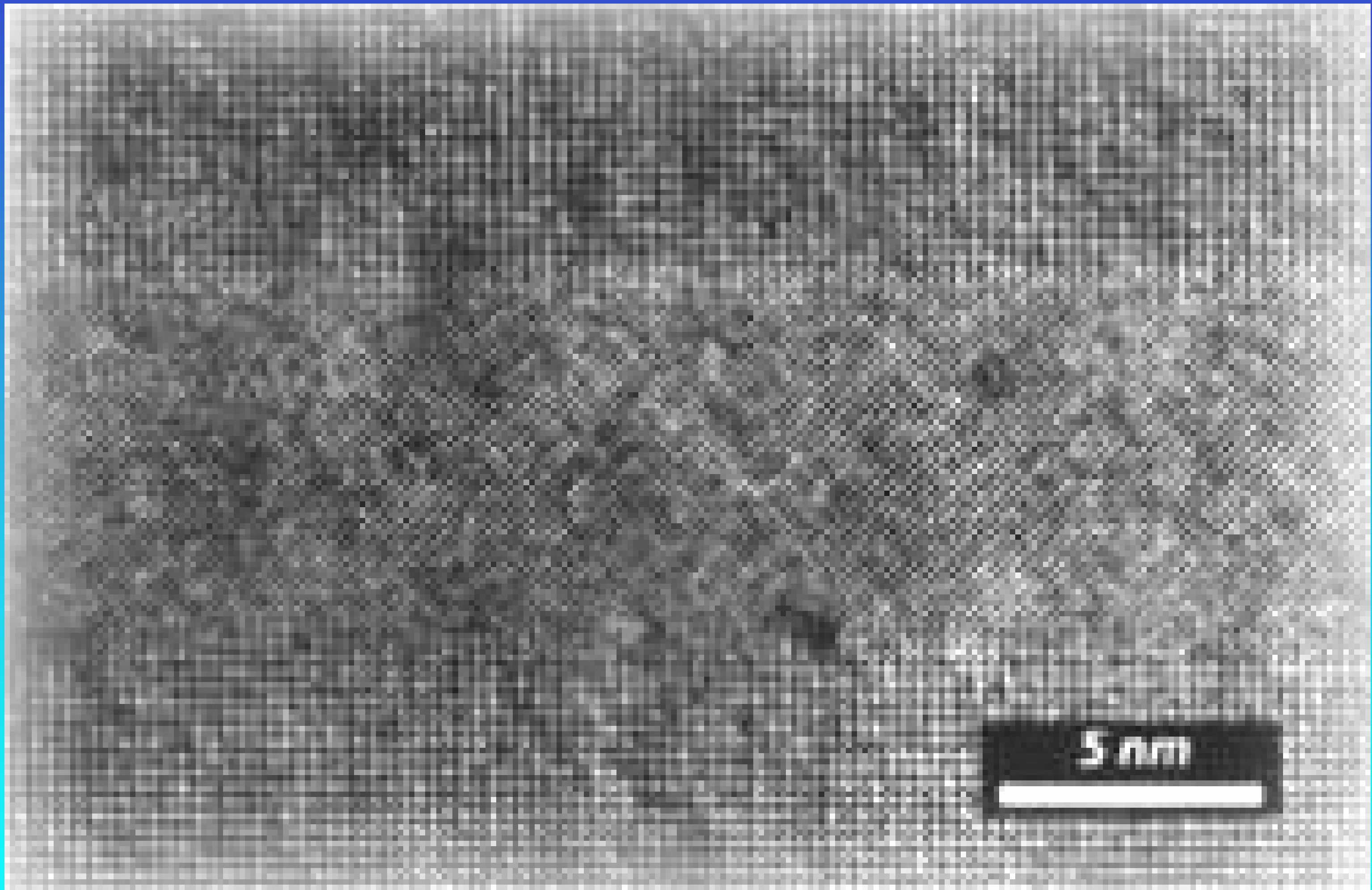
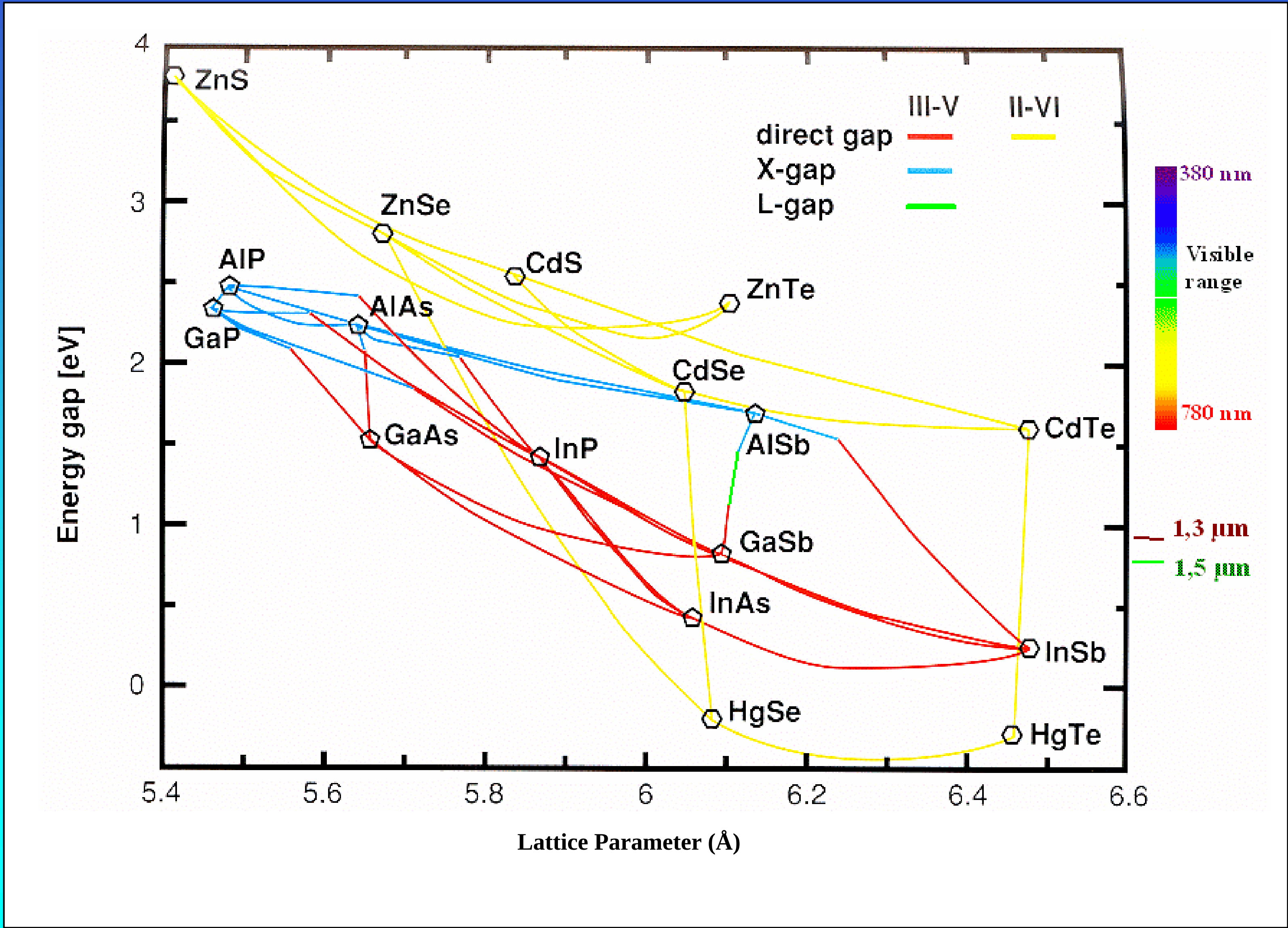
# Semiconductor Heterojunctions

