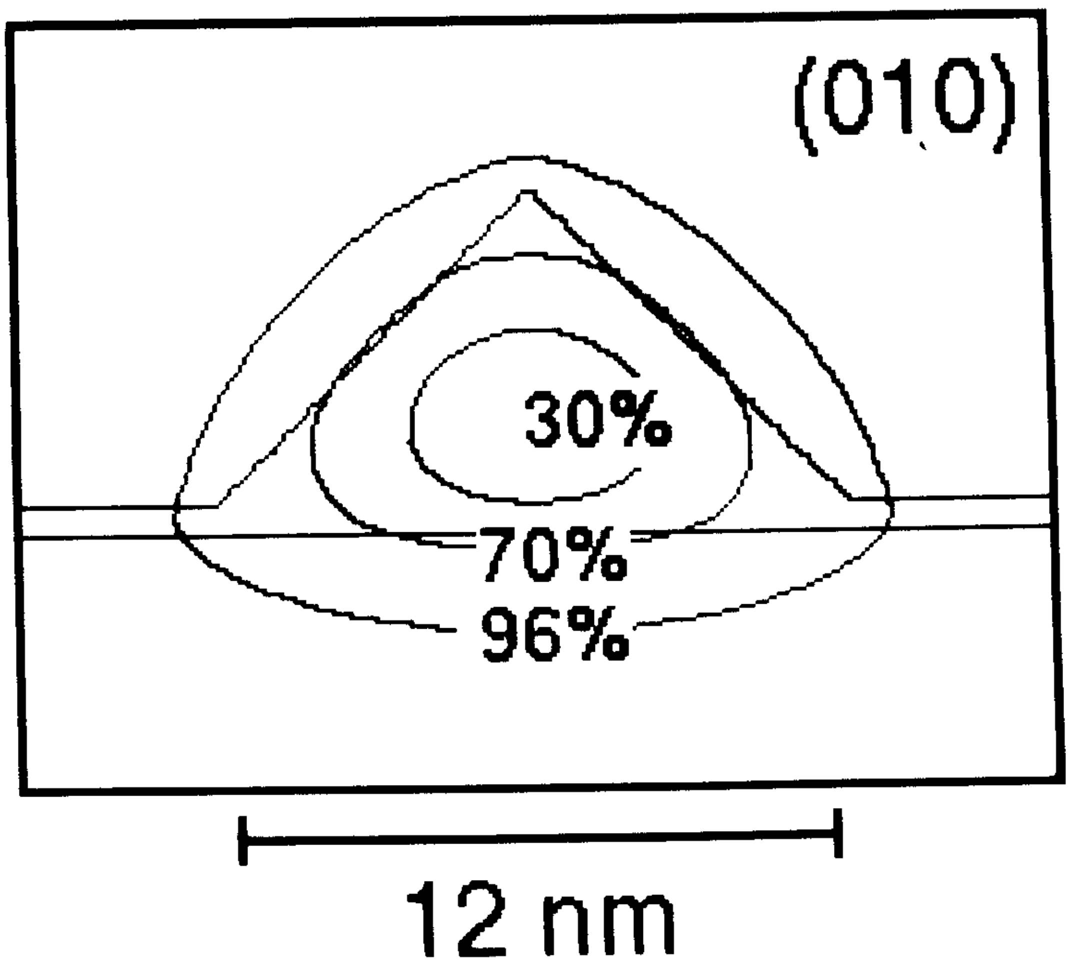
- 3D Strain distribution in dot, wetting layer and surrounding barrier
- Confinement potential
- 3D effective mass Schrödinger equation
- Electron and Hole levels

Confinement Potentials in Strained InAs/GaAs Pyramid

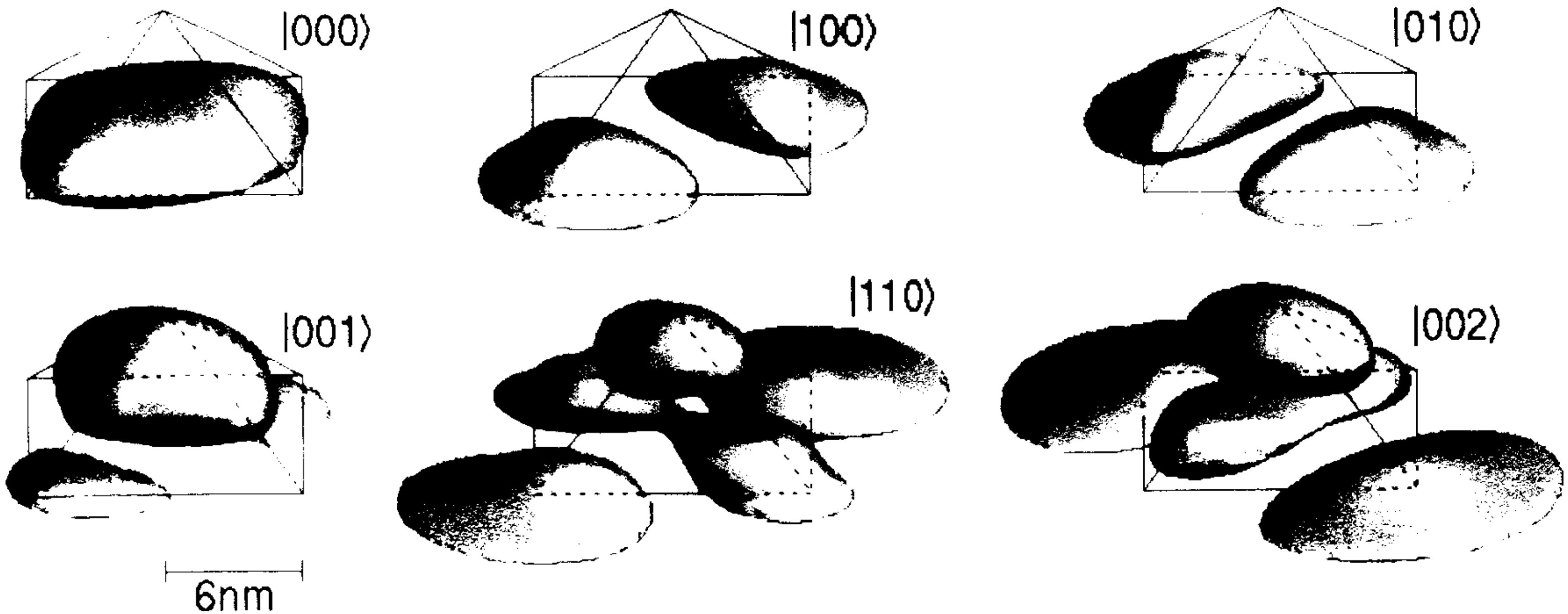


Electron Ground State in InAs/GaAs Quantum Pyramid

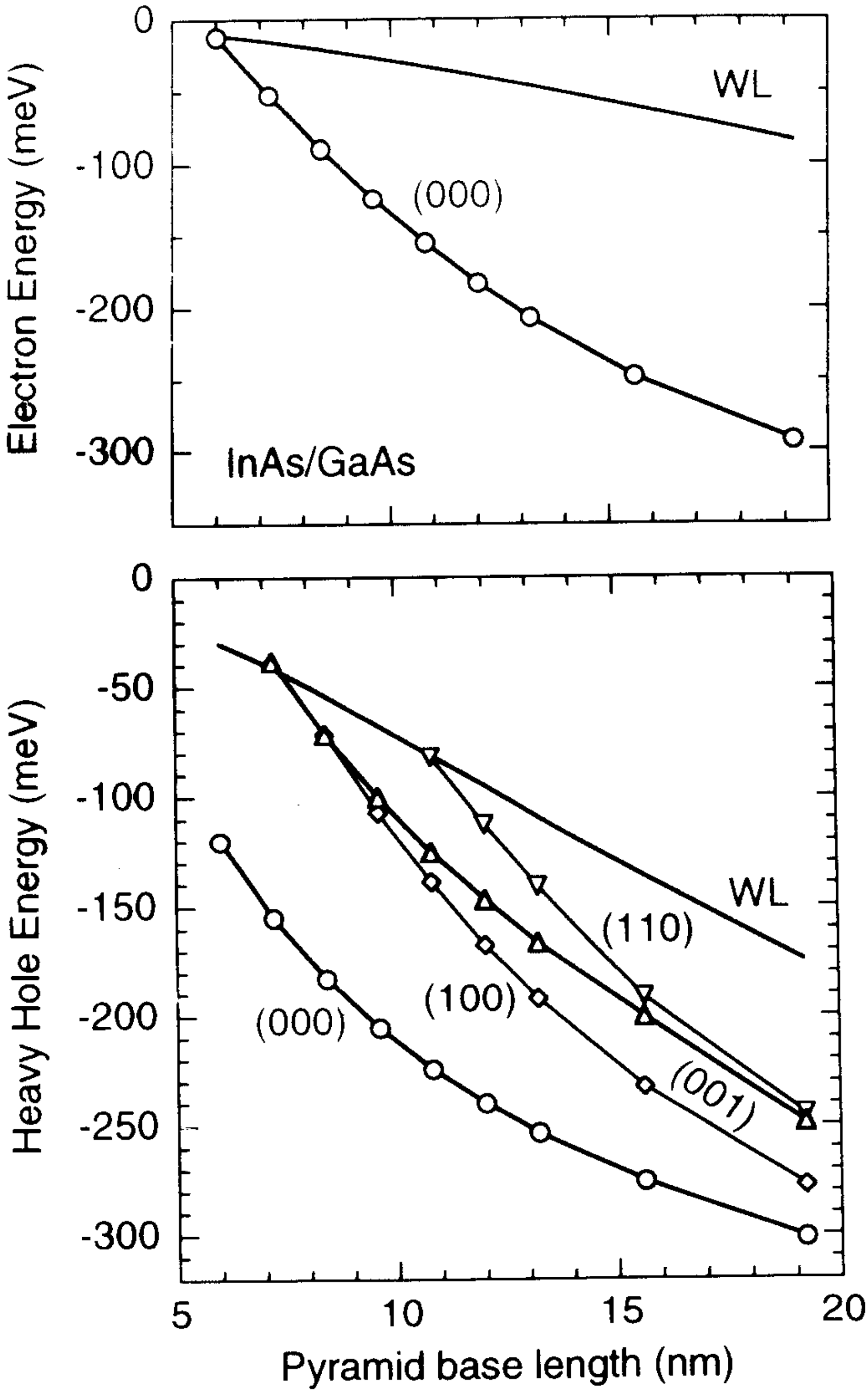




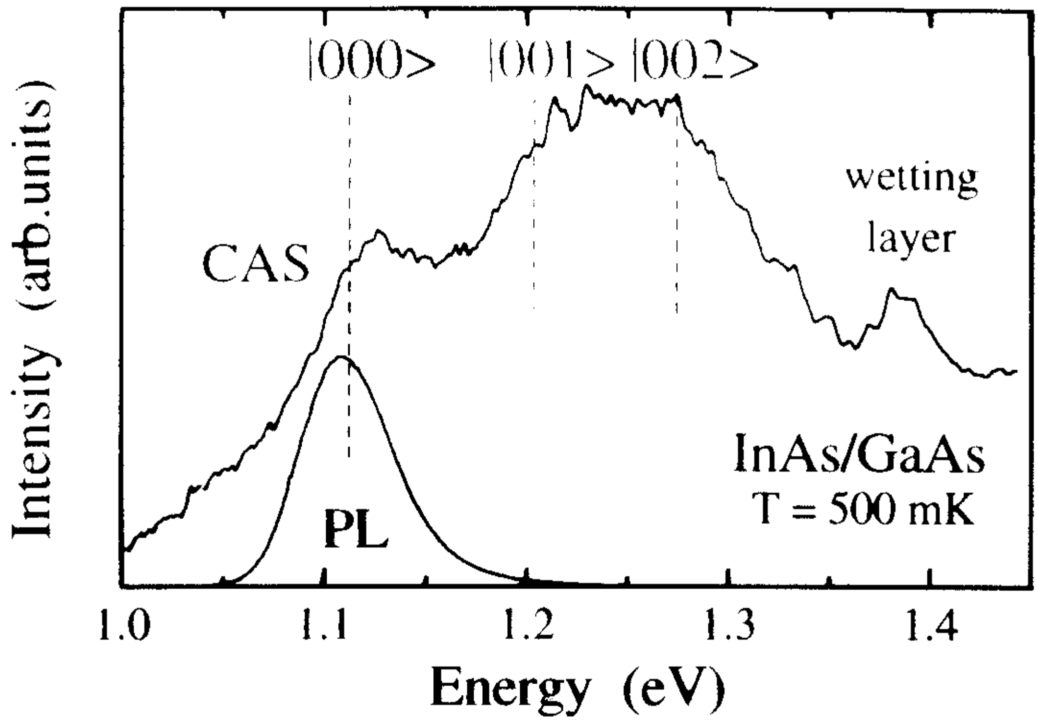
Hole Wavefunctions in 12nm InAs/GaAs Quantum Pyramid with Piezoelectric Potential

