

Nanophotonics

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Plan of Presentation

- Size effects in semiconductors: the genesis of quantum dots
 - Epitaxial Self-assembled quantum-dot nanostructures
 - Applications of quantum dots in photonics

- Photonic crystals
 - Group velocity dispersion engineering
 - Applications of photonic crystals

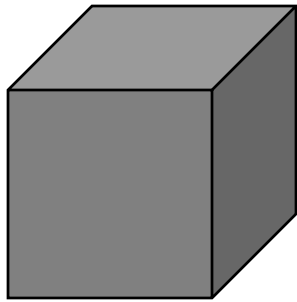
- Challenges

- Summary

Hierarchy of Solid Matter



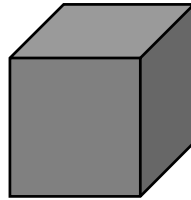
1 cm



Macroscopic

Volume Materials
(e.g. semiconductors)

1 μm



Wavelength
of light
Waveguide

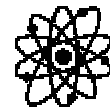
10 nm



de Broglie
wavelength at
300K

Quantum dot

1 \AA



atom

Band Structure

Levels

Size and Length Scale

- Physical size of a dot is on the order of the mean free path of an electronic carrier
- de Broglie wavelength $\lambda = \frac{h}{p} = \frac{h}{\sqrt{3m_e^*kT}}$
- For a type-I heterostructure with conduction band offset

$$\Delta E_c = \frac{\hbar^2 k^2}{2 m_e^*} \rightarrow \frac{\hbar^2 \pi^2}{2 m_e^* d_{\min}^2}$$
$$\Rightarrow d_{\min} = \frac{\pi \hbar}{\sqrt{2 m_e^* \Delta E_c}}$$

- lower bound on size
- Upper bound on size

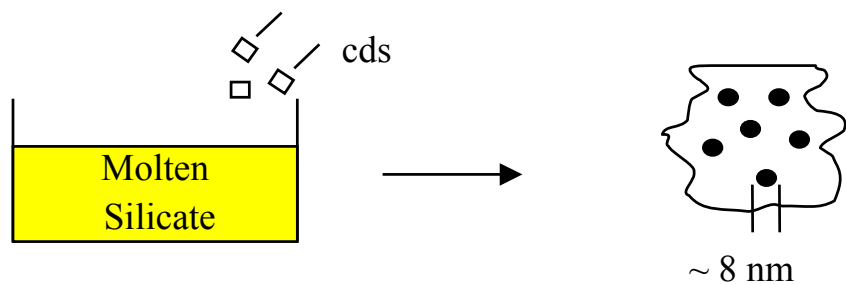
$$kT \leq \frac{1}{3}(E_2 - E_1)$$

- Lateral extent 3 - 5 nm to 12 - 20 nm

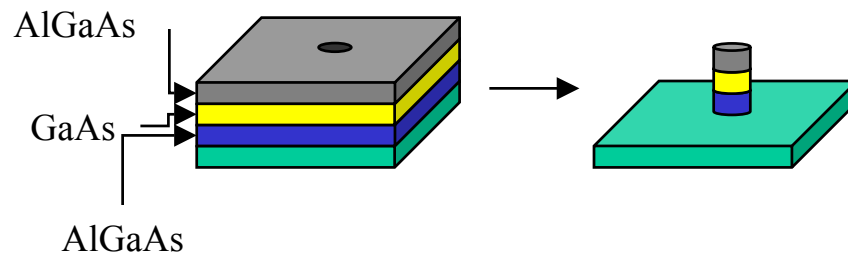
Density of Electronic Energy States

Dimension	3	2	1	0
$\rho(k)$	$\frac{k^2}{\pi}$	$\frac{k}{\pi L_z}$	$\frac{2}{\pi L_x L_y}$	$\frac{2 \delta(k)}{L_x L_y L_z}$
$\rho(E)$	$\frac{1}{2\pi^2} \left(\frac{2m^*}{\hbar^2} \right)^{3/2} \sqrt{E}$	$\frac{m^*}{\pi \hbar^2 L_z}$	$\frac{2}{\pi L_x L_y} \left(\frac{2m^*}{\hbar^2} \right)^{3/2} \frac{1}{\sqrt{E}}$	$2\delta(E)$
Structure	Bulk	Quantum Well	Quantum Wire	Quantum Dot

