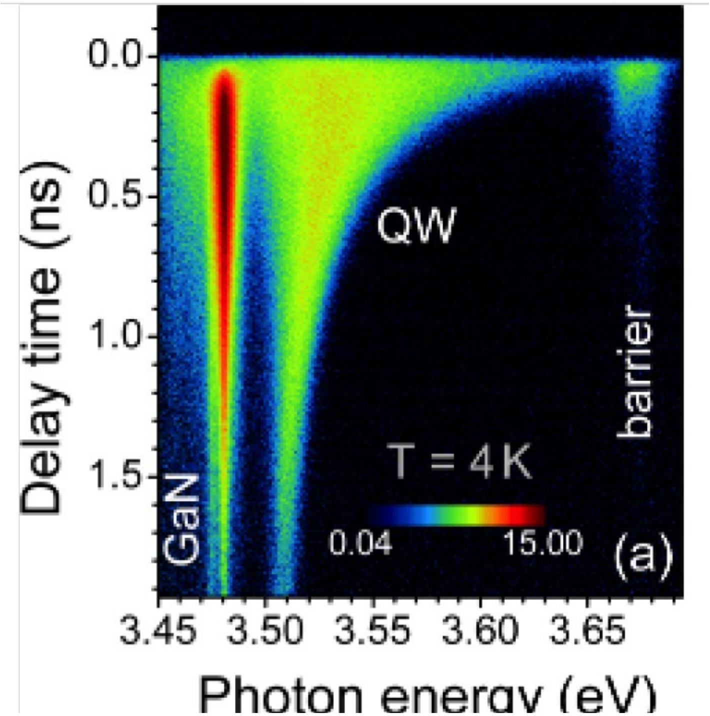
Advanced III-nitride semiconductor devices



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Optical devices

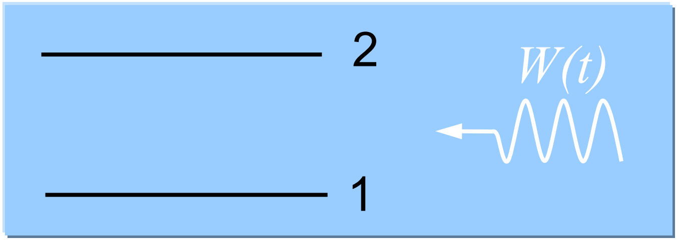
- Optical properties and basics

- Quantum wells

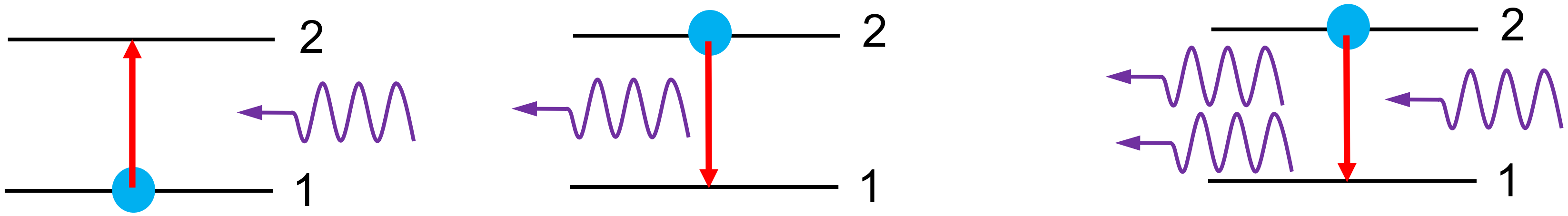
Introduction

Light-matter interaction

Electron-photon interaction



2 level system



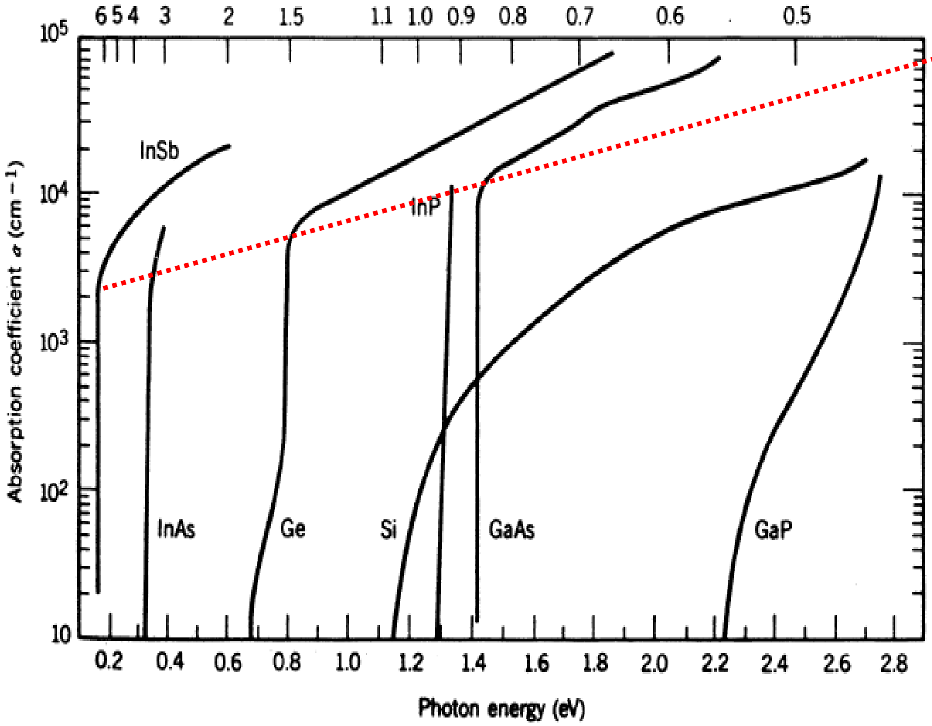
Absorption Spontaneous emission Stimulated emission

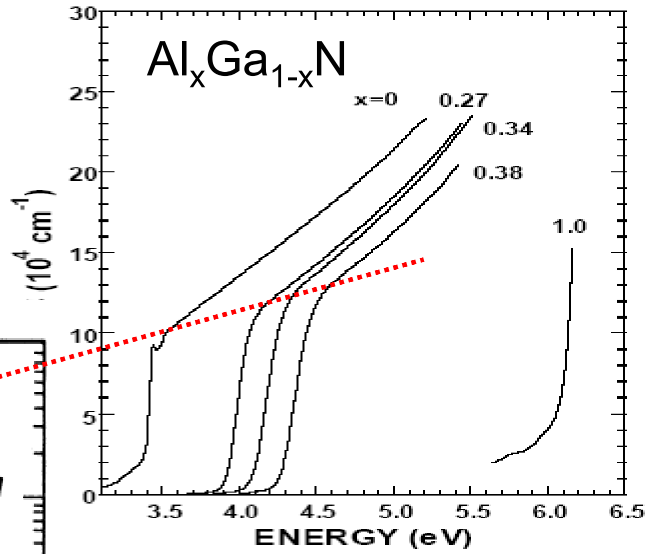
Optical properties

Absorption coefficient: bandgap dependence

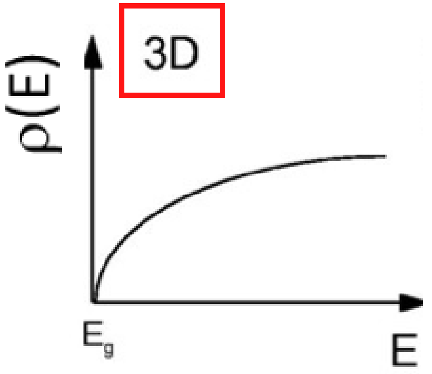
$$I(z) = I_0\, e^{-\alpha z}$$

α is the absorption coefficient





Bulk

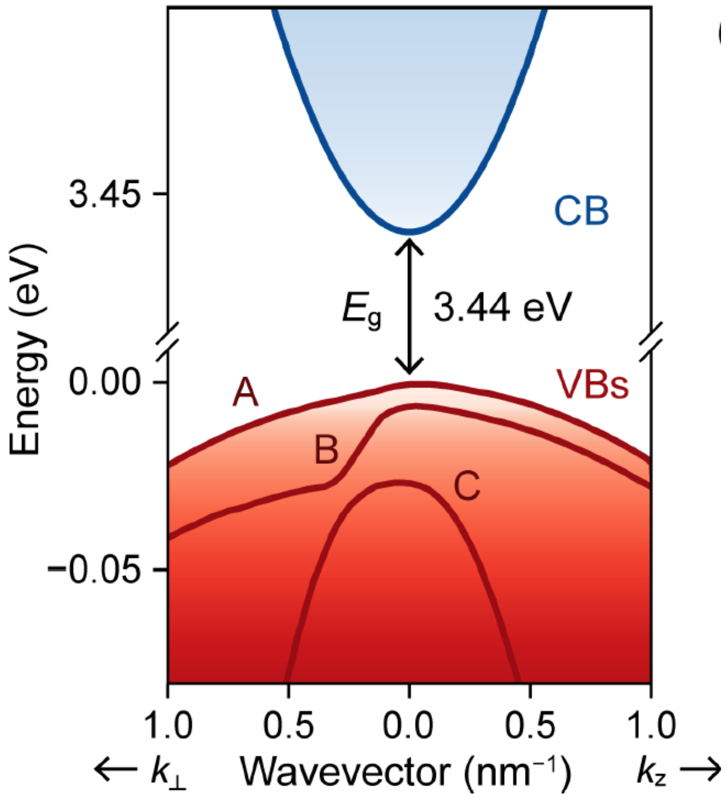


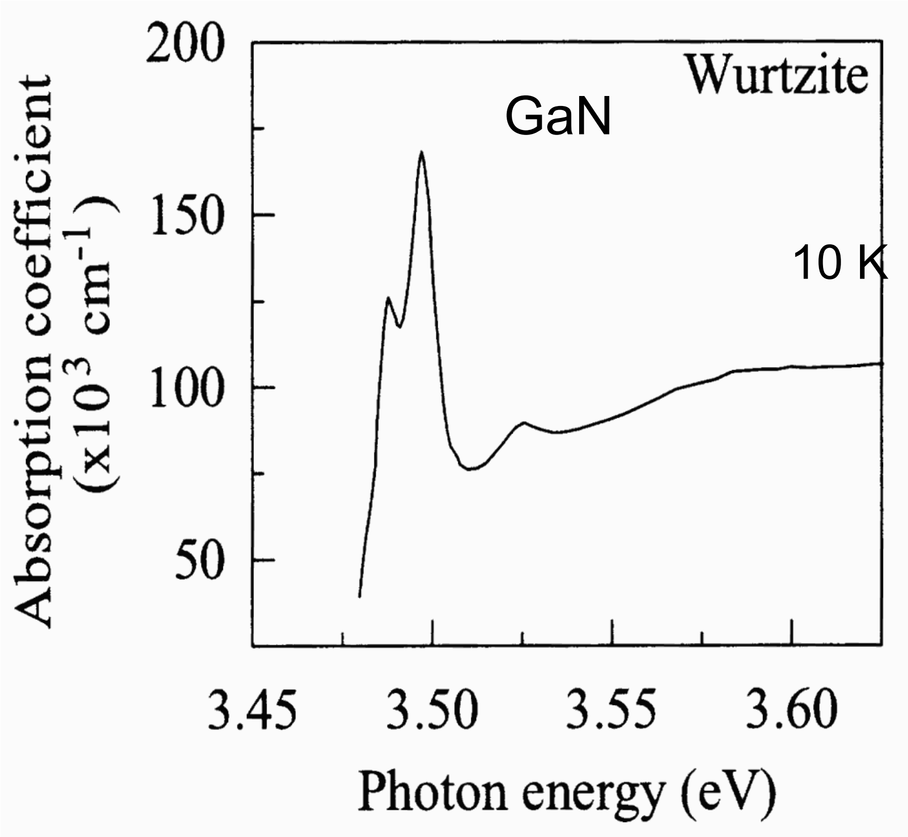
The absorption coefficient α, defined at the absoption edge, increases with the band gap energy

$$\rho_{3D}(E) = \frac{dN_{3D}(E)}{dE} = \frac{1}{2\pi^2}\left(\frac{2m^*}{\hbar^2}\right)^{3/2}\sqrt{(E - E_0)}$$