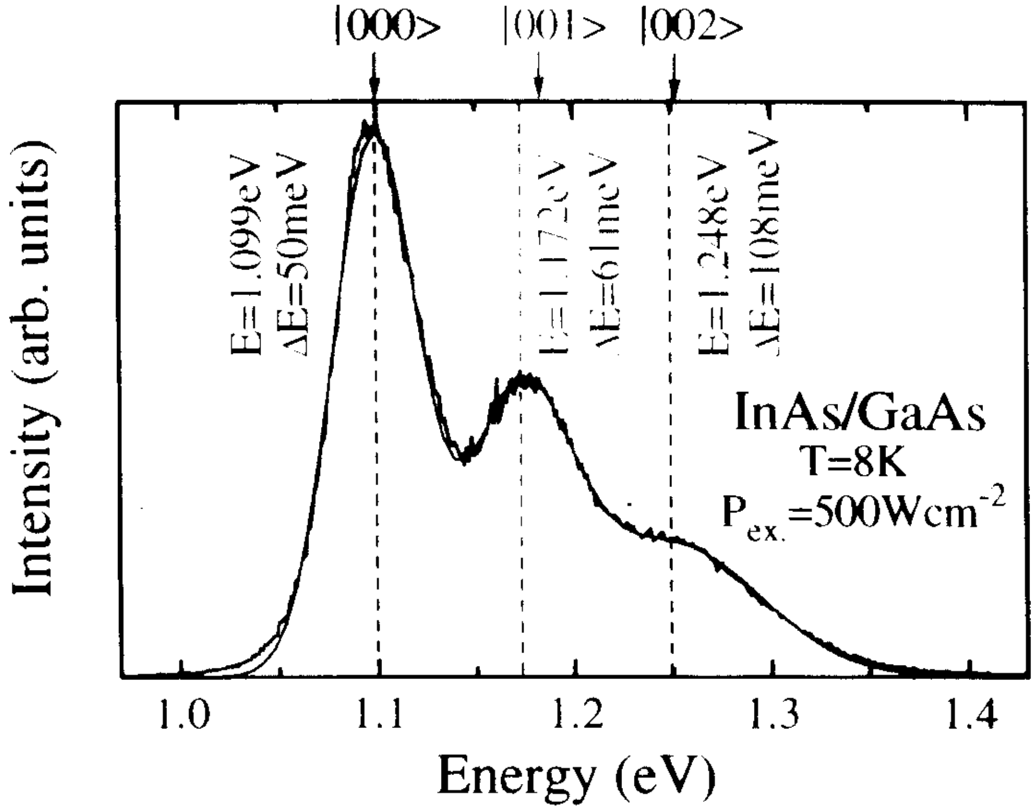


Quantum Dot Levels as a Function of Size

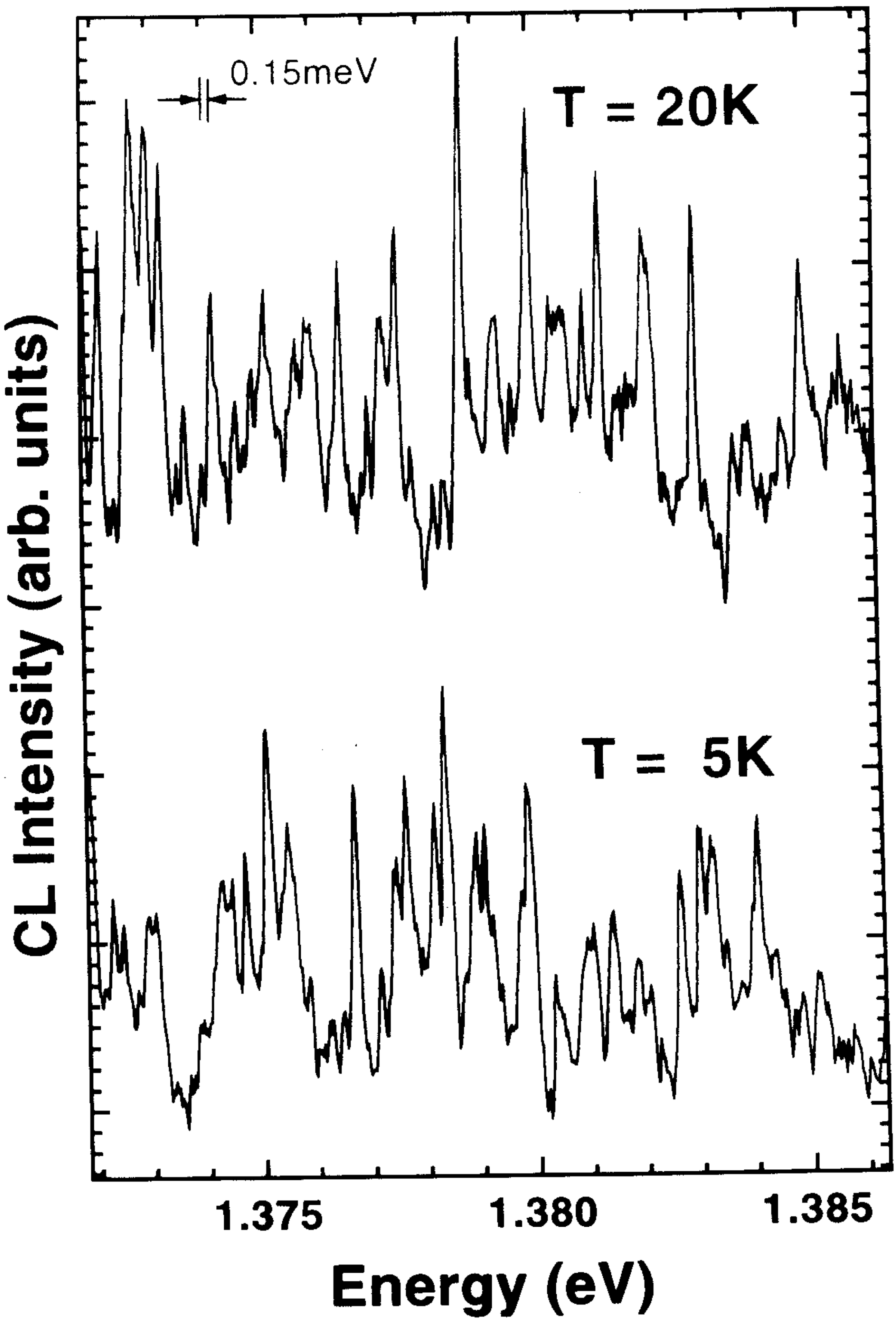


Excited States of InAs/GaAs Quantum Dots

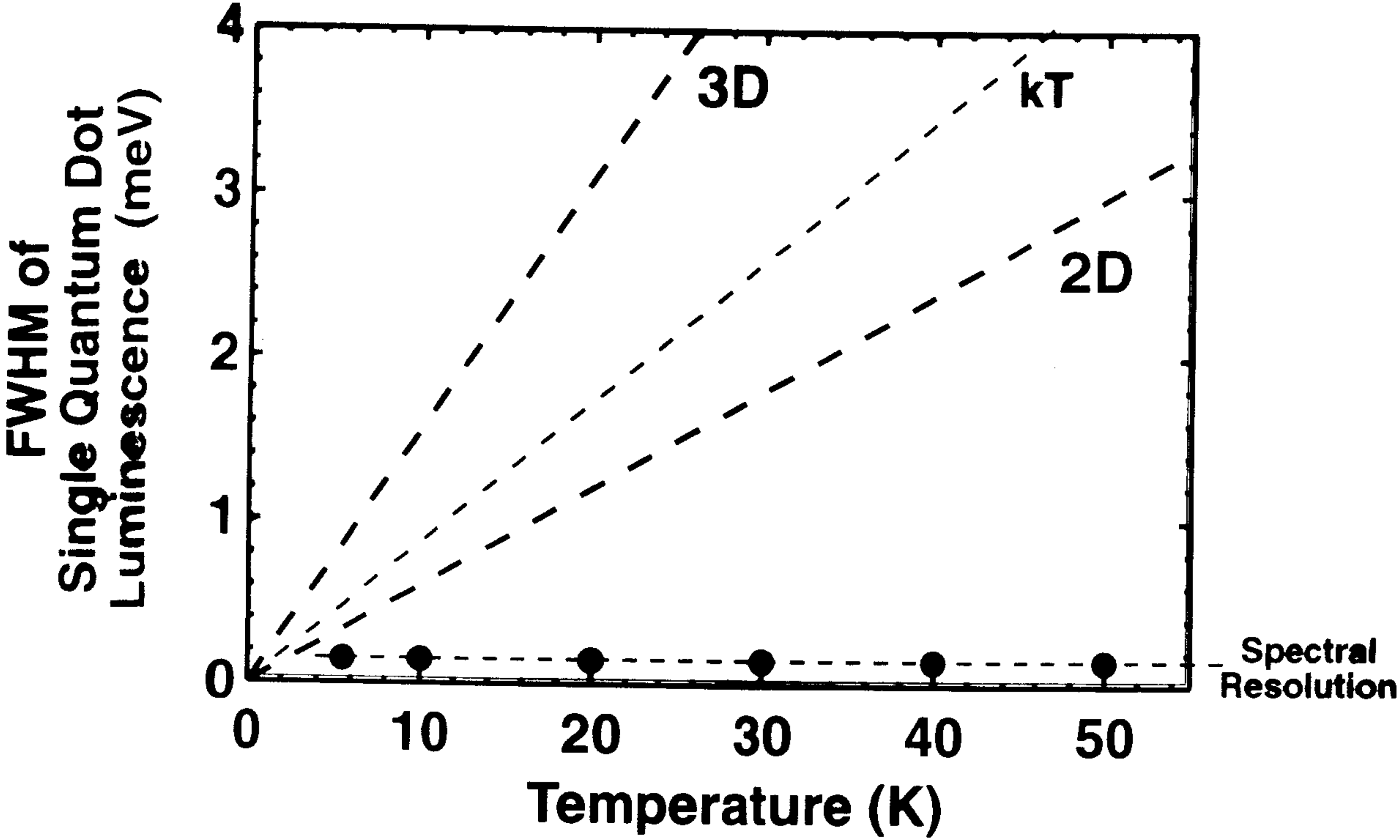




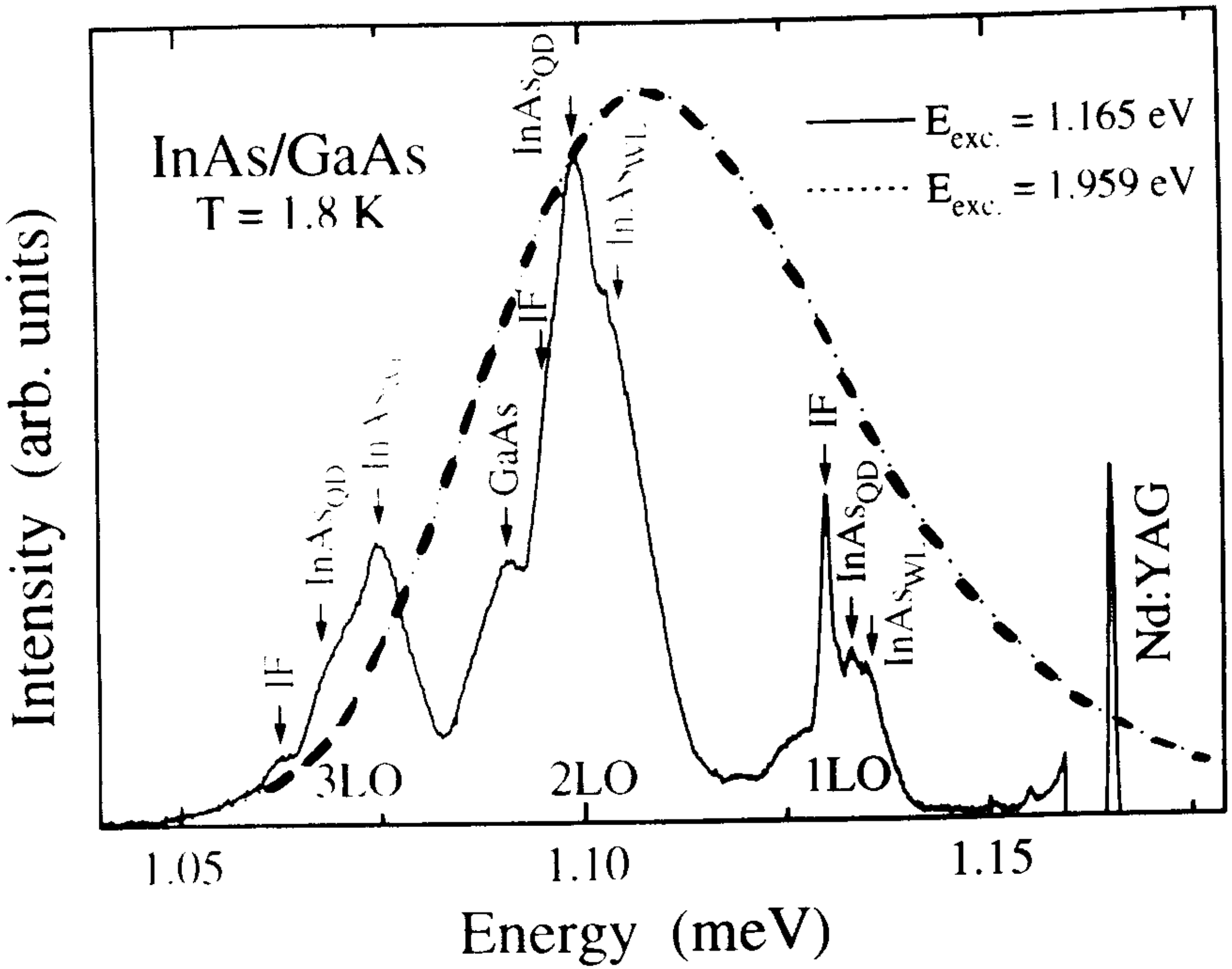
Spot Focus CL Spectra of InAs/GaAs Dots

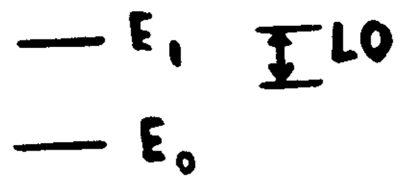


δ-function-like Density of States



Selectively Excited Luminescence of InAs/GaAs Dots





Phonon modes:

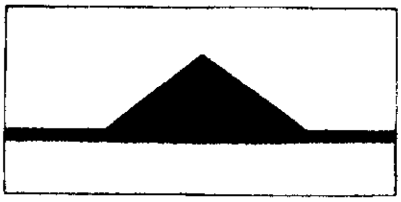
$InAs_{WL}$ = 29.6 meV

$InAs_{QD}$ = 31.9 meV

IF = 35.0 meV

GaAs = 36.6 meV

Optical Properties in Quantum Dots



Quantum Dot Phonon
$h\nu_{LO}$ (InAs) = 31.9 meV

δ-function like ($\Gamma < 0.15$ meV) ground state luminescence is resonant with δ-function like absorprtion.

NO STOKES SHIFT BETWEEN ABSORPTION AND EMISSION FOR EACH DOT.

For the same ground state energy there are different energies of excited states for different dots due to shape and strain nonuniformities.

