CLASE 7 - martes 20/04/2021

**La clase pasada vimos:**

Pozos cuánticos dobles y parabólicos

Aproximación de masa efectiva: impureza hidrogenoide

**En esta clase veremos:**

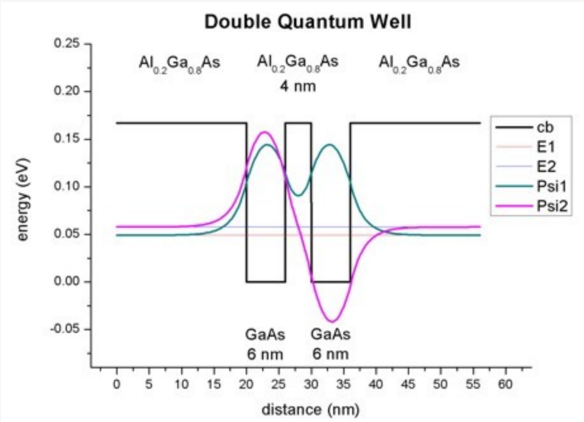
Nanoestructuras: cables y puntos cuánticos

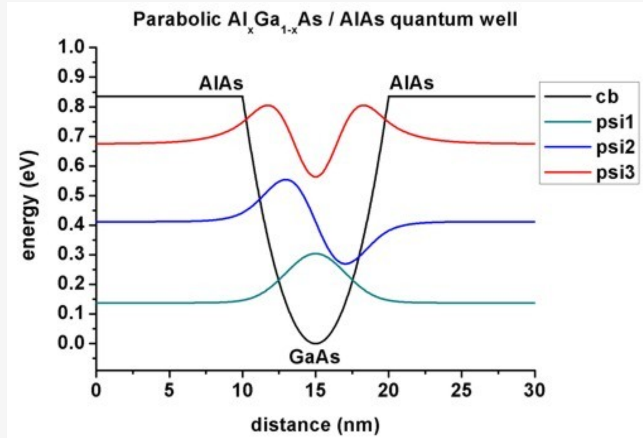
Aproximación de masa efectiva en heteroestructuras

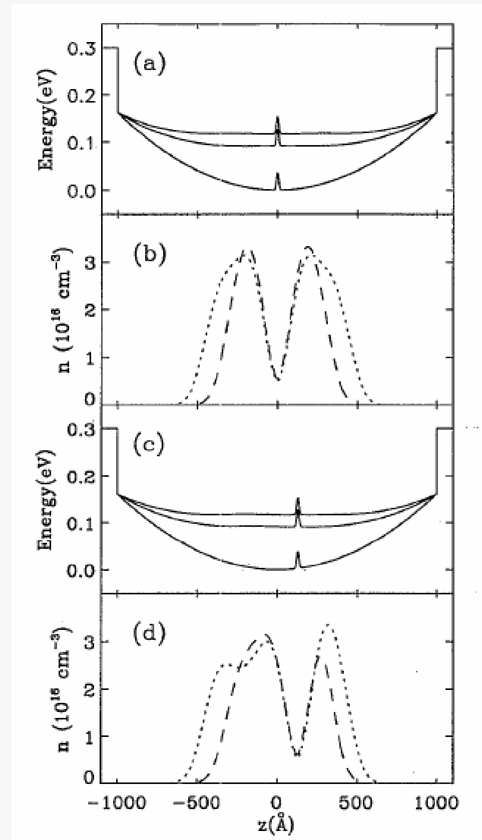
Dopaje remoto

REPASO

# Pozos cuánticos dobles y parabólicos



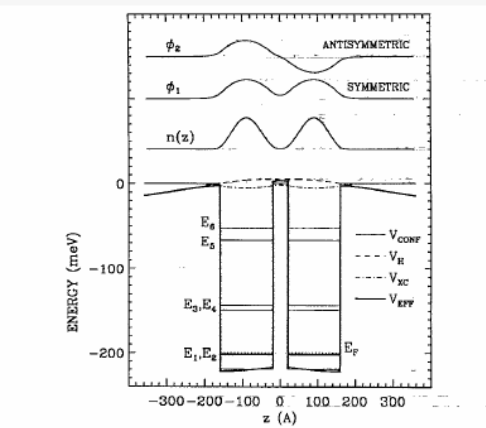




FIG. 1. The typical double quantum well structure ($N_S = 10^{11}$ cm$^{-2}$) with the self-consistent local-density-approximation calculated energy levels and wave functions for the symmetric-antisymmetric levels. The bare ($V_{conf}$), Hartree ($V_H$), and exchange-correlation ($V_{xc}$) contributions to the effective potential ($V_{EFF}$) are shown. (The SAS gap $\Delta_{SAS} = |E_2 - E_1|$.)