Optical properties

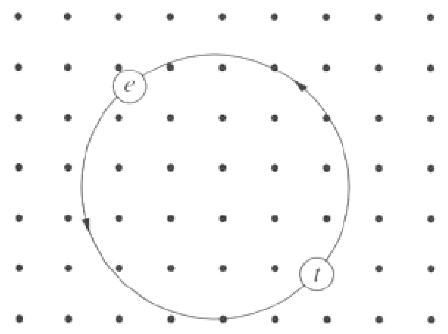
Absorption in bulk GaN



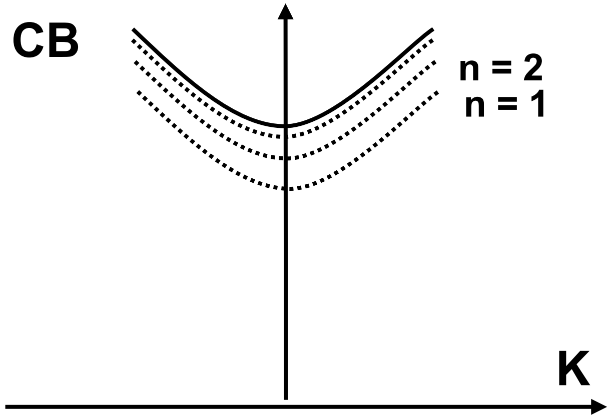


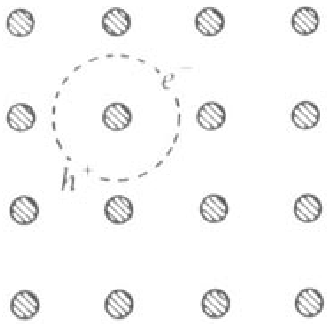
Optical properties

Exciton: electron-hole pair in coulomb interaction



Wannier exciton





Frenkel exciton

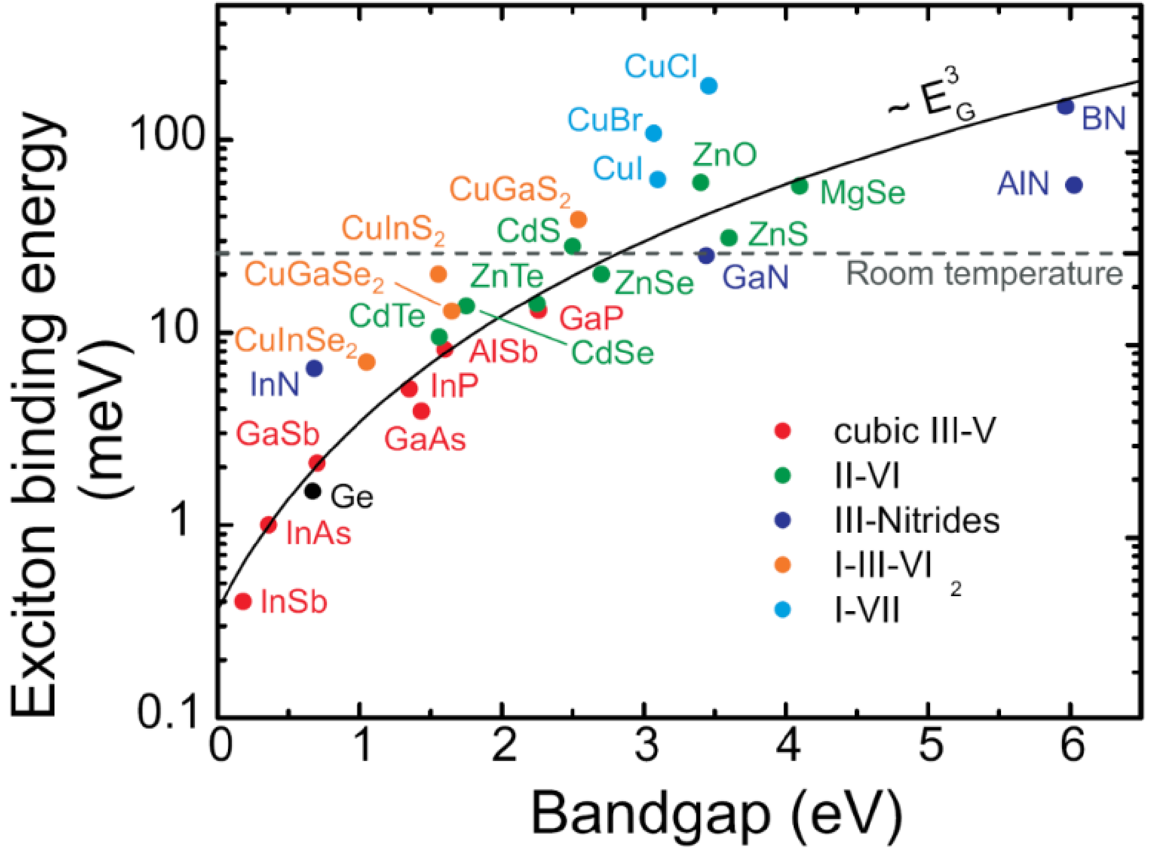
Hydrogenoid model

$$E_{nK} = E_g + \frac{\hbar^2 K^2}{2M} - \frac{Ry^*}{n^2}, \qquad n = 1, 2 \ldots,$$

$$Ry^* = \frac{m_r}{m_0} \frac{\varepsilon_0^2}{\varepsilon^2} Ry \qquad 1/m_r = 1/m_e + 1/m_h$$

Optical properties

Exciton: electron-hole pair in coulomb interaction



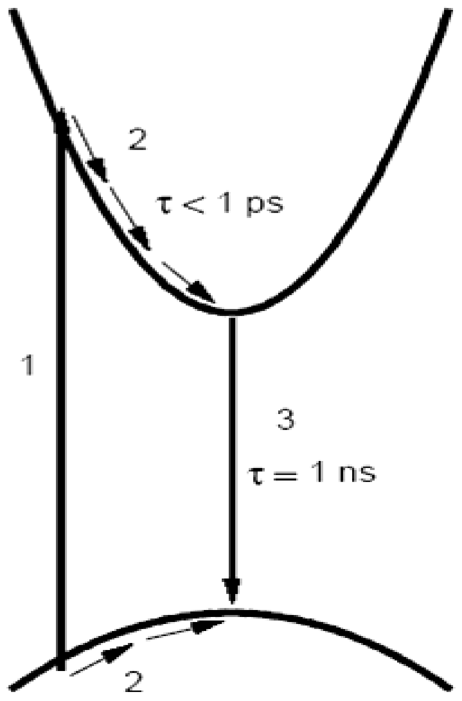
GaN: binding energy of 25 meV

⇨ 65% of the carrier population is excitonic at 300 K

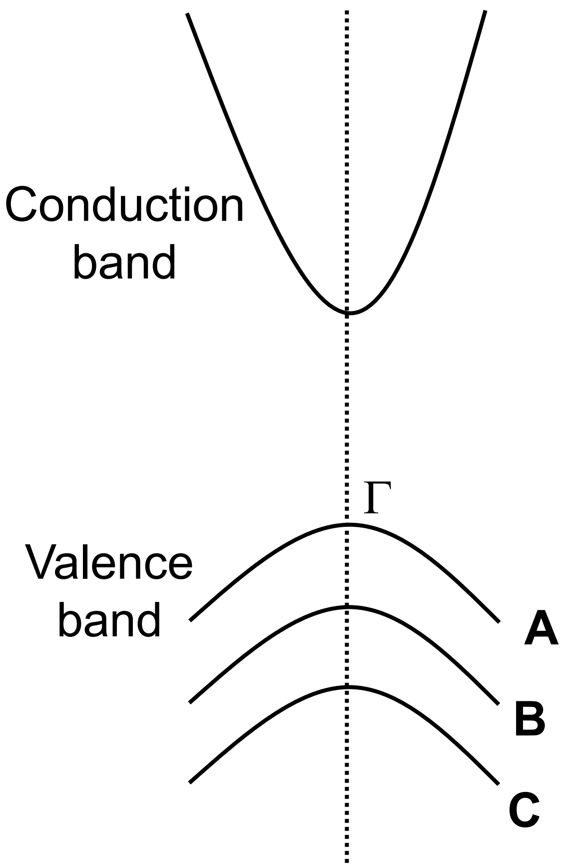
Optical properties

Spontaneous emission - photoluminescence

Photoluminescence and reflectivity (GaN)



“hot” carriers (electrons and holes) release their kinetic energy via optical and acoustic phonon emission

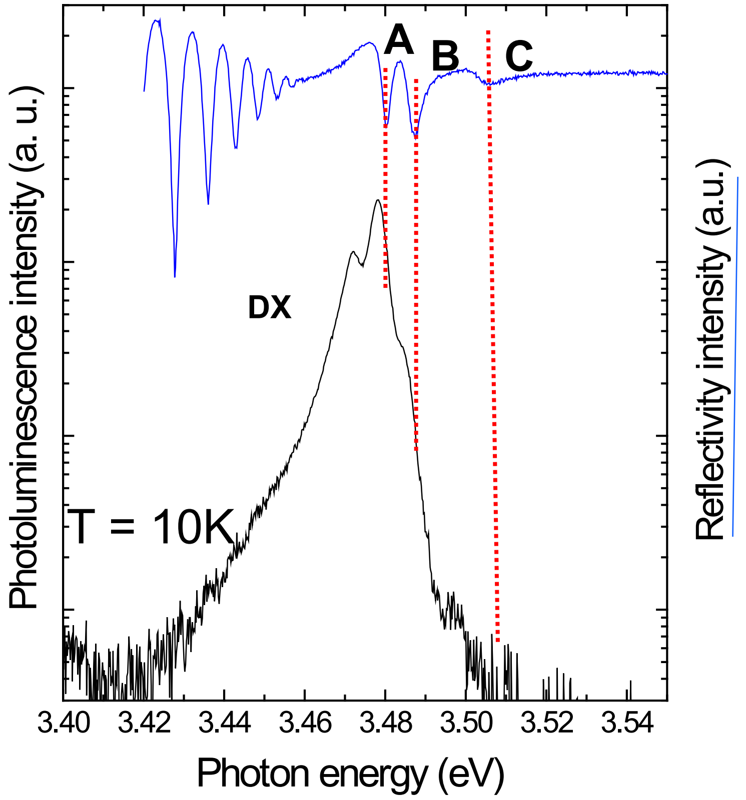


Unstrained GaN:

E_A = 3.478 eV

E_B = 3.485 eV

E_C = 3.503 eV



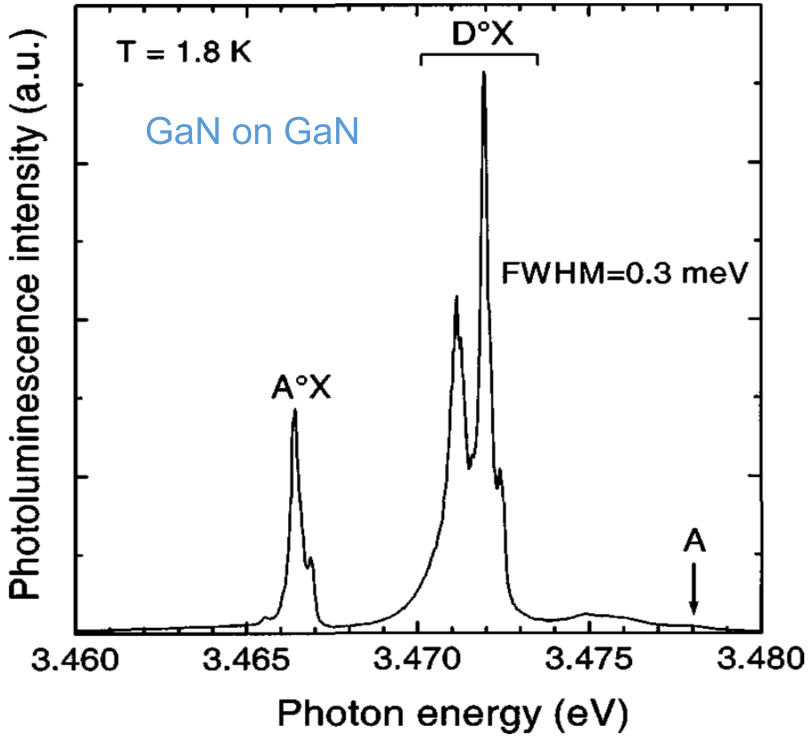
Optical properties

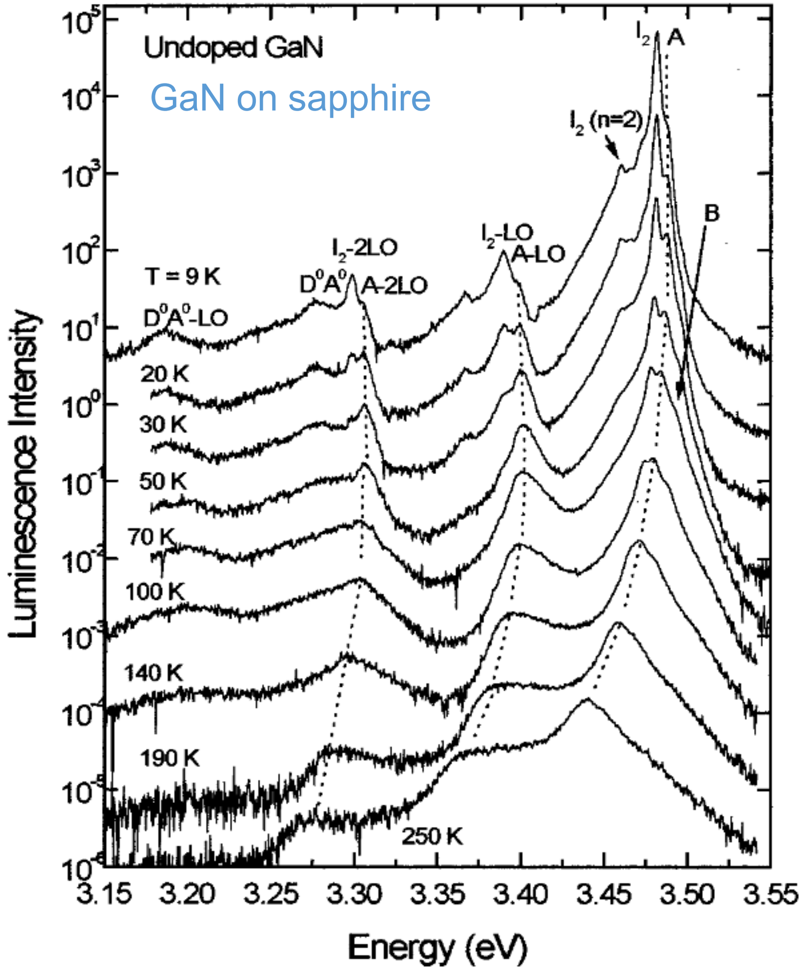
Photoluminescence of bulk GaN

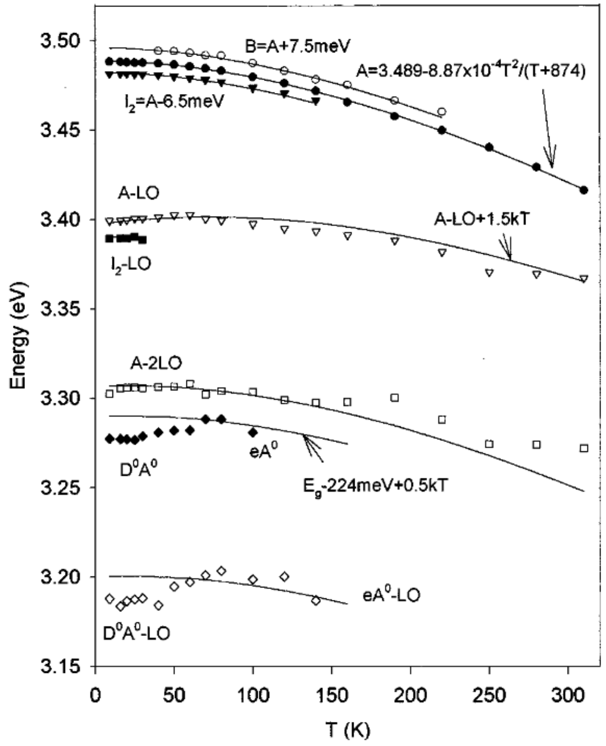
JOURNAL OF APPLIED PHYSICS VOLUME 86, NUMBER 7 1 OCTOBER 1999