PLE SPECTRA REPRESENT COMBINATION OF ABSORPTION AND RELAXATION PROCESSES.

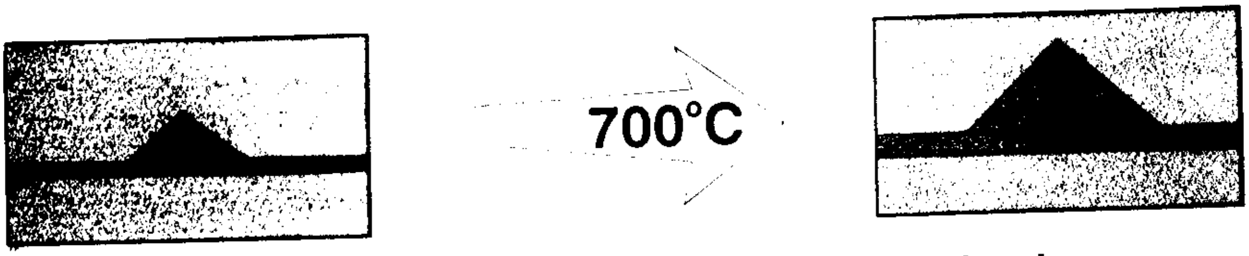
Different LO phonons participate in scattering: InAsQD, InAsWL, IF, GaAs.
Phonon resonances are broad indicating participance of acoustic phonons.

EFFICIENT MULTI-PHONON RELAXATION MECHANISM BY PASSES THE PHONON BOTTLENECK EFFECT ($\tau^{CAPTURE} < 1$ ps, $\tau^{RELAX} < 40$ ps)

INCREASED OSCILLATOR STRENGTH AND TUNING OF QD PL AND ABSORPTION PEAKS BY COUPLING OF QDs.

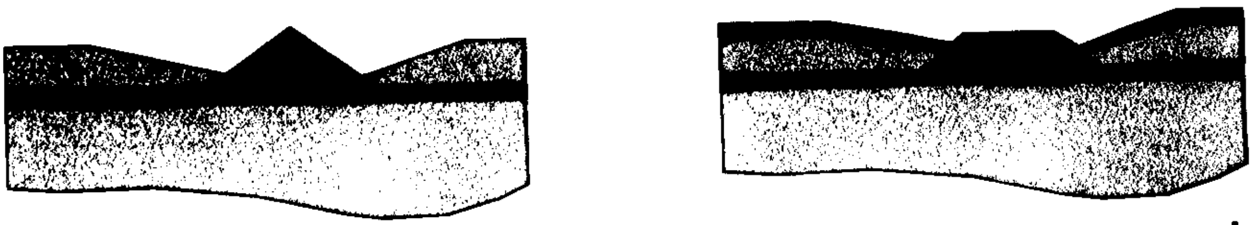
Shape Transformation Effects

Annealing



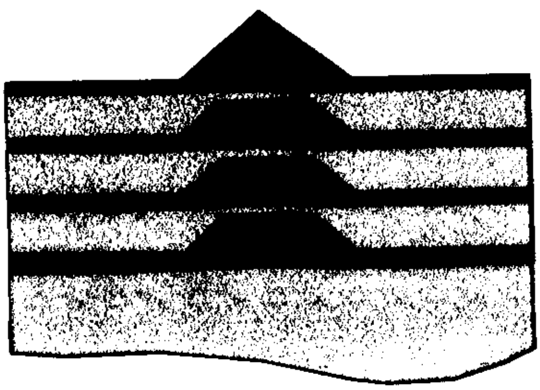
Size increases
Indium composition decreases
Pyramid like shape is maintained
High energy shift of QD luminescence

Growth Interruption



InAs molecules evaporate from pyramids and cover free GaAs surface

Growth of vertical stacks



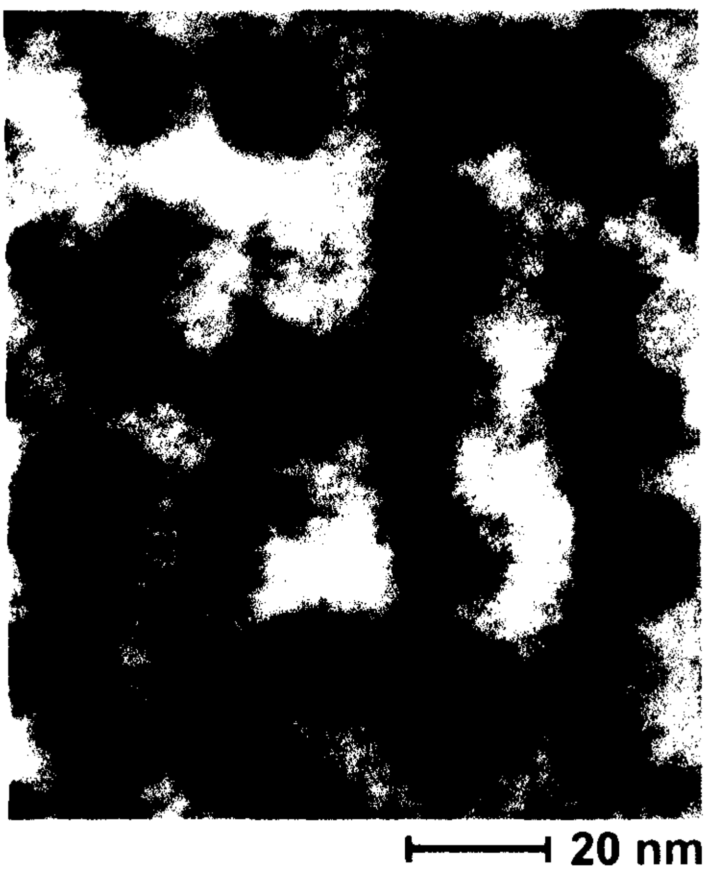
Formation of quantum dot superlattice

Vertically Coupled Quantum Dots

Ledentsov et al. 1995 (Ioffe Inst., TU Berlin, MPI Halle)