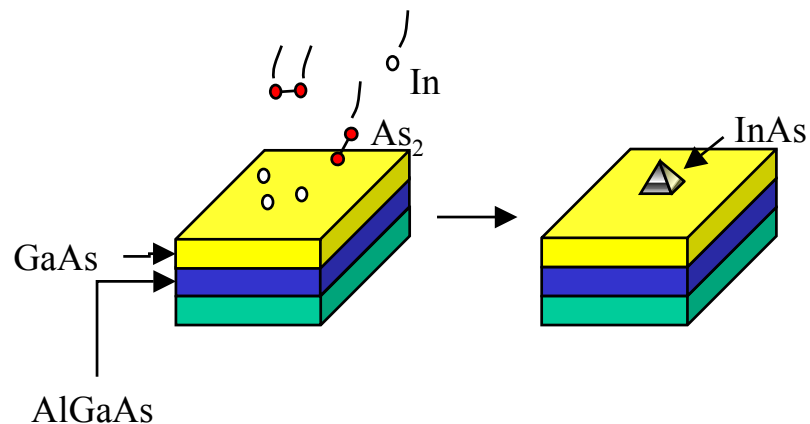
Fabrication of Nanostructures



Microcrystallites in glass

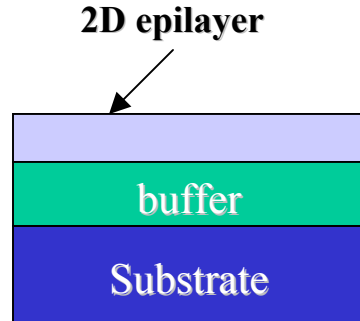


Artificial patterning

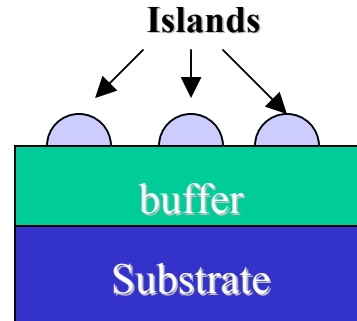


Self-organization

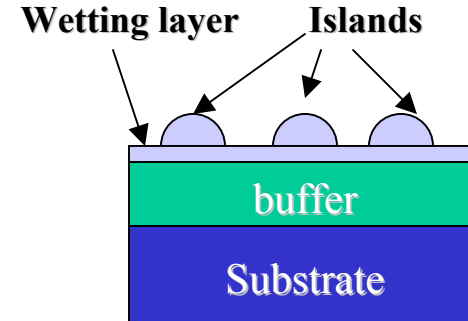
Epitaxial Crystal Growth Modes



Layer-by-layer growth
Frank-van der Merwe

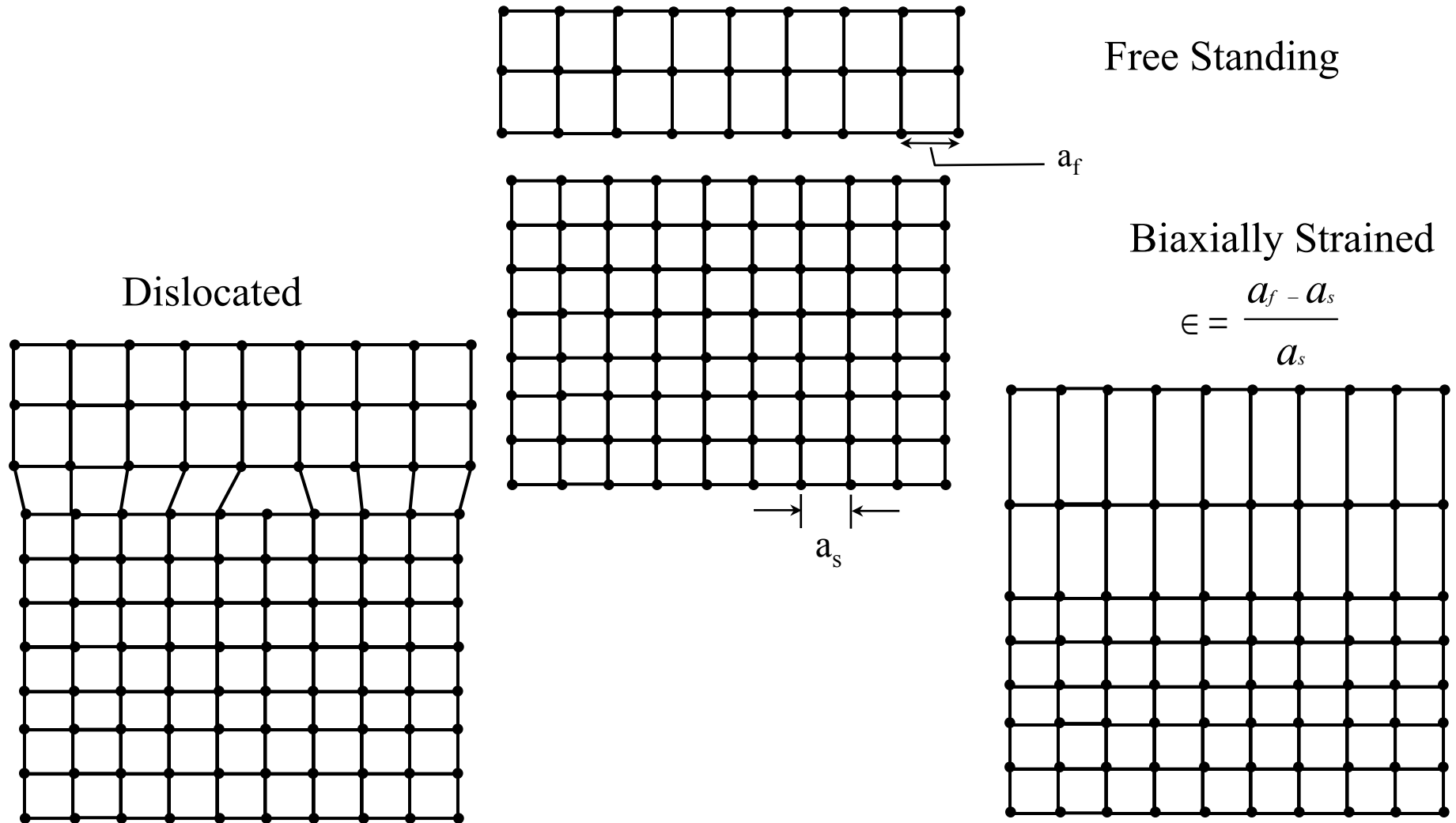


Direct island growth
Volmer-Weber



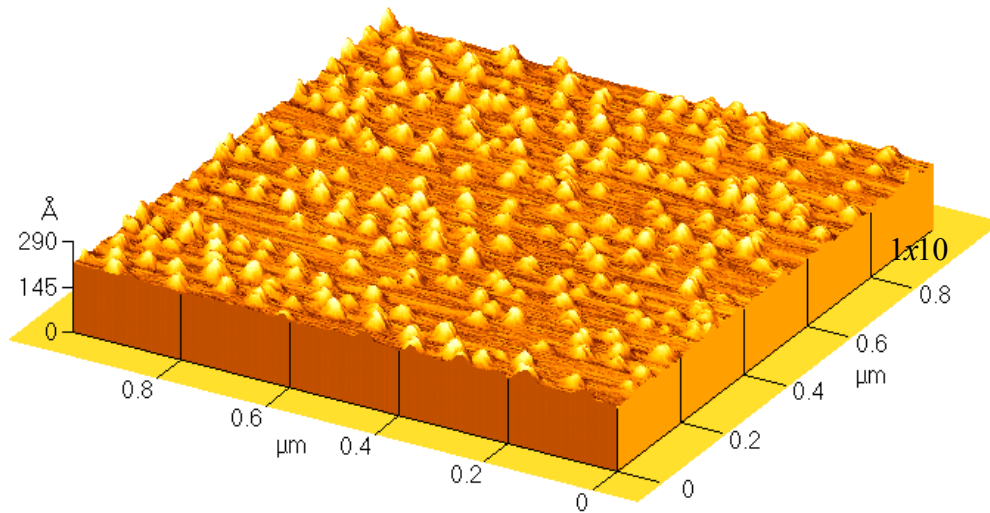
Layer-and-Island growth
Stranski-Krastanow

Pseudomorphic Epitaxy

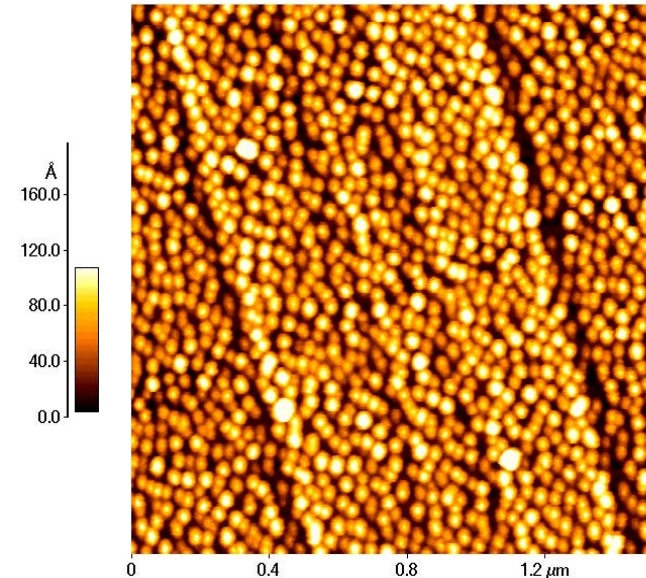


Self-organized Epitaxial (In,Ga)As/GaAs Quantum Dots

Dots have no lateral order

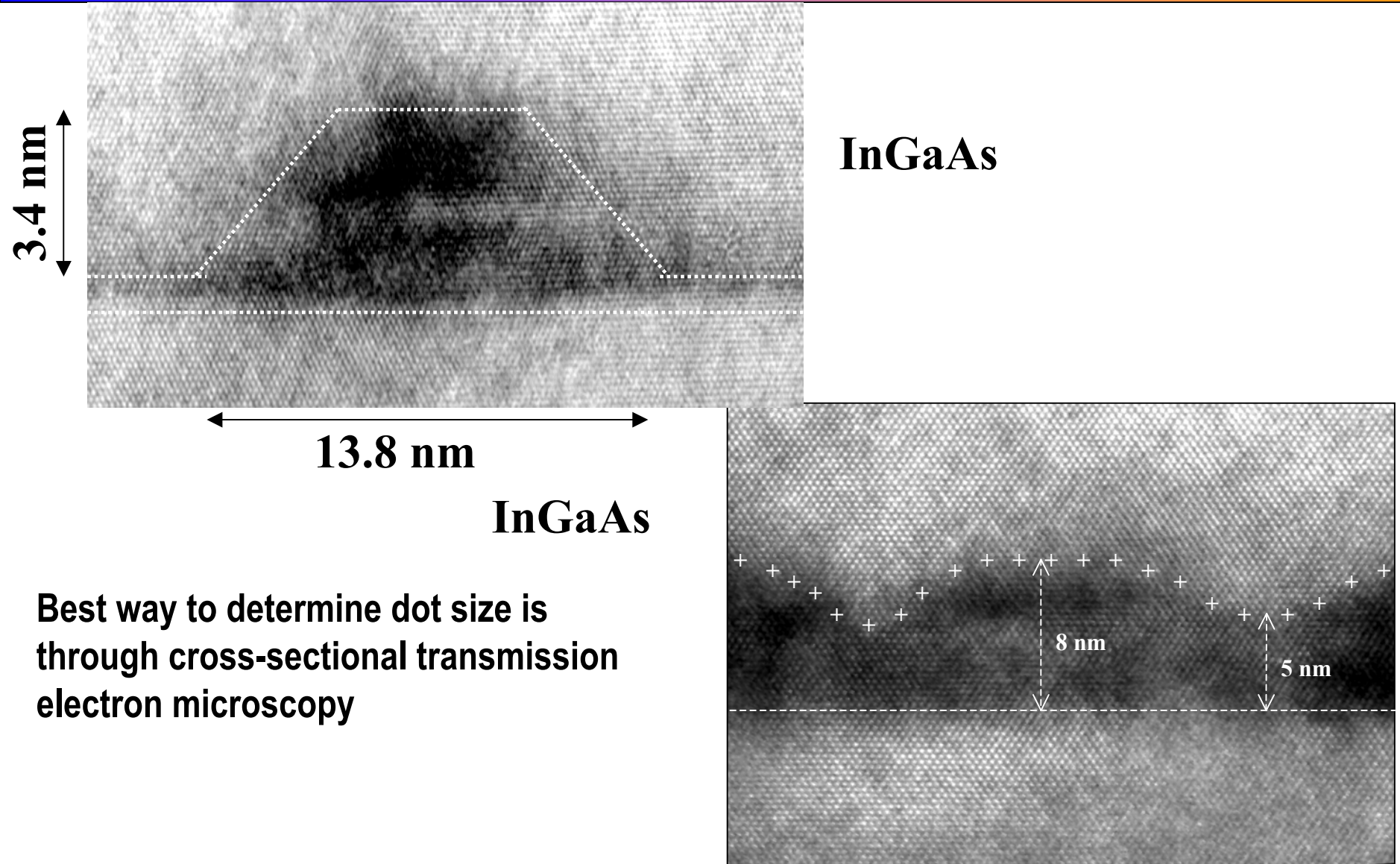


Dots with some lateral order



□ Atomic Force Microscope images of InGaAs quantum dots on a GaAs substrate (the dots are ~15 to 20 nm in lateral extent and range from ~3 to 8 nm)