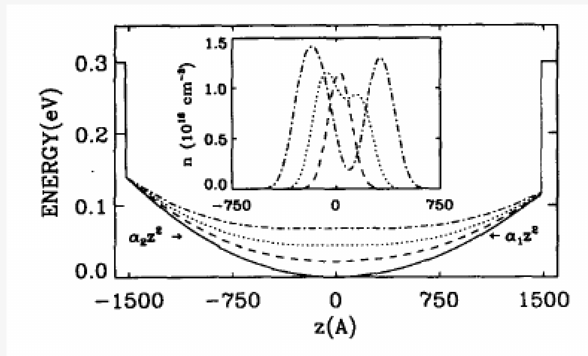
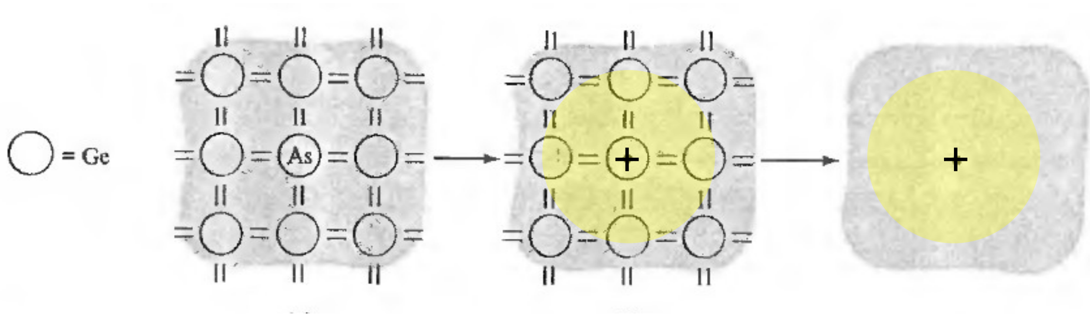



Fig. 1. Model bare potential of the asymmetric parabolic well (solid line), and calculated self-consistent potentials with an in-plane magnetic field of $B = 5.8\ T$, for $N_s = 2.4$ (dash line), 4.7 (dotted line), and $7.5 \times 10^{10}\ cm^{-2}$ (dash-dot line); inset: corresponding calculated self-consistent densities.

REPASO

# Aproximación de masa efectiva: impureza hidrogenoide




Impureza sustitucional

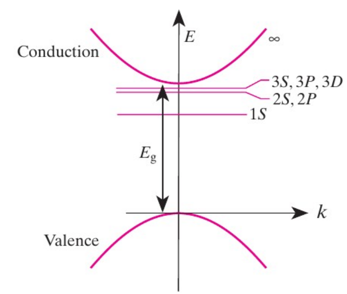
Ecuación de Schrödinger para el electrón donado al material:

$$[\hat{H}_{\text{per}} + V_{\text{imp}}(\mathbf{R})]\psi(\mathbf{R}) = E\psi(\mathbf{R})$$

Aproximaciones: (1) una sola banda (2) Integrar *k* cerca del mínimo

$$\longrightarrow \quad \psi(x) \approx \phi_{n0}(x) \int_{-\pi/a}^{\pi/a} \tilde{\chi}(k) \exp(ikx) \frac{dk}{2\pi} = \phi_{n0}(x)\, \chi(x)$$

Y la función envolvente satisface: $$\left[\varepsilon_n\left(-i\frac{d}{dx}\right) + V_{\text{imp}}(x)\right]\chi(x) = E\chi(x).$$



Confinamiento adicional:

Nanoestructuras - cables y puntos cuánticos

# Confinamiento adicional:
# Nanoestructuras - cables y puntos cuánticos

Estamos usando:

THE PHYSICS OF
LOW-DIMENSIONAL
SEMICONDUCTORS

AN INTRODUCTION

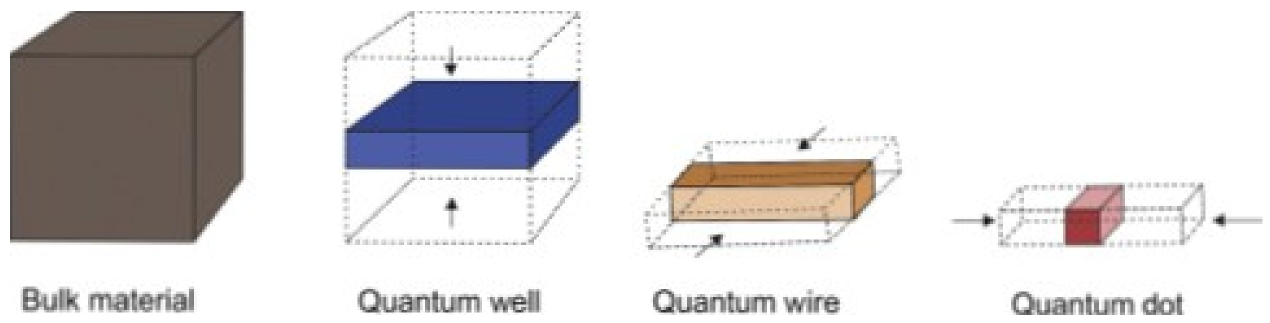
JOHN H. DAVIES
*Glasgow University*

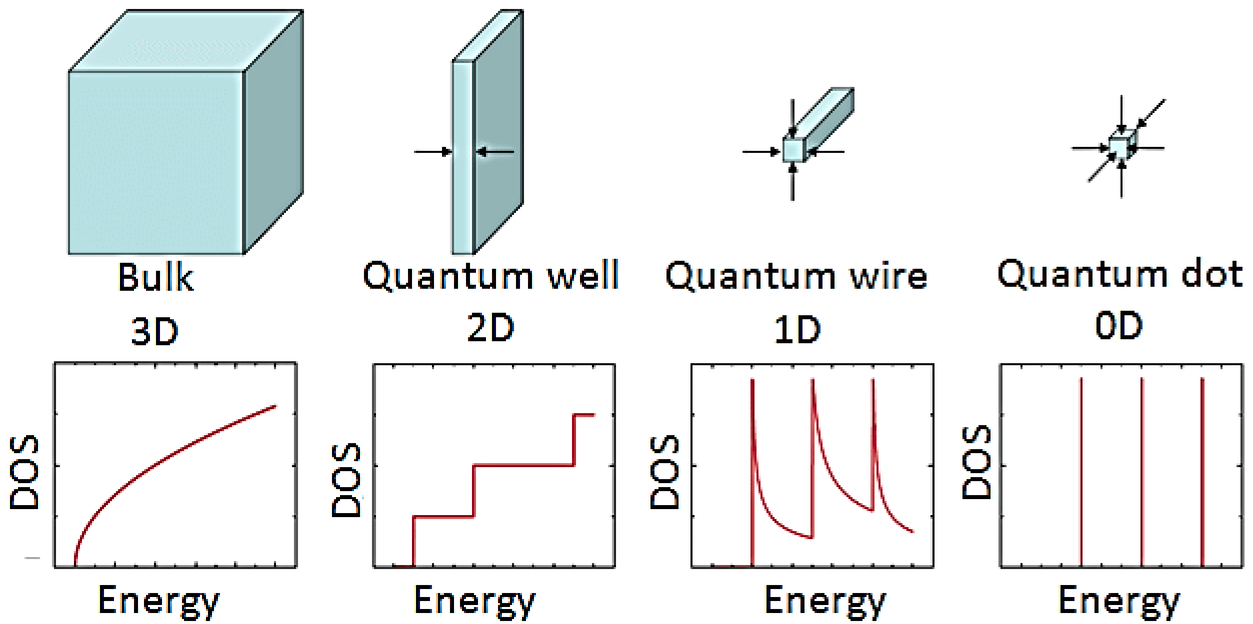
Otro libro especializado:

**QUANTUM WELLS, WIRES AND DOTS**
**Theoretical and Computational Physics of Semiconductor Nanostructures**

**Paul Harrison**
**The University of Leeds, UK**

# Confinamiento adicional: Nanoestructuras - cables y puntos cuánticos



# Cables cuánticos

## Quantum Wires

To make the transition from a 2D electron gas (quantum well) to a 1D electron gas (quantum wire), the electrons should be confined in two directions and only 1 degree of freedom remain. The **x direction** remains the **only one** for **free-electron propagation**.