Cross section

Plan view

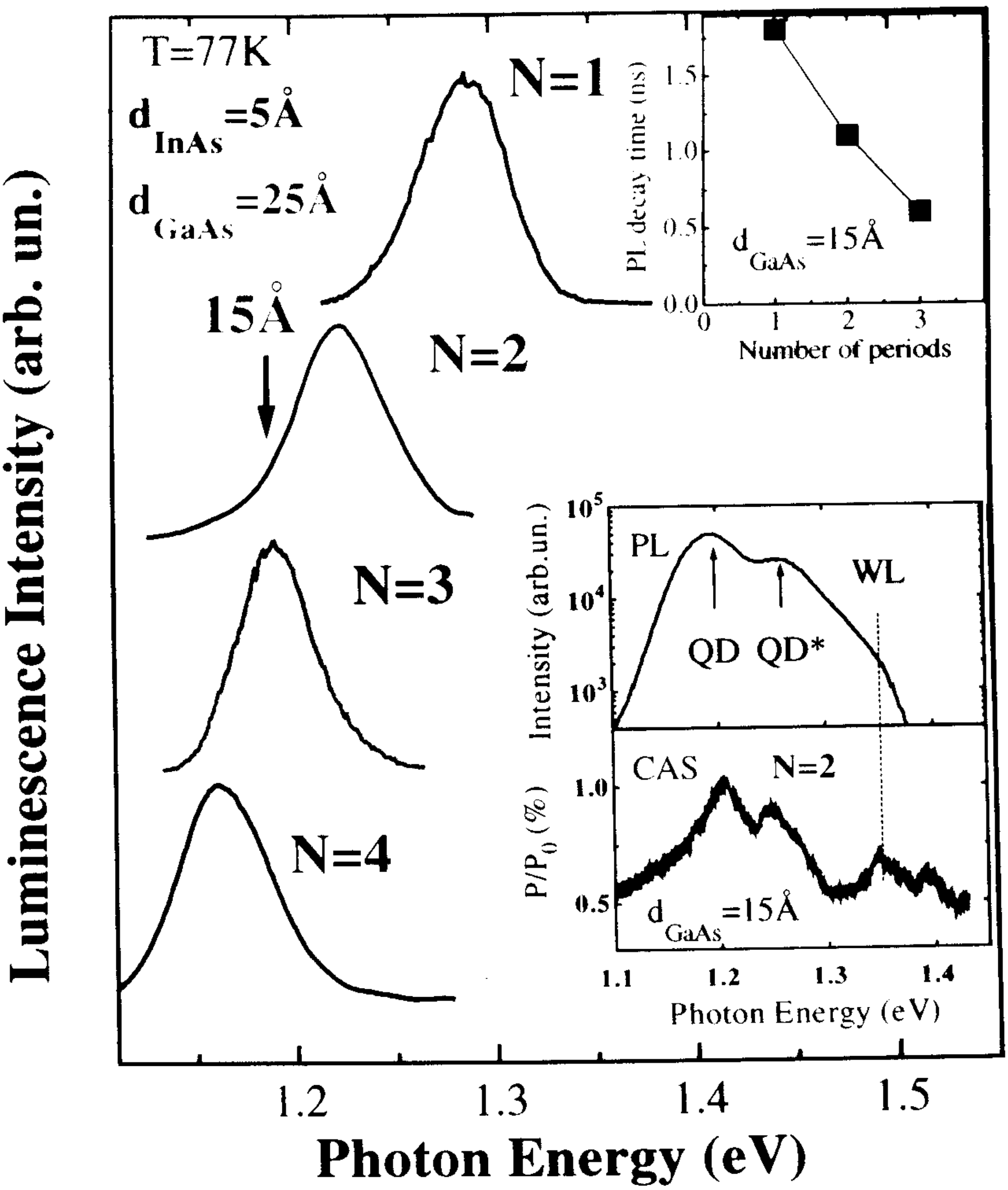


Arrangement of quantum dots in 3-dimensional tetragonal lattice

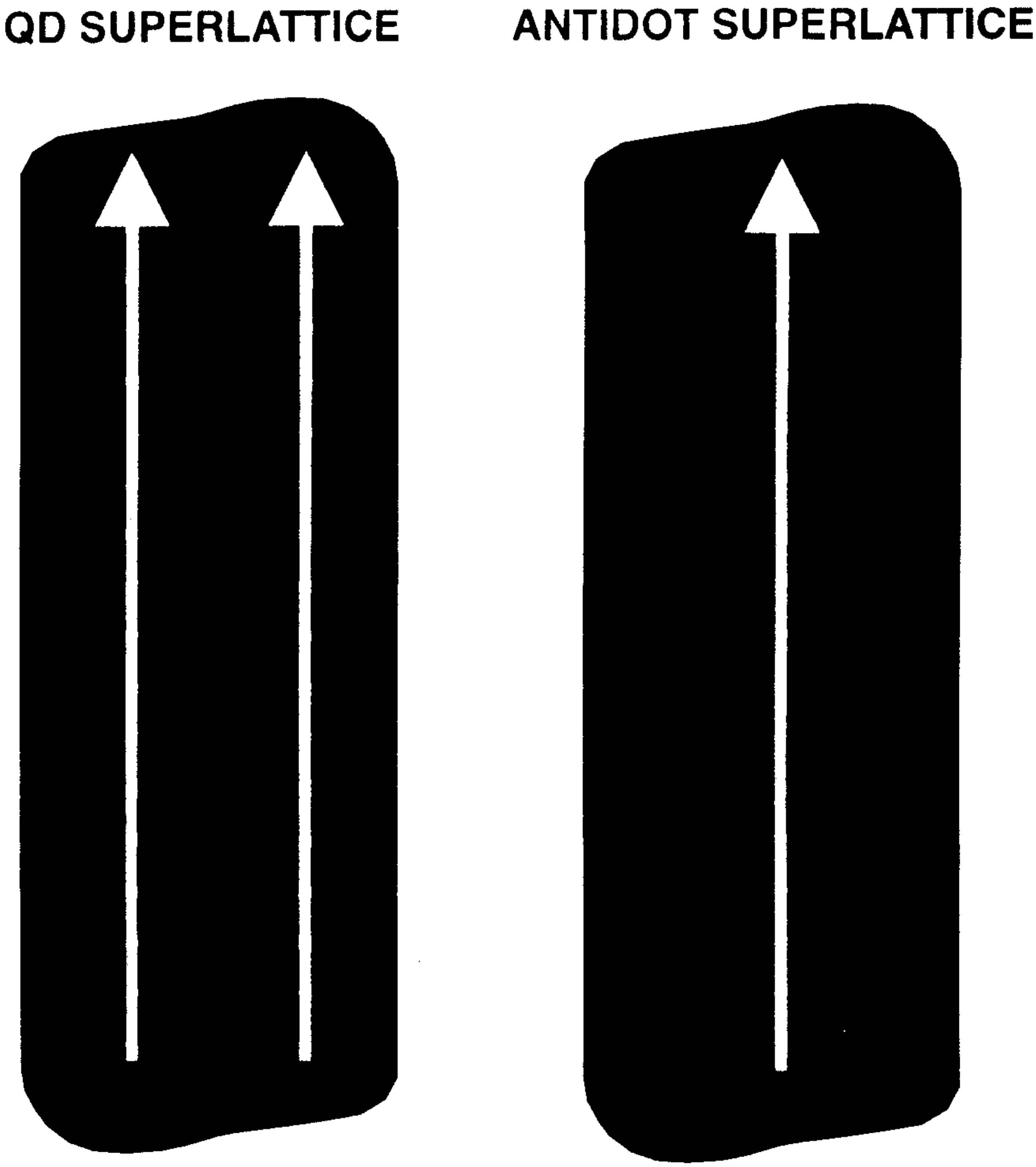
[010]

[100]