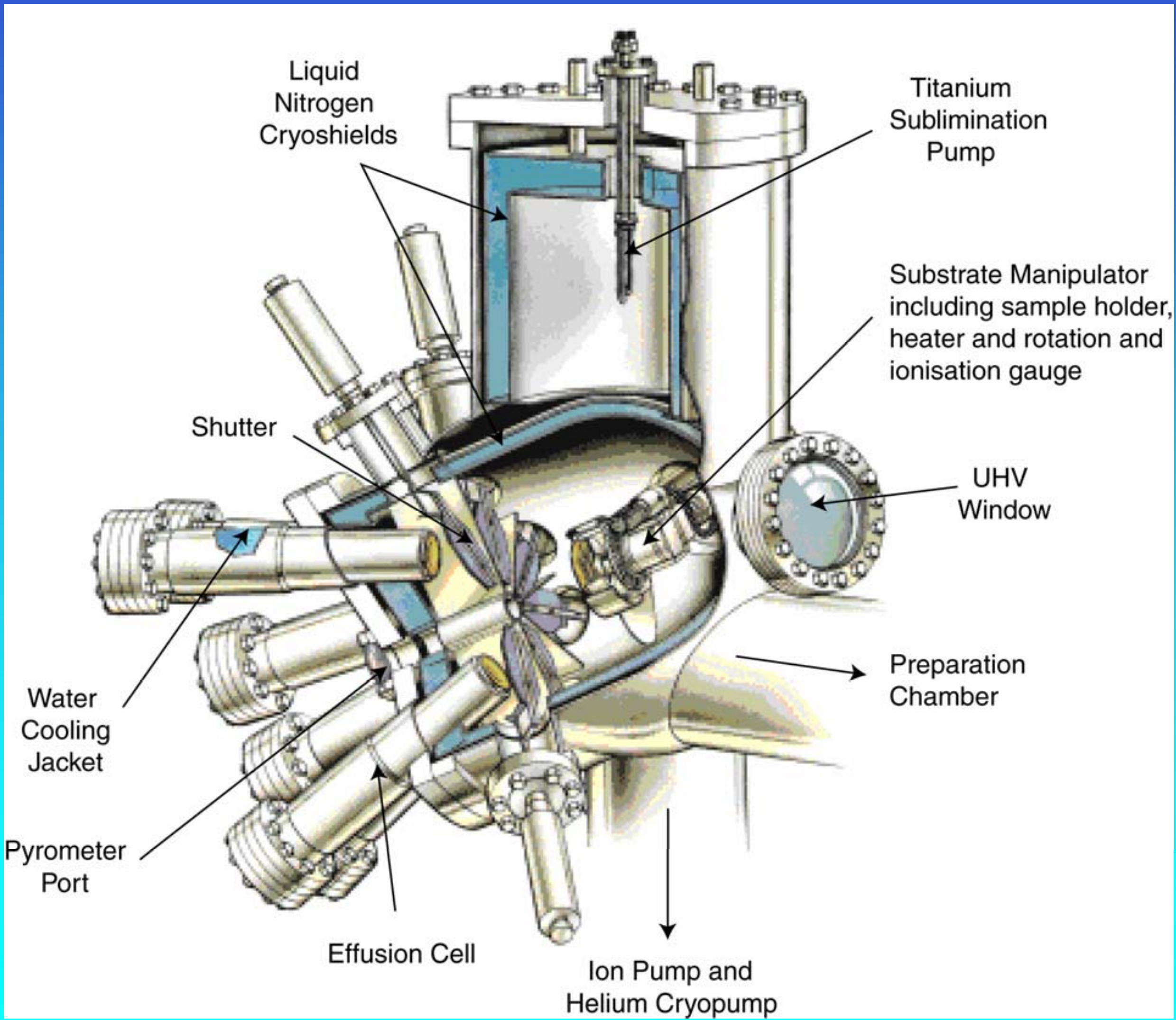



**HRTEM image of a 6.4 nm AlGaAs/InGaAs strained layer heterostructure**

# Energy gap *vs* lattice parameter



# MBE Growth Chamber




- Growth, preparation and loadlock chambers
  - Stainless steel
  - Copper gasket seals
- Ion, turbo- and cryopumps
- $LN_2$ cryoshield (400L/day)
- Very long bakes at 200$^{o}$C
- Outgassing of sources
- Outgassing of substrates
- Ultra-high vacuum
  - $10^{-11}$mbar total
- Pressure of impurities
  - $10^{-15}$ mbar
- Growth of thick layers to bury contamination – up to 6 months to clean up.

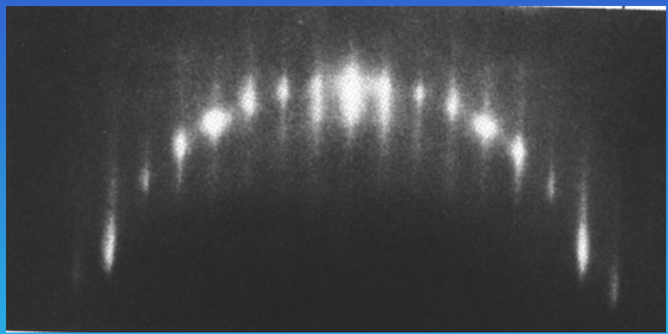
# Production MBE System
## VG Semicon V150

- Launched 1999
- Automated
- Simultaneous growth on four 6 inch wafers
- 20,000 6 inch wafers per year
- Laser diodes, LEDs, HBTs, PHEMTs
- Cost £2M