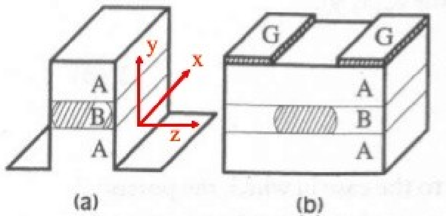
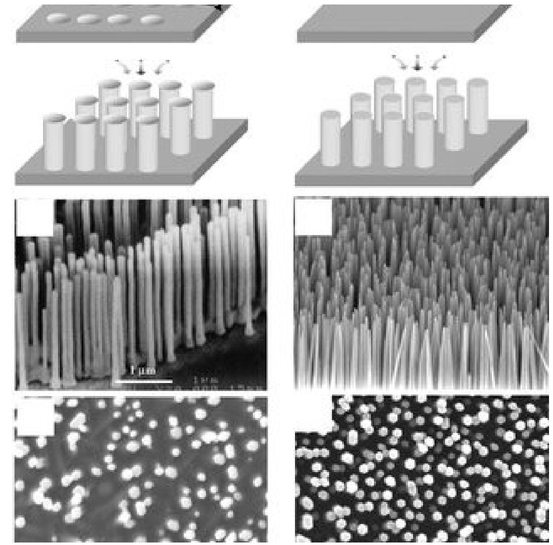



Figure 3.11. Two of the simplest examples of structures providing electron confinement in two dimensions: case (a) uses an etching technique, while case (b) is based on the split-gate technique.

## Nanowhiskers o nanorods



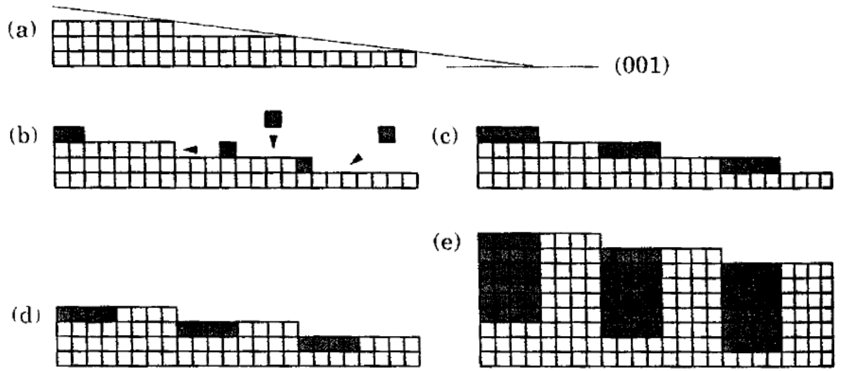
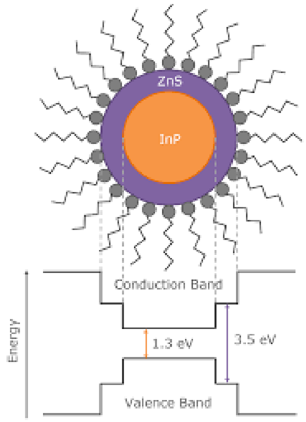
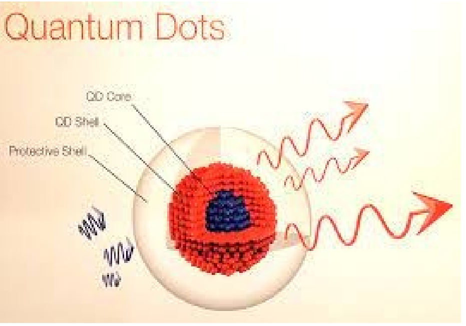


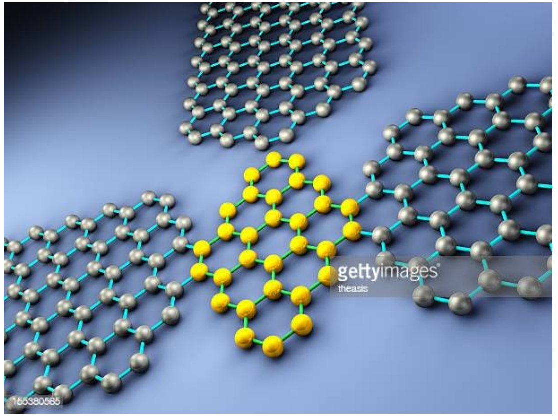

FIGURE 3.18. Growth of wires on a vicinal substrate. (a) Substrate before growth, showing steps and terraces on the vicinal (off-axis) surface. (b) Flux of AlAs applied, with motion of atoms over surface to steps where they stick. (c) Completion of a half-monolayer of AlAs. (d) Growth of a further half-monolayer of GaAs. (e) Growth of many layers, showing development of superlattice.