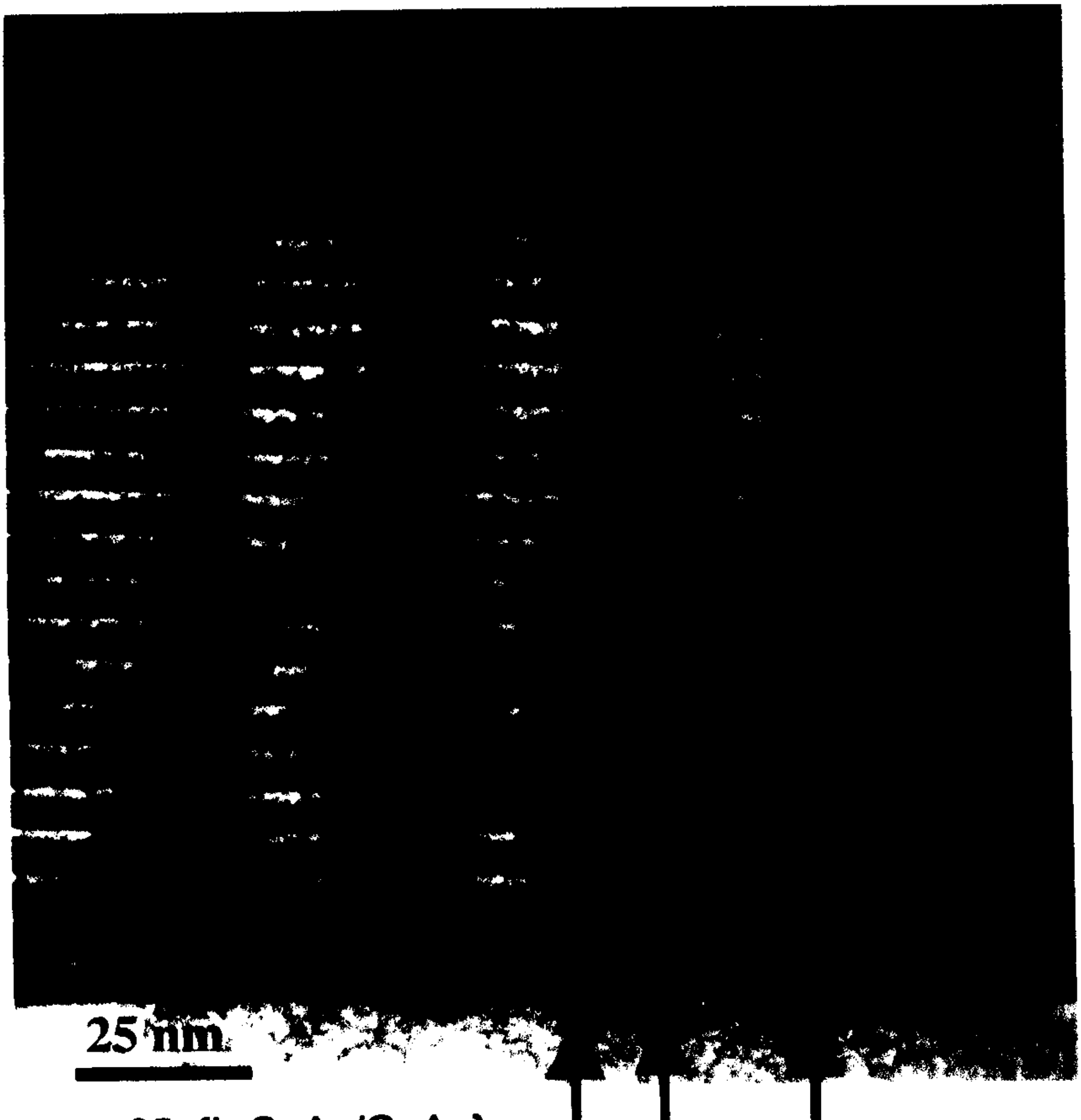
Electronically Coupled Quantum Dots



Electron Transport in Quantum Dot Superlattices



InGaAs-GaAs Quantum Dot Superlattice

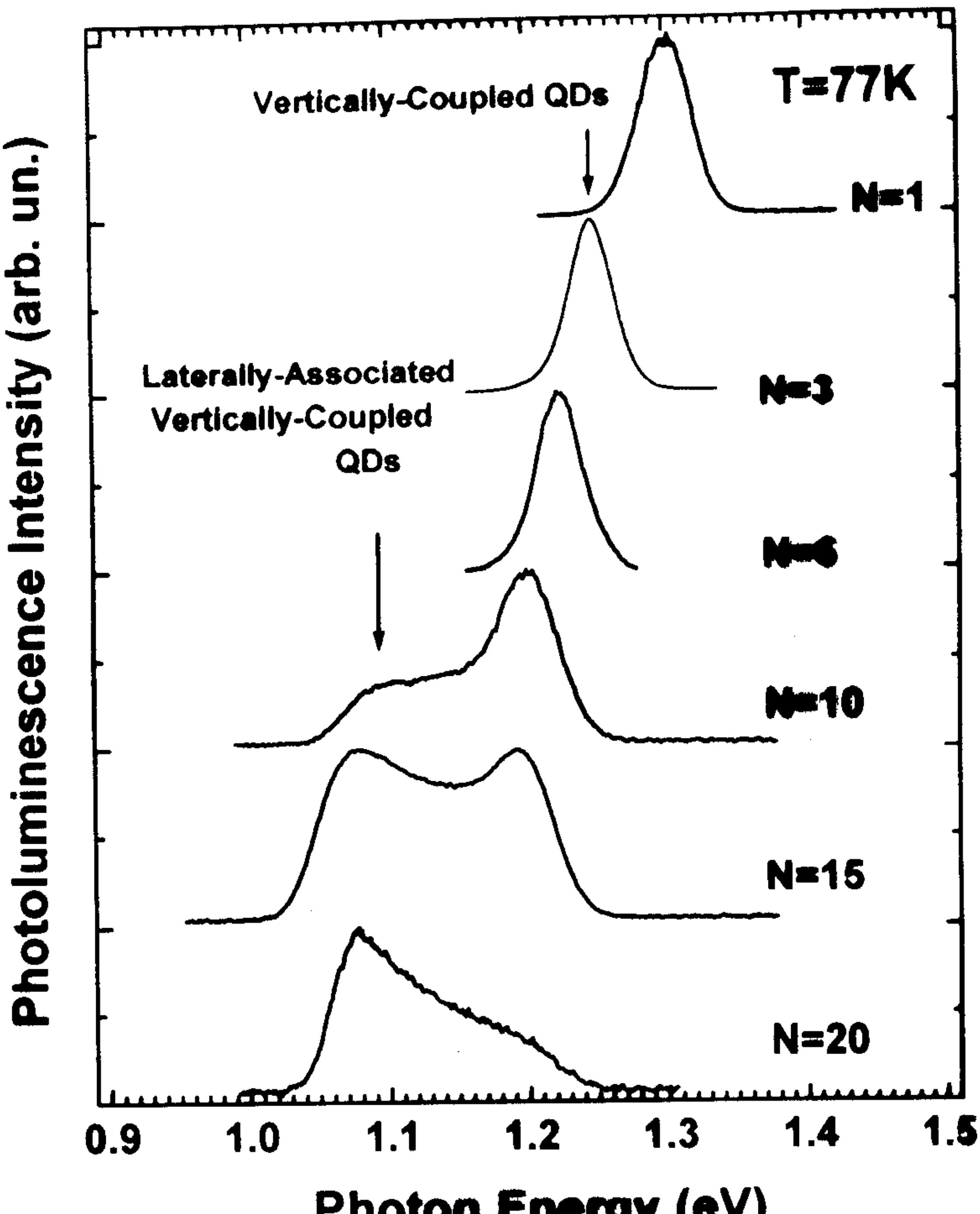


25x{InGaAs/GaAs}

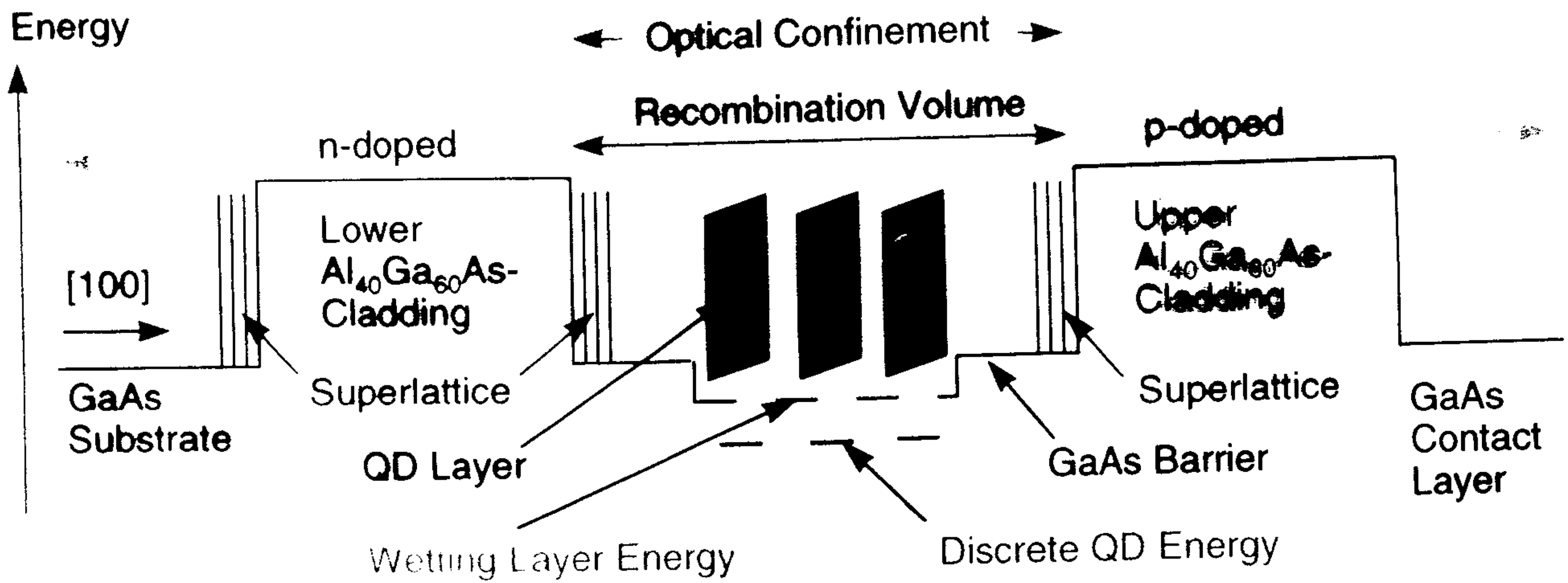
DENSE ARRAY OF COLUMNS

CONTINUITY OF COLUMNS THROUGH THE STRUCTURE

Laterally-Associated Vertically-Coupled Quantum Dots



[redacted]



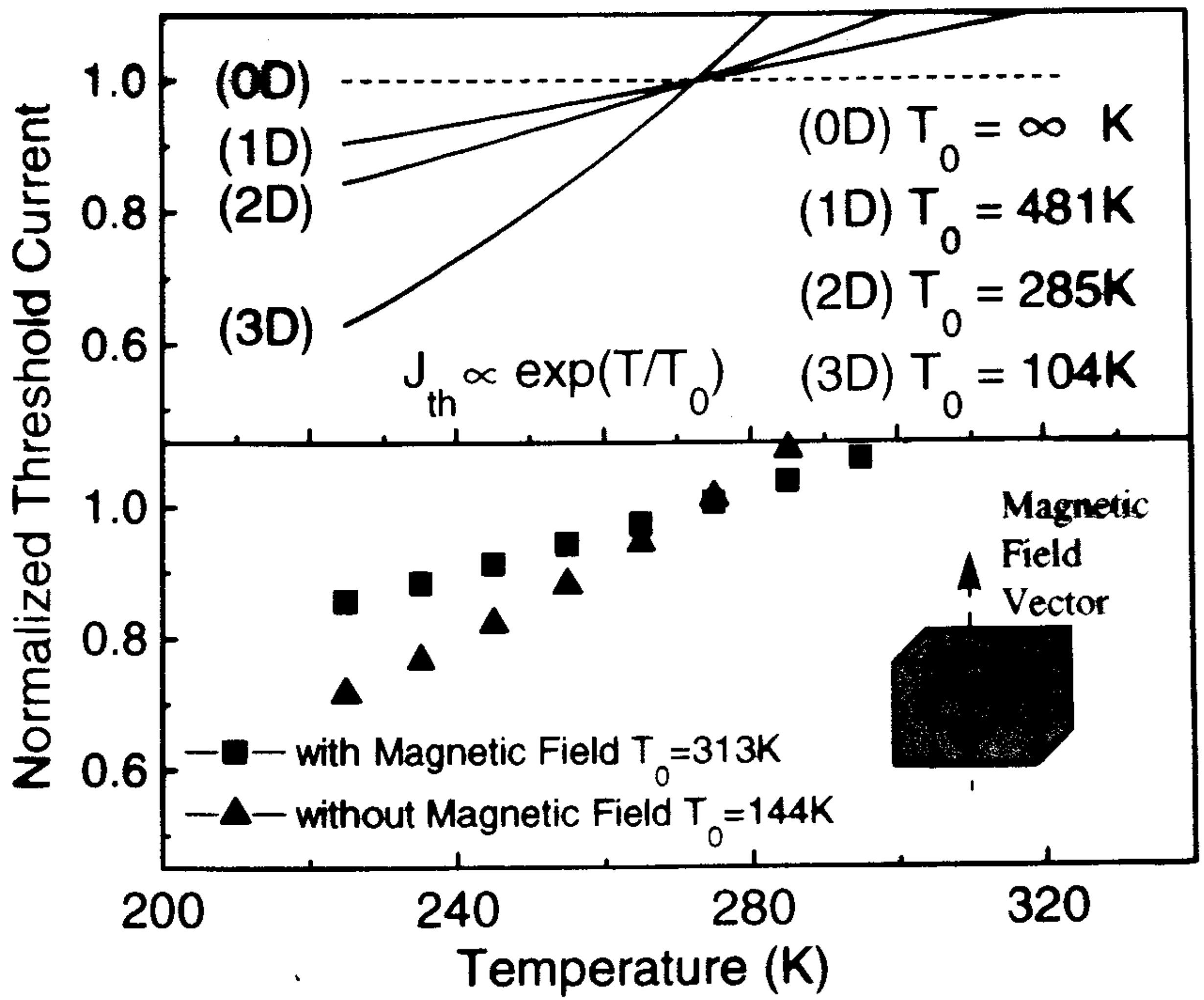
Energy
Optical Confinement
Recombination Volume
n-doped
p-doped
Lower
Al40Ga60As-
Cladding
Upper
Al40Ga60As-
Cladding
[100]
GaAs
Substrate
Superlattice
QD Layer
Wetting Layer Energy
Discrete QD Energy
GaAs Barrier
Superlattice
GaAs
Contact
Layer

[redacted]