Dot Size Determination

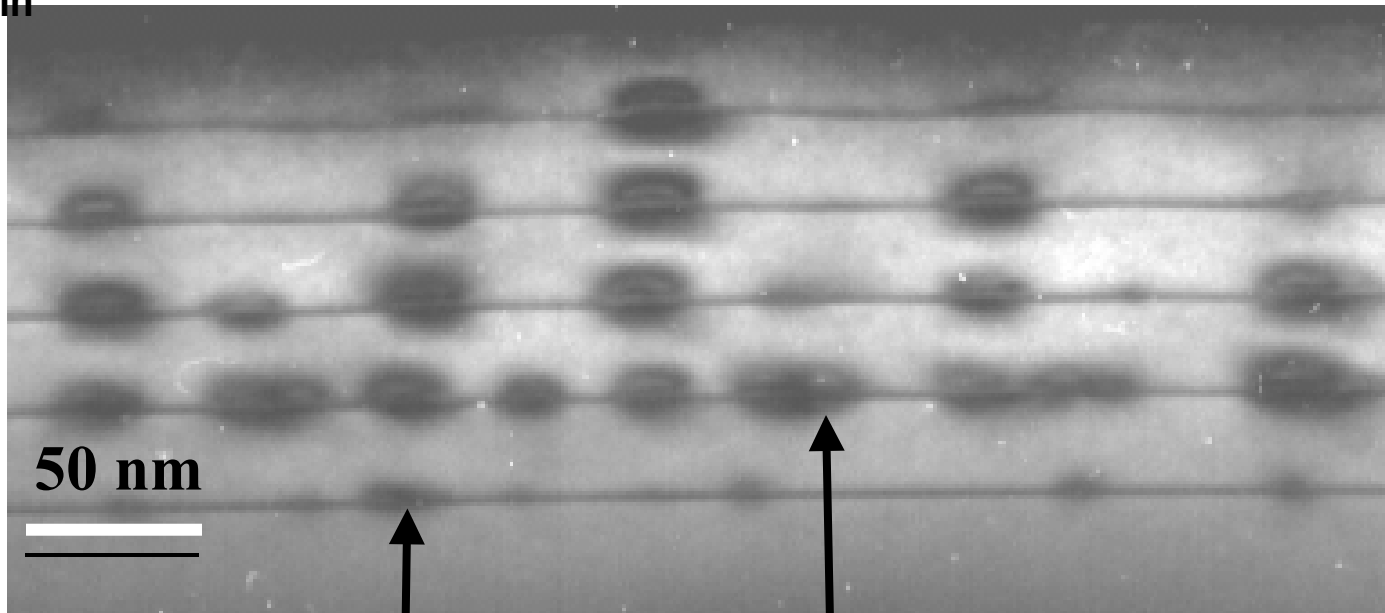


TEM Micrograph of Initial Stages of Vertical Ordering of (In,Ga)As/GaAs Quantum Dots

Vertical ordering of dots



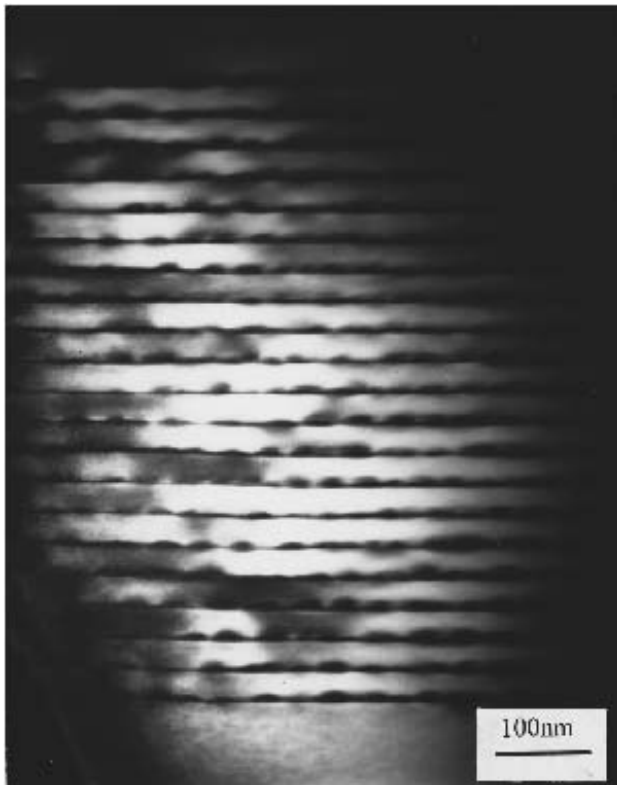
An attempt at ordering the dots through use of lattice-mismatch induced strain



50 nm

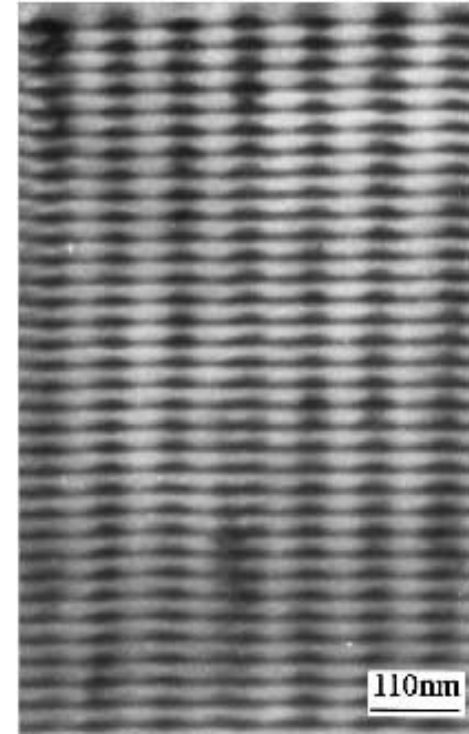
Creation and annihilation of dots

Vertical Order and Disorder in Quantum-dot Superlattices



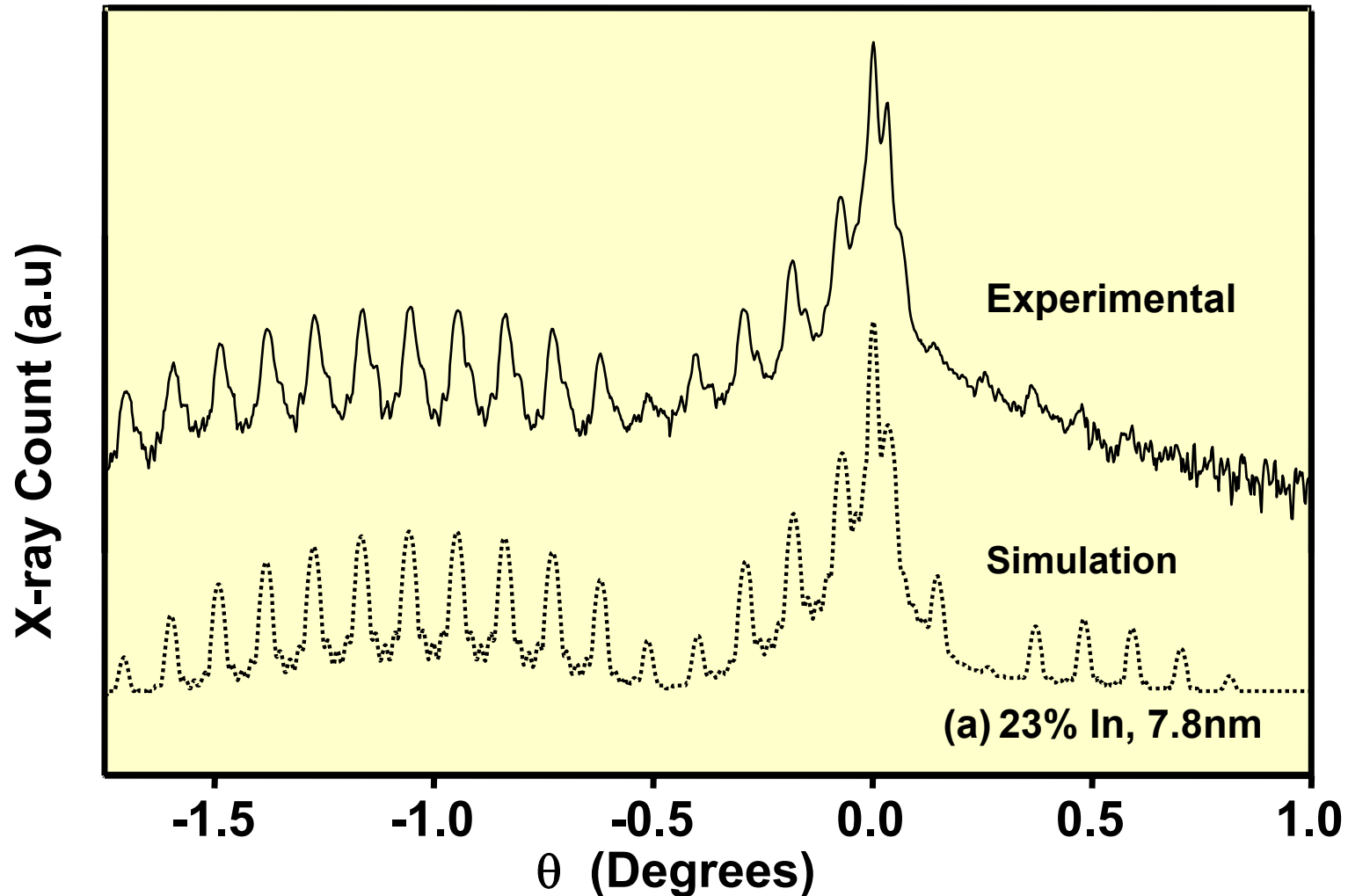
From vertically
← disordered

To vertically
ordered →



□ Transmission Electron Microscope image of disordered and ordered dots. These structures are used in the active regions of electronic and photonic devices