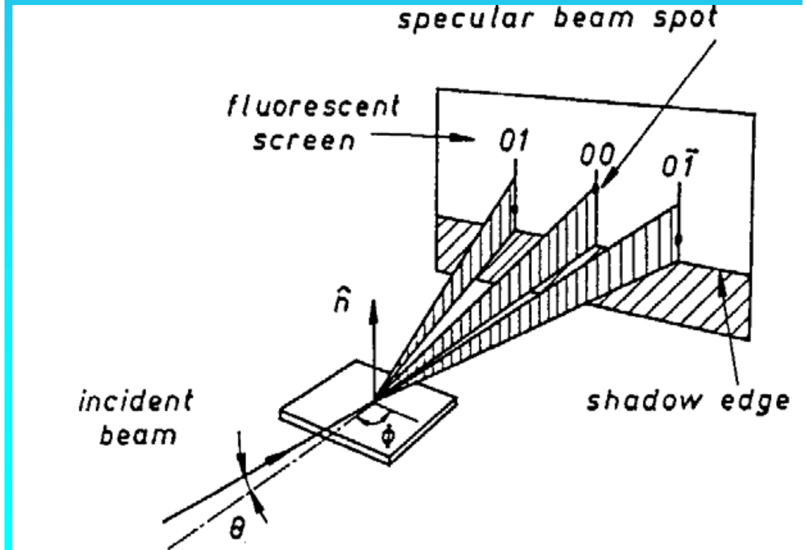
VG Semicon

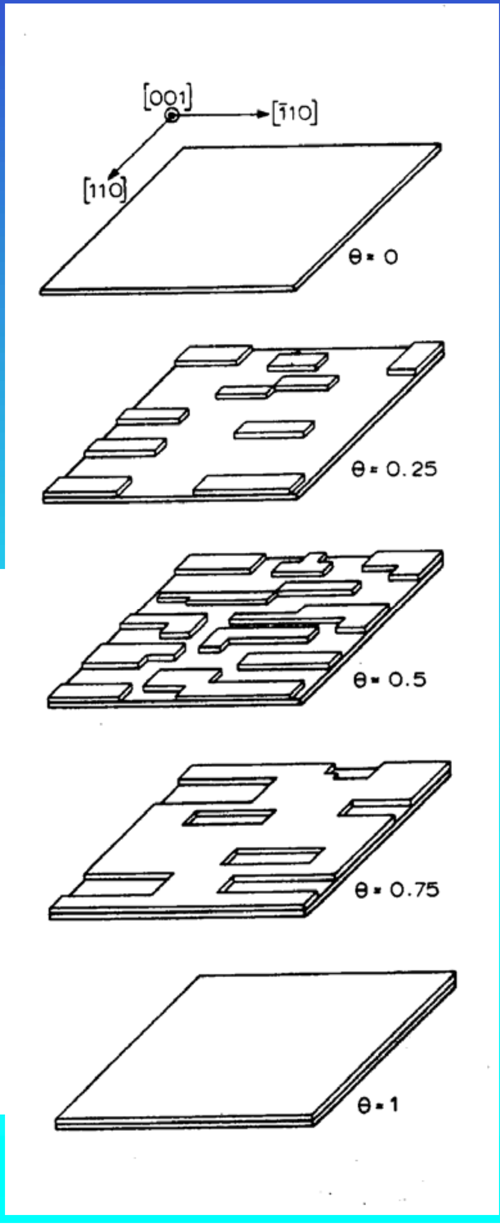
# RHEED Oscillations

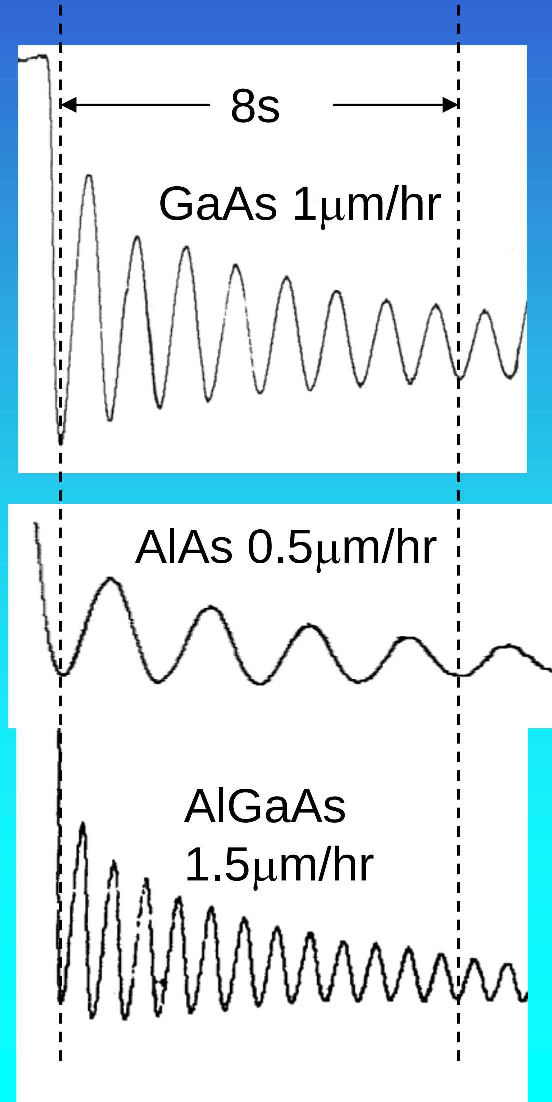
## (Observation of growth monolayer by monolayer)



2x4 pattern $(\bar{1}10)$ direction



# MOCVD Growth System

- Chemical reaction of elements bonded in volatile organic compounds

- e.g. $(CH_3)_3Ga + AsH_3 \rightarrow$
  $GaAs + 3CH_4$

- Reaction takes place on a heated substrate and growth is also 'epitaxial'

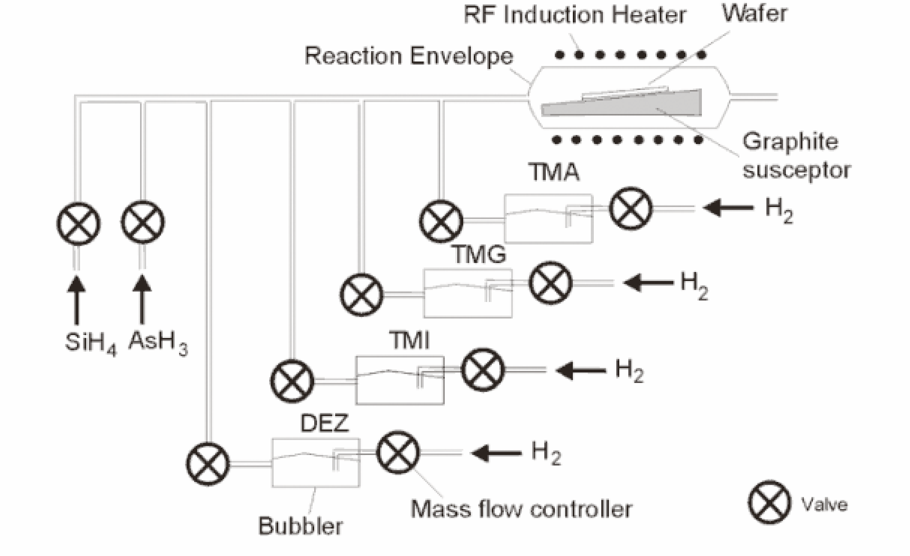
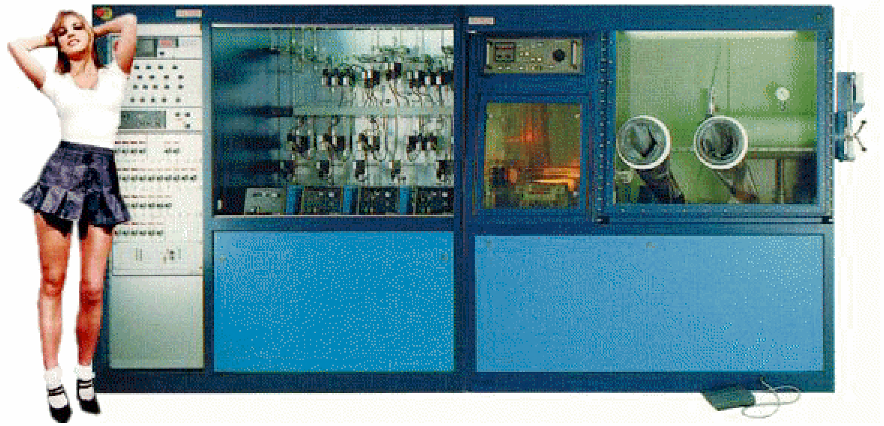