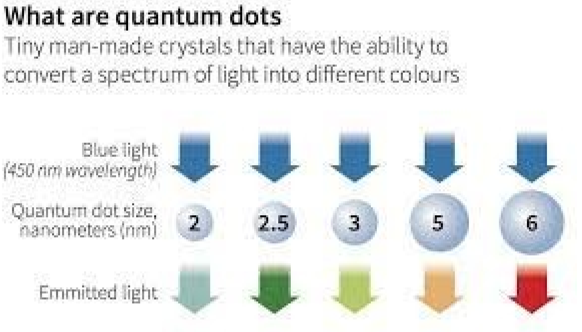
# Puntos cuánticos (de químicos)



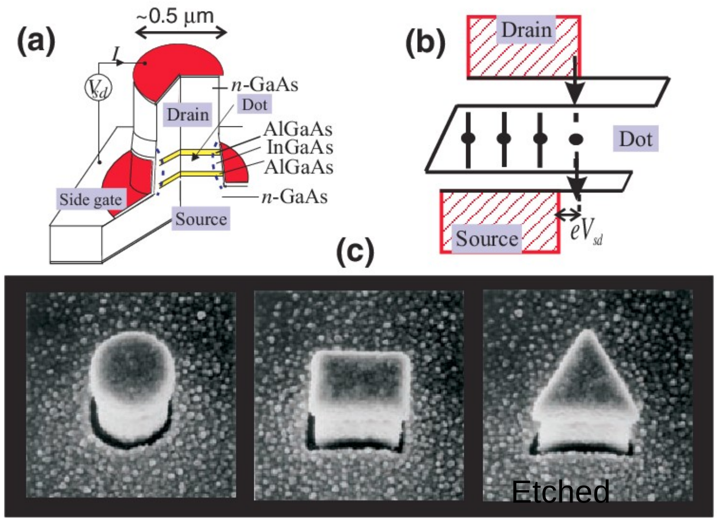



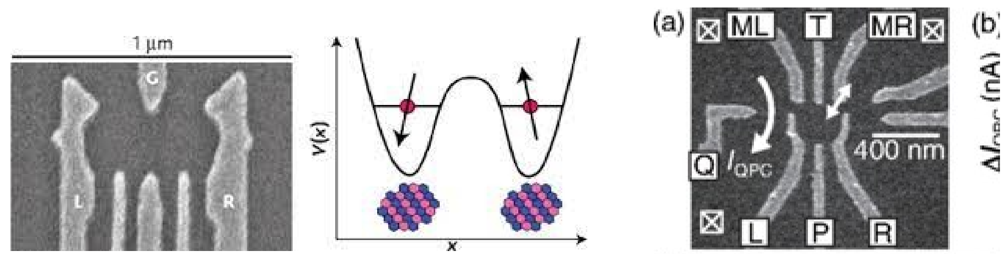




# Puntos cuánticos (de físicos)




Con voltage gates

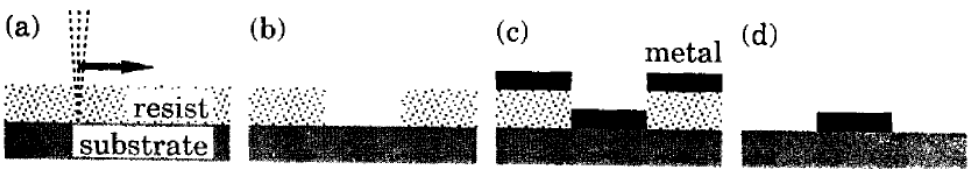
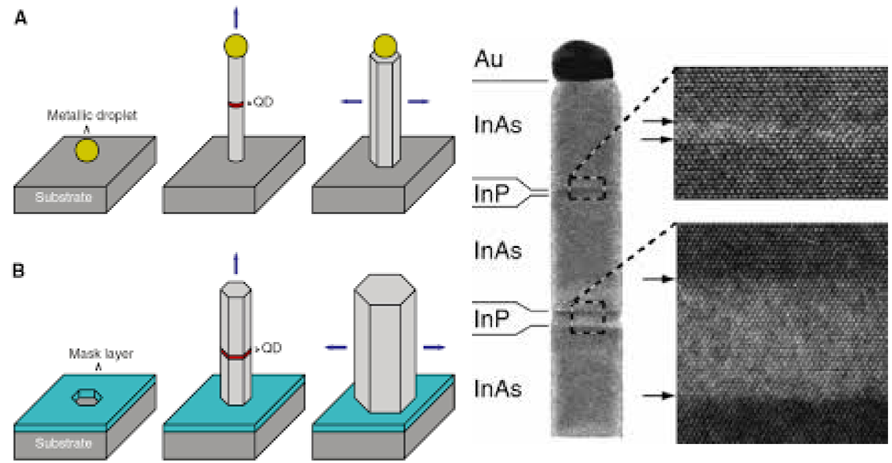