High-resolution X-ray Diffraction Spectra of Epitaxial (In,Ga)As/GaAs Quantum dots



Optical Properties

Determine:

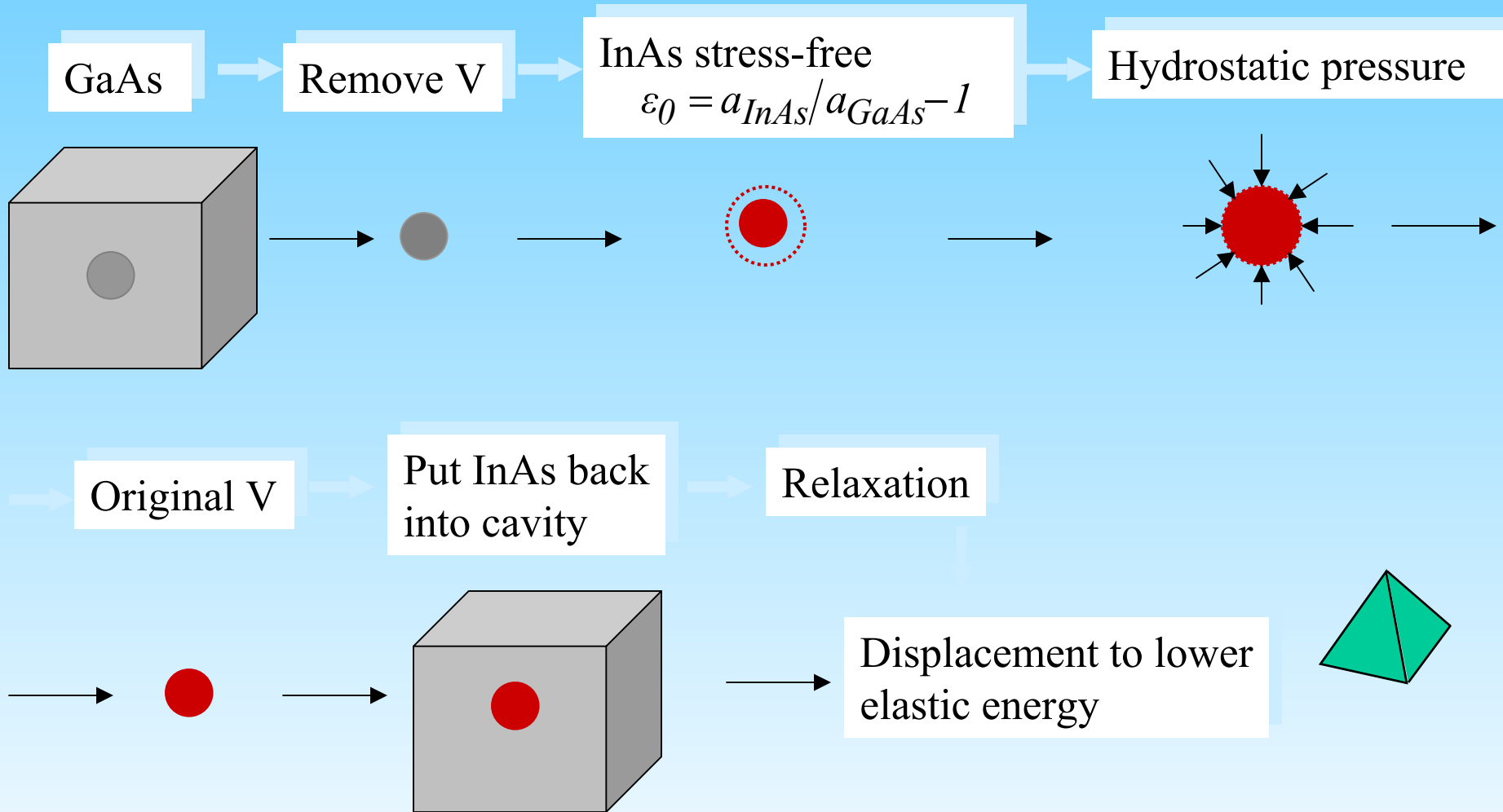
Strain Field

Confinement Potentials

Band Structure via $\bar{\mathbf{k}} \cdot \bar{\mathbf{p}}$

Optical transition energies,
oscillator strength, emission
and absorption

Eshelby's Inclusion Theory



Eshelby(1957): how does the presence of an inclusion disturb the stress field?

Mathematical Methodology

Linear superposition of stresses:

$$\sigma_{ij}^V(r) = \iiint_V \sigma_{ij}^{(sph)}(r - r_0) d^3 r$$

$$\sigma_{ij}^V(r) = \oint_{\partial V} A_{ij} dS + \delta_{ij} \frac{E \varepsilon_0}{1 - \nu} \iiint_V \delta(r - r_0) d^3 r$$

r_0 = point on surface

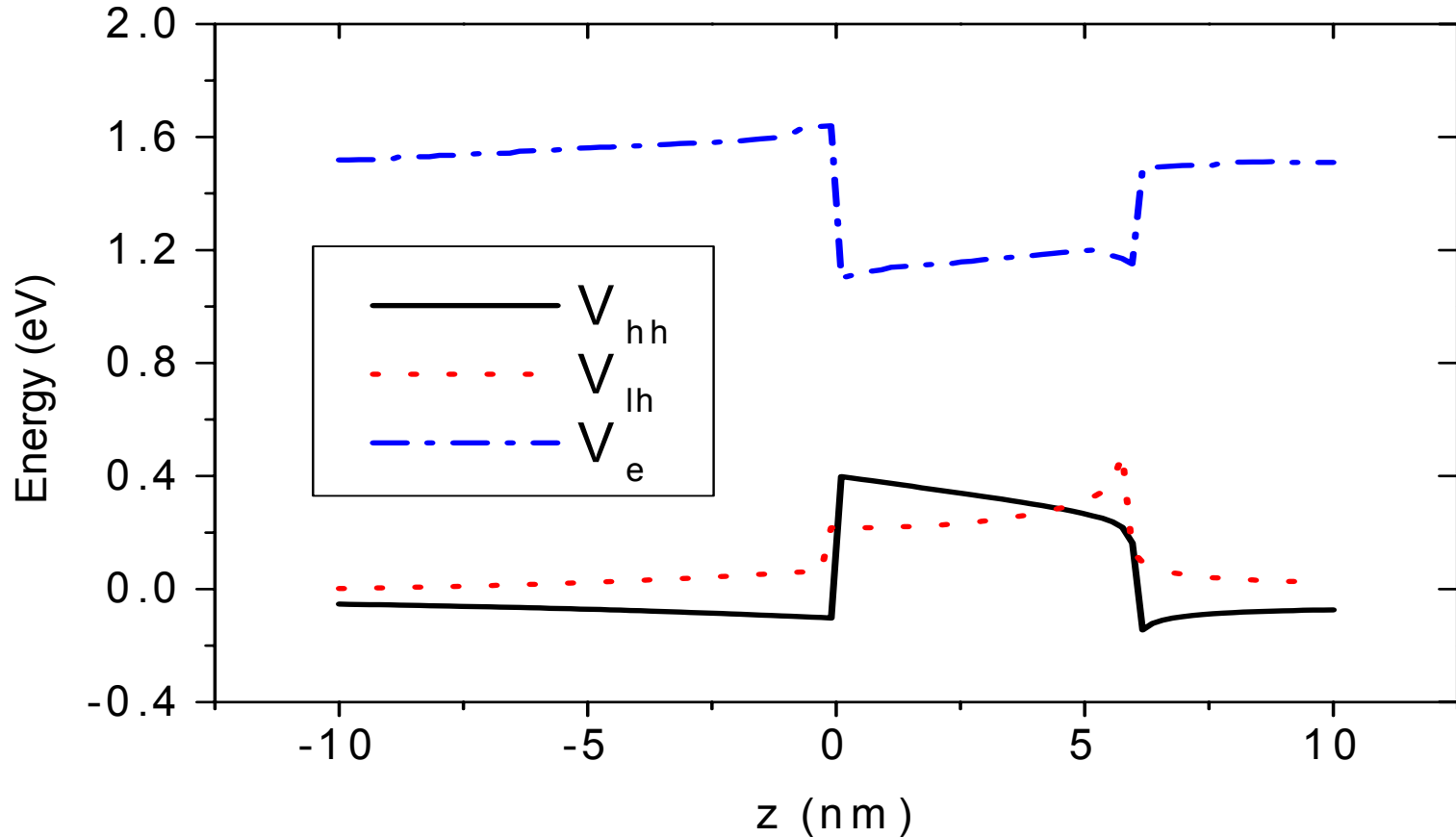


Numerical integration over facets: ε_{xx} , ε_{yy} and ε_{zz}

hydrostatic strain: $\varepsilon_h = \varepsilon_{xx} + \varepsilon_{yy} + \varepsilon_{zz}$