Temperature quenching of photoluminescence intensities in undoped and doped GaN

M. Leroux, N. Grandjean, B. Beaumont, G. Nataf, F. Semond, J. Massies, and P. Gibart

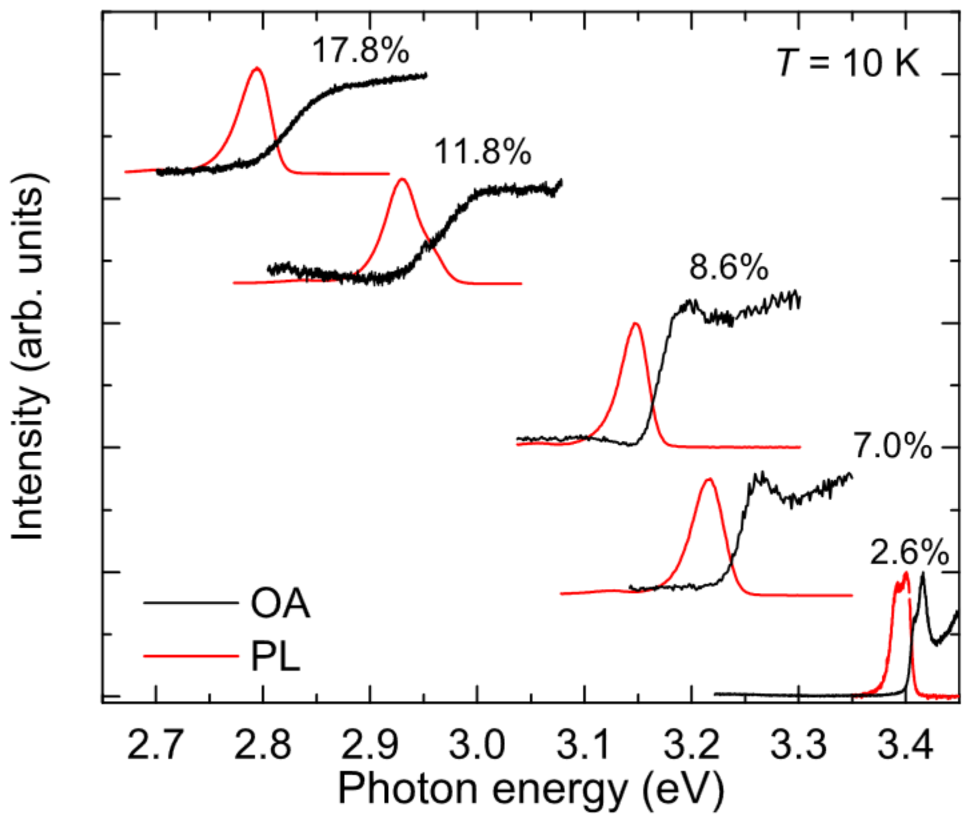


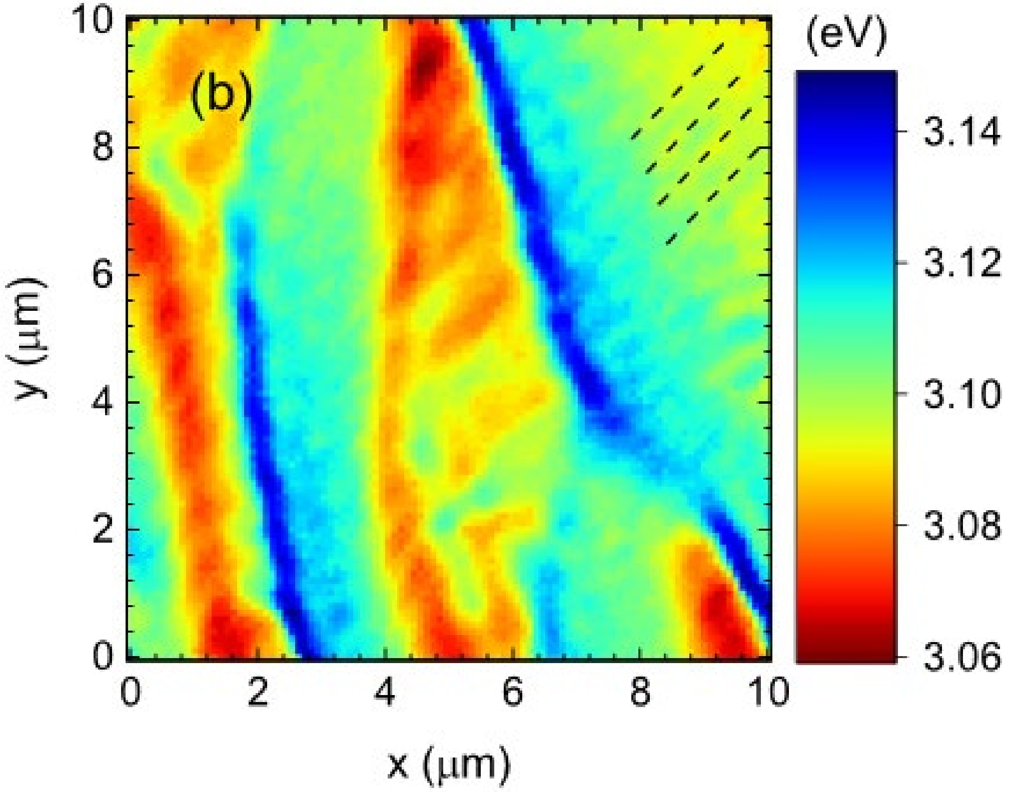




Optical properties

Photoluminescence of bulk InGaN alloy

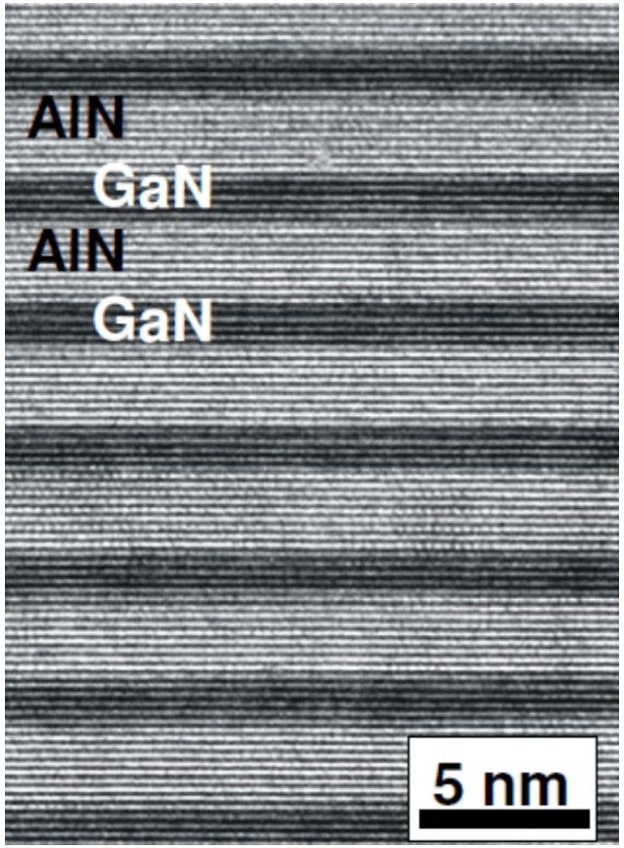




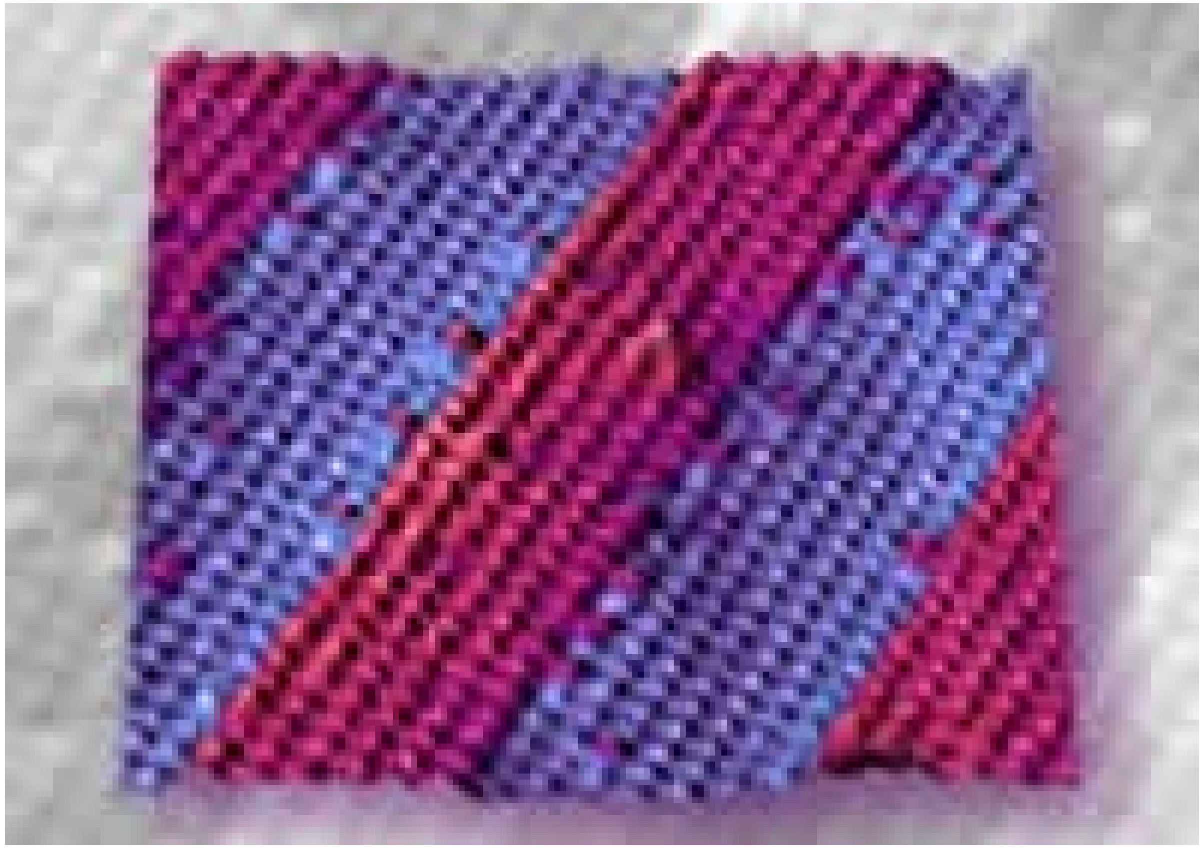
Photoluminescence mapping

Electronic properties of quantum wells

Transmission electron microscopy

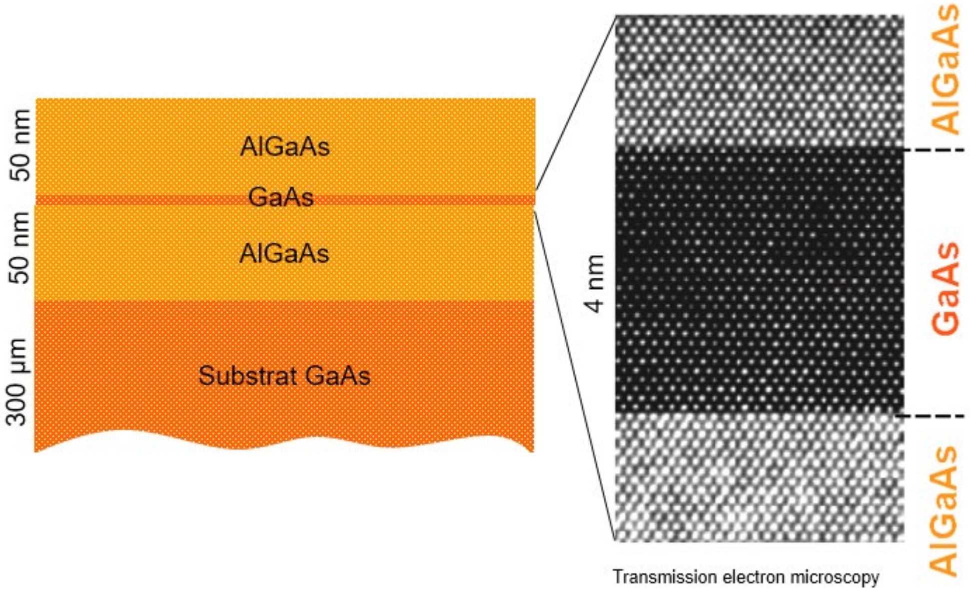


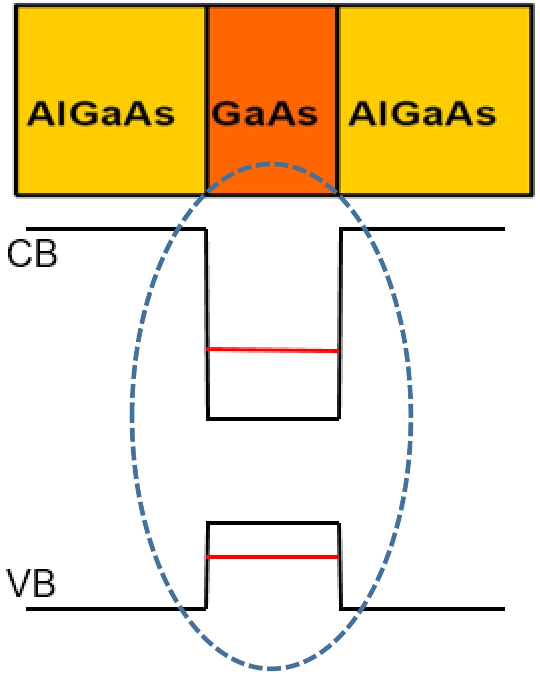
Scanning tunneling microscopy

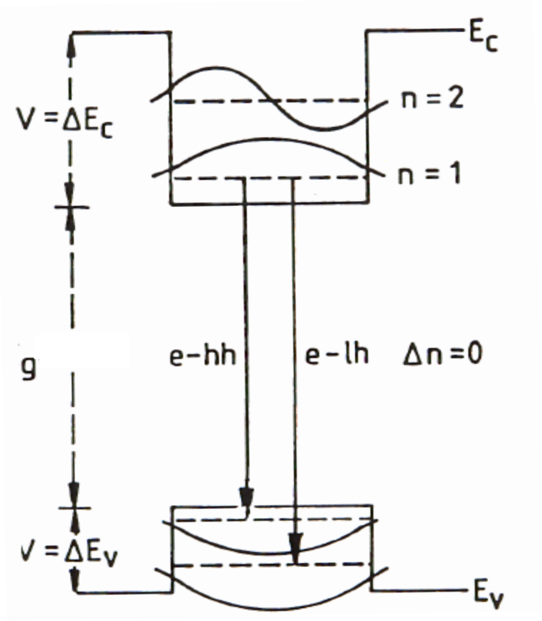


Electronic properties of quantum wells

Quantum well: 2D heterostructure (1 confinement axis)