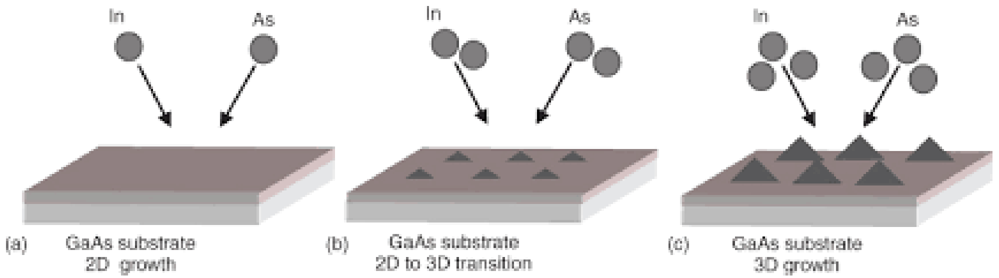

**FIGURE 3.16.** Production of a metal gate by electron-beam lithography and lift-off. (a) Exposure of resist by electron beam, (b) development of resist, (c) deposition of metal, and (d) lift-off to leave metal gate.

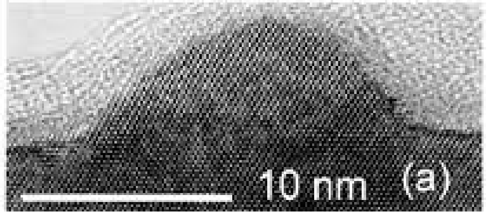


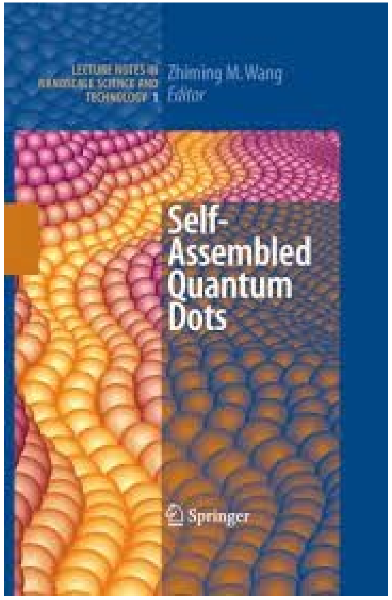

Dentro de nanorods

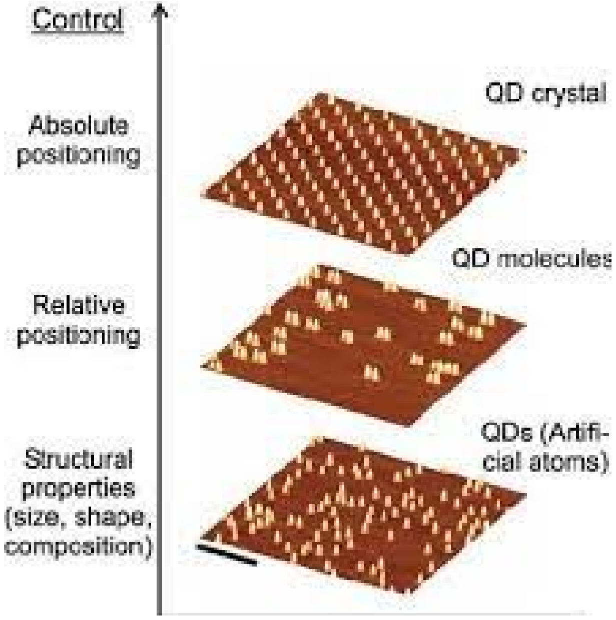
# Puntos cuánticos (de físicos)

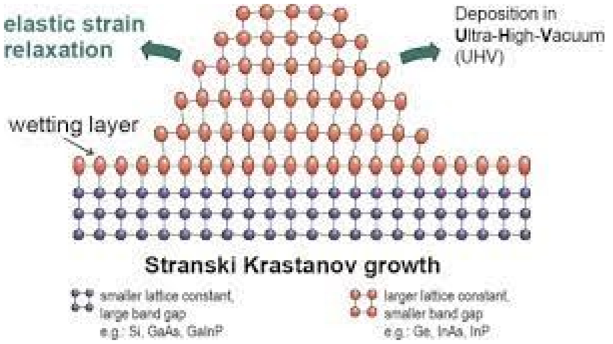
## Self-assembled quantum dots



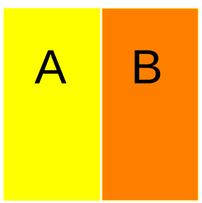
# Aproximación de masa efectiva en heteroestructuras