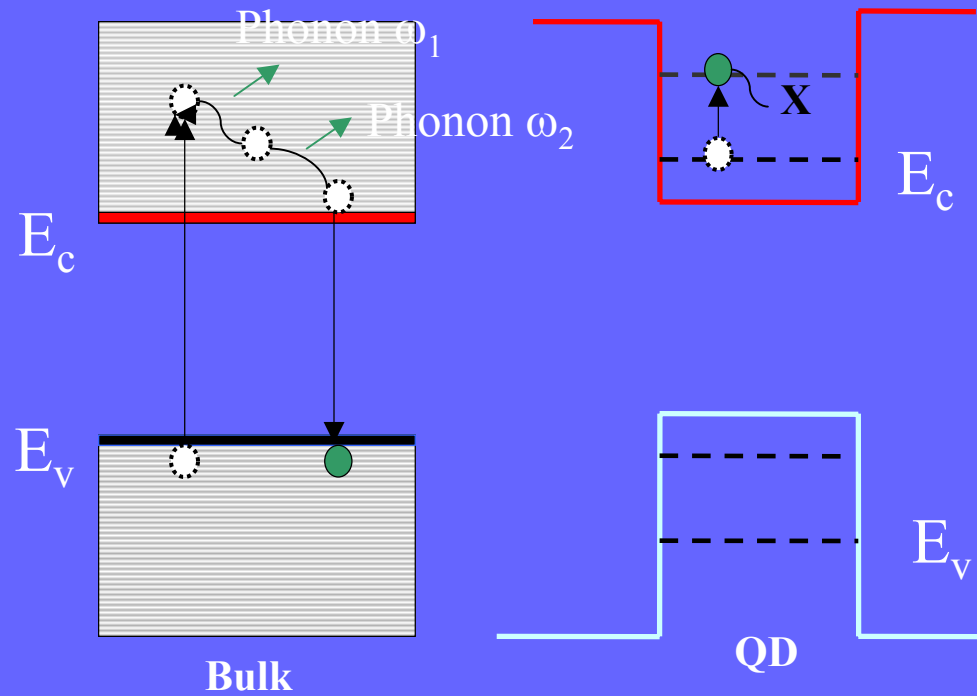
biaxial strain: $\varepsilon_b = 2\varepsilon_{zz} - (\varepsilon_{xx} + \varepsilon_{yy})$

Confining Potentials



Electron, Heavy- and Light- hole potentials along z-axis

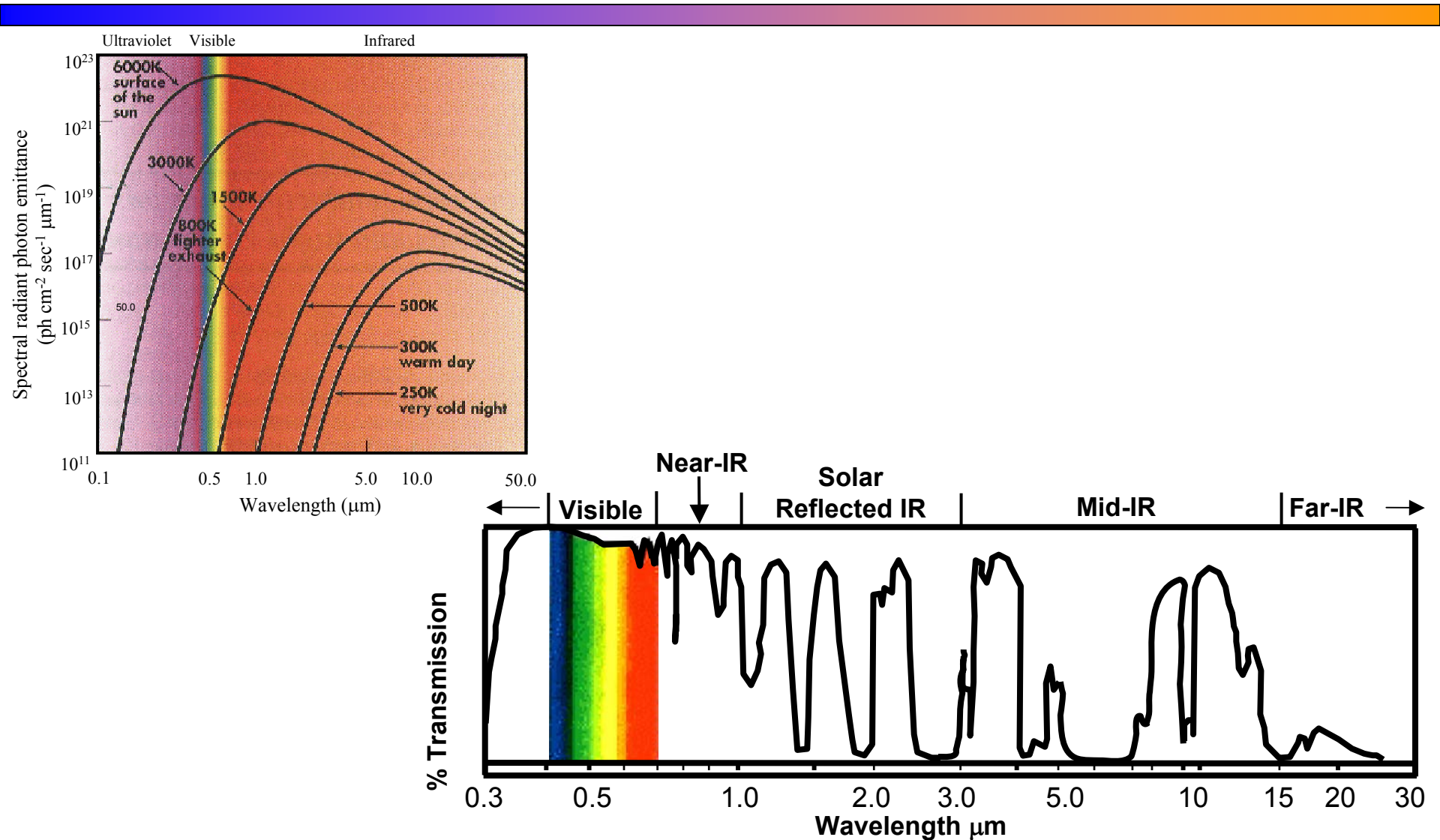
Energy States in Bulk/Quantum-Dot Semiconductor



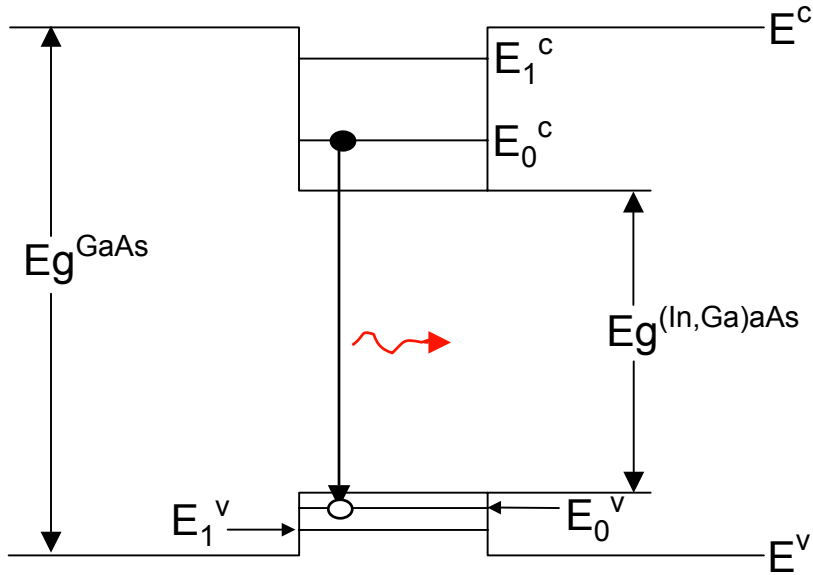
Applications of Quantum Dots

- Electronic devices
 - Single electron transistors
 - Storage elements (memory)
- Biological bar-coding
 - Tags for cells (genotyping)
 - Blood assays
- Optical devices
 - Lasers
 - Detectors