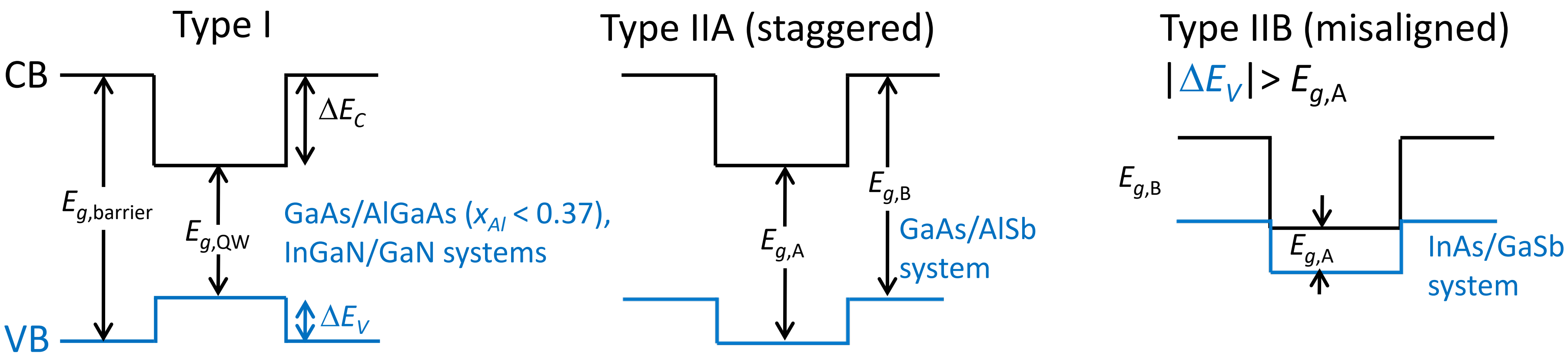


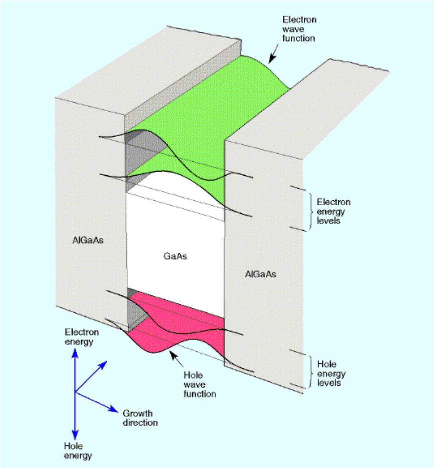
QW band structure:

$\Rightarrow$ defined by the bandgaps, the valence band offset, the fermi level, and the electric field

Electronic properties of quantum wells

Single quantum well – band structure





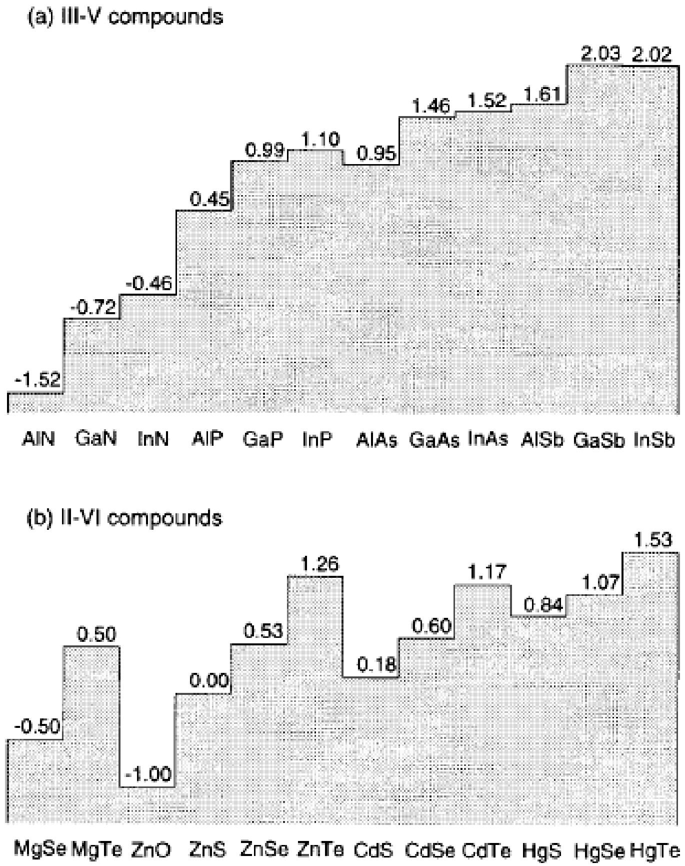
Quantized energy levels in CB and VB

Parameters to be considered:
- Well thickness
- Barrier height
- Carrier effective mass
- Dielectric mismatch

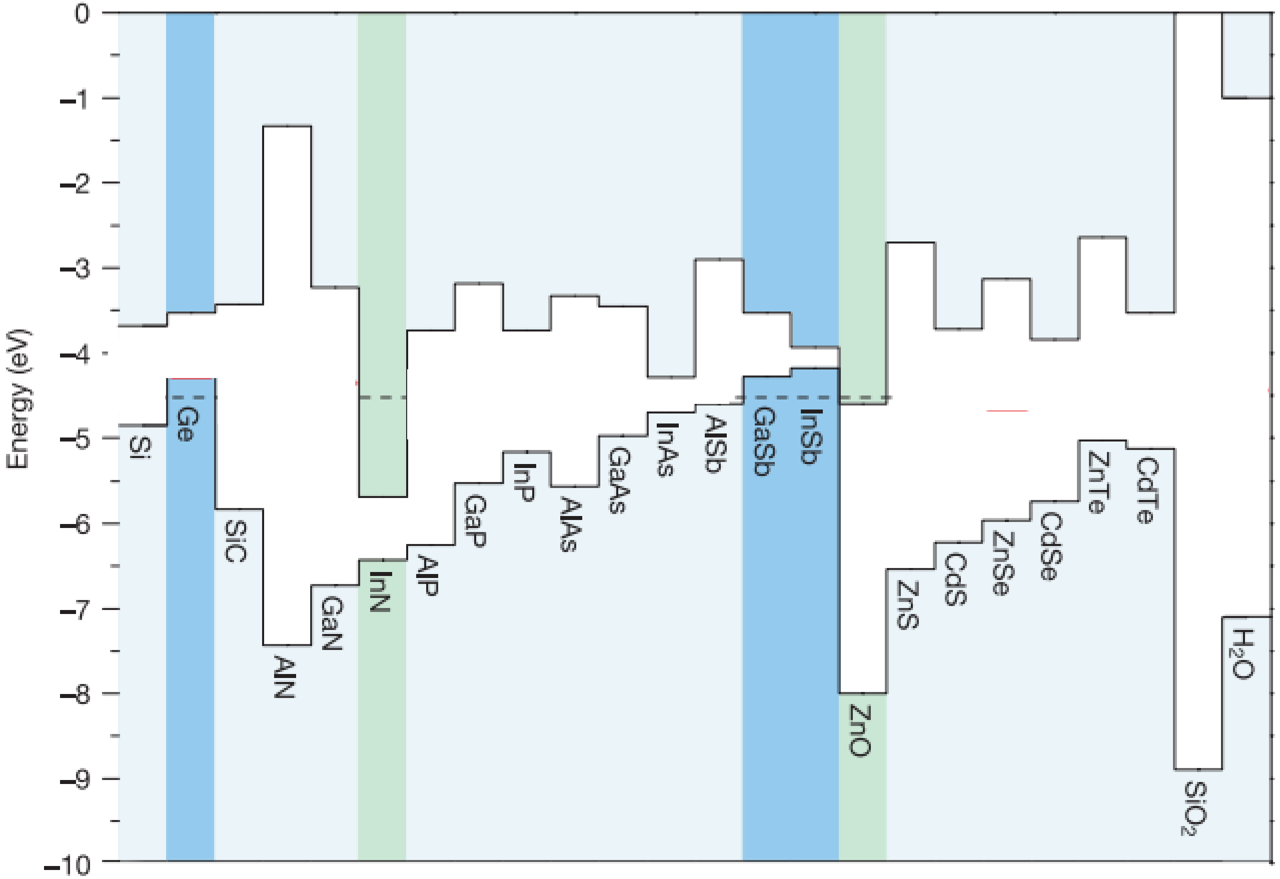
In III-V semiconductor compounds sharing the same anion: $\Delta V_{VB} = 0.3 \times \Delta E_g$

Electronic properties of quantum wells

Valence band edge and band-offset



Applied Physics Letters 72, 2011 (1998



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theoretical predictions

Electronic properties of quantum wells

Single quantum well: electronic states

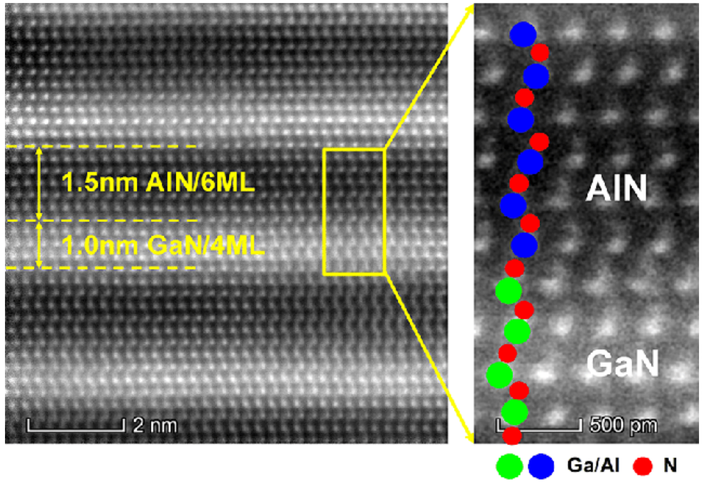
Envelope function formalism G. Bastard Phys. Rev. B **24**, 5693 (1981)

$$\psi = \sum_{A,B} e^{i\mathbf{k}_\perp . \mathbf{r}} u_{c\mathbf{k}}^{A,B}(\mathbf{r})\, \chi_n(z)$$

envelope wavefunction (n is the level energy)

Periodic part of Bloch wavefunction

⇒ *Separation of in-plane (x-y) and vertical (z) components*



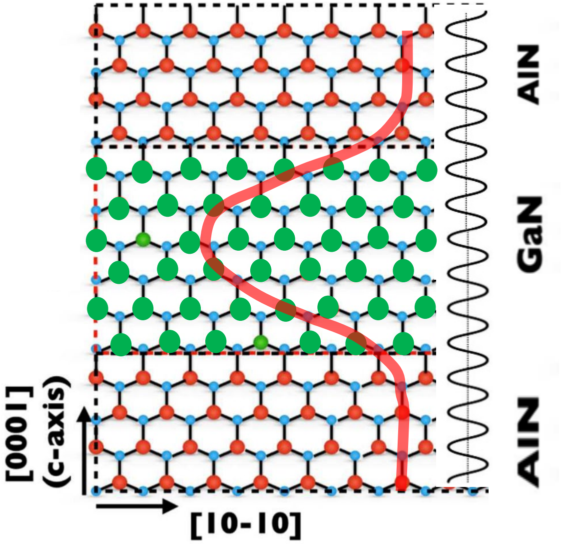
1D Schrödinger-like equation :

$$\left(-\frac{\hbar^2}{2m_e^*(z)}\frac{\partial^2}{\partial z^2} + V_C(z)\right)\chi_n(z) = \varepsilon_n \chi_n(z)$$

electron effective mass

defined by the CB edge

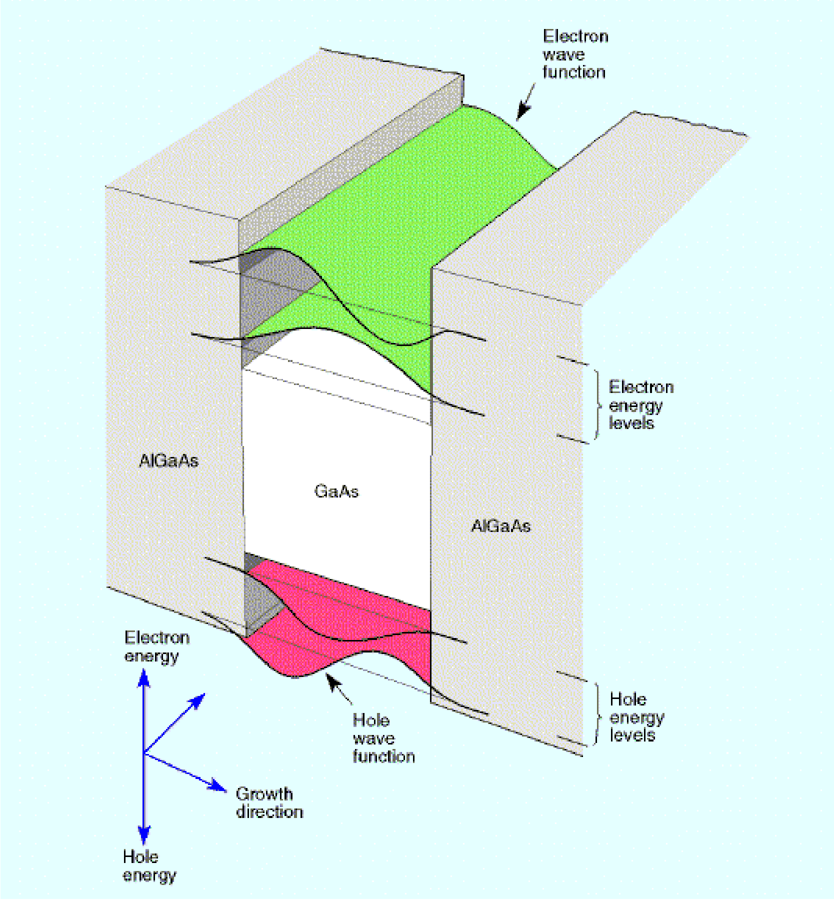
confinement energy of the carriers

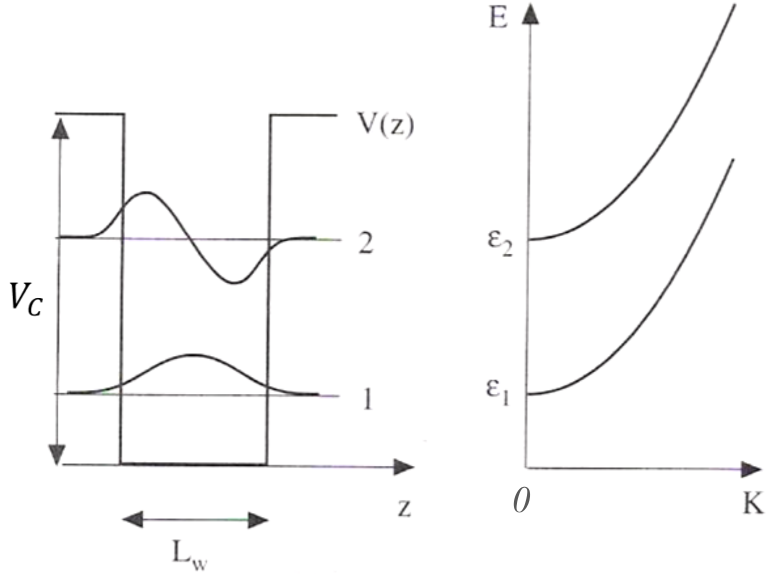


• The quantized energies are calculated by applying the continuity at the interfaces of the wave function $\chi_n(z)$ and the particle current $(1/\, m_e^*)(\partial\chi/\partial z)$