# Aproximación de masa efectiva en hetero-estructuras

Habíamos visto que en presencia de un potencial externo (sumado al del cristal) la función de onda de electrón se podría factorizar:

$$\psi(x) \approx \phi_{n0}(x) \int_{-\pi/a}^{\pi/a} \tilde{\chi}(k) \exp(ikx) \frac{dk}{2\pi} = \phi_{n0}(x)\, \chi(x).$$

¿Qué pasa en la interfaz entre dos materiales diferentes en una heteroestructura?




Idealmente, matching de

$\phi_{n0}(x)$

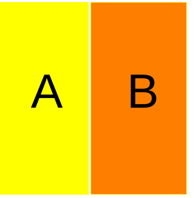
- Mismo punto en la 1era zona de Brillouin
- Similitud entre ambos lados
- Happily, detailed calculations confirm that effective-mass theory remains acceptable despite the different Bloch functions.

$\chi(x)$

- El problema del cambio en la masa efectiva

# Aproximación de masa efectiva en hetero-estructuras

Envelope function $\chi(x)$




$E_c^B$

$E_c^A$

$$\Delta E_c = E_c^B - E_c^A$$

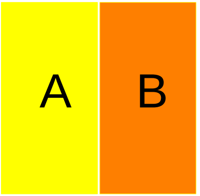
$$\begin{cases} \left(E_c^A - \dfrac{\hbar^2}{2m_A m_0}\dfrac{d^2}{dz^2}\right)\chi(z) = E\chi(z). \\ \left(E_c^B - \dfrac{\hbar^2}{2m_B m_0}\dfrac{d^2}{dz^2}\right)\chi(z) = E\chi(z) \end{cases}$$

$$\chi(0_A) = \chi(0_B), \qquad \left.\frac{d\chi(z)}{dz}\right|_{z=0_A} = \left.\frac{d\chi(z)}{dz}\right|_{z=0_B}$$

$$\chi(0_A) = \chi(0_B), \qquad \left.\frac{1}{m_A}\frac{d\chi(z)}{dz}\right|_{z=0_A} = \left.\frac{1}{m_B}\frac{d\chi(z)}{dz}\right|_{z=0_B}$$

# Aproximación de masa efectiva en hetero-estructuras

Envelope function $\chi(x)$




$$-\frac{\hbar^2}{2m_0 m(z)}\frac{d^2\chi}{dz^2} + V(z)\chi(z) = E\chi(z). \qquad (3.20)$$

This is not Hermitian (or of Sturm–Liouville form) if $m(z)$ varies, and many of the

Versión más correcta:

$$-\frac{\hbar^2}{2m_0}\frac{d}{dz}\left[\frac{1}{m(z)}\frac{d\chi}{dz}\right] + V(z)\chi(z) = E\chi(z)$$