Critical Spectral Bands



Engineered Emission and Absorption Wavelengths



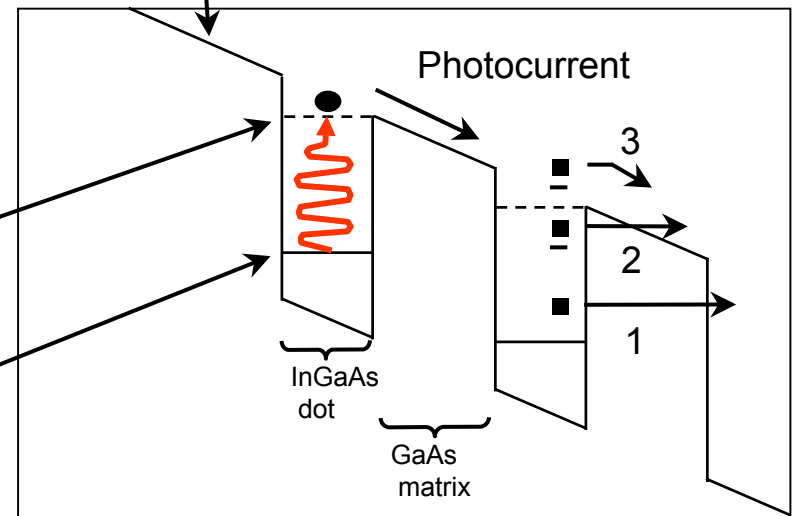
For interband light sources

For intraband photodetection

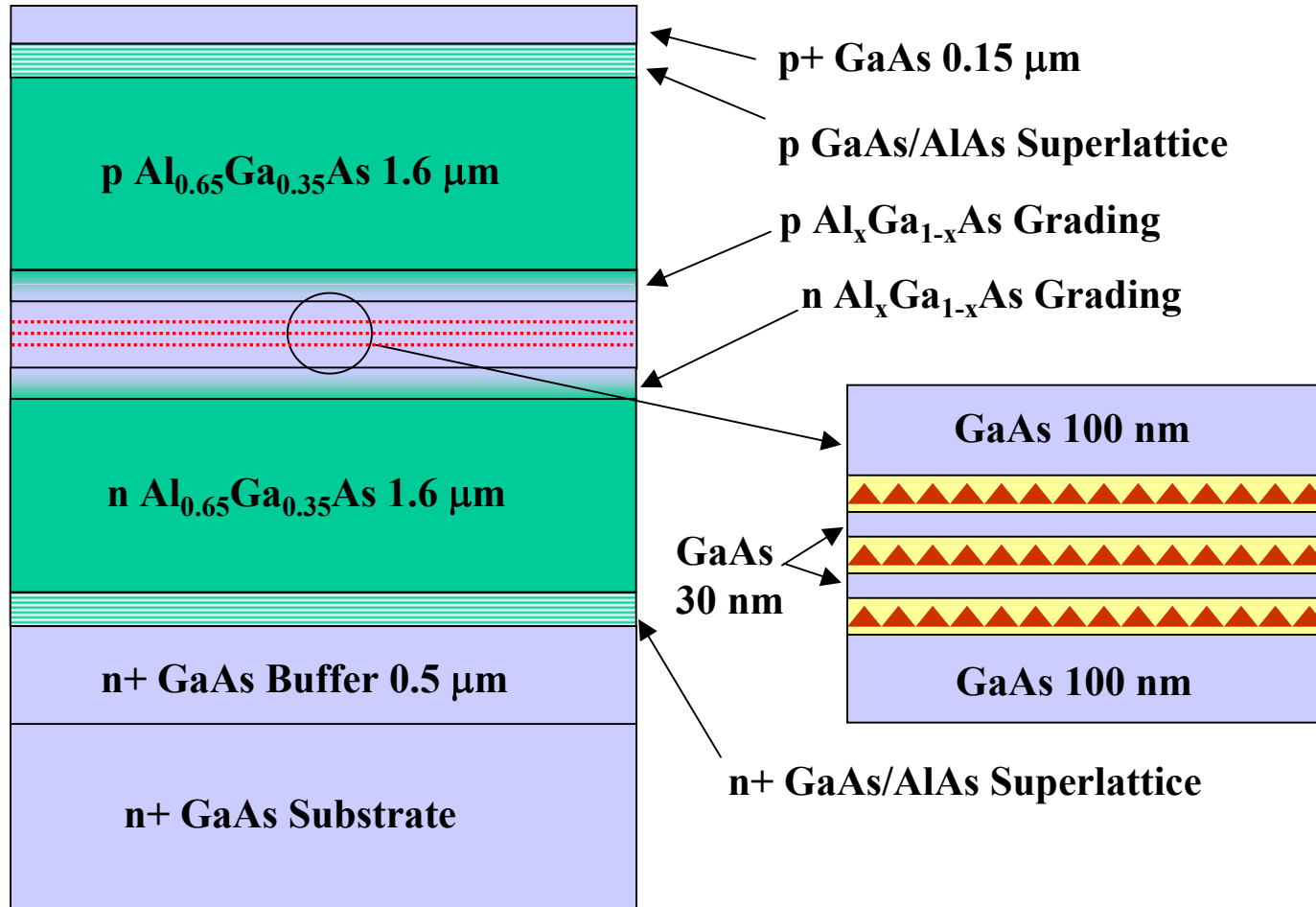
Quasi-bound excited state

Ground state
(photon is absorbed)