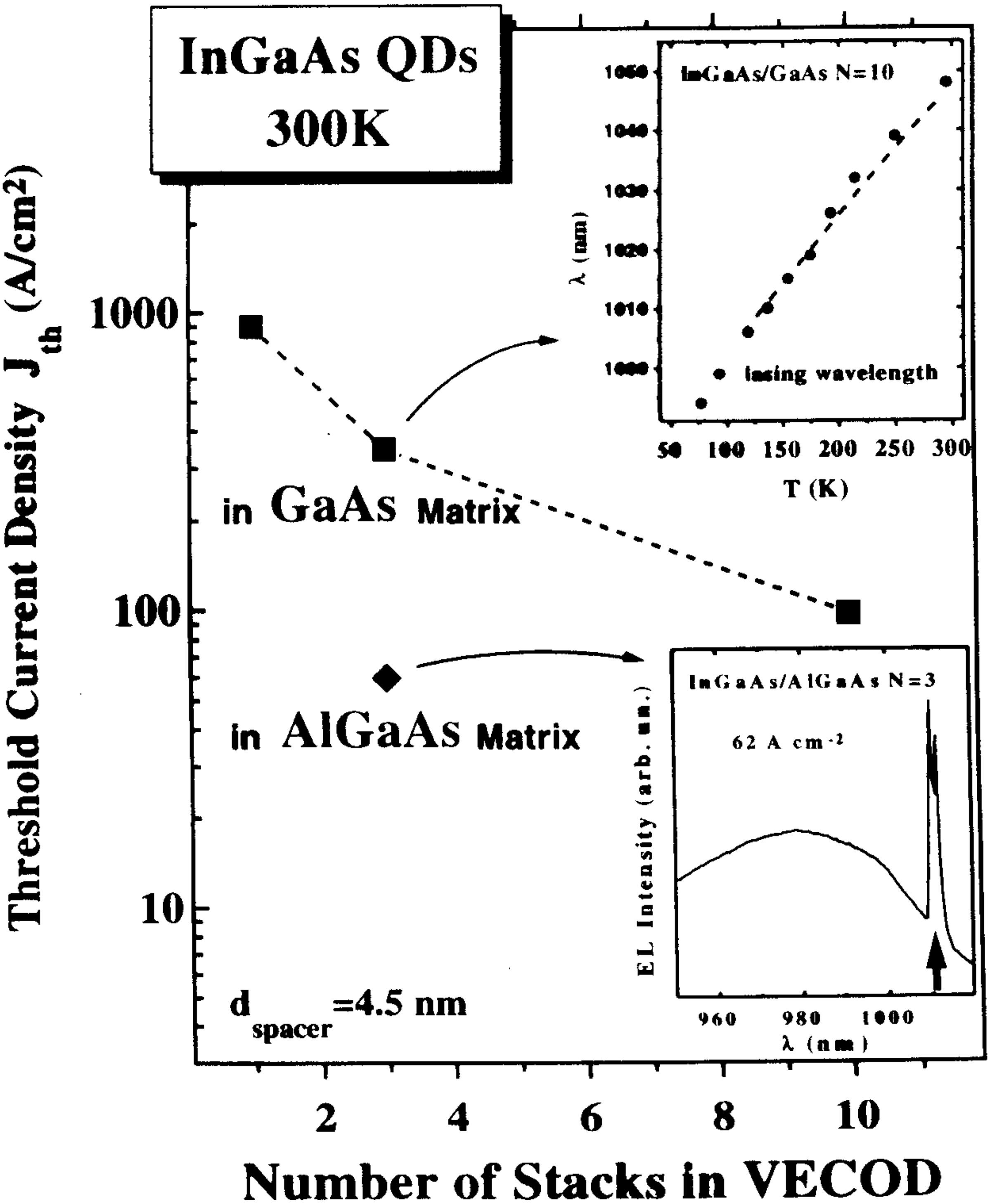
Prediction

First Evidence for an Increase of T_o of a Bulk Laser placed in a Magnetic Field

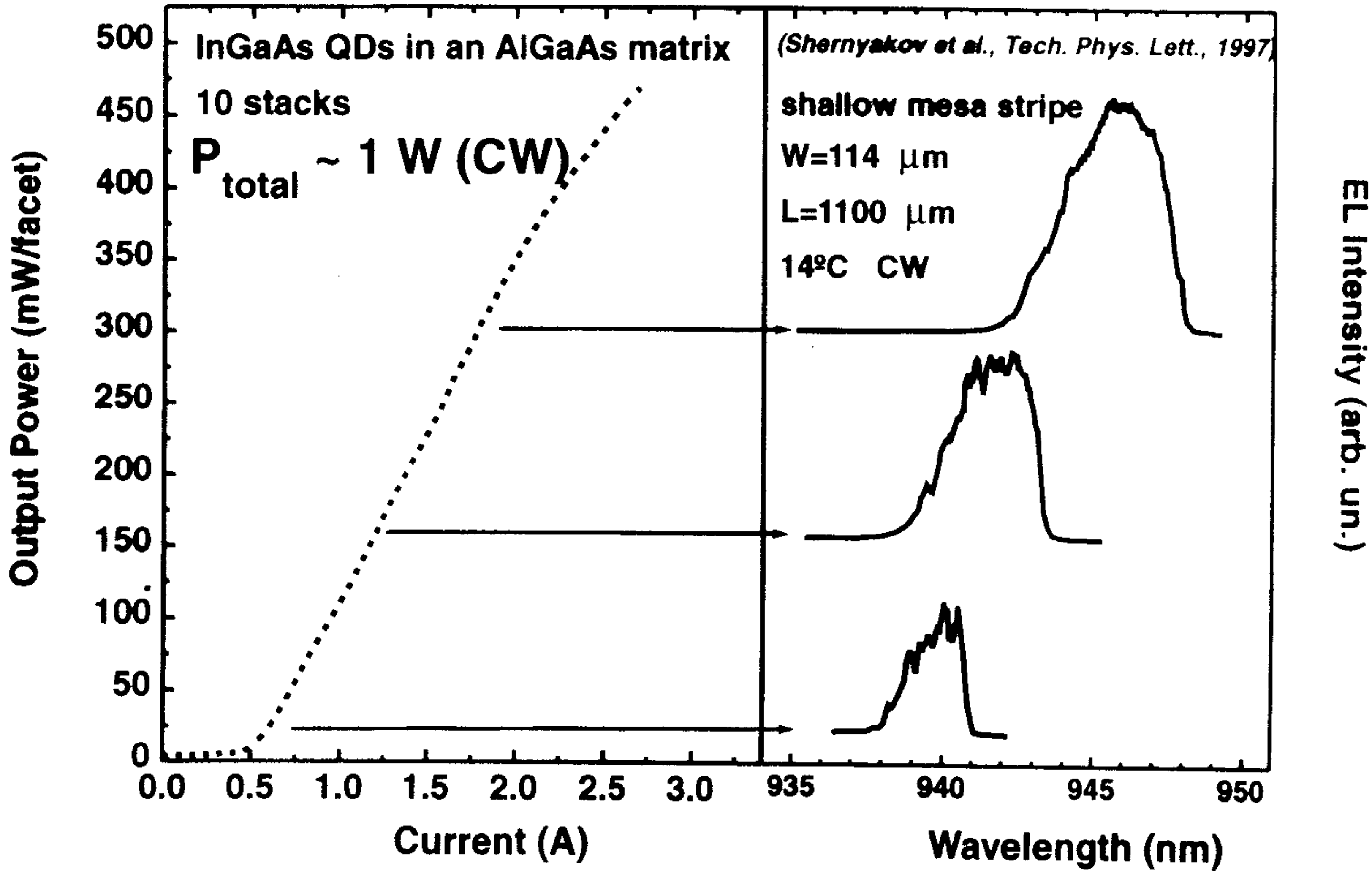
(Arakawa and Sakaki, 1982)



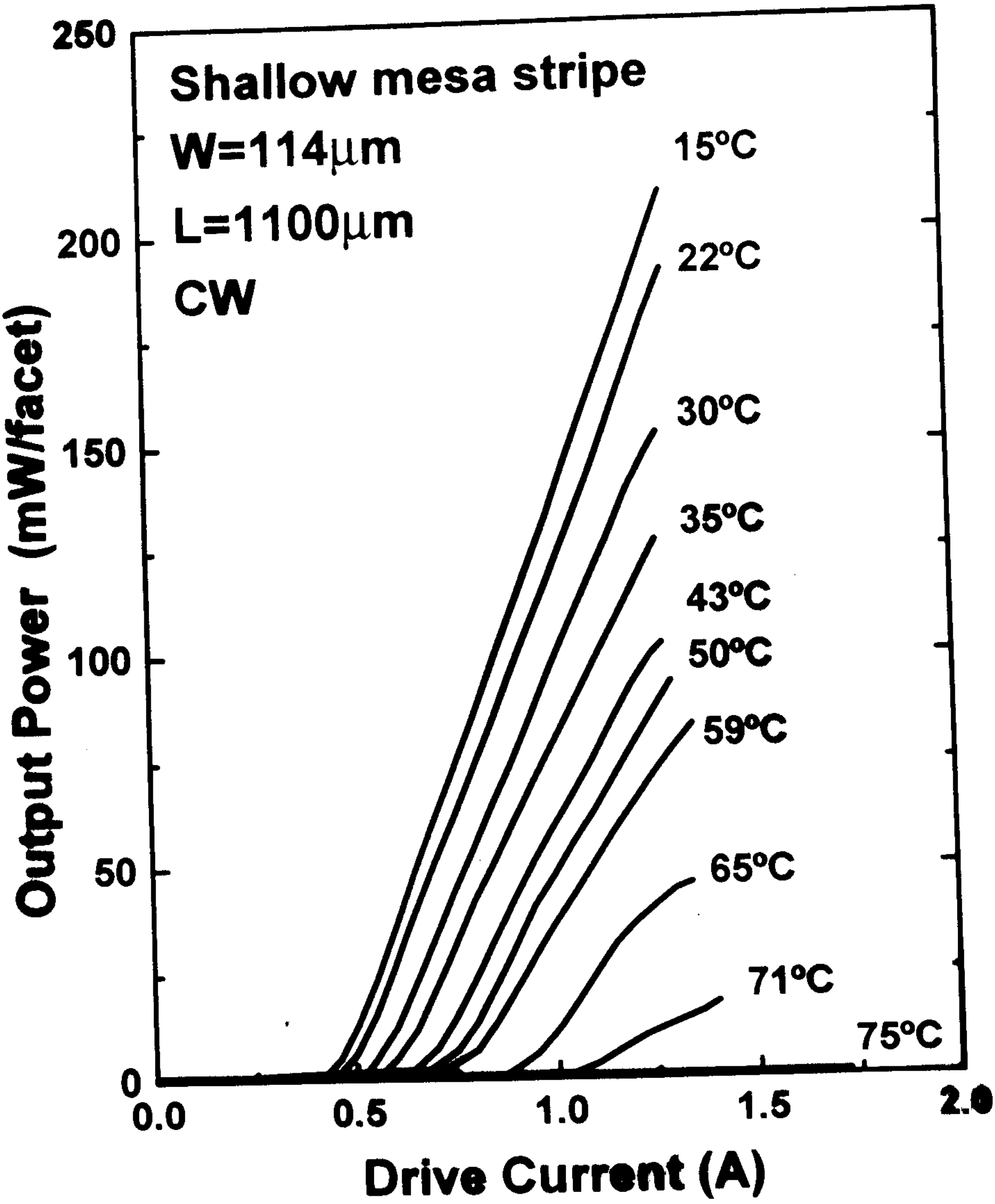
Lasers Based on Vertically Coupled Quantum Dots



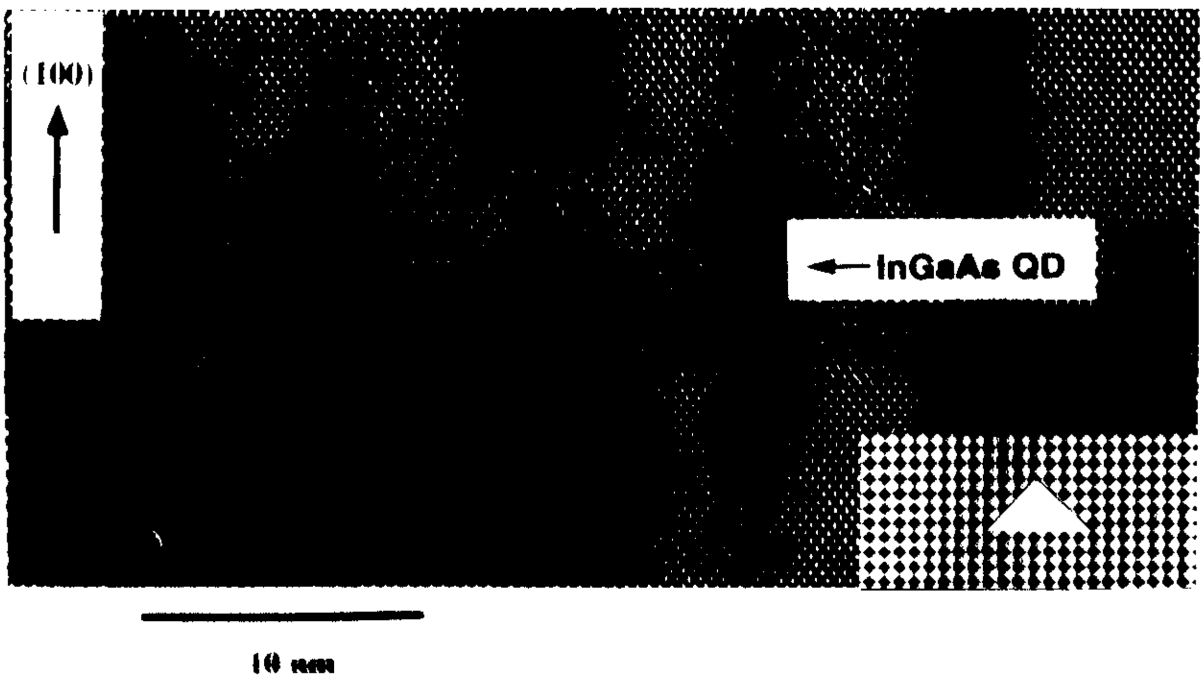
RT High Power CW Operation of a QD Diode Laser