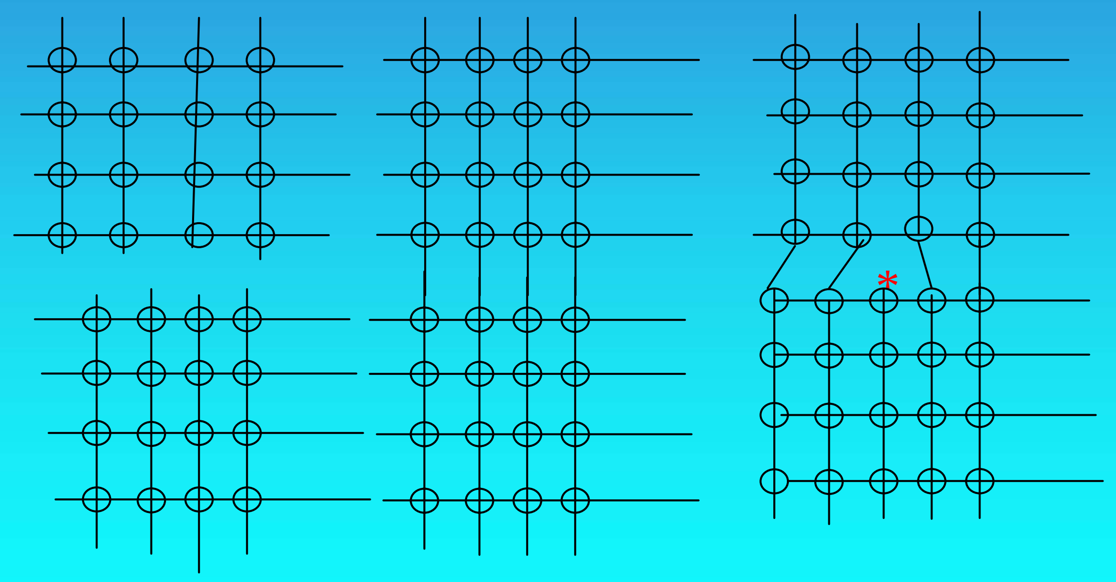

Figure 4. Schematic diagram of the MOCVD process



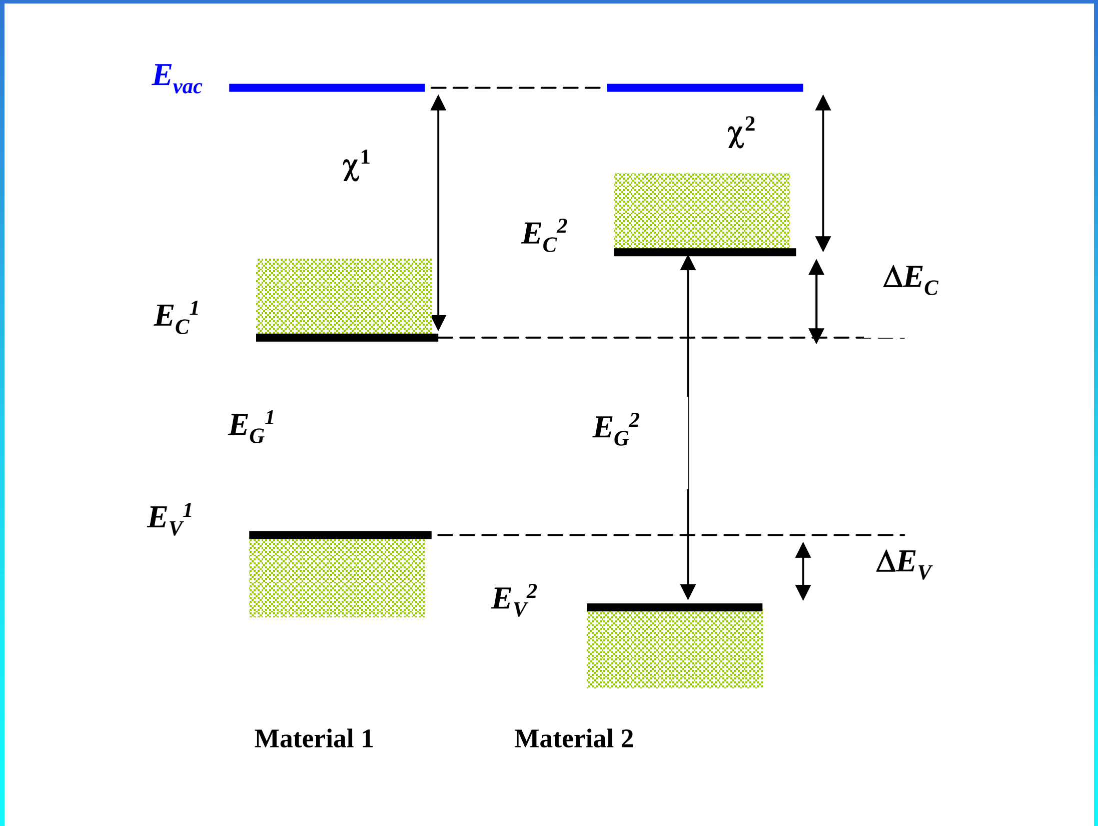
# strain due to lattice mismatch

InGaAs

GaAs



# Energy band offsets

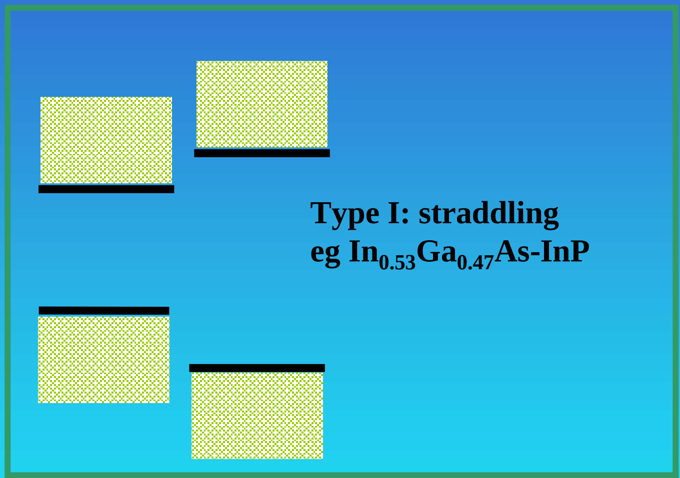


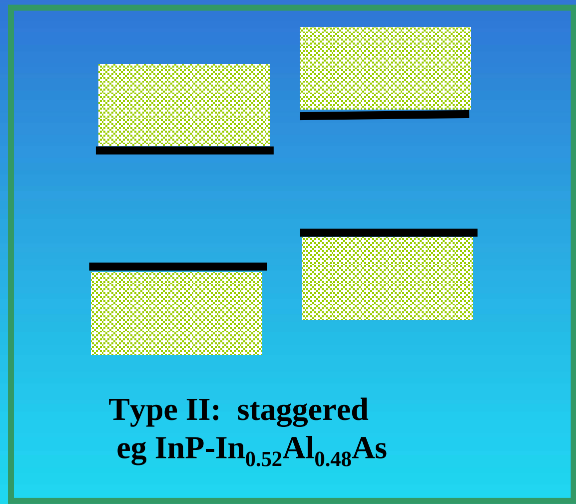

***Electron affinity*** **$\chi$: Energy required to remove an electron from the conduction band and take it to the vacuum.**