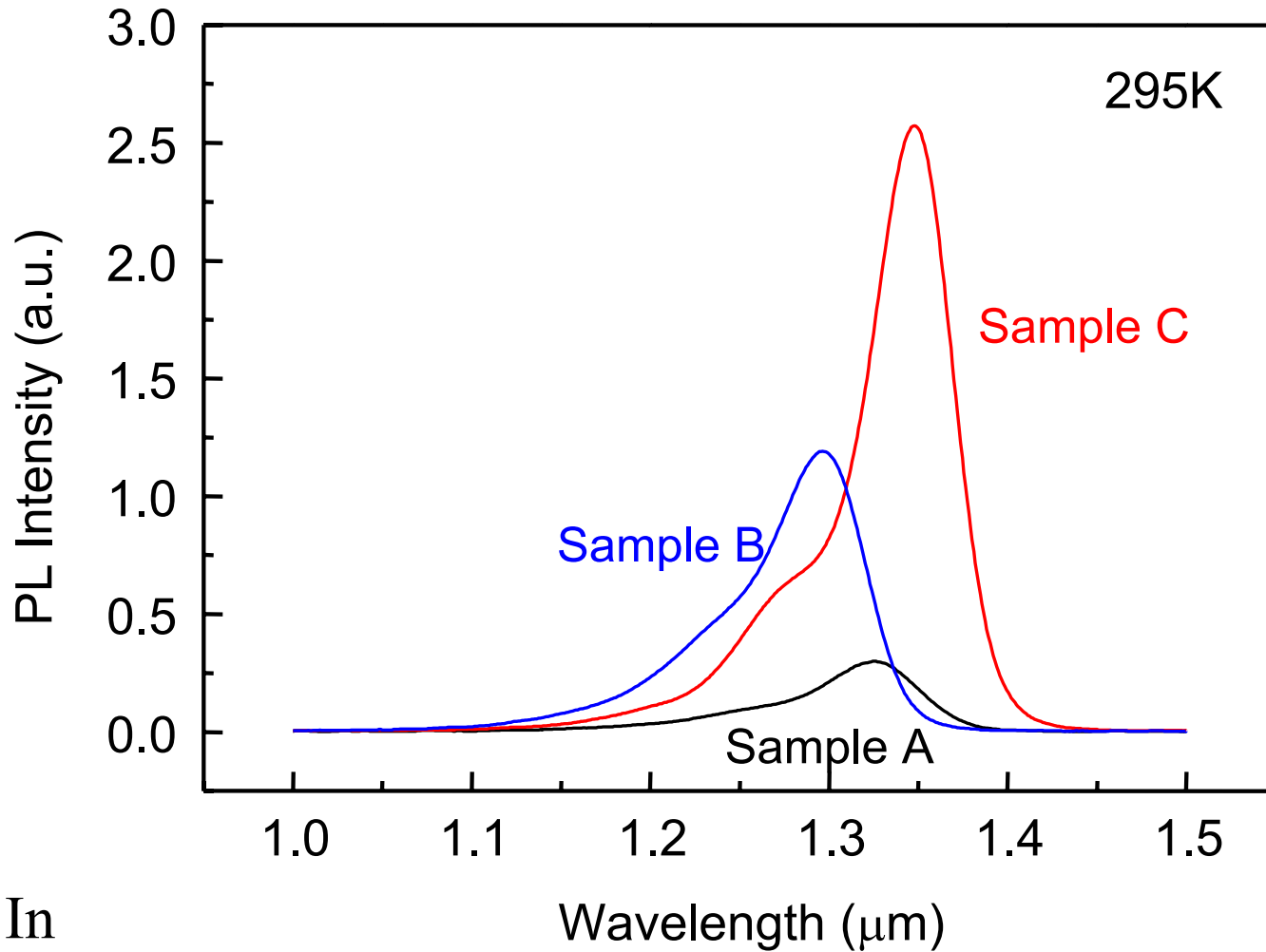
Conduction band



Schematic of a Typical QD Laser Structure

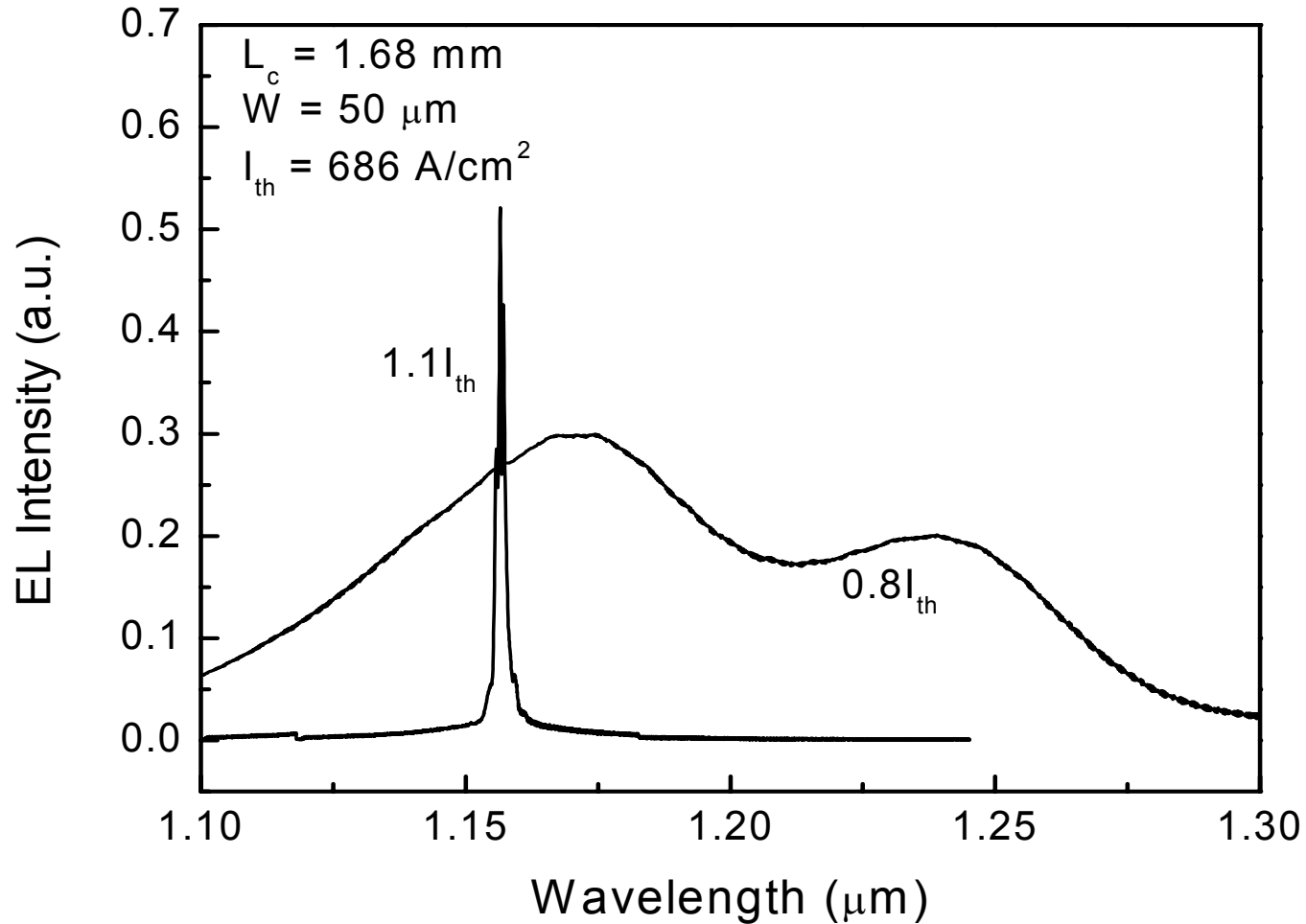


The emission intensity of (In,Ga)As QDs

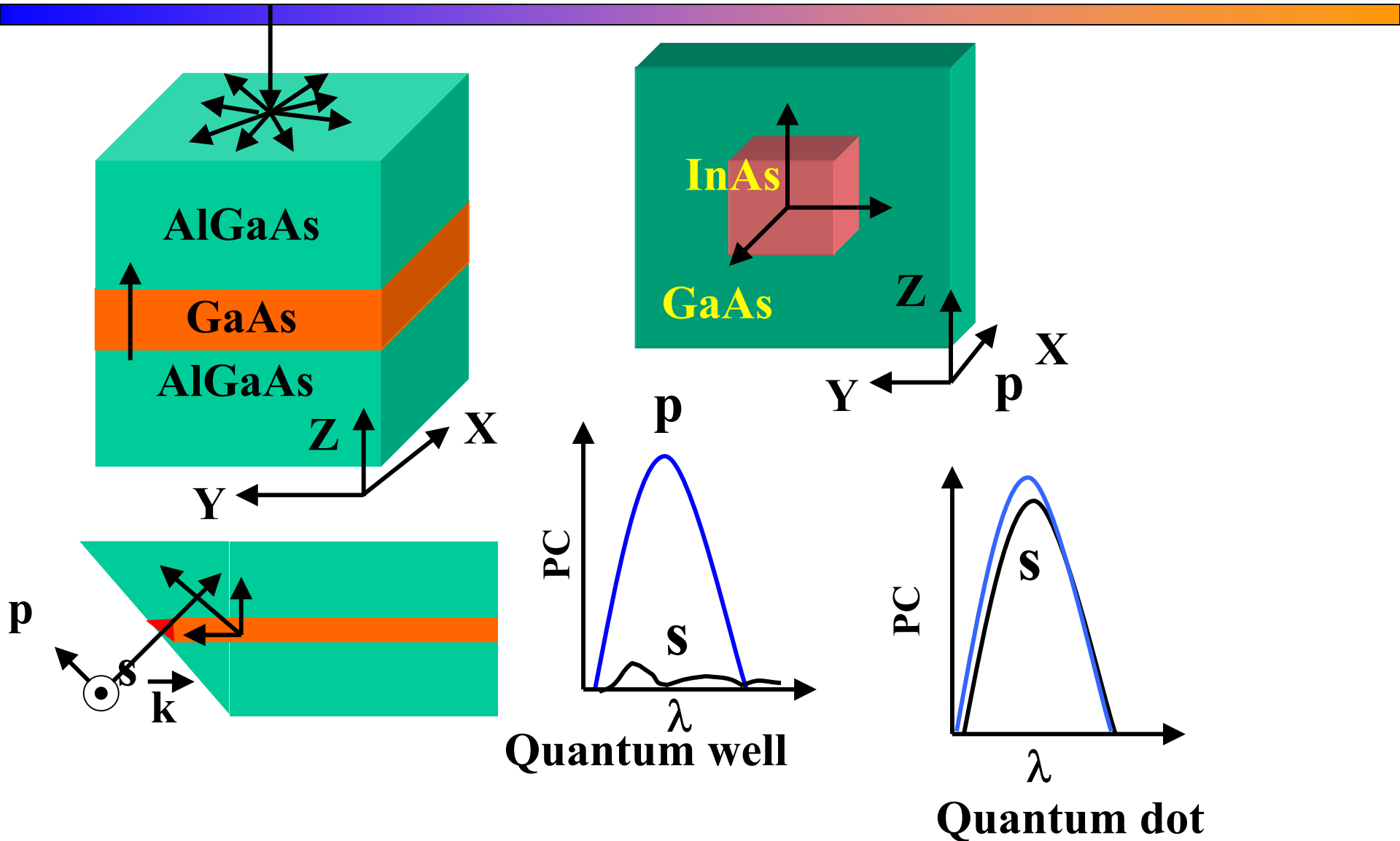


25% In

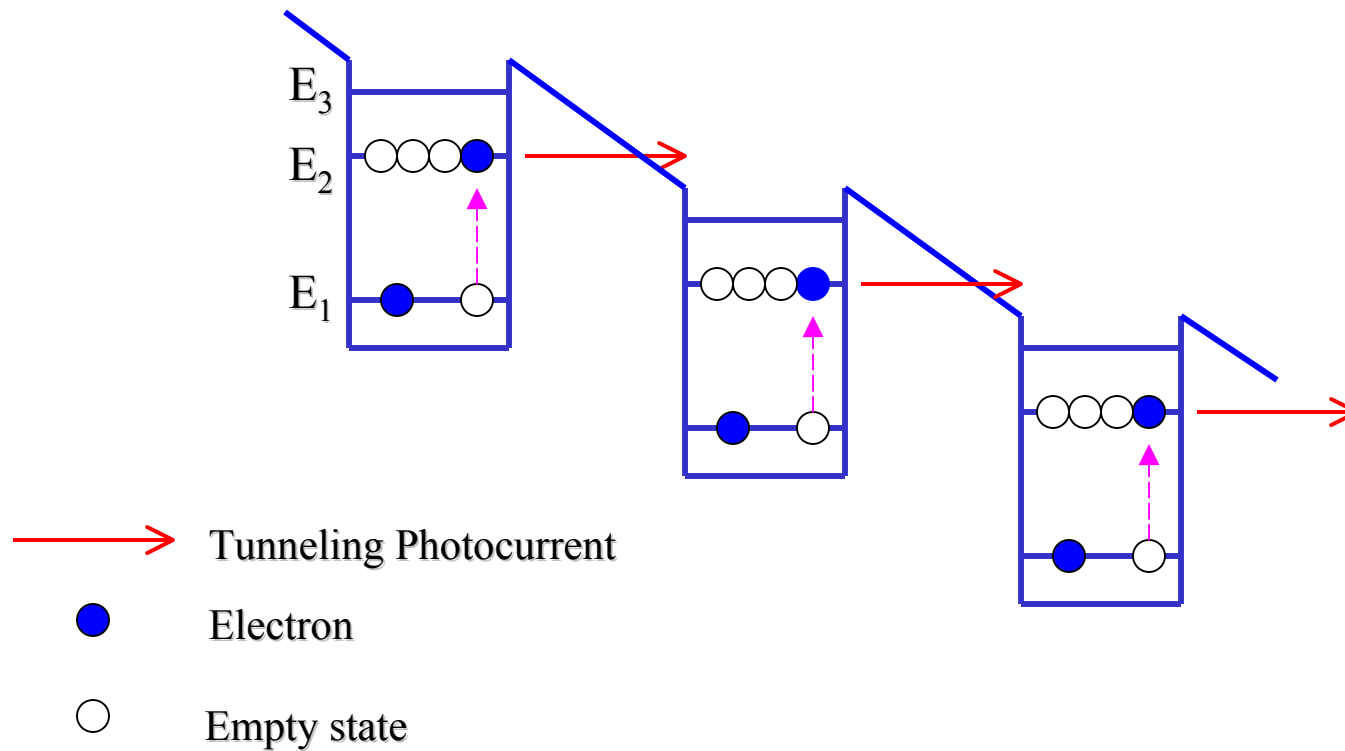
Electro-luminescence Spectra



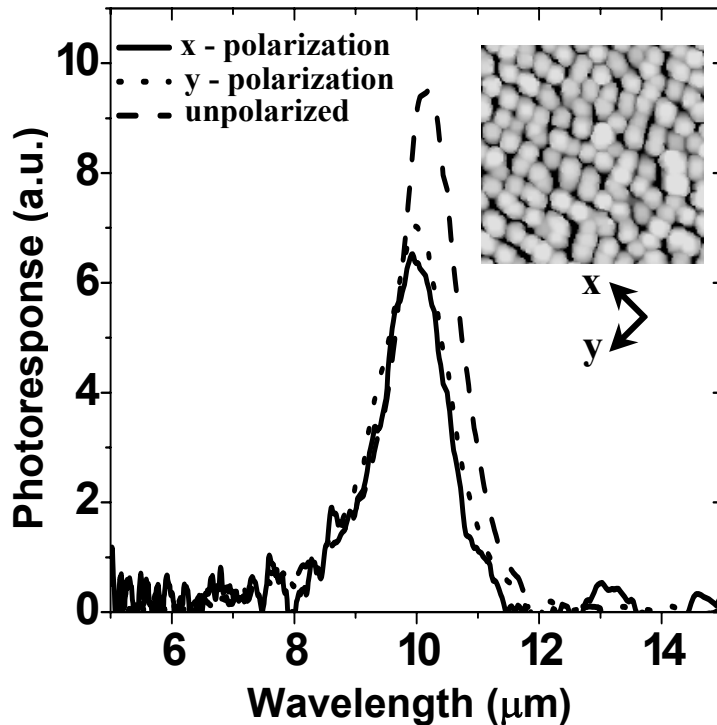
Quantum Mechanical Absorption Rules



Operation of Quantum-dot Infrared Photodetectors (Transport)



Anisotropic in-plane inter-sublevel absorption of (In,Ga)As quantum dots



- In-plane anisotropic photoresponse for polarized and unpolarized light at 78 K
- Goal: to synthesize uniform-size dots so that the in-plane photoresponse is isotropic

Outline

- Size effects in semiconductors: the genesis of quantum dots
 - Self-assembled quantum-dot nanostructures
 - Applications of quantum dots in photonics
- Photonic crystals
 - Group velocity dispersion engineering
 - Applications of photonic crystals
- Summary
- Challenges

Light Waves in Periodic Media: Photonic Crystals

Waves in periodic media can:

- Propagate without scattering
- Have regions of frequency bands that are not allowed to propagate

Mathematically, the propagation is described by Maxwell's Wave Equation

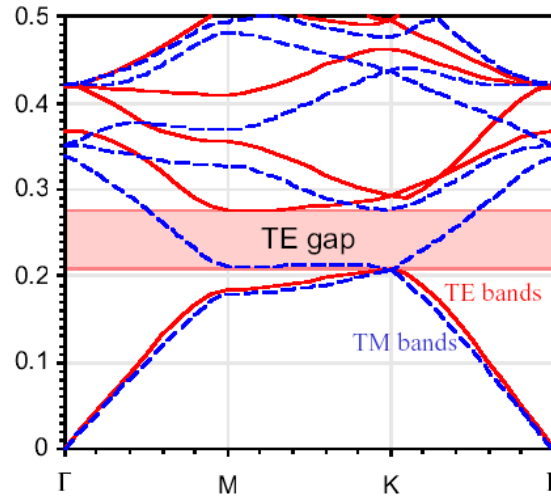
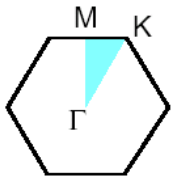
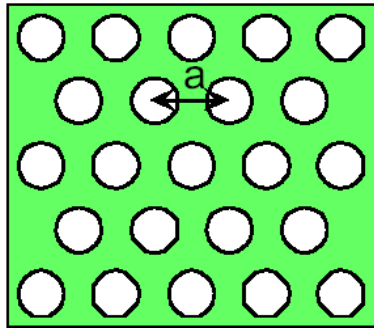
$$\left[(\nabla + j\vec{k}) \times (\nabla + j\vec{k}) \times \right] \vec{H}_{\vec{k}} = \epsilon(x) \left(\frac{\omega_n(\vec{k})}{c} \right)^2 \vec{H}_{\vec{k}}$$

↑
Periodic dielectric constant