# Aproximación de masa efectiva en hetero-estructuras

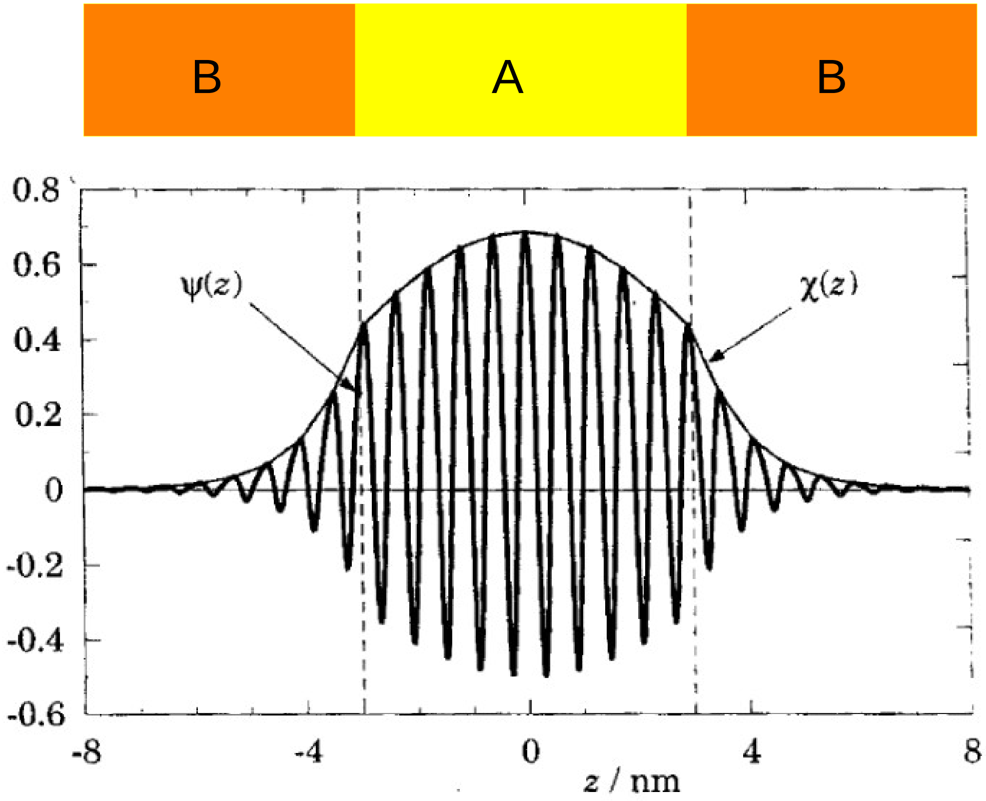



FIGURE 3.22. Wave function for the lowest state in a 6 nm quantum well in a heterostructure, including the Bloch functions. The thin curve is an approximate envelope function joining the peaks of the full wave function. [Redrawn from Burt (1994).]

Modulation doping - dopaje remoto

# Modulation doping - dopaje remoto

WIKIPEDIA

# Modulation doping

Modulation doping is a technique for fabricating semiconductors such that the free charge carriers are spatially separated from the donors. Because this eliminates scattering from the donors, modulation-doped semiconductors have very high carrier mobilities.

## History

Modulation doping was conceived in Bell Labs in 1977 following a conversation between Horst Störmer and Ray Dingle,[1] and implemented shortly afterwards by Arthur Gossard. In 1977, Störmer and Dan Tsui used a modulation-doped wafer to discover the fractional quantum Hall effect.

# Modulation doping - dopaje remoto

Dopaje: agregar átomos que ceden electrones o huecos al material.

Problema: los iones que quedan son centros de scattering que reducen la mobility

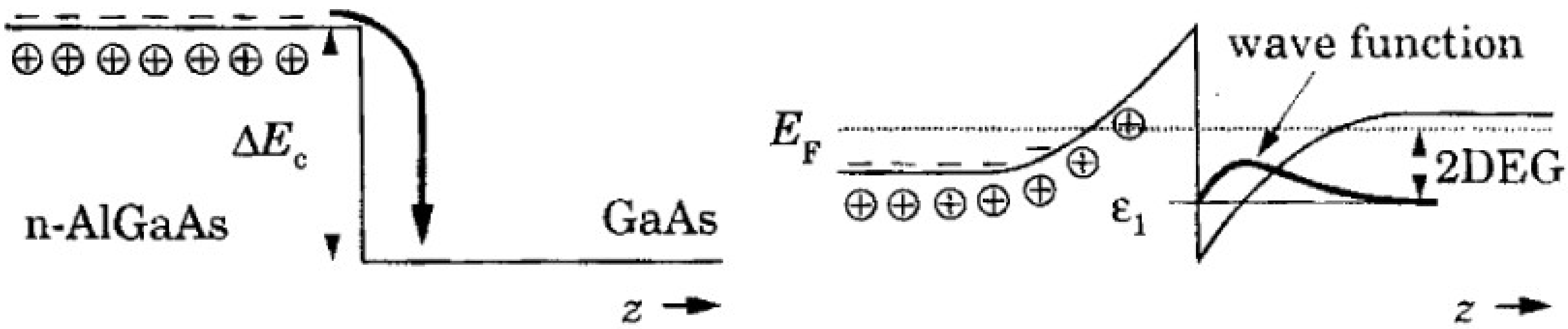



FIGURE 3.9. Conduction band around a heterojunction between n-AlGaAs and undoped GaAs, showing how electrons are separated from their donors to form a two-dimensional electron gas.

Los electrones migran de una región a otra y evitan las colisiones con los iones (cargados atractivamente)

# Resumen de la clase 7

Cable y puntos cuánticos

Aproximación de masa efectiva en heteroestructuras

Dopaje remoto