Electronic properties of quantum wells

Single quantum well: electronic states



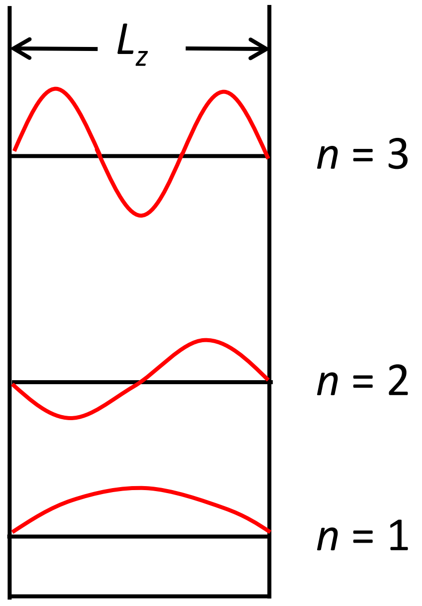


The 1D quantization is along the growth axis. The carriers are free to move in the plane. The total energy of an electron (n^{th} level) is

$$\boxed{E_n = \varepsilon_n + \frac{\hbar^2 K^2}{2m^*}}$$

Electronic properties of quantum wells

QW with infinite barrier height (1D case), $V_c = \infty$



$$-\frac{\hbar^2}{2m_e^*}\frac{\partial^2 \chi_n}{\partial z^2} = \varepsilon_n \chi_n \quad \Rightarrow \quad \frac{\partial^2 \chi_n}{\partial z^2} + k_n^2 \chi_n = 0 \quad \text{with} \quad k_n^2 = \frac{2m_e^* \varepsilon_n}{\hbar^2}$$

Solutions have the general expression:

$$\chi_n(z) = A\sin(k_n z) + B\cos(k_n z)$$

with the boundary conditions:

$$\chi_n(0) = \chi_n(L_z) = 0$$

$$\text{hence} \quad \chi_n(z) = A\sin(k_n z) \quad \text{with} \quad k_n = \frac{n\pi}{L_z}$$

Determination of the constant A: $\int_{-\infty}^{+\infty} |\chi_n(z)|^2\, dz = 1 = A^2 \int_0^{L_z} \sin^2(k_n z)\, dz = A^2 \frac{L_z}{2} \quad \Rightarrow A = \sqrt{\frac{2}{L_z}}$

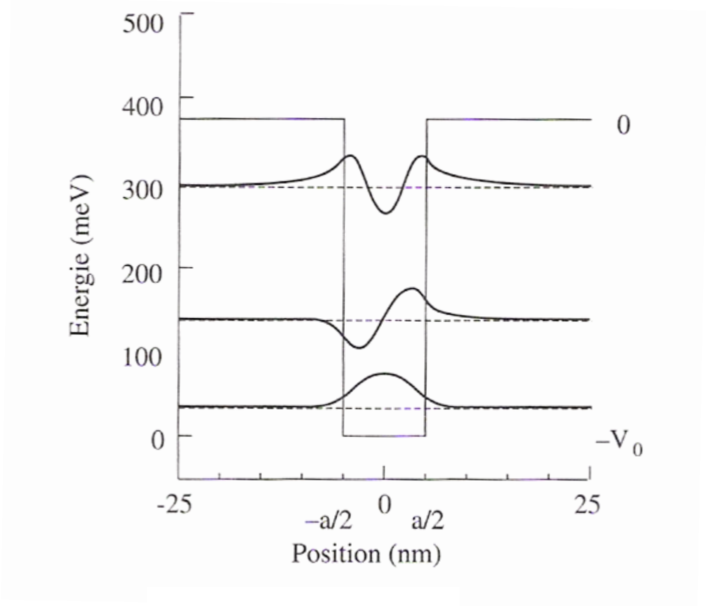
$$\boxed{\chi_n = \sqrt{\frac{2}{L_z}}\sin\left(\frac{n\pi z}{L_z}\right)}$$

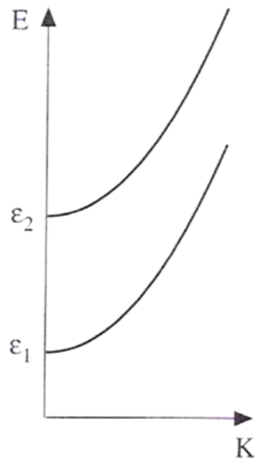
Energy of the n^{th} level: $\boxed{\varepsilon_n = \frac{n^2\pi^2\hbar^2}{2m_e^* L_z^2}}$

χ_n dimensionality with $d \propto L^{-d/2}$

Quantum confinement

QW with finite barrier height[1]





$$-\nabla \frac{\hbar^2}{2m^*(z)} \nabla \psi(r) + V_0(z)\psi(r) = E\psi(r)$$

The function ψ can be written as follows

$$\boxed{\psi(r) = \chi_n(z) \exp(i\mathbf{K}.\mathbf{R})}$$

$$\left[-\frac{d}{dz}\frac{\hbar^2}{2m^*(z)}\frac{d}{dz} + V_0(z)\right]\chi_n(z) = \varepsilon_n \chi_n(z)$$

$$\text{with} \quad E_n = \varepsilon_n + \frac{\hbar^2 K^2}{2m^*}$$

[1]G. Bastard, Phys. Rev. B **24**, 5693 (1981) and Phys. Rev. B **25**, 7584 (1982)

Electronic properties of quantum wells

QW with finite barrier height : determination of ε_n

Wavefunctions:

Even case

$$\chi_n(z) = A\cos kz, \quad \text{for } |z| < L/2$$
$$= B\exp[-k(z-L/2)] \quad \text{for } z > L/2$$
$$= B\exp[k(z+L/2)] \quad \text{for } z < -L/2$$

Odd case

$$\chi_n(z) = A\sin kz, \quad \text{for } |z| < L/2$$
$$= B\exp[-k(z-L/2)] \quad \text{for } z > L/2$$
$$= -B\exp[k(z+L/2)] \quad \text{for } z < -L/2$$

$$\text{where } \varepsilon_n = \frac{\hbar^2 k^2}{2m_A^*} \text{ inside the well and } \varepsilon_n = V_0 - \frac{\hbar^2 \kappa^2}{2m_B^*} \text{ outside the well}$$

Determination of ε_n

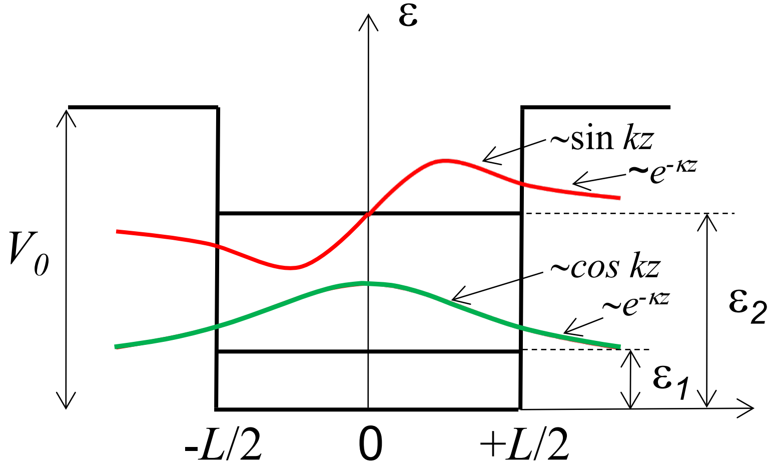
Continuity conditions[1] at $z = \pm\frac{L}{2}$ yield

$$\left(\frac{k}{m_A^*}\right)\tan\left(\frac{kL}{2}\right) = \frac{\kappa}{m_B^*}$$

$$\left(\frac{k}{m_A^*}\right)\cot\left(\frac{kL}{2}\right) = \frac{-\kappa}{m_B^*}$$

Eqs. solved numerically or graphically to determine the energies of the bound states

eg. Series 2, Ex. 4



Inversion symmetry around the center of the well
⇒ parity of the wave function

In the barrier :

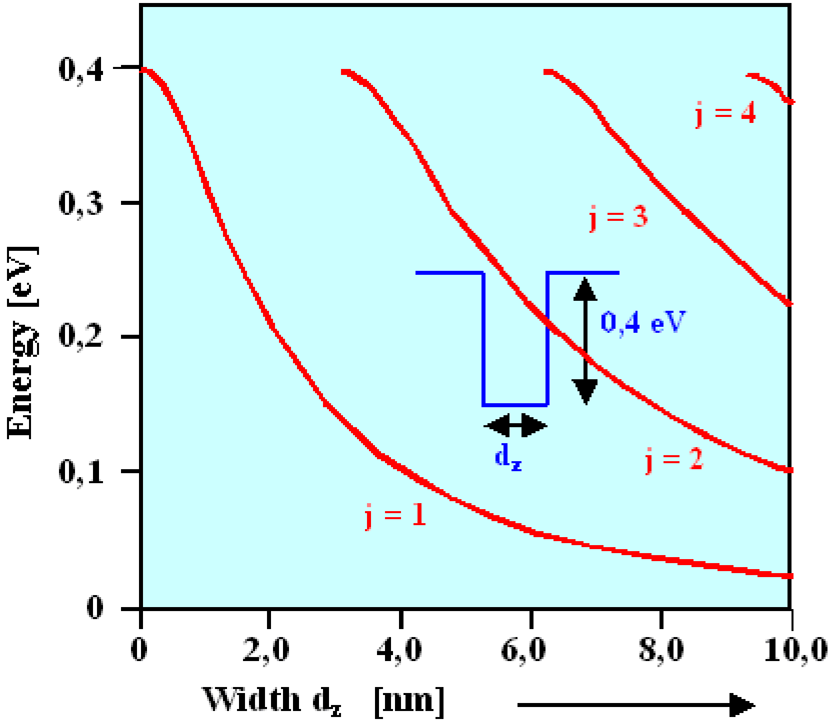
$$\boxed{k = \frac{\sqrt{2m_B^*(V_0 - \varepsilon_n)}}{\hbar}}$$

The extension of the wavefunction in the barriers depends on k

[1] Continuity at the interfaces of $\chi_n(z)$ and particle current $(1/m_e^*)(\partial\chi/\partial z)$

Electronic properties of quantum wells

QW with finite barrier height



Energy variation of quantized levels as a function of the well width

$\Rightarrow$ Confinement energy, band offset and well width will define the possible number of confined states

Number of bound states :

$$\boxed{1 + \mathrm{Int}\left[\left(\frac{2m_A^* V_0 L^2}{\pi^2 \hbar^2}\right)^{\frac{1}{2}}\right] \quad \text{if } m_A^* = m_B^*}$$

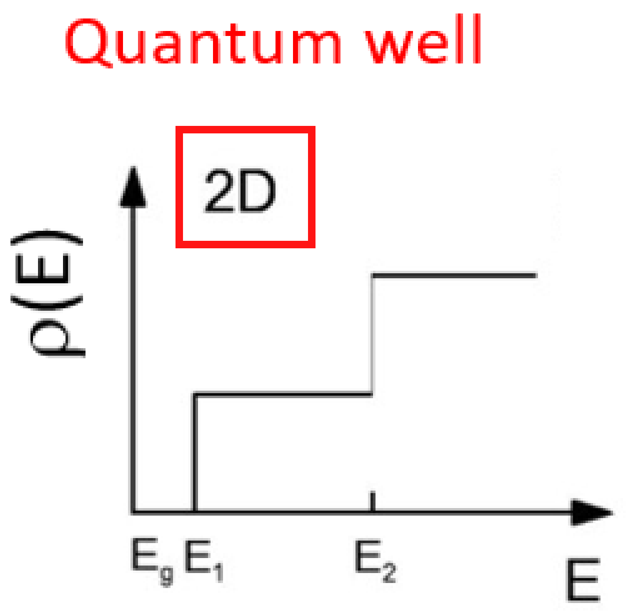
A and B the well and barrier materials, respectively

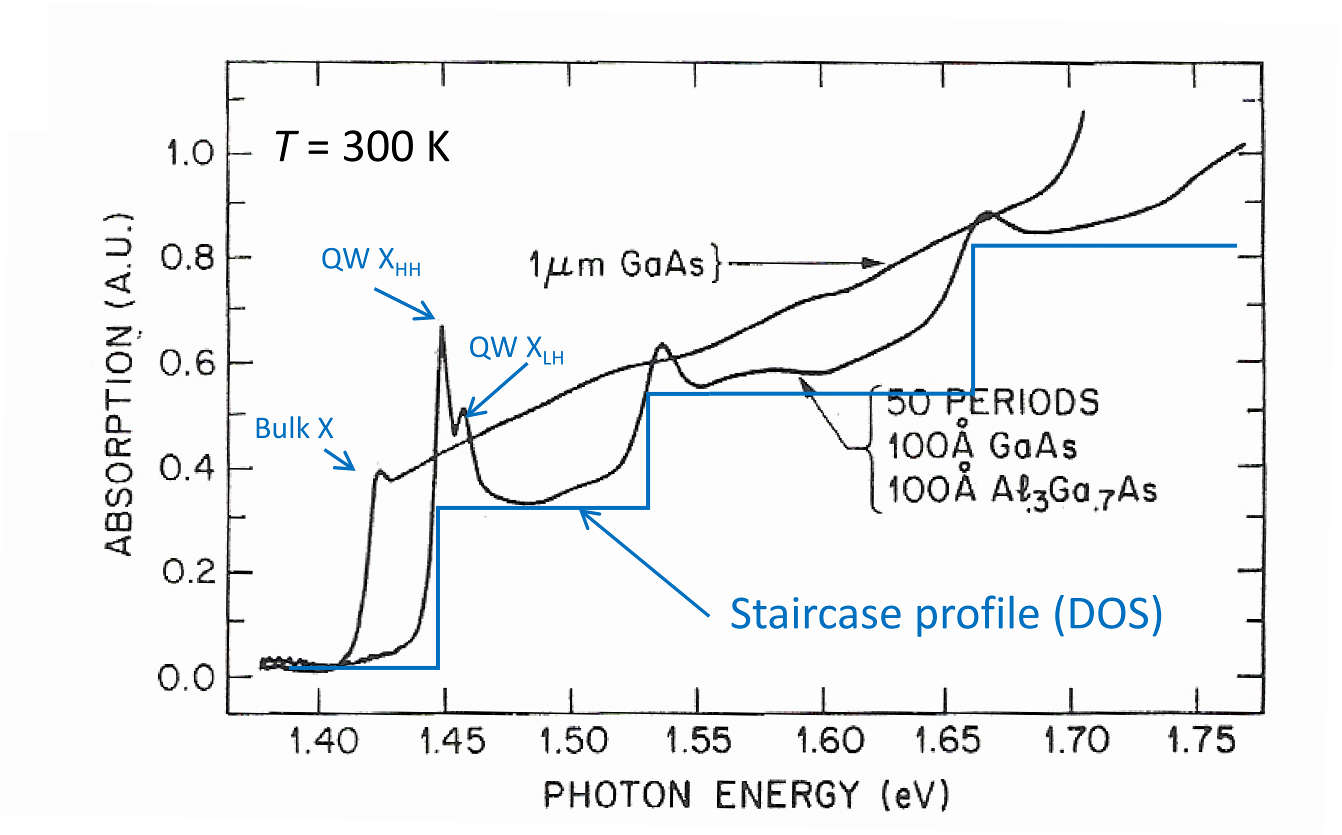
Rem: the design of the quantum wells depends on the devices and materials constraints