Eigen problem---Solutions are of the Bloch form:

$$\vec{H} = e^{j(\vec{k} \cdot \vec{x} - \omega t)} \vec{H}_{\vec{k}}(\vec{x})$$

Nanostructured Materials: Photonic Crystals

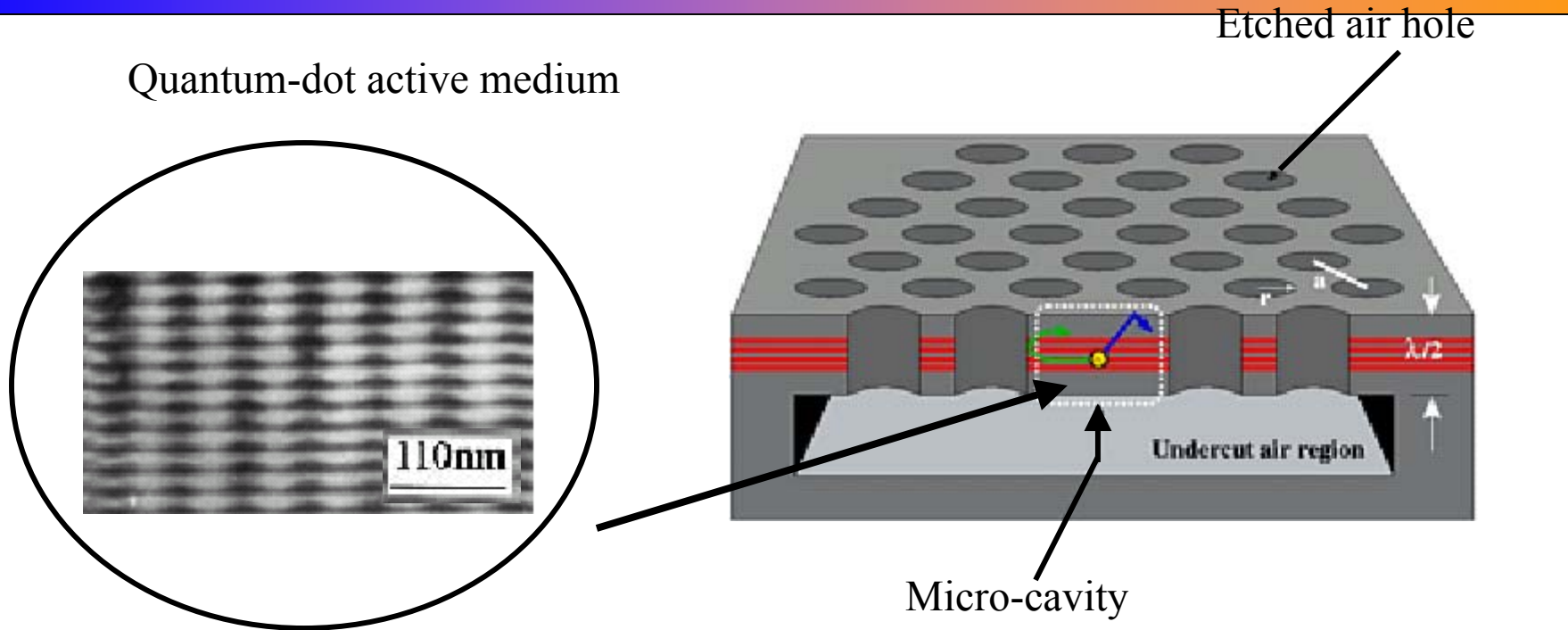


➤ Photonic crystals have “band gaps,” and can be “doped” to control the behavior of photons.

S. Johnson et al. APL [77](#), 3490 (2000)

➤ Photonic crystals are periodically nanostructured 1-D, 2-D or 3-D dielectric or semiconducting materials that mold the flow of photons in a medium the way semiconductors control the propagation properties of electrons through them.

Photonic Crystal Based Micro-cavity Lasers



Photon confinement:

—▶ Total internal reflection

—▶ Bragg reflection

Challenges

➤ Quantum Dots:

- To date, there are no known ideal methods for ordering self-assembled quantum dots in all three dimensions
- Lithographic or non-lithographic (self-assembled) templates may offer an option

➤ Photonic Crystals:

- Difficult to minimize scattering losses from non-perfect features
- Fabrication requires sophisticated tooling and time (expensive)

Summary

- Pristine nanostructured materials are challenging to fabricate
- They offer novel properties that can be used in the design of new optical devices
- There is a potential for the design of truly integrated photonic circuits

Education – the mix of technical foundation

Liang Chen (**EE**)

Debdas Pal (**Materials Science**)

Dong Pan (**Materials Science** and **Physics**)

Gabby Storelu (**Physics**)

and

Stephen Kennerly (**EE** and Physics), ARL

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