High Temperature Operation of a Quantum Dot Laser



Cross-Section HRTEM Image of MOVPE (In,Ga)As Quantum Dot on GaAs (100)



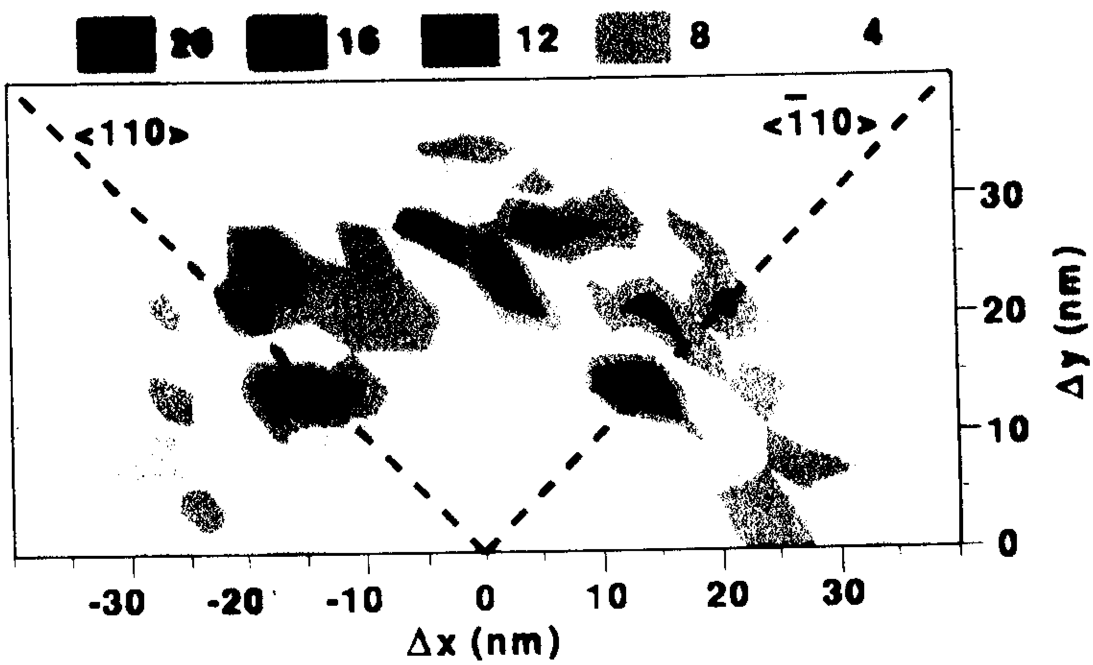
- Pyramidal shape (20 nm in base)
- Bright PL at 1.36 μm (300 K)
- Possibility of Vertcal Coupling

Ledentsov et al. APL 69, 1095 (1996)

QD Self Organization in MOCVD

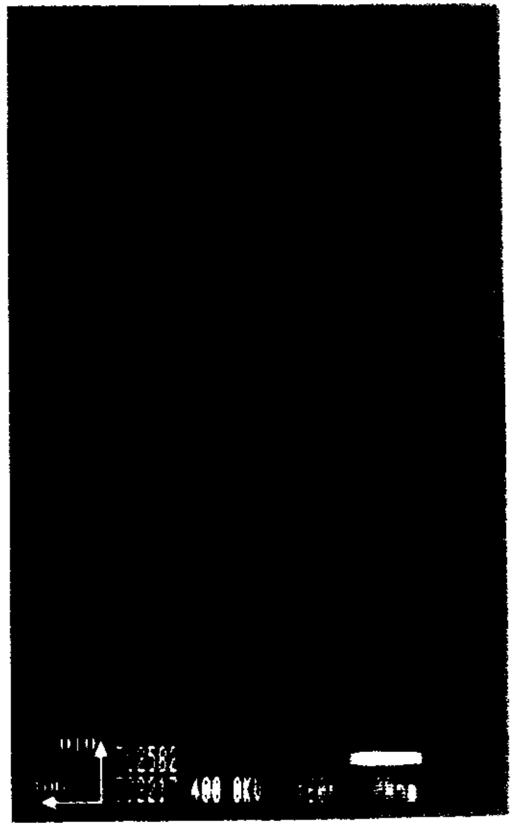
- Chainlike ensemble alignment along <110>
- (100) oriented square QD base (in larger magnification)

F. Heinrichsdorff et al., APL 68 (23) 1996



*MOCVD growth of **InAs**/GaAs QDs*

"Normal" growth conditions

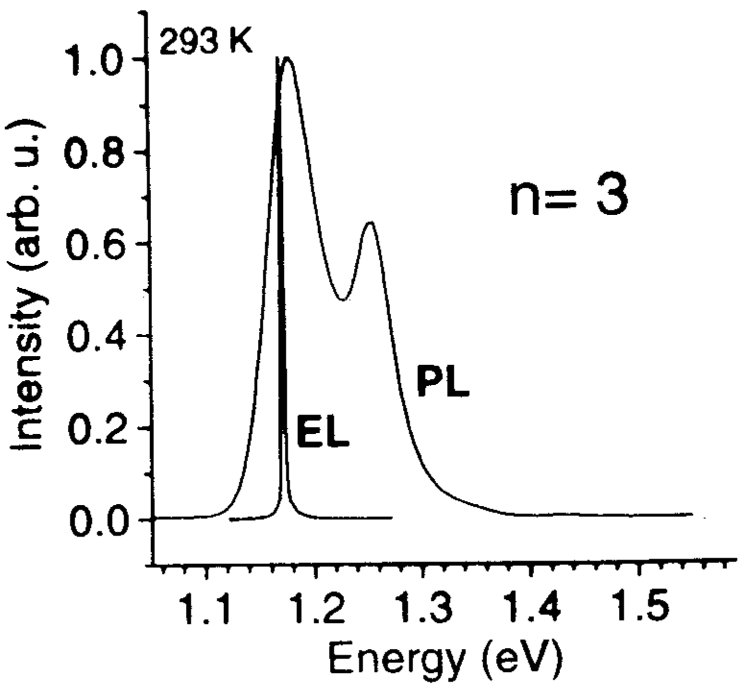


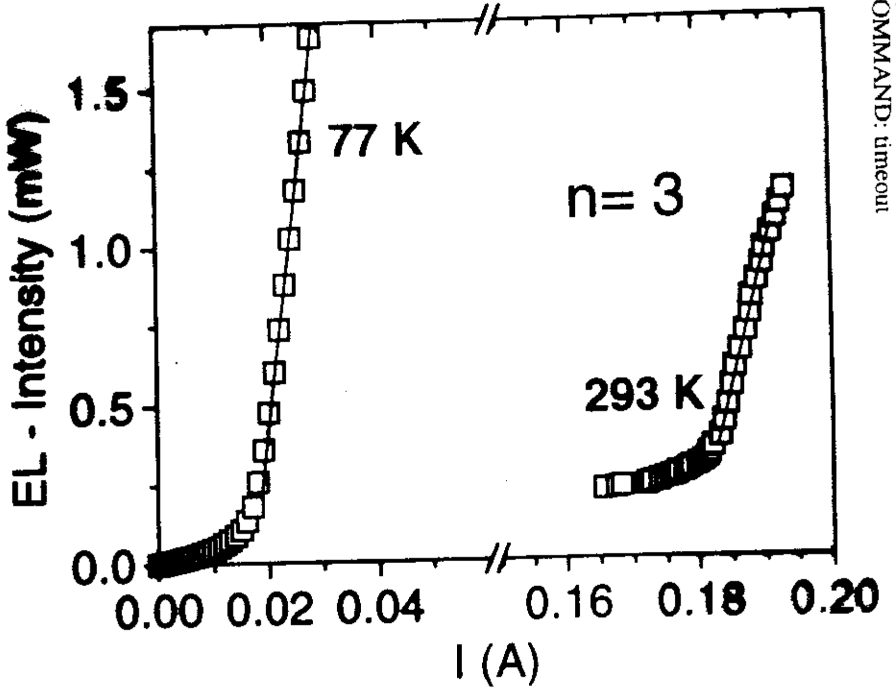
Minimized As pressure for growth and growth interruption

- Lateral densities up to 1.5×10^{11} cm^{-2}
- Coupled and decoupled QD stacks possible

F. Heinrichsdorff et al.,
Jpn. J. Appl. Phys. *36 (1997) in print*

MOCVD InAs/GaAs Quantum Dot Lasers





- Stacked QD laser: Ground state lasing (220 A/cm^2), cw operation at RT
- Single sheet QD laser: 12.7 A/cm^2 at 100 K (ground state),
  181 A/cm^2 at 293 K (excited state)

F. Heinrichsdorff et al.
Appl. Phys. Lett. 71 (27), 1997 in print

Quantum Dot Injection Lasers
Room Temperature (300K) Operation

Figures of Merit

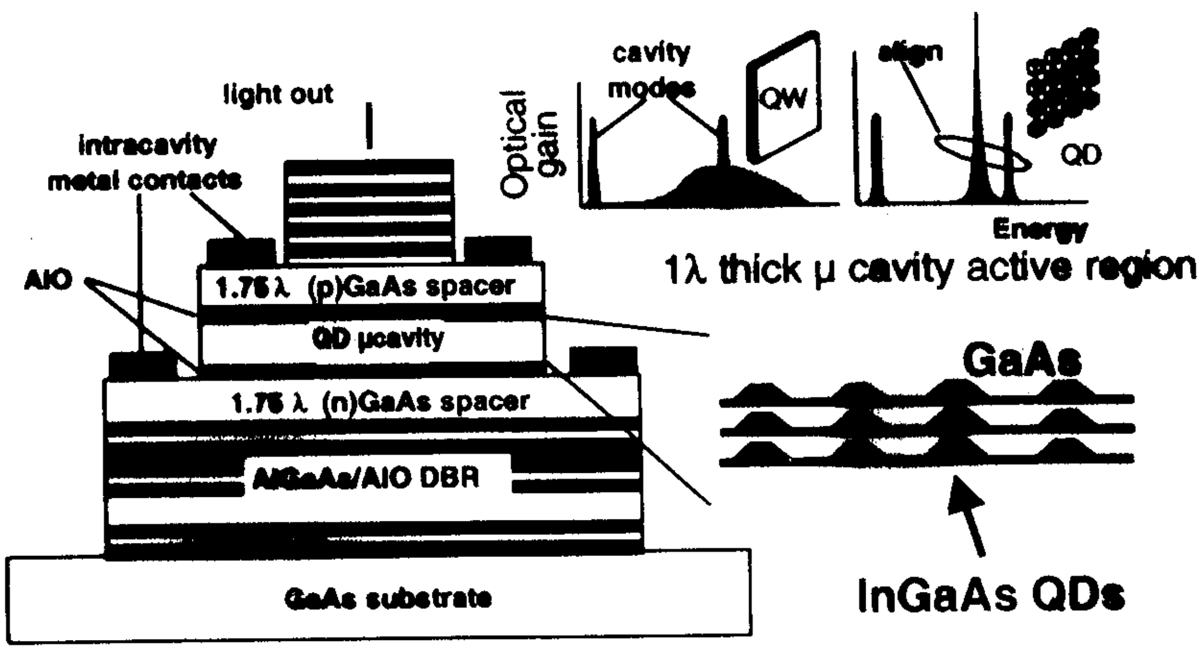
- QD electroluminescence and photoluminescence coincide in energy: Lasing on QD ground state
- High temperature stability (T_0=385K)
- Low thresholds (j_{th}=60A/cm^2)
- Differential quantum efficiency up to 70%