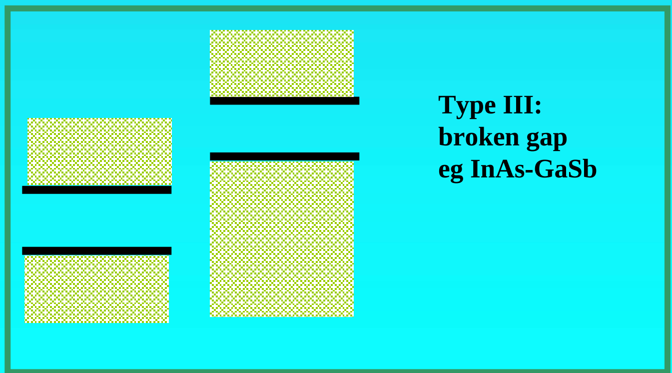
$$\Delta E_C = \chi^1 - \chi^2$$

$$\Delta E_V = E_G^1 - E_G^2 - \Delta E_C$$

# Heterostructure band alignment



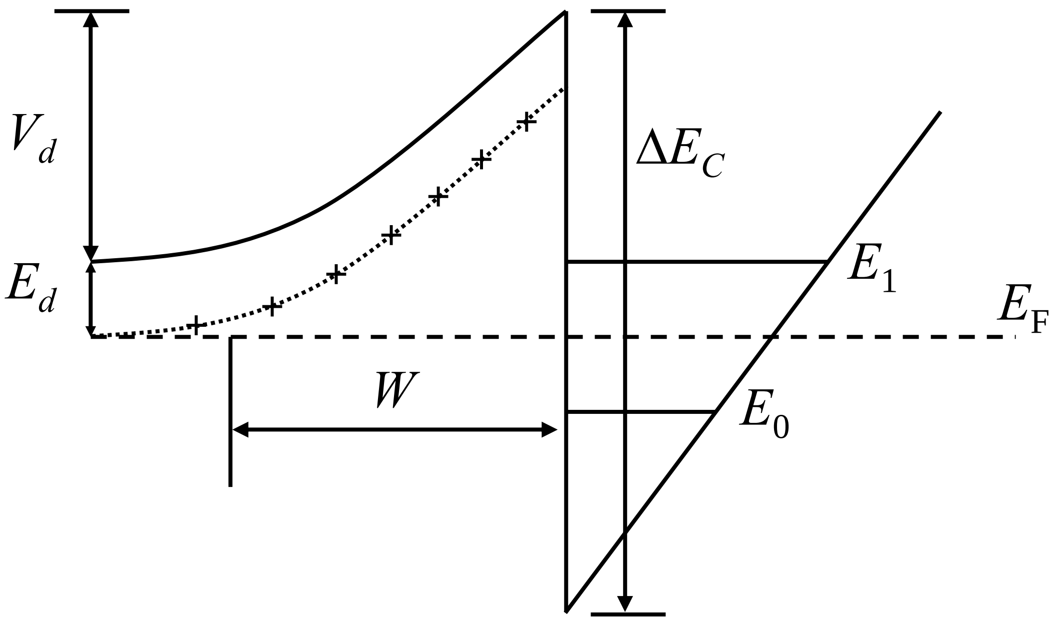



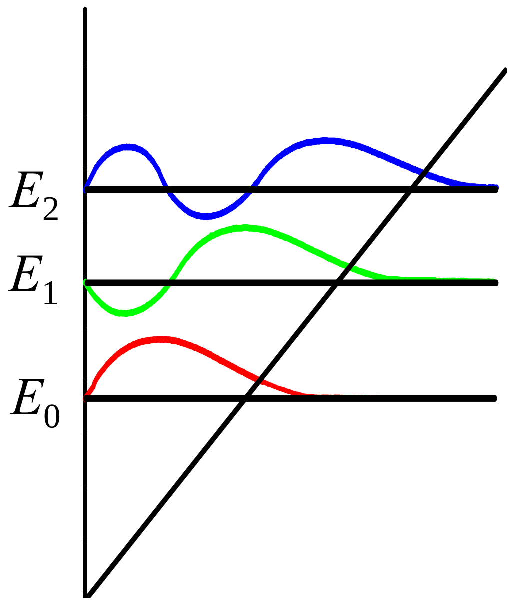

**These examples of band alignment show how the potential barrier across a *pn* junction may be increased (Type I), electronic states can be made "spatially indirect" (Type II), or semi-metallic behaviour can be produced due to overlapping conduction and valence bands (Type III).**

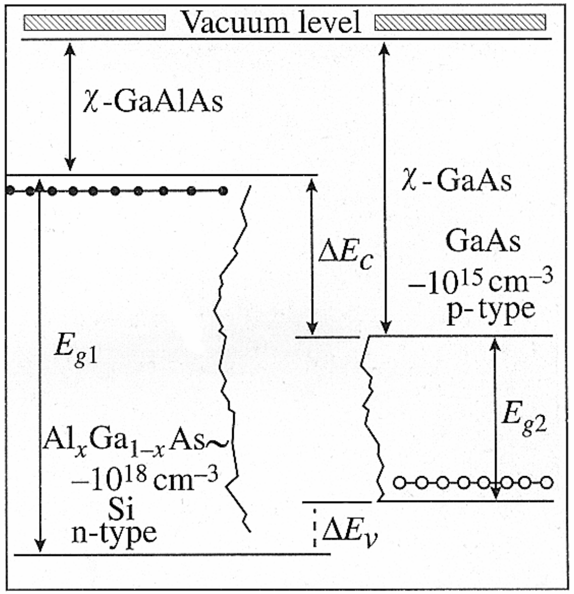
# A single heterojunction

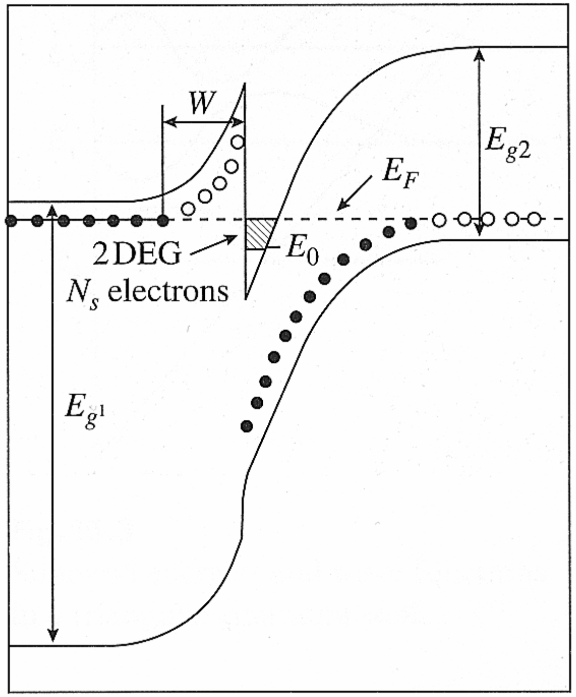
## energy bands




## wavefunctions






# A single heterojunction

$$\Im = \frac{N_s e}{\varepsilon_0 \varepsilon_r}$$ and for $z > 0$ for a triangular well:

$$\varphi(z) = -\Im z$$ so solving Schrodinger's equation gives:

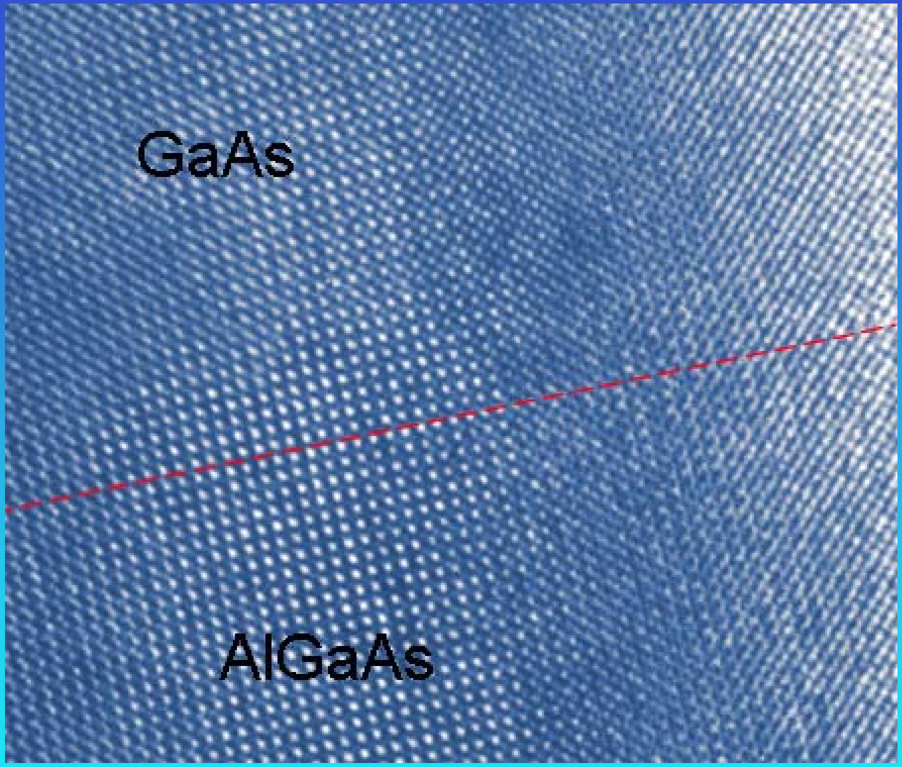
$$E_n = -\left(\frac{e^2 \Im^2 \hbar^2}{2m^*}\right)^{1/3} a_n$$

$$a_n \cong -\left[\frac{3\pi}{2}\left(n + 3/4\right)\right]^{2/3}, \qquad n = 0, 1, \ldots$$

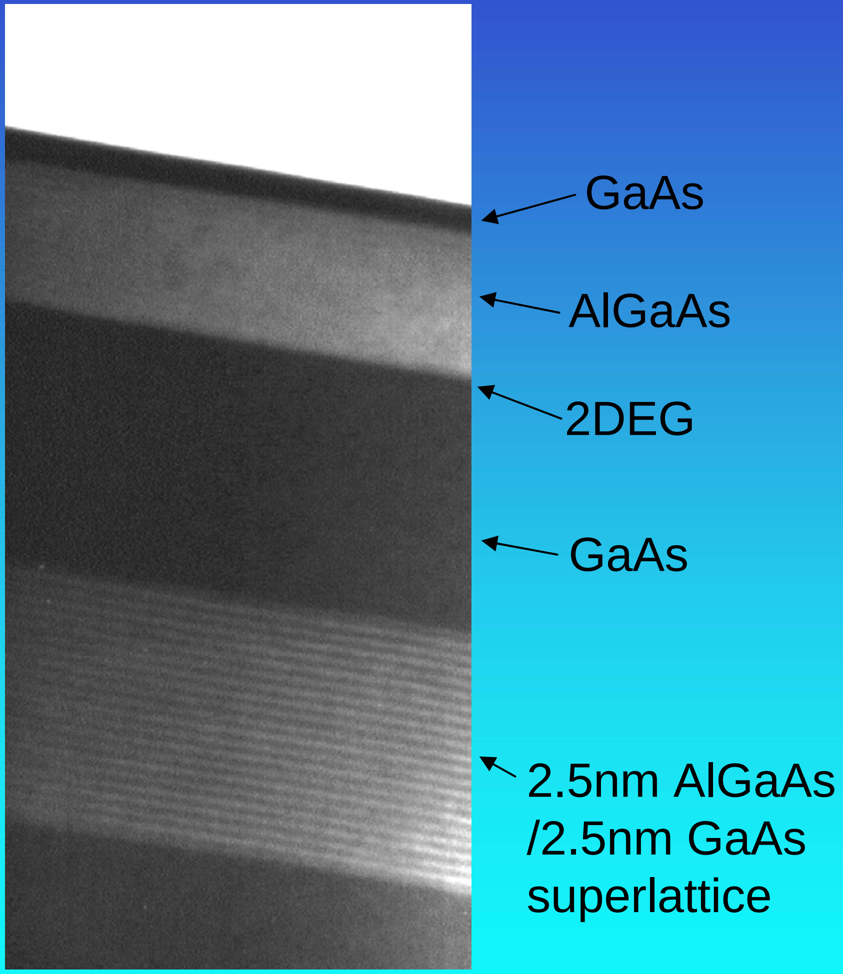
$$E_n \cong \left(\frac{\hbar^2}{2m^*}\right)^{1/3} \left[\frac{3\pi e \Im}{2}\left(n + 3/4\right)\right]^{2/3}$$ and eliminating $\Im$

$$E_0 \cong \left(\frac{\hbar^2}{2m^*}\right)^{1/3} \left(\frac{9\pi e^2 N_s}{8\varepsilon_0 \varepsilon_r}\right)^{2/3}$$

# A perfect junction?




High Resolution TEM GaAs/AlGaAs interface (T Walther, Materials)




TEM of GaAs/AlGaAs 2DEG structure with superlattice buffer (W M Stobbs, Materials)

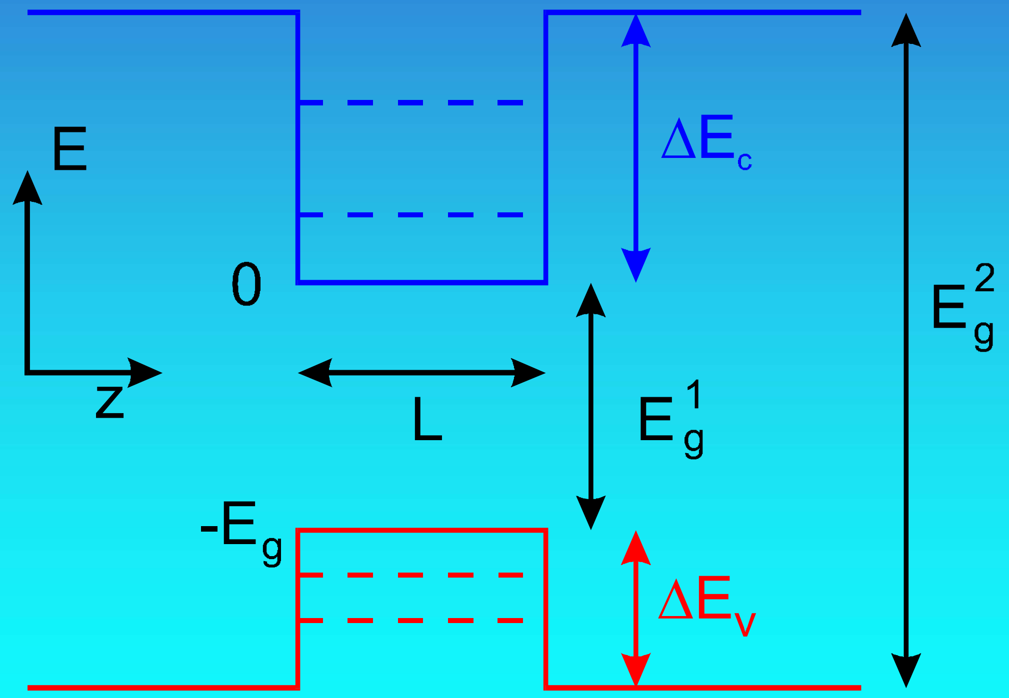
# Quantum Well - Type I

Typical Materials: 1: GaAs ($E_g$ = 1.5 eV) 2: $(Al_{0.35}Ga_{0.65})As$ ($E_g$ = 2.0 eV)

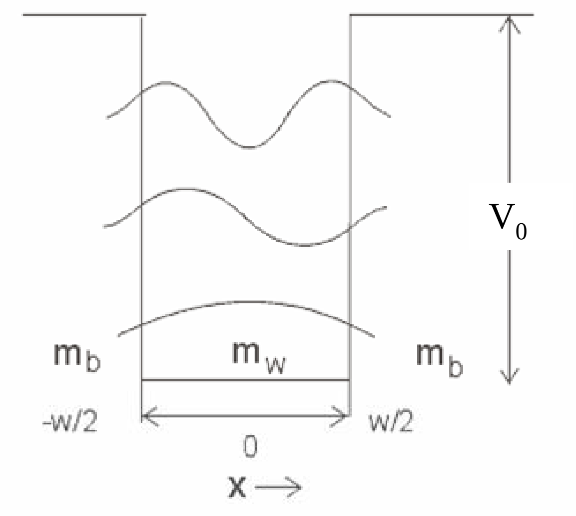
Energy levels are quantized in z-direction with values $E_n$ for both electrons and holes ∴

$$E = E_n + \hbar^2 k_\perp^2/2m^*$$

↑ 1-D ↑ 2-D



# particle in a finite potential well




The continuity conditions at the interfaces are that $\psi$ and $\frac{1}{m}\frac{\partial\psi}{\partial x}$ should be continuous.

$$\left(-\frac{\hbar^2}{2m_w}\frac{\partial^2}{\partial^2 x}-V_0\right)\psi_n(x)=\varepsilon_n\psi_n(x)$$

$$\left(-\frac{\hbar^2}{2m_b}\frac{\partial^2}{\partial^2 x}\right)\psi_n(x)=\varepsilon_n\psi_n(x)$$

$$\begin{aligned}
\psi_n(x) &= A\cos kx && for\ |x|<w/2\\
&= B\exp\left[-K\left(x-\frac{w}{2}\right)\right] && for\ x>w/2\\
&= B\exp\left[+K\left(x+\frac{w}{2}\right)\right] && for\ x<-w/2
\end{aligned}$$

$$\begin{aligned}
\psi_n(x) &= A\sin kx && for\ |x|<w/2\\
&= B\exp\left[-K\left(x-\frac{w}{2}\right)\right] && for\ x>w/2\\
&= B\exp\left[+K\left(x+\frac{w}{2}\right)\right] && for\ x<-w/2
\end{aligned}$$

# Eigenvalues for finite potential well

$$A\cos\left(\frac{kw}{2}\right)=B$$

$$\frac{k}{m_w}A\sin\left(\frac{kw}{2}\right)=\frac{KB}{m_b}$$

$$\therefore \frac{k}{m_w}\tan\left(\frac{kw}{2}\right)=\frac{K}{m_b}$$

$$A\sin\left(\frac{kw}{2}\right)=B$$

$$\frac{k}{m_w}A\cos\left(\frac{kw}{2}\right)=-\frac{KB}{m_b}$$

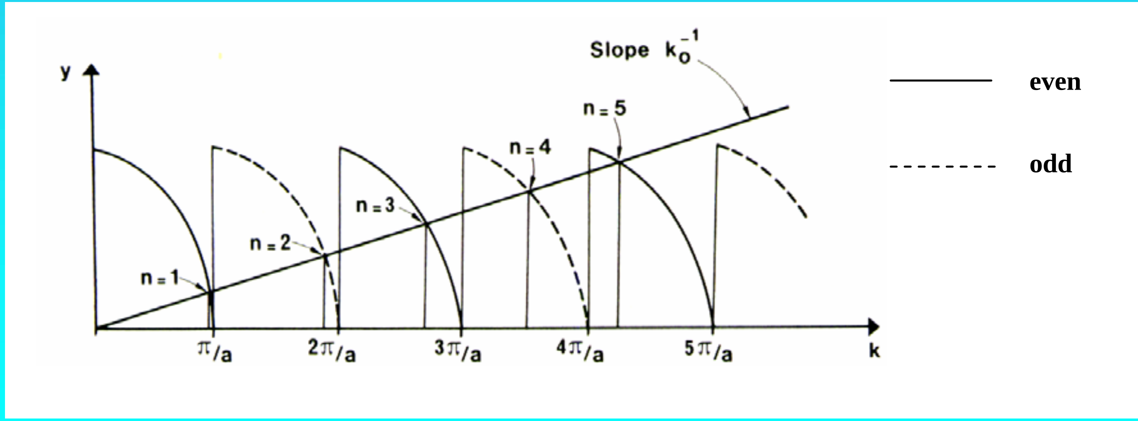
$$\therefore \frac{k}{m_w}\cot\left(\frac{kw}{2}\right)=-\frac{K}{m_b}$$

$$m_w \neq m_b$$

$$\cos\frac{kw}{2}=\frac{k}{k_0} \quad \text{for} \quad \tan\left(\frac{kw}{2}\right)>0$$

$$\sin\frac{kw}{2}=\frac{k}{k_0} \quad \text{for} \quad \tan\left(\frac{kw}{2}\right)<0$$

$$k_0^2=\frac{2mV_0}{\hbar^2}$$




$$m_w = m_b$$

# Density of States

Travelling waves

$e^{ikx}$ $(e^{i\mathbf{k}.\mathbf{r}})$

Periodic boundary conditions

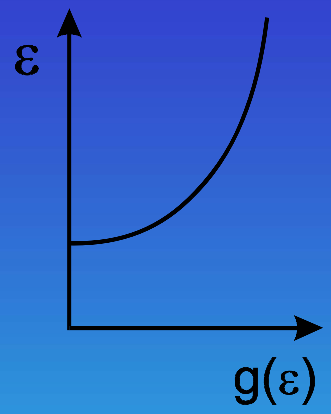
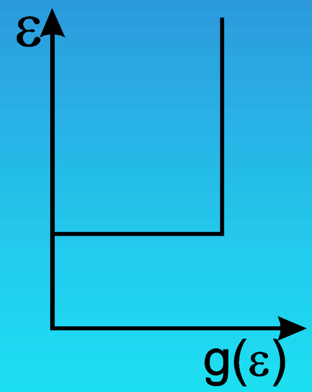
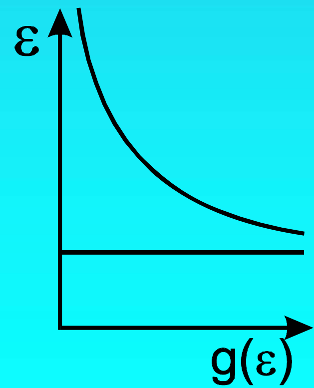
$\psi(x) = \psi(x + L)$

$\therefore\ e^{ikL} = 1 \ \rightarrow\ k = \pm 2n\pi/L$

$\rightarrow\ \delta k = 2\pi/L$

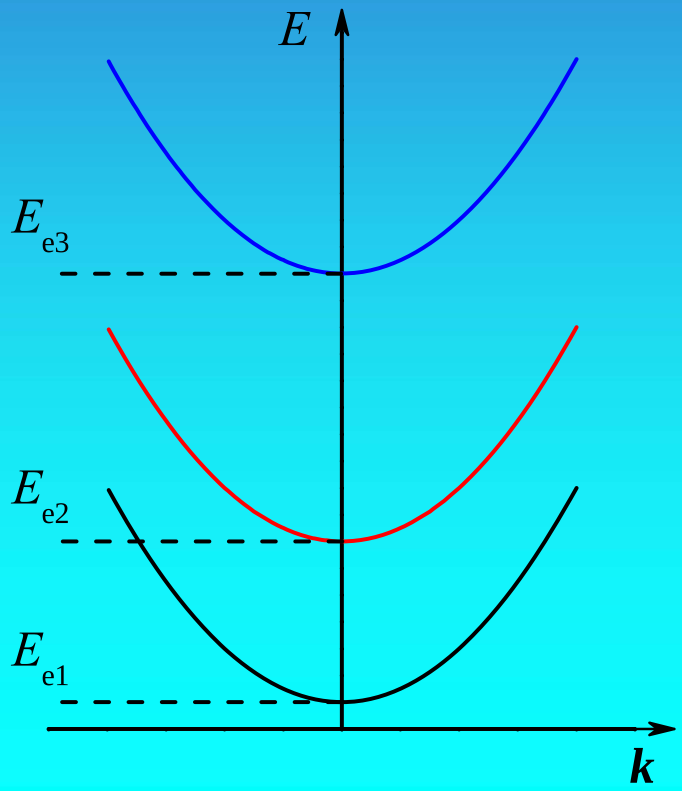
$\varepsilon = \hbar^2 k^2/2m^*,$

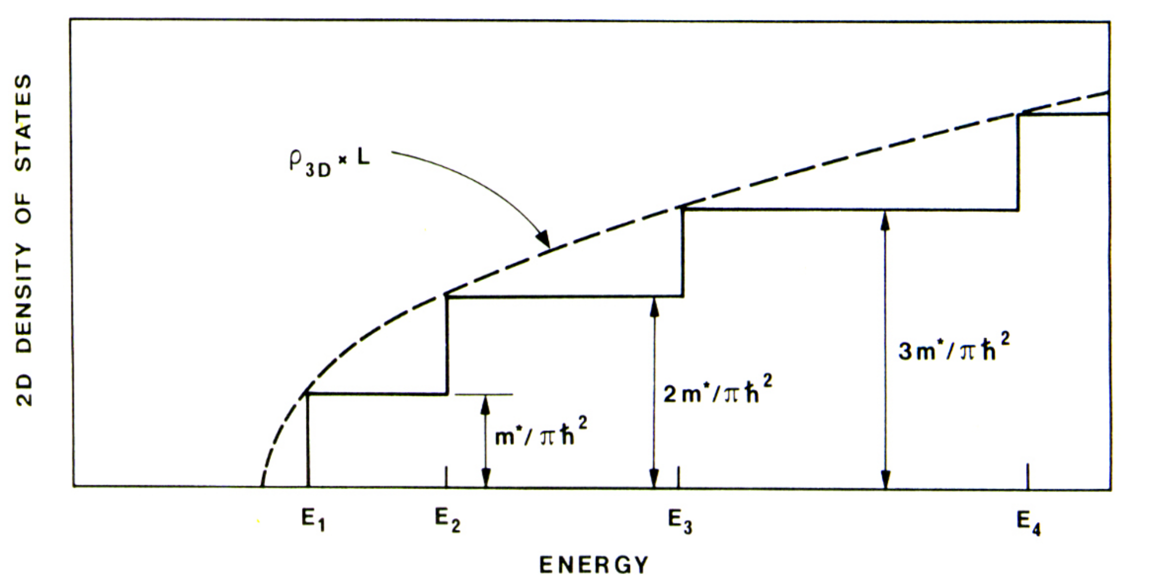
$d\varepsilon = (\hbar^2/2m^*)\, 2k\, dk$

| | g(k)dk | g(ε)dε | |
|---|---|---|---|
| 3-D | $\dfrac{4\pi k^2 dk}{(2\pi/L)^3}$ | $\dfrac{V}{(2\pi)^2}\left(\dfrac{2m^*}{\hbar^2}\right)^{3/2}\varepsilon^{1/2}d\varepsilon$ |  |
| 2-D | $\dfrac{2\pi k\ dk}{(2\pi/L)^2}$ | $\dfrac{A}{4\pi}\left(\dfrac{2m^*}{\hbar^2}\right)d\varepsilon$ |  |
| 1-D | $\dfrac{2dk}{2\pi/L}$ | $\dfrac{L}{2\pi}\left(\dfrac{2m^*}{\hbar^2}\right)^{1/2}\varepsilon^{-1/2}d\varepsilon$ |  |

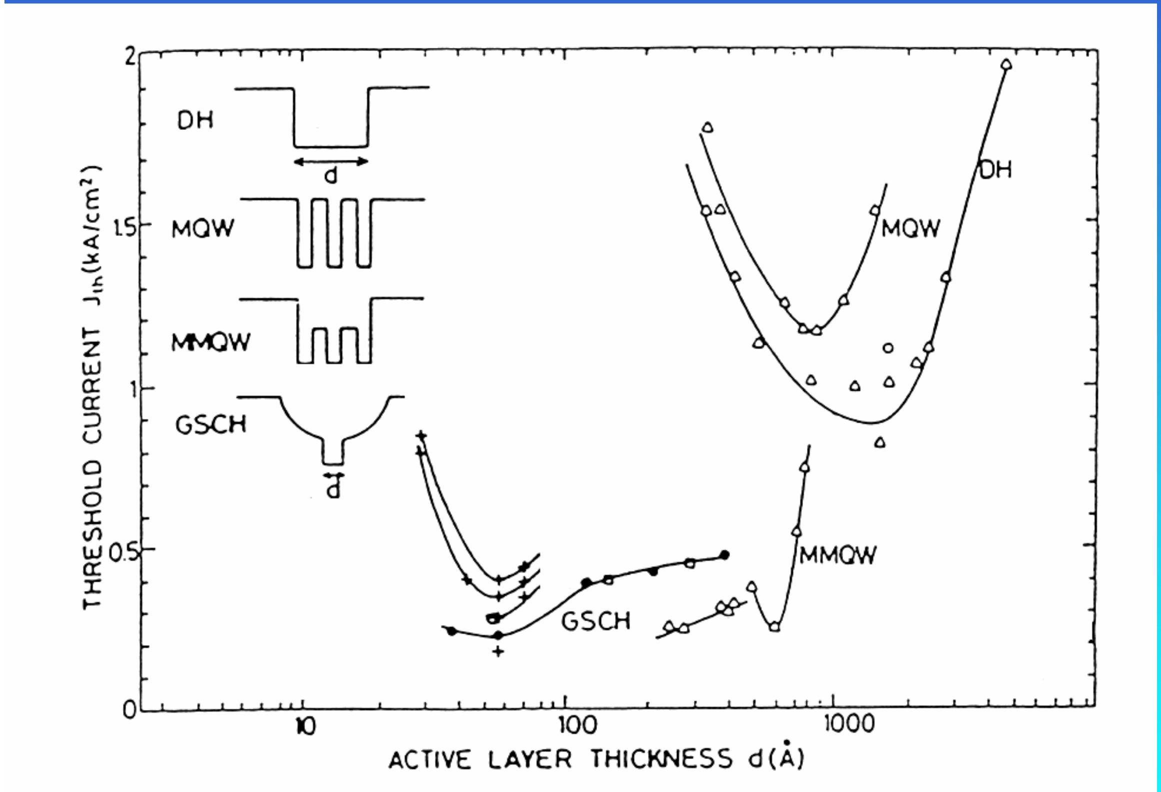
# Two-dimensional density of states

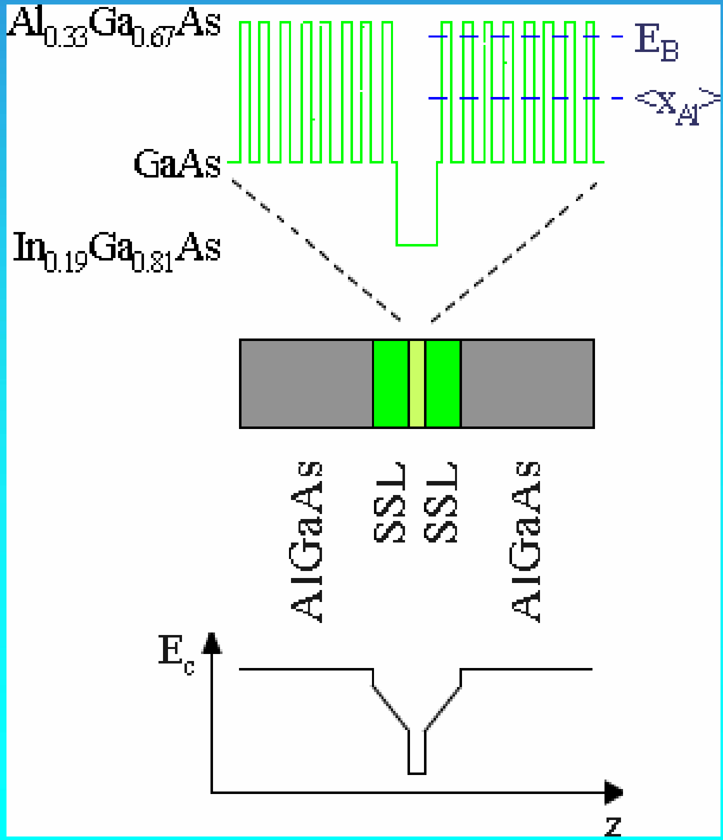
$$E_n = \frac{\pi^2 \hbar^2 n^2}{2m^* w^2} + \frac{\hbar^2 k_x^{\ 2}}{2m^*} + \frac{\hbar^2 k_y^{\ 2}}{2m^*}$$



# Quantum well lasers



# Band structure engineering of a quantum well laser