Electronic properties of quantum wells

Absorption in quantum wells

$$\rho_{2D}(E) = \sum_l \rho_{l,2D}(E) = \frac{m^*}{\pi\hbar^2}\sum_l H(E - E_l)$$





⇒ additional absorption peak due to excitons (X)

Electronic properties of quantum wells

Excitons in QWS: case of finite barriers

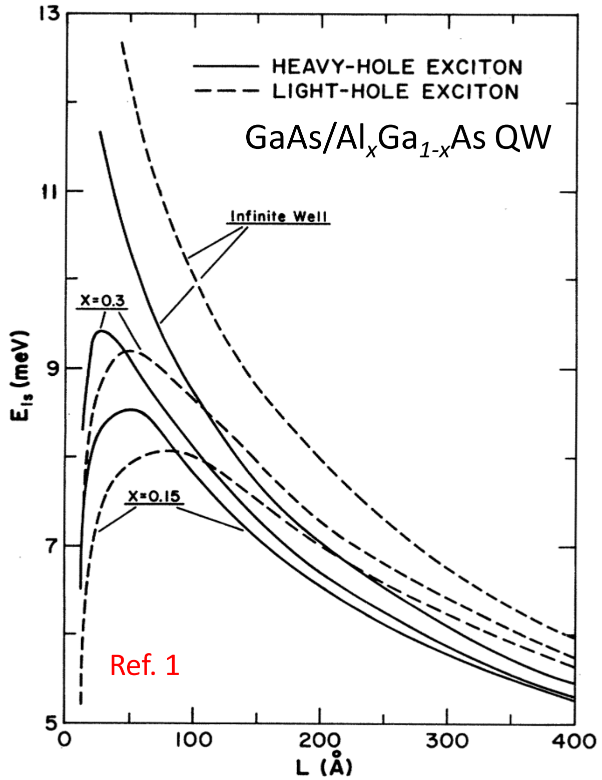
Binding energy Ry^{2D} of excitons is increased compared to the 3D case

determination of *Ry*^{2D} when taking in finite well depth (simple parabolic hole bands)[1] and valence-band mixing, dielectric mismatch, Coulomb coupling between subbands, nonparabolicity effects[2]
Introduction of a fractional-dimensional space $1 \leq \alpha \leq 3$:[3]

$$E_n^\alpha = E_g - \frac{Ry^*}{\left[n + \frac{\alpha - 3}{2}\right]^2}, \quad n = 1,2,\ldots \quad a_{B,n}^\alpha = \left[n + \frac{\alpha - 3}{2}\right]^2 a_B$$

$Ry^{2D} > Ry^{3D}$ case (e.g., 4-5 meV in bulk GaAs) ⇒ optical properties can be dominated by excitonic effects even at 300 K

⇒ large electro-optic coefficients

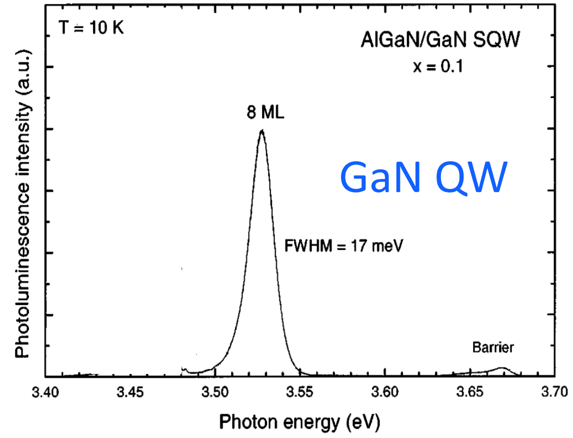


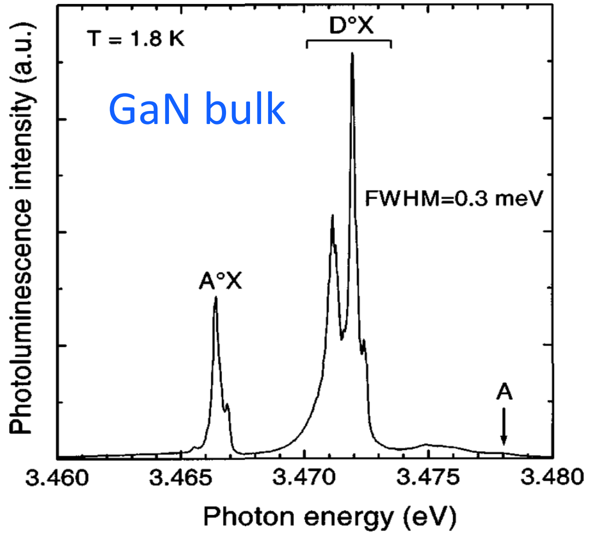
[1] R. L. Greene *et al.*, Phys. Rev. B **29**, 1807 (1984).
[2] L. C. Andreani and A. Pasquarello, Phys. Rev. B **42**, 8928 (1990).
[3] X.-F. He, Phys. Rev. B **43**, 2063 (1991); H. Mathieu *et al.*, Phys. Rev. B **46**, 4092 (1992).

Electronic properties of quantum wells

Spontaneous emission - photoluminescence

Photoluminescence





- Narrow PL linewidth (FWHM) at low temperature

- Disappearance of optical transitions due to bound excitations ascribed to[1]:
  - smearing of the related luminescence bands
  - change in the symmetry of the impurity ground-state wavefunction $\Rightarrow$ reduced oscillator strength (transition probability)

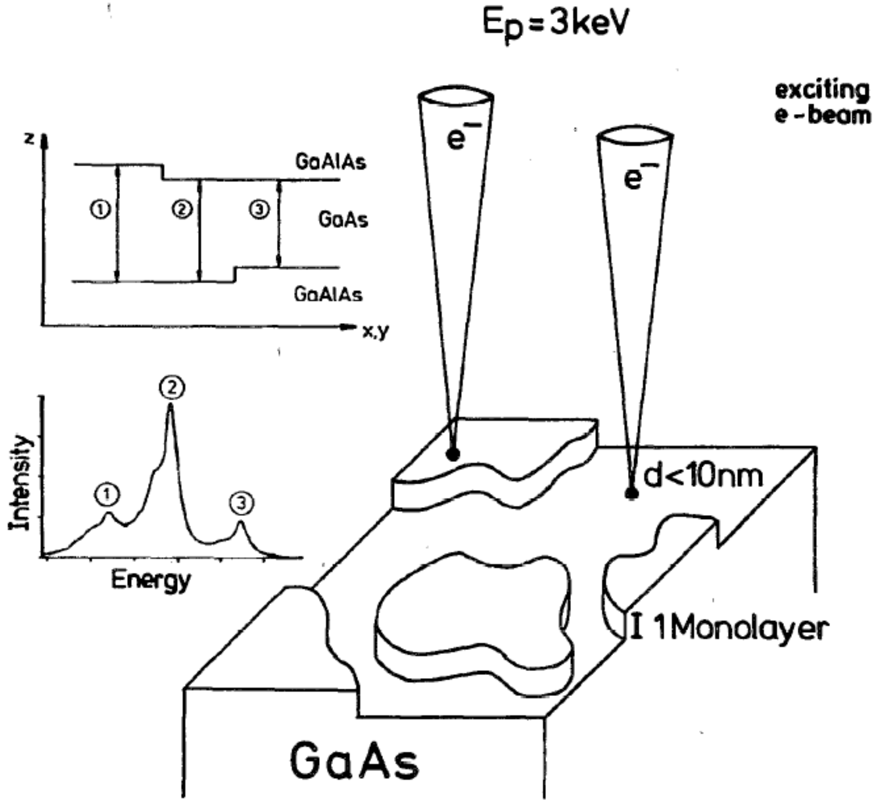
$\Rightarrow$ QW PL spectra dominated by instrinsic radiative transitions in high quality QWs

PL spectra of QW heterostructures are usually much simpler than their bulk counterparts.

[1]C. Weisbuch *et al.*, Solid State Commun. **37**, 219 (1981)

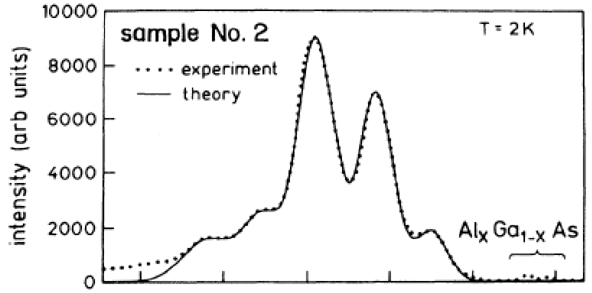
Electronic properties of quantum wells

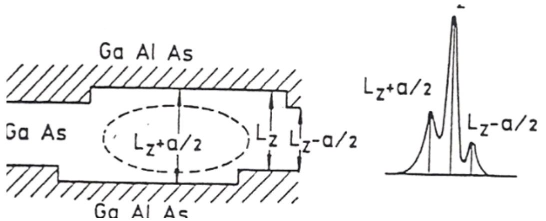
Localization of Excitons in QW: impact of interface disorder

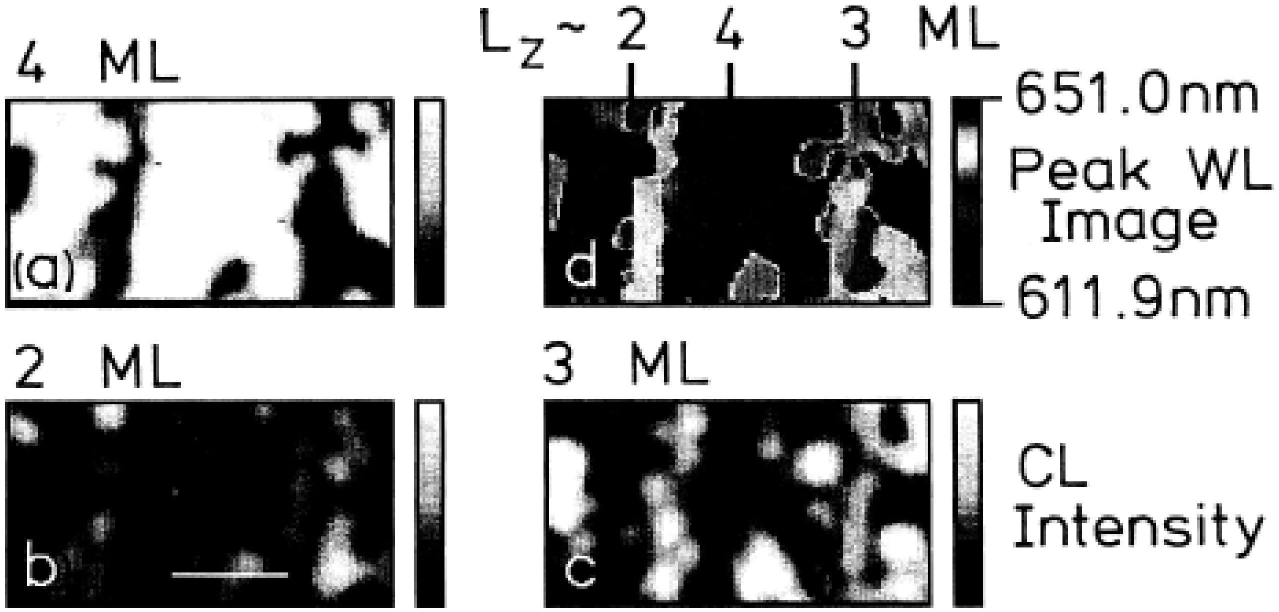


Cathodoluminescence mapping

Journal of Applied Physics 70, R1 (1991)





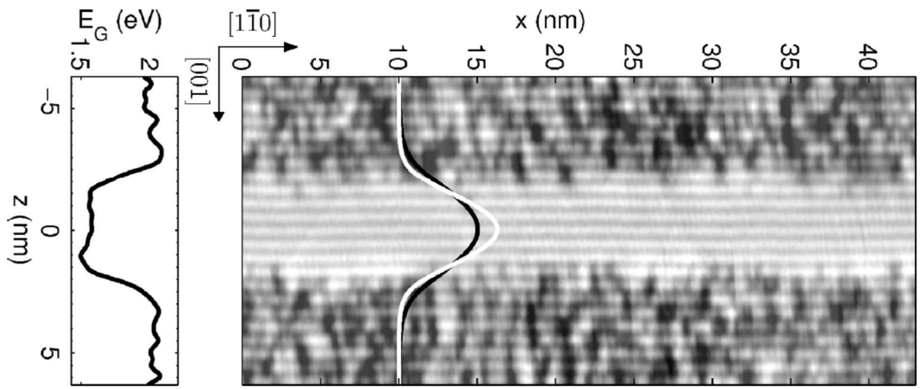


Phys. Rev. B **44**, 8792 (1991)

Electronic properties of quantum wells

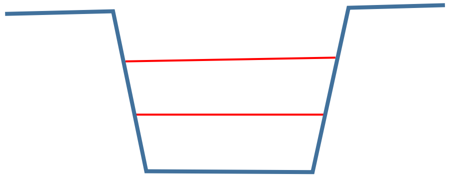
Quantum well interface morphology

Intermixing/diffusion

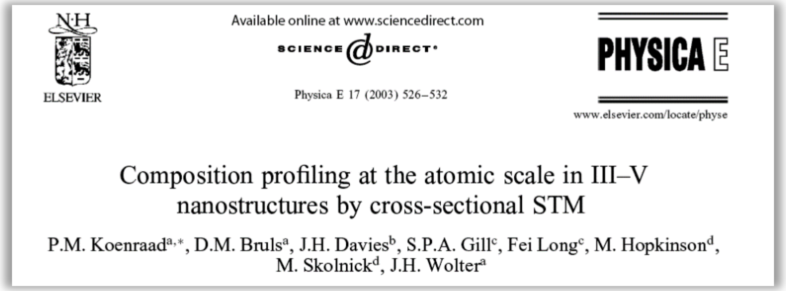


Scanning tunneling microscopy (STM) in cross-section

Band profile



Surface segregation



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Physica E 17 (2003) 526–532

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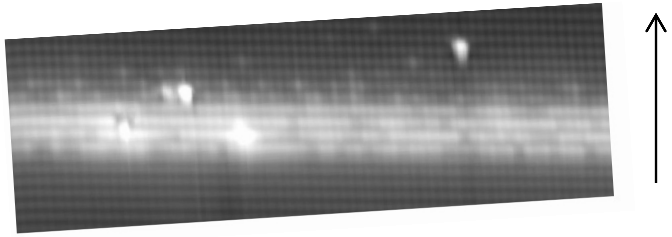
Composition profiling at the atomic scale in III–V nanostructures by cross-sectional STM

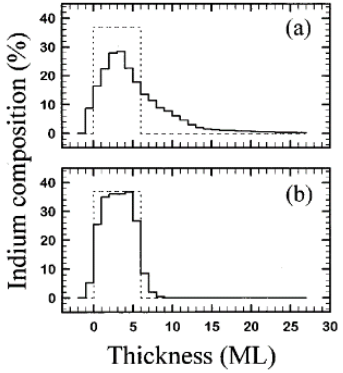
P.M. Koenraad[a,*], D.M. Bruls[a], J.H. Davies[b], S.P.A. Gill[c], Fei Long[c], M. Hopkinson[d], M. Skolnick[d], J.H. Wolter[a]



Growth

Band profile

Phys. Rev. B 53, 998 (1996)

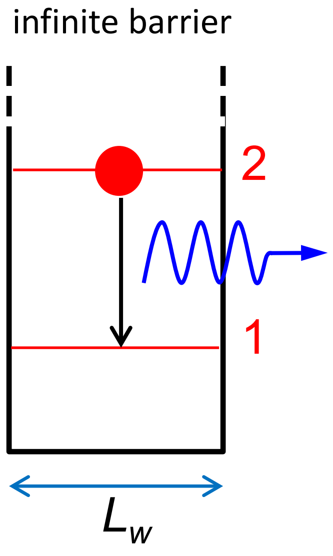


High temperature growth

Low temperature growth

Optical properties of QWs

QW dipolar matrix element r_{12}



1) Energy level

$$E_n = n^2 \frac{\hbar^2 \pi^2}{2m^* L_w^2}$$

Then $\hbar\omega_{12} = E_2 - E_1 = E_{12} = 3\frac{\hbar^2 \pi^2}{2m^* L_w^2}$

2) Dipole element r_{12}

$$r_{12} = \langle \Psi_2(x)|x|\Psi_1(x)\rangle \quad \text{with} \quad \Psi_1(x) = \sqrt{\frac{2}{L_w}}\cos(\pi x/L_w) \quad \text{and} \quad \Psi_2(x) = \sqrt{\frac{2}{L_w}}\sin(2\pi x/L_w)$$

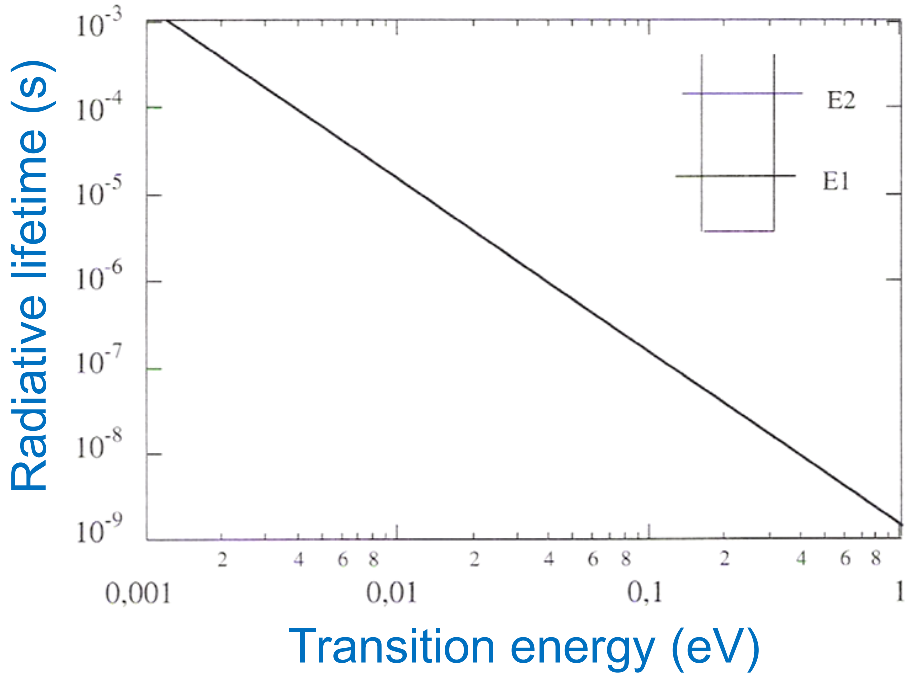
$$\text{Finally,} \quad r_{12} = \frac{2^4 L_w}{3^2 \pi^2} \quad \text{and} \quad \boxed{r_{12}^2 = \frac{2^7 \hbar^2}{3^3 \pi^2 m^*} 1/E_{12}}$$

Optical properties of QWs

Radiative lifetime

$$\boxed{\tau_{sp} = \frac{3^4 \pi^3 m^* c^3 \hbar^2 \varepsilon_0}{2^7 q^2 n_{op}} \frac{1}{E_{12}^2}}$$

n_{op}: refractive index



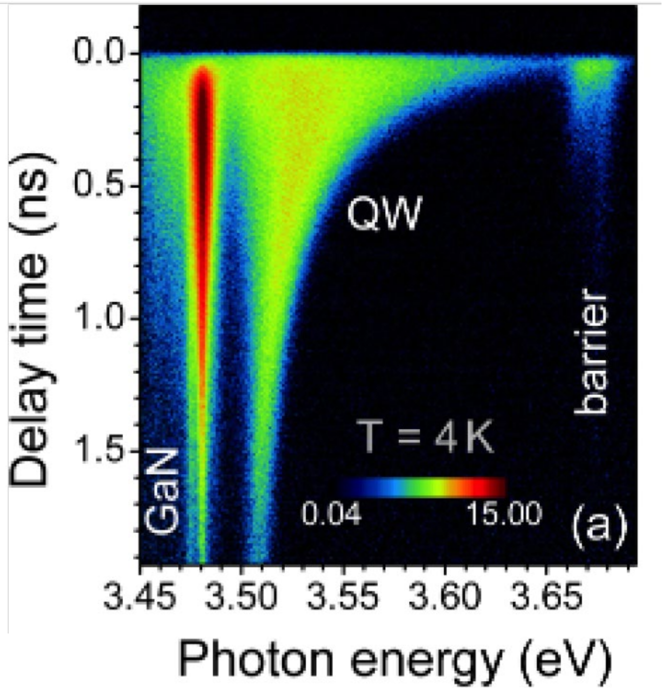
Transition energies > 1 eV
$\Rightarrow$ radiative lifetime ~1 ns

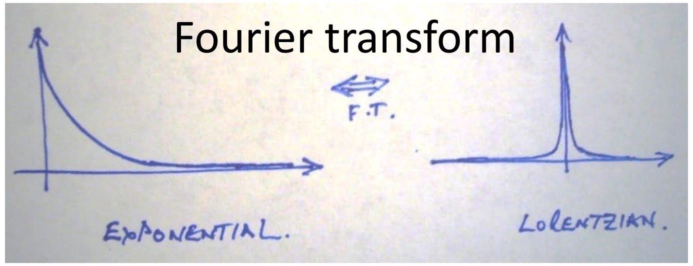
Rem: Intersubband optical transitions are expected to be slower than interband ones.

Optical properties of QWs

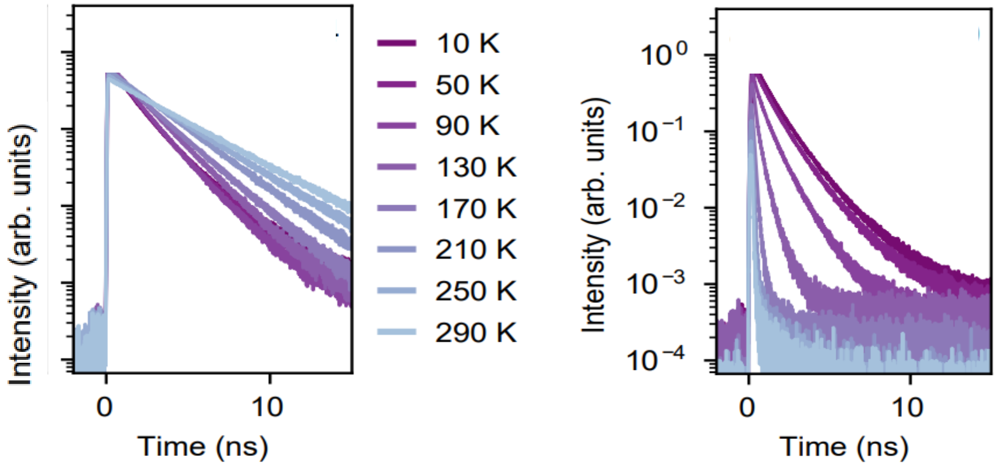
Spontaneous emission - photoluminescence

Time-resolved photoluminescence

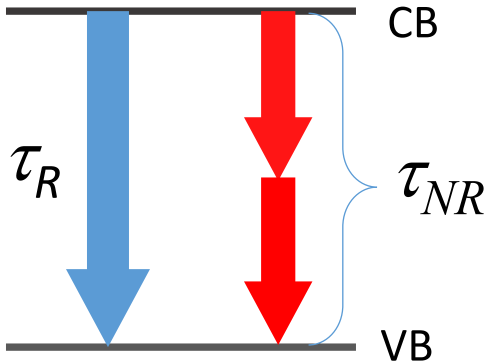




QW with purely radiative recombination



QW with non-radiative recombination



Recombination rate (PL decay time):

$$I_{PL} = I_0\, exp(-t/\tau)$$

$$with\ 1/\tau = 1/\tau_R + 1/\tau_{NR}$$

$1/\tau_R$: radiative recombination time

$1/\tau_{NR}$: non-radiative recombination time

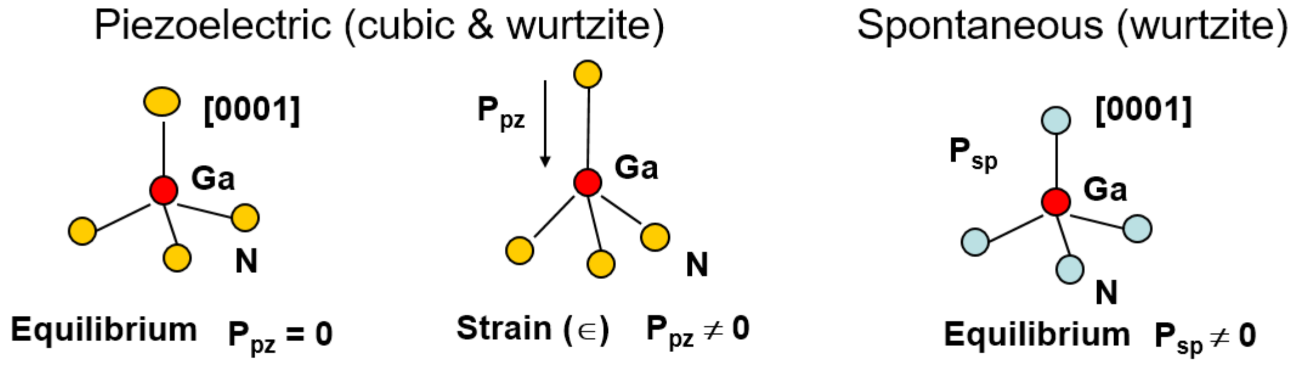
τ_R: radiative lifetime

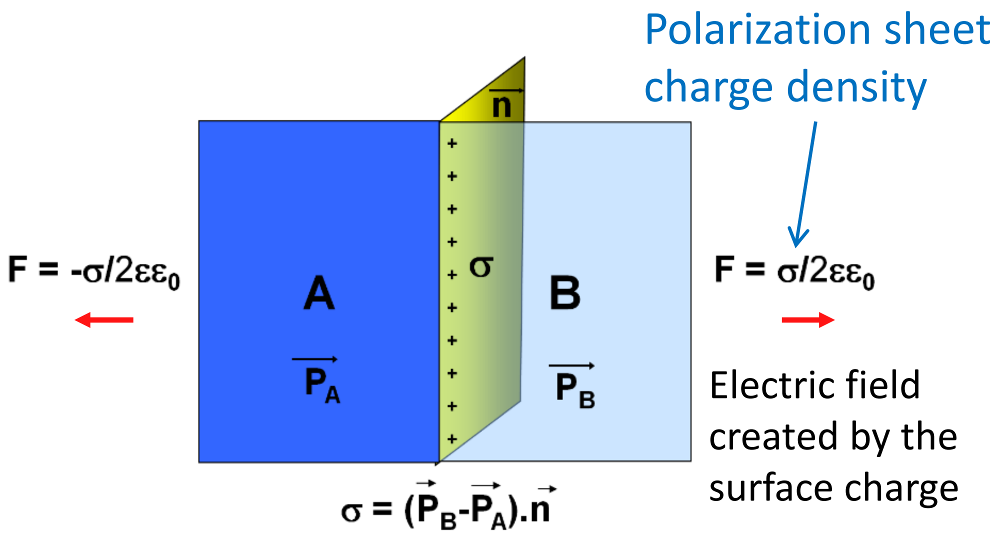
τ_{NR}: non-radiative lifetime

Impact of an electric field

2) Piezoelectric and spontaneous polarization in non-centrosymetric crystals

III-N, ZnO

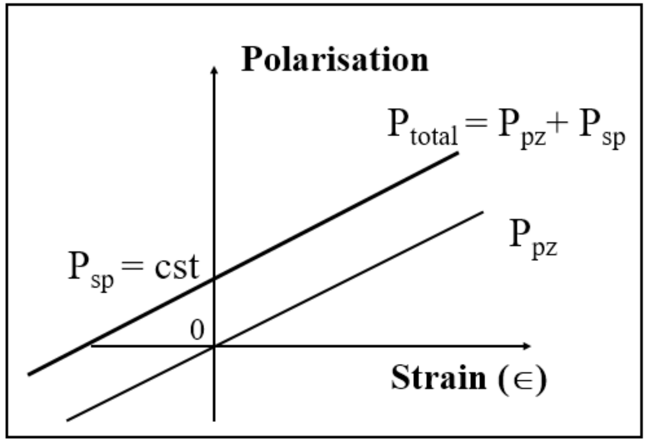


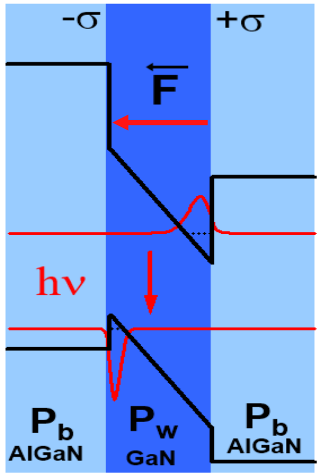


Macroscopic polarization:

Difference between the barycenters of positive and negative charges

$$\mathbf{P_{total} = P_{pz} + P_{sp}}$$

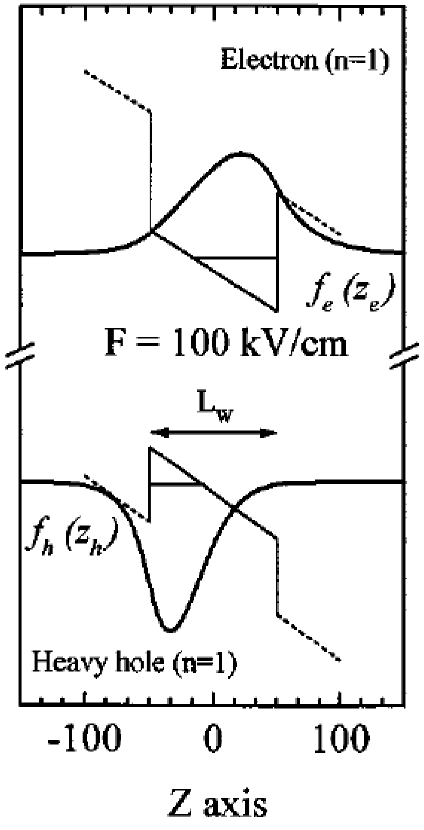




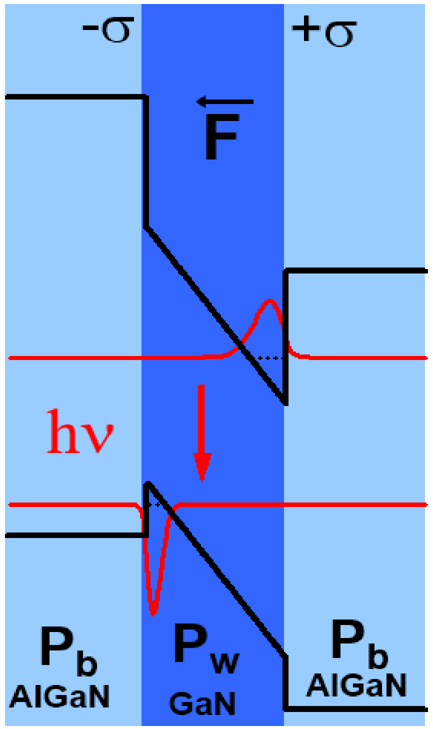
$$\boxed{F_{QW} = \frac{\sigma}{\varepsilon\varepsilon_0}}$$

Impact of an electric field

Quantum confined Stark effect



1) Electric field in a pn (pin) junction



2) Piezoelectric and spontaneous polarization

- finite dipole between electron and hole $\delta = e\,(z_h - z_e)$
- red-shift of the QW transition energy

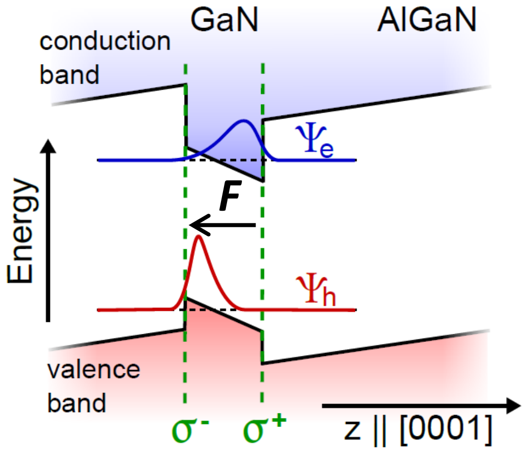
$$E = E_g + E_e + E_h - eL_W F\ (-E_b)$$

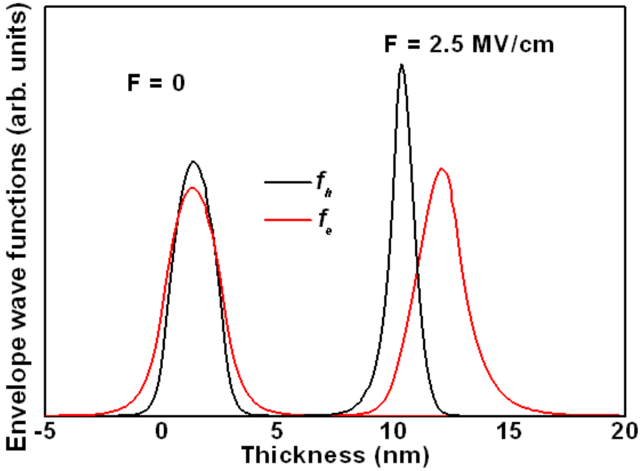
E_b: exciton binding energy

- Decrease of the oscillator strength

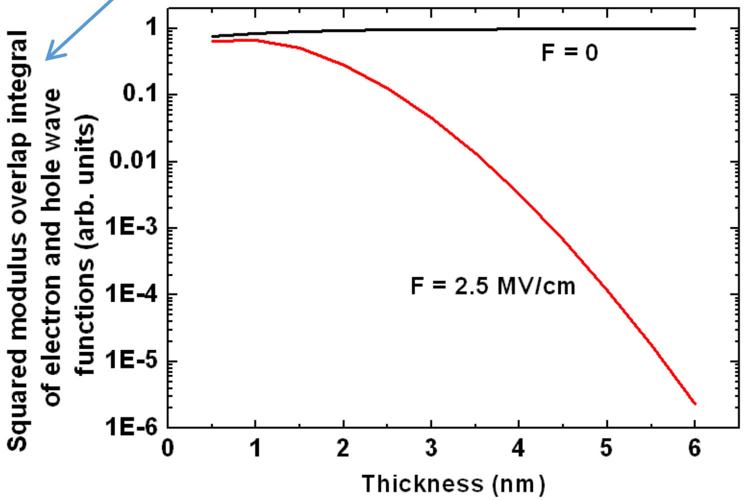
Impact of an electric field

Quantum confined Stark effect





Quantity ∝ oscillator strength



Triangular shape of confining potential, QCSE ⇒

(1) redshift of fundamental optical transition

(2) spatial separation of electron and hole wavefunctions

$$\tau_{rad} = \frac{2\pi\varepsilon_0 m_0 c^3}{n_{op} e^2 \omega_{CV}^2 f_{osc}}$$

(3) decrease in oscillator strength f_{osc} of optical transition and exciton binding energy

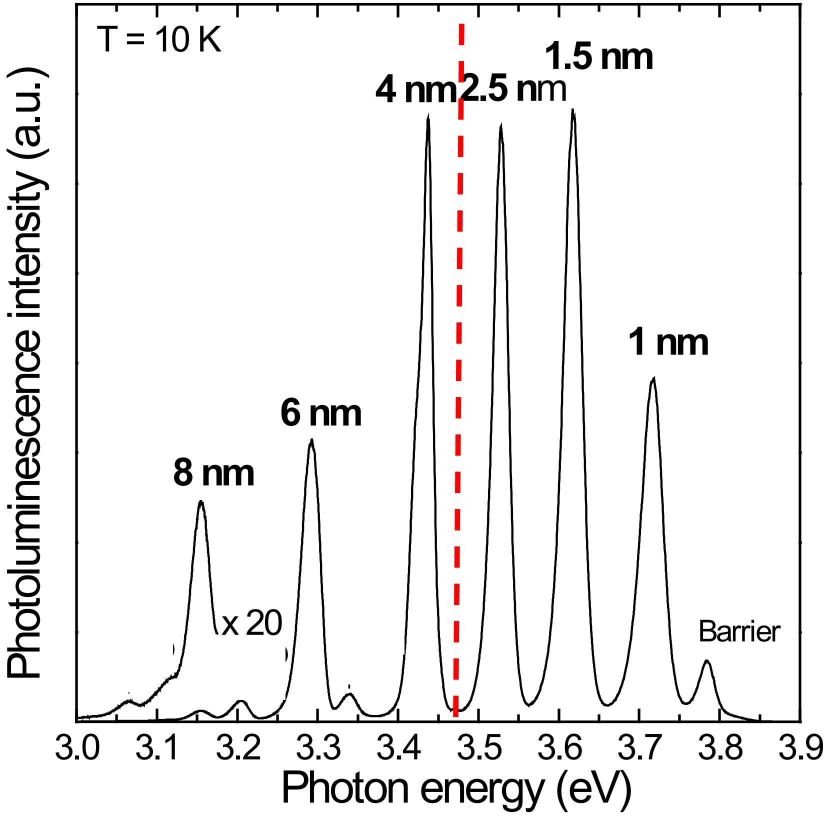
(increase in radiative lifetime)[1]

[1]J. Feldmann *et al.*, Phys. Rev. Lett. **59**, 2337 (1987)

Impact of an electric field

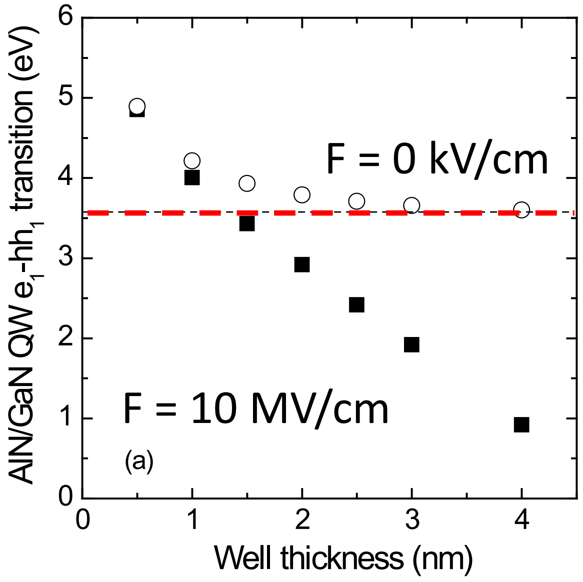
Quantum confined Stark effect

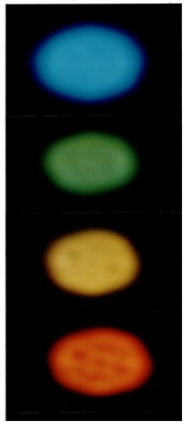
AlGaN/GaN QWs

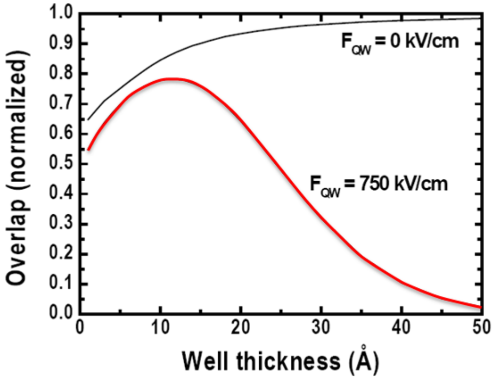


Journal of Applied Physics **86**, 3714 (1999)

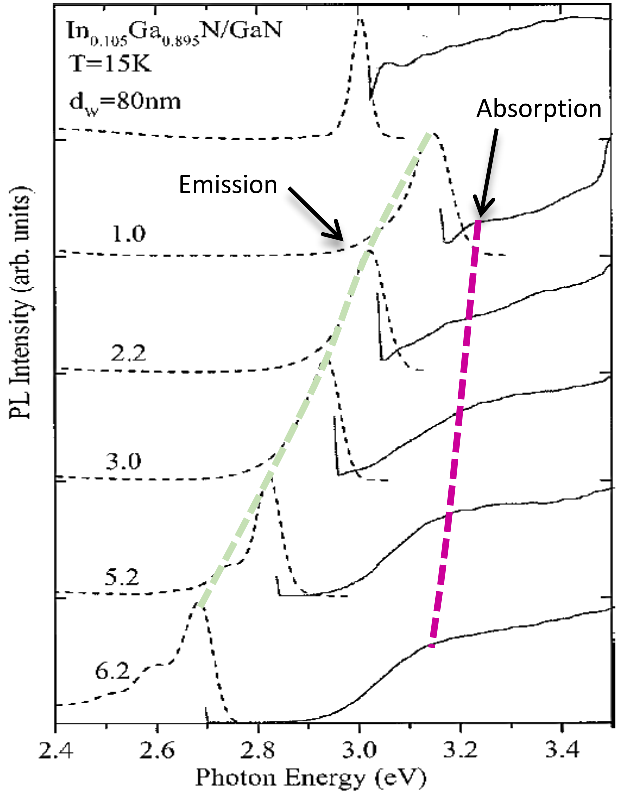
Appl. Phys. Lett. 75, 962 (1999)







InGaN/GaN QWs

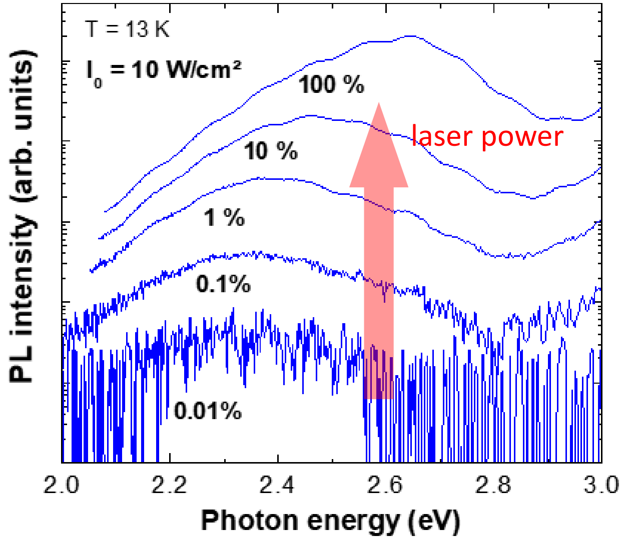


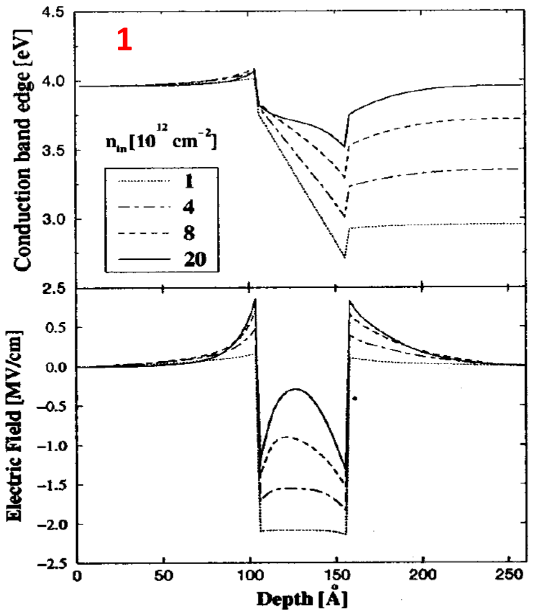
E. Berkowicz *et al.*, Phys. Rev. B 61, 10994 (2000)

Impact of an electric field

Quantum confined Stark effect

InGaN/GaN quantum wells





Self-consistent Schrödinger-Poisson calculations

$$\frac{d}{dz}\left[\varepsilon_0\varepsilon_r\frac{d}{dz}V(z)\right] = -e\left[-n_{3D}(z) + p_{3D}(z) - \frac{dn_{2D}(z)}{dz}\right]$$

[1]V. Fiorentini *et al.*, Phys. Rev. B **60**, 8849 (1999)

Application : microLED displays

https://www.insightmedia.info/porotech-announces-worlds-first-all-in-one-full-color-microled-display/