Design Principles

- Stacked sheets of quantum dots, N~10 — gain ↑
- Increase of barrier height — escape rate ↓

Quantum Dots for VCSELs

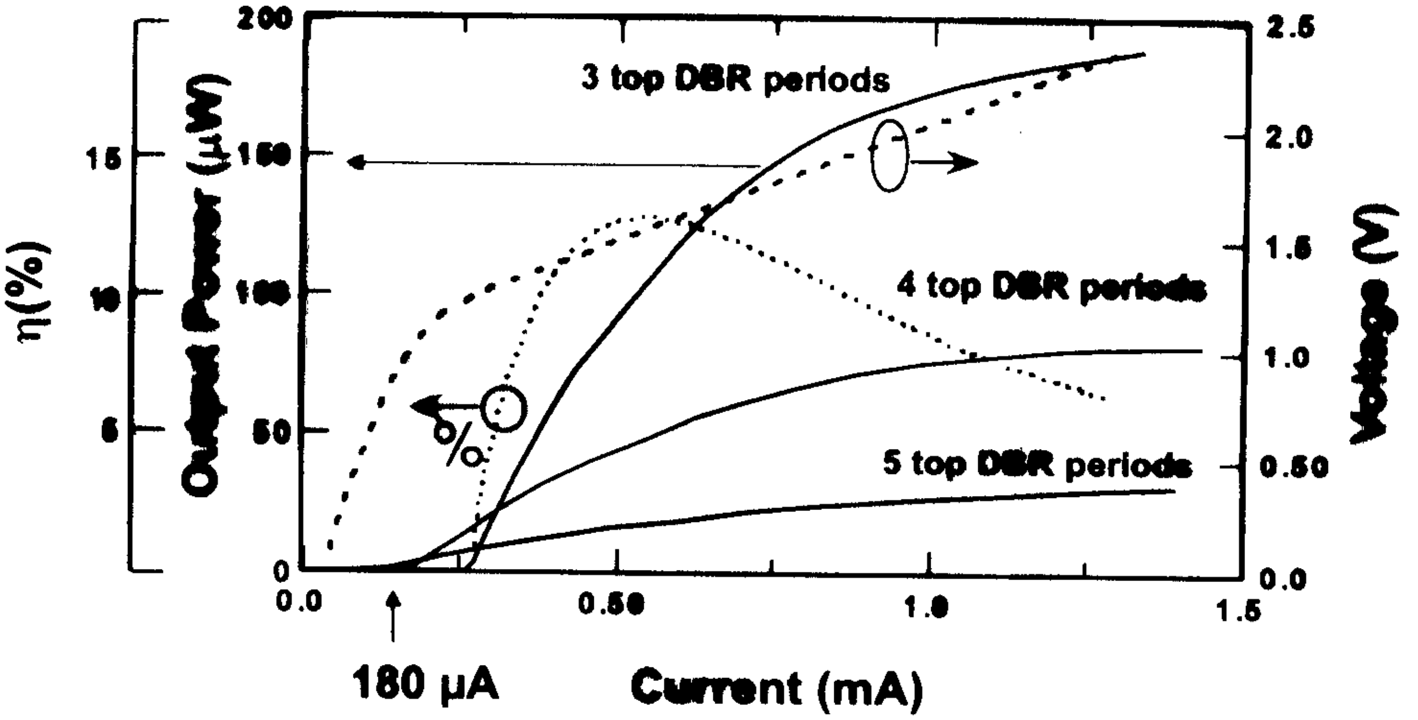
- Basic Advantages of Quantum Dots
- No interface recombination at oxide-defined apertures
- Reduced lateral spreading of carriers out of the aperture region



Single Quantum Dot Laser at ultralow Threshold Current is possible

3-Fold QD VCSELs at 300 K

QDs as novel gain medium for oxide-defined aperture VCSELs: threshold, *I*-*V*, light output

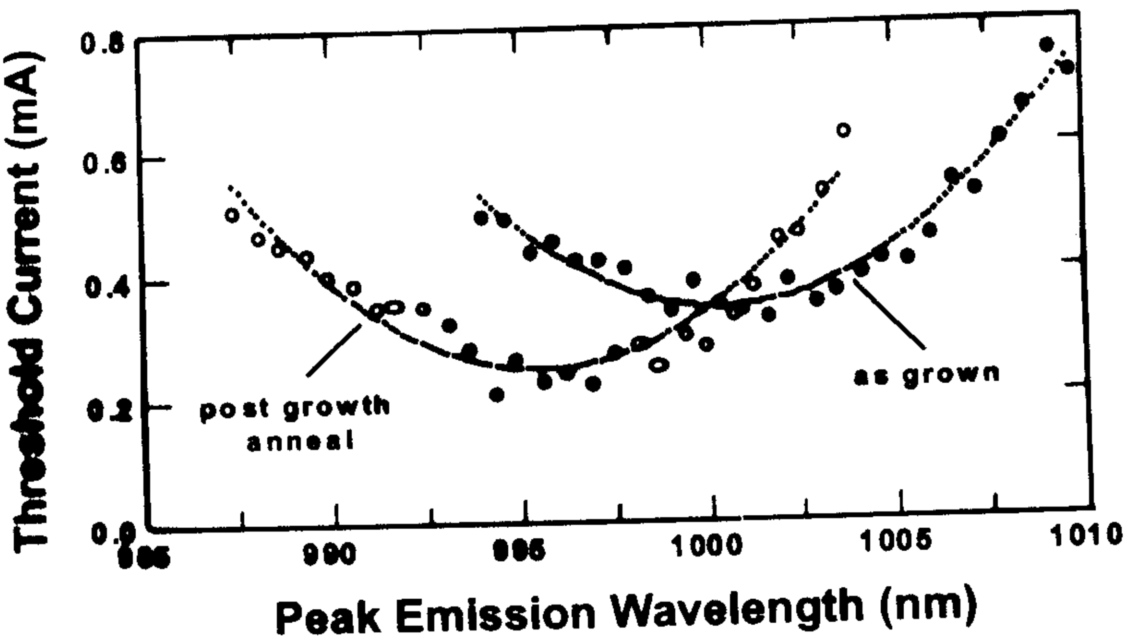


Ultralow threshold currents.

CW output power: 180 μW

Influence of Annealing

Tuning of Properties by Post-Growth Processing

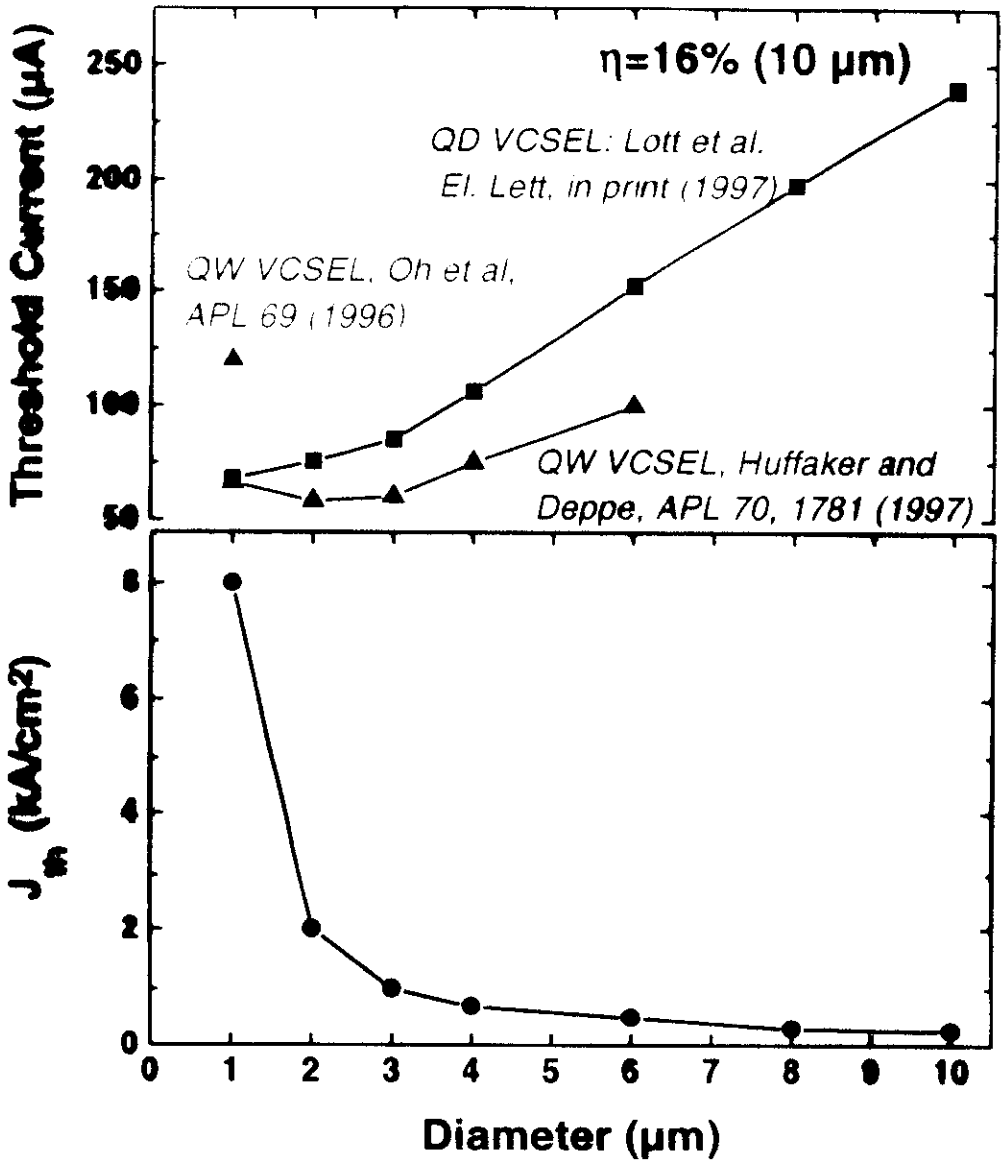


Decrease in threshold current.

Shorter wavelengths.

QD VCSEL:

Ultrasmall Threshold Currents



68 μA for 1 μm aperture
fits to the best QW VCSEL values

Future Trends

Lasers:

Ultralow threshold current density (~10 A cm^{-2})
for reasonable QD size dispersion (10%)
(Theory: L. Asryan, R. Suris, 1995)

Ultrahigh temperature stability.
Ultrahigh material gain. Ultrahigh differential gain.

No transport of nonequilibrium carriers:
- reduced surface recombination,
- no overheating of facets, high power lasers,
- lasers in highly dislocated or type-II matrices (e.g. InAs QDs in Silicon).

1.3 μm and 1.5 μm wavelength range using GaAs substrates.

QD lasers will replace QW lasers for most of the applications.

Infrared Detectors:

Lifting of the *k*-selection rule for infrared light.
No need in surface gratings.

Microelectronics:

Quantum Dot Cellular Automata. Memory Devices.

...

Conclusions:

around 4 years passed since the first report on lasing in self-organized QDs
Ledentsov **et al. Semiconductors 28, 832 (1994), submitted December 29, 1993**

- ***QDs and VCQDs Can Be Used in a New Generation of Devices***

- ***VCQDs Allow Realization of High Quality Lasers***

InGaAs-AlGaAs VCQD Edge-Emitting Lasers:

- ***- Low Threshold Current Density (60 A/cm^2, 300K)***
- ***- High Quantum Efficiency (>90%)***
- ***- High Differential Efficiency (70%)***

COMPARABLE WITH THE BEST VALUES FOR EDGE EMITTING QW LASERS

InGaAs-GaAs VCQD Vertical Cavity Lasers:

- ***- Low Threshold Current Densities (170 A/cm^2, 300 K)***
- ***- Low Total Currents (<70 μA)***

FITS TO THE BEST VALUES FOR QW VERTICAL CAVITY LASERS

NEXT STEP: TO OVERCOME BEST QW